Climate Protection, Resource Efficiency, and Sustainable Engineering

Transdisciplinary Approaches to Design and Manufacturing Technology
The big societal challenges, such as climate change and public health, call for innovative approaches to address them. The contributors of this book present new ways to tackle these challenges by inter- and transdisciplinary collaborations in light weight engineering. They introduce a framework for transdisciplinary collaboration, explore the potential of light weight engineering in the areas of climate protection, resource efficiency, and sustainable mobility. To do so, they exemplify results and limitations of transdisciplinary collaboration based on three case studies: the optimization of rescue tools, the re-design of products to foster re-use and recycling processes in companies and society, and the additive manufacturing of individualized assistive tools and prostheses.

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For further information:
www.transcript-verlag.de/en/978-3-8376-6377-8
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Introduction

Ilona Horwath, Swetlana Schweizer, Thomas Tröster

“Carried out at the interface of society and science, transdisciplinary research explores and finds solutions for societal problems by making these problems, and the societal actors involved, a central reference point of research and by further developing the scientific research tools it has employed.”

(Bergmann et al., 2012, p. 14)

Increasingly, interdisciplinary and transdisciplinary research and teachings are considered to be crucial approaches for solving complex problems (Gibbs et al., 2018), such as big societal challenges (Wissenschaftsrat, 2015; Riegraf & Berscheid, 2018b). Transdisciplinary research draws on the assumption that effective solutions to complex problems require exchanging knowledge and experience among a diversity of disciplines with stakeholders in both public and private spheres (Gibbs et al., 2018, p. 3). Thus, it aims to produce more socially robust knowledge and to bridge knowledge and practises gaps between science and society (Gibbons & Nowotny, 2001).

Scholars of transdisciplinarity distinguish between two modes of transdisciplinary research. Mode 1: research is practised within the traditional boundaries of scientific disciplines, institutions and epistemologies; it integrates epistemics from different branches of a discipline (Scholz & Steiner, 2015, p. 527). Mode 2 goes further in that it integrates or relates different epistemics from science and practise (Scholz & Steiner, 2015, p. 527). In addition to disciplinary perspectives, standards, validity, and quality, Mode 2 research also assesses the potential social impact of results and solutions (Scholz & Steiner, 2015, p. 530). In order to do so, the inclusion of societal stakeholders and practitioners into the problem definition, the research process and the formulation of results and solutions as well as mutual learning among scientists and practitioners is key for transdisciplinary Mode 2 processes (Scholz & Steiner, 2015). In short, Mode 2 “makes it harder to say where science ends and society begins” (Gibbons & Nowotny, 2001, p. 77). Hence, while
traditional communication between science and the public assumes that there is a one-sided knowledge gap that has to be filled with information (“science to public”), transdisciplinary Mode 2 research is transgressive: “If knowledge is transgressive, then we need to open up the process to the whole range of reverse communication” (Gibbons & Nowotny, 2001, p. 80), that is: public to science. Scholz & Steiner (2015, p. 531) define Mode 2 transdisciplinarity as “(...) a facilitated process of mutual learning between science and society that relates a targeted multidisciplinary or interdisciplinary research process and a multi-stakeholder discourse for developing socially robust orientations about a specific real-world issue (either a problem or a case).”

The quality of transdisciplinary research and results then goes beyond scientific excellence (which, of course, remains one criterion of quality control) in that it should also integrate societal value into the definition of “good science” (Gibbons & Nowotny, 2001, p. 71; Pohl, 2011). It aims to produce not only reliable but also socially more robust knowledge and thus better technological solutions as well. In lightweight design, this touches the question of social acceptance of such technologies and potential future controversies of whether, how and where such methods and materials may be applicable and accepted by the public, and where other approaches may be more sustainable and less harmful to the environment. However, it is important to note that our research group did not use transdisciplinarity as a means to gain acceptance for lightweight methods and materials, though this might be one effect of our work (and a frequent expectation in traditional engineering work environments). Rather, it served to explore the contexts, implications, and limitations for a sustainable use of lightweight design regarding products and processes, and to develop better technical solutions (Gibbons & Nowotny, 2001, p. 79) which meet the needs of society. The results of these endeavours are presented in this book. The first main part introduces the development of our research context, aims, methods and transdisciplinary research strategy. The second part presents our case studies and results. Finally, we assess the scientific and societal outcomes and provide our conclusions in the last chapter.

Research context: Transdisciplinary lightweight design, complexity, and big societal challenges

The approaches, methodological strategies and results presented in the following chapters were elaborated within the research network of the Forschungskolleg “Light-Efficient-Mobile” (FK-LEM). Founded in 2014 (under its previous name “Fortschrittskolleg”), the FK-LEM is a PhD programme for the development of lightweight construction technology, but with a special emphasis on how lightweight design connects to different areas of society, to various societal actors and technology users, and to the needs of a diversity of social groups. During its sec-
second research period 2019-2022, thirteen PhD candidates from the natural sciences, engineering and social science worked on that topic. Thereby, we could draw on lessons learned from a first generation of FK-LEM researchers (2014-2018, see Riegraf & Berscheid [2018a], Berscheid [2019]).

Lightweight design refers to an optimisation of technological solutions, either in a way that reduces the weight of a product while maintaining its full functionality, or in a way that maintains the weight of the product but extends its particular functionality and/or improves its properties (see Lightweight Design in this book). Thus, lightweight design can be considered a strategy to increase the resource efficiency in production processes, and to reduce the energy required for the use of a product. Lightweight design can be used in many areas of application, entailing a vital and creative development of materials, structures, and processes. Currently, a main focus of application is automotive construction. However, proponents and researchers in lightweight design are also looking for new fields of application, and it is an open discussion as well as an empirical question to which degree and in which areas lightweight design can also be considered a (more) sustainable solution compared to conventional approaches – for instance, to supply assisted-living technologies in order to improve the everyday life of humans with specific needs. This raises profound scientific and societal questions regarding the reuse and recycling potential of materials, the efficiency of processes and the consequences for the environment in addition to the economic and social sustainability of particular areas of lightweight application. Against this background, the FK-LEM sought to explore the potential and limitations of sustainable lightweight design as a solution to societal challenges. In order to achieve this, the FK-LEM research and development approach was grounded in transdisciplinarity.

The aim to combine lightweight design with transdisciplinary research is as innovative as it is challenging. Particular challenges regarding transdisciplinary research on lightweight design refer to the complex and multi-layered topics which are difficult to convey to lay people, and to the culture in engineering, trained to focus on technological and economic aspects rather than societal effects. The FK-LEM provided the space and the resources to overcome such traditional limitations and to bring together science and society (Horwath et al., 2018). Traditionally, engineering education is very compact and specialised. Critics claim that it does not encourage students to acknowledge ethical and social responsibilities or public welfare concerns – nor does it provide students with the skills to reflect upon how their work and engineering more generally may influence society and diverse social groups both positively and negatively (Cech, 2014; Cech, 2013). Although lightweight design requires interdisciplinary cooperation between natural sciences and engineering, the contributing disciplines are highly specialised, and disciplinary or topical specialisation entails a fragmentation of thought and action (Neuhauser, 2018).
However, the problem with specialisation and fragmentation of thought and action are also true for sociology, philosophy and cultural studies. In addition, members of these disciplines face the challenge of gaining a basic understanding of lightweight design and engineering, materials and properties, and the complexity of bringing technological and societal issues together. This requires time, continuous involvement, and a preparedness to learn about unfamiliar topics as well as to participate in and contribute to the mutual learning and research process. Social scientific education tends to focus on theoretical expertise; graduates have limited experience regarding empirical research. Their motivation to expand empirical research competence, to participate in the time-consuming interdisciplinary collaboration, and to embark on untraditional pathways with open outcome is further limited by the highly individualistic and competitive academic culture. In addition to the structural underrepresentation of social sciences in the FK-LEM setting (see below, Structural and Cultural Challenges), this meant that the elaboration of social-scientific research dimensions and methods (which are essential for conceptualising and conducting the transdisciplinary research agenda) entailed a significant extra effort from the rest of the team to compensate this lack.

Thus an expectation often posed by funding agencies that transdisciplinarity can simply be “added” as a research dimension within the processes and practices of traditional research approaches is bound to be disappointed. Transdisciplinarity requires professional skills, resources, methods and a willingness and commitment to collaborate and to learn from each other in a culture of openness and mutual respect. A solid research strategy in order to advance the methods, results, and to achieve meaningful transdisciplinarity in lightweight engineering is necessary (see also Berscheid (2018, p. 241)). We could draw on the experience and results of a first generation of transdisciplinary research in lightweight design (Riegraf & Berscheid, 2018a; Berscheid, 2019) in the development of our particular transdisciplinary research strategies and methods.

Lessons learned from the first generation

We started our transdisciplinary work in the second funding period by evaluating the results of the first funding period, or generation of FK-LEM, respectively. Over the course of four years, the research group had established a common understanding of a transdisciplinary research process among the participating disciplines (Riegraf & Berscheid, 2018a; Berscheid, 2019). However, there were some challenges in the process of putting the concept into research practise (for a detailed analysis see Berscheid (2018)).

As Berscheid (2018) describes: The main challenges and obstacles included a high workload for participants who, in addition to their daily workload, should
also perform transdisciplinary research in an attempt to extend and advance their PhD topics by questions of how their work can contribute to solve the so-called “Big Societal Challenges”. Moreover, regular meetings were dominated by organisational tasks and topics rather than scientific exchange and advancement of transdisciplinary research. This was also due to the lack of a methodological framework as a prerequisite to enable advances in transdisciplinary research, and methodological strategies as well as theoretical approaches to integrate the manifold forms of knowledge arising in the process of transdisciplinary work. Finally, to find and gain societal partners in order to build up transdisciplinary research cooperation turned out to be difficult, not in the least due to a certain des-orientation regarding the who, why and how of such collaborations (ibid).

In order to address these obstacles faced by the first generation and to enable a more prosperous interdisciplinary and transdisciplinary research collaboration for the second generation we took the following measures:

- **Introduction of a Research Seminar on interdisciplinary and transdisciplinary collaboration**: The seminar was held fortnightly during each term of the funding period of FK-LEM. It served to introduce participants to the societal, political and scientific background of transdisciplinary research (Riegraf & Berscheid, 2018b; Wissenschaftsrat, 2015; Grunwald, 2015; Schneidewind, 2015; Schneidewind & Singer-Brodowski, 2014; Strohschneider, 2014), to provide insights regarding the philosophy of science (Fleck, 2012; Schiebinger & Schraudner, 2011; Barad, 2007; Haraway, 1988; Harding, 1986) and to elaborate theoretical and epistemic concepts which enable transdisciplinary cooperation (Pohl et al., 2017; Pohl, 2011; Pohl & Hirsch Hadorn, 2008; Pohl et al., 2008; Bergmann et al., 2012; Harding, 2015), and to provide participants with a range of transdisciplinary and social-scientific research methods (and the related methodologies; Rosenthal, 2018; Atteslander, 2010; Kirchhoff et al., 2010; Di Guilo & Defila, 2018) in order to enable the participants’ transdisciplinary ambitions to strive towards successful collaboration with societal partners connected to their PhD topics. The Research Seminar also served to develop three research clusters, where participants worked together on the transdisciplinary elaboration of the topics of climate protection, resource efficiency, and mobility. The assignment to each cluster was based on the particular relationship to the participants’ individual PhD topics. This way, the synergetic development of individual and collective research was enhanced. The seminar proved to provide the appropriate space for discussion, for the elaboration of the transdisciplinary case studies of our research clusters, and for developing common scientific practises, mutual understanding and learning opportunities as well as, to a certain degree, a common identity and orientation as transdisciplinary researchers.
• **Introduction workshop into interdisciplinary writing**: To provide an introduction into interdisciplinary writing techniques and start the wrap-up and writing of the results of the research clusters.

• **Advancement of the concept of the “Thought School” (“Denkschule”)**: The Thought School was introduced by the first generation of FK-LEM to provide a dialogue forum for scientists, societal stakeholders, and industry. Drawing on the Documentary Method (Bohnsack, 2008), we advanced the “Thought School” from a “science to public” event to a format which allows reverse communication – “public to science” - as well, and which could be used as a transdisciplinary research method (Horwath et al., 2018; Horwath & Terhechte, 2018). During the course of FK-LEM, the “Thought School” enhanced our joint problem formulation, the production of new knowledge, and it helped to continuously render our research activities socially relevant and to build up networks and common activities with societal stakeholders such as Fridays4Future and Lippe Zirkulär (a regional consortium to foster and advance circular economy).  

• **Networking activities and active membership**: In order to establish meaningful cooperation with relevant societal organisations during the second funding period, we not only cooperated with societal partners, but several participants of the FK-LEM also became active members of relevant networks themselves. For instance, FK-LEM participants founded Engineers Without Borders Paderborn, acted as firefighters and members of firefighting networks or joined the Lippe Zirkulär consortium. This not only allowed a continuous transdisciplinary collaboration and exchange with societal partners, but also the build-up of new infrastructures for knowledge transfer and engagement.

• **Evaluation of the research results and processes of the first generation**: Drawing on Pohl’s (2011) concept of progress in transdisciplinary research, we evaluated the results and the research progress of – and together with – the first generation of FK-LEM. Pohl defines four areas of progress in the development of transdisciplinary research: to analyse and process issues in a way that (1) grasps the complexity of the issue, (2) takes the diverse perspectives on the issue into account, (3) links abstract and case-specific knowledge and (4) develops descriptive, normative, and practical knowledge that promotes what is perceived to be the common good (Pohl, 2011, p. 620). We found that 12 PhD candidates of the first generation had achieved a common understanding of the complexity of the issues in their PhD theses, the transdisciplinary research topics respectively (1); that they were able to take diverse perspectives on the issues into account (2) and, at least to some degree, managed to link abstract

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1 https://www.lippe-zirkulaer.de/
and case-specific knowledge. However, there was room to improve results on (3) and (4) through the work of the second generation. This was a task, which required advanced methods and skills of transdisciplinary research as well as more time for elaboration. As the aim was to develop the research of the second generation towards advances in (3) and (4), we implemented three research clusters to enable participants to focus on the task. It should be stated that progress on (3) and (4) is only possible through extensive collaboration and time resources. Therefore it is not surprising that the first generation could not achieve comprehensive results in these dimensions as, compared to the second generation, they had to start their research on how lightweight design can contribute solutions to the big societal challenges from scratch. In addition, literature on transdisciplinary methods, learning, research practises and dimensions as well as quality criteria advanced tremendously since the first generation had started its work. Thus, the first generation provided us with a solid base of knowledge and experience (Riegraf & Berscheid, 2018a) to start our work, and the joint evaluation of the results of the first period facilitated the transfer of the most important “lessons learned” to the second generation.

- Lecture series: Another helpful kick-off for our work was the lecture series "Crossing Borders. Inter- and Transdisciplinarity in the Context of Sustainability and Transformation" (Grenzüberschreitungen - Inter- und Transdisziplinarität im Kontext von Nachhaltigkeit und Transformation), which marked the transition from the first to the second generation of FK-LEM researchers in the academic year of 2017/18.

Structural and cultural challenges for interdisciplinary and transdisciplinary collaboration

The structural conception of the FK-LEM posed further challenges to interdisciplinary and transdisciplinary collaboration. There was a major imbalance in the construction of the professional positions of the participating disciplines: the eight participants from engineering got full positions (100%), whereas the three participants from the natural sciences got 75% positions, and the two from sociology, philosophy and cultural studies got 65% positions. In addition, a certain degree of fluctuation amongst participants was to be expected as some only participated at FK-LEM for a couple of months, others longer, in addition to colleagues from science and engineering who participated as associated members but without being employed at the FK-LEM. Hence, we developed a research design based on research clusters responsible for the common topics to strengthen the continuity of the elaboration of our research.

The structural imbalance amongst the participating disciplines implied a quantitative and cultural “dominance” of the engineering disciplines (Berscheid,
2018), while the research questions of the FK-LEM suggested that a major contribution from social scientists was necessary to ensure a successful performance. This might be one reason why it turned out to be extremely difficult to fill the 65% positions (for a critical discussion see also Bahr et al. (2022), pp. 80-81). In an attempt to mitigate the imbalance and to provide the FK-LEM with expertise in interdisciplinary and transdisciplinary methodologies, a junior professorship for technology and diversity in engineering was implemented in 2017 to facilitate the work of FK-LEM.

With regard to the first generation, the structural imbalance also entailed a cultural and epistemic imbalance in that the research logic and strong orientation towards industries and markets prevailed (Berscheid, 2018). For sociologists, such environments can come with expectations or even demands to deliver “socially relevant” results to accompany the work of engineers and contribute to the social acceptance of their products, respectively. In contrast, participants from social and cultural studies tended to focus on their individual PhD topics and were hard to motivate to contribute to the common topics. Thus, the structural imbalance and the narrow disciplinary cultures as well as the dogmatic conventions typical for the organisation of science and research at neoliberal universities had to be overcome in order to enhance substantial interdisciplinary and transdisciplinary collaboration and to create research spaces where innovative thinking could thrive.

A last challenge refers to a meaningful commitment to interdisciplinary and transdisciplinary cooperation aiming to tackle the big societal challenges with lightweight design – a willingness to cooperate is essential, especially from the side of the participating professors (Berscheid, 2018, p. 242). As stated above, the transdisciplinary research dimension requires additional work to the daily tasks and to the work related to the PhD thesis of the participating PhD candidates and supervising professors which not everyone associated with FK-LEM was ready to perform (Berscheid, 2018, p. 243). However, most professors participated actively in the workshops, the Thought School and thus the elaboration of our transdisciplinary research; in addition, the work within our research clusters, particularly during the Research Seminar, fostered a culture of collaboration and identification with the transdisciplinary goals of FK-LEM among most of our PhD candidates. It provided the space to develop our own research community and culture of transdisciplinary cooperation, similar to what Klein (2018, p. 18) describes as a “Transdisciplinary Orientation in Team Science”, a “(...) synergistic combination of values, attitudes, beliefs, skills, knowledge, and behaviours that predisposes individuals to collaboration. They promote team participation marked by willingness to learn about unfamiliar theories and methods and to adjust individual disciplinary schema to fit the demands of teamwork” (Klein 2018, p. 13).
A Model and a strategy for transdisciplinary research in lightweight design

The ISOE Model of Transdisciplinary Research (Bergmann et al., 2012, Jahn et al. 2012, see Figure 1) served to illustrate the general idea of a transdisciplinary research strategy, and our work draws strongly on the integrative approach of transdisciplinary research. It defines transdisciplinary research as

“(…) a reflexive research approach that addresses societal problems by means of interdisciplinary collaboration as well as the collaboration between researchers and extra-scientific actors: its aim is to enable mutual learning processes between science and society: integration is the main cognitive challenge of the research process” (Jahn et al., 2012, p. 4).

Figure 1: ISOE Model of Transdisciplinary Research (Bergmann et al., 2012, p. 35)

An integrative approach to transdisciplinary research means to pursue two epistemic paths simultaneously: first, the real-world approach defining real-world problems, often with practitioners and experts in the fields; the research goal here is to produce knowledge that can be used to solve a practical problem (Bergmann et al., 2012, p. 32f). Second, the science-focused approach addresses complex internal scientific issues (which can be part of an overarching real-world problem), not the least of which problems are those which arise during the research process; here the goal is to improve scientific research and results, and/or to define new
research needs (Bergmann et al., 2012, p. 33). As the integrative approach to transdisciplinary research implies

“(…) striving for research results serving two totally different purposes, it is particularly important to come up with a careful design of the concept at the very beginning of a research project” (Bergmann et al., 2012, p. 35f).

The design of our concept was realised continuously within a series of formats. The Thought School as a public dialogue forum served to examine the complexity of the issues, to capture diverse perspectives and descriptions of real-world problems, and to analyse values and practical knowledge that promote what is perceived to be the common good in our areas of concern (for a detailed description of the methodology and results of this approach see Horwath et al. (2018), Horwath & Terhechte (2018)). The second and internal part of the Thought School served the FK-LEM research group to integrate these results, identify gaps in knowledge and methods, and revise the research concept iteratively. The theories and methods required were then provided and applied in the Research Seminar. Finally, the Thought School also served as a continuous forum of dialogue between FK-LEM scientists and the public and to fill specific knowledge gaps on sustainable mobility through public expert workshops (Thought School 2018), particular materials and sustainable and responsible engineering (Thought School 2019). Importantly, the Thought School also entailed opportunities to respond to societal needs in a more immediate fashion than research processes would allow; for instance, we provided a workshop on the reflection of social privilege for members of Fridays4Future and developed and promoted a catalogue of requirements together in order to move Paderborn University towards a sustainable, CO₂-neutral University. In addition to the Thought School, science cafés for pupils were also provided. This was a format to promote exchange with young potential future scientists and to provide insights into the work of FK-LEM, which required us to present our research topics in an accessible manner and through “hands-on” exercises. A further format, the PhD colloquium, focused on the discussion and advancement of the individual PhD topics in FK-LEM in terms of disciplinary perspectives and quality criteria.

The first phase of a transdisciplinary research process consists of the formation of a common research object derived from societal and scientific problems. In transdisciplinary research, problems are formulated from the very beginning within a dialogue among a large number of different actors and their perspectives (Gibbons & Nowotny, 2001, p. 69). Against this backdrop, transdisciplinary research coined the term “problem transformation”, which means that both aspects, the contribution to practical problem solutions for actors and to scientific progress, are understood as essential parts of the research dynamic (Becker & Jahn, 2006, p. 290, in: Bergmann et al. 2012, p. 42). In other words, a societal and a sci-
Scientific problem are linked to form a common research object (Jahn et al., 2012), the so-called boundary object. Boundary objects are then “transformed into epistemic objects by means of developing or applying theories or concepts”, and epistemic objects are the basis from which research questions are derived (Jahn et al. 2012, p. 5). The process of problem transformation proved to be one of intense collaboration both with societal partners and within the research communities and supported the process of team formation for our three research clusters.

Once a problem description and the formulation of the research questions have been accomplished, the second phase is to plan the research concept, including the design of the integration, which requires a consideration of which actors must work together, when and how (Bergmann et al., 2012, p. 40). In this phase, the production of new knowledge is crucial, which we understood and realised as “an interplay of specialized work in subteams (e.g. including both researchers and extra-scientific actors) and dedicated stages of integration of the epistemologically pluralistic [...] outcomes of the work” (Jahn et al., 2012, p. 5).

Transdisciplinarity focusing on societal problems mainly aims at producing three types of knowledge: system knowledge (the knowledge involved in the understanding of an issue); orientation knowledge (required for determining the possibilities and boundaries of decision-making); and transformation knowledge (knowledge of the ways and means of practically realising such decisions). However, a diversity of knowledge including practical experience has to be integrated in order to gain transdisciplinary results (Jahn et al., 2012, p. 8).

The requirement for integration work is shown in the middle column of Figure 1. According to Bergmann et al. (2012, p. 43), the integration work needs to combine both the practical path aimed at action to solve societal problems and the scientific path aimed at producing new theoretical and empirical knowledge. With regard to the broad yet highly specialised nature of interdisciplinarity related to FK-LEM research, the integration of social and natural science was additionally challenging, not because of “cultural differences” but because of the heterogeneity of the knowledge bases. Hence, we had to take into account that a technologically reasonable solution can usually be found – but that the question remains as to whether the solution is also reasonable according to criteria such as practicability, social acceptability or sustainability. Technologies that do not comply with the structures, practises and values in the particular societal field of application may not be accepted and used whereas a societally desirable solution might come with restrictions and constraints related to technology or natural sciences (Bergmann et al., 2012, p. 46).

To address these issues, we designed a “circular” or – a term more familiar for engineers – an “iterative” approach to knowledge production and integration,
which facilitated a reflective monitoring of the research process and helped to maintain close ties between scientific and societal problem descriptions throughout the whole research process (Jahn et al., 2012). A reflexive approach “proactively considers the dynamics, interests and concerns, roles and responsibilities, the collaboration culture within a project, and the connectivity to the context of action addressed” (Lux et al., 2019, p. 183).

This process is very time-consuming and could only be realised through continuous and engaged collaboration of FK-LEM researchers within the various formats developed for the second generation of FK-LEM, in particular the Research Seminar, where the production of new knowledge (in collaboration with the societal partners) could unfold under constant (peer) reflection and revision of the societal and scientific dimensions of our epistemic objects and the related research activities.

The third and last phase of the transdisciplinary research process is the transdisciplinary integration of results. Transdisciplinary integration can be understood as a form of assessment of the integrated results, asking for their possible contribution to both societal (validity and relevance for the original global issue) and scientific progress (new insights within and beyond disciplines). Assessment procedures can involve mutual critique among all process participants, to examine what is the “added value”, an assembly of products for science and society, or to measure the impact of the project on the societal and scientific discourses. It also includes a targeted or non-targeted knowledge transfer by both scientists and societal actors (Jahn et al., 2012, p. 7).

It should be mentioned that due to the diverse nature of the epistemic objects derived and elaborated within our research clusters, and due to the consequential variety of knowledge gaps to be closed and methods to be applied in order to do so, as well as the following differences in time scales and schedules of the cluster projects, we did not (yet) conduct a comprehensive evaluation of the second generation of FK-LEM. At the time of writing this book, one cluster concerned with Re-Use and Recycling (Re-Use and Recycling Cluster) had gone through the whole cycle of (an ideal) transdisciplinary research process, including the evaluation of the collaboration process and the critical assessment of results. The research cluster on Emergency and Rescue Equipment for First Responders (Rescue Cluster), in contrast, had already generated a myriad of new empirical knowledge but was still occupied with the integration of this knowledge and the transformation into new prototypes of rescue tools, i.e., the construction of demonstrators. The cluster on additive manufacturing of medical devices (Medicine Cluster), with its great possibilities to respond to the demands of societal members in a very immediate way – at least as far as the mere production of 3D printed assistive technologies is concerned – focused on doing exactly that, thereby examining the legal
requirements and technological challenges related to their collaborative activities systematically.

Compared to the ideal-typical model of a transdisciplinary research process, in a research practise which draws on an iterative research design, the ideal phases and the production and integration of both disciplinary and transdisciplinary knowledge are much more interwoven. In addition, the intensity and the role of the involvement of societal partners in transdisciplinary projects can differ, as the type of involvement depends on the particular problem, the specific lack of knowledge and the agreement on knowledge and values (Jahn et al., 2012, p. 8).

The societal impact is hard to measure as it can contain short term and long term effects, depends on framework conditions, the historicity (of the problem), the heterogeneity of actors, the general environment, the funding conditions (Lux et al., 2019, p. 185). The framework conditions in which transdisciplinary research processes are embedded are of high relevance in fostering or hindering the societal effectiveness of transdisciplinary research (Lux et al., 2019, see also Lam et al. 2021).

**Formation of a common research object**

**a) Big societal challenges**

“Big Societal Challenges” refers to a complex of problems which are reflected in politics, science policy and governance (e.g. Wissenschaftsrat, 2015; European Union, n.d.). The solutions we, as scientists and members of society, develop in order to tackle the “Big Societal Challenges” will crucially determine not only the quality of life of future generations but also the habitability of the planet in general. Science policy calls for a transformation of these pressing societal challenges into research topics and questions and thereby promotes a transformation of the role of science in society. The goal is that by the joint forces of scientists and practitioners in order to address the challenges, innovative scientific, technological as well as social solutions can be found and implemented. This way, science is expected to contribute to “the common good” (Wissenschaftsrat, 2015). However, what that “common good” actually is or should be, in particular from the perspective of a multitude of participants in transdisciplinary research and development processes, is an empirical question involving ecological, economic, technological and social dimensions (see below for the empirical results from our workshops).

In North Rhine-Westphalia (NRW), where our research took place, the „Forschungsstrategie Fortschritt NRW“ (MIWF, 2013) focused on the following challenges:

- Climate protection
- Resource efficiency and raw materials
- Secure, clean and efficient energy
- Food security, sustainable agriculture
- Smart, green and integrated transport
- Health, demographic change and wellbeing
- Participation, inclusive, innovative and reflective societies in a changing world

A series of projects, regional networks and funding opportunities were implemented to set up an infrastructure and processes to tackle the challenges (MIWF, 2013). The FK-LEM is one of these projects. In addition to taking up research questions and providing technological and scientific approaches to solutions, we also aimed to contribute by educating a new generation of engineers equipped with professional competence and experience in interdisciplinary and transdisciplinary sustainability research.

Against this backdrop, the areas of climate protection, resource efficiency, and mobility were predefined as the main fields of activity in the FK-LEM research design (see Figure 2). Thought School and Research Seminar served to refine the research programme iteratively based on systematic exchange with the public and practitioners specialised in the relevant areas, occupations, and professions.

Of immense value, the research design for the second generation was designed in the transition period from the first to the second generation FK-LEM. Even though some challenges for teamwork arose through the fluctuation, the

*Figure 2: Spheres of activity (Handlungsfelder) and research cluster: general research framework*
transition period still permitted us to involve the insights, findings, experience, and advice of the former FK-LEM participants.

From the general question of how to apply lightweight design “for the common good” in the predefined areas of action, we derived specific, empirically grounded research topics.

As a first step, we invited the interested public to discuss perceived urgencies and related problems in the three areas from the perspective of practitioners at the Thought School. In 2017, the public forum of the Thought School focused on climate protection and the workshops, where problem formation took place, addressed the societal areas of rescue and security services, medical care, mobility and assisted living, and sustainable resources and climate protection (for a detailed description of the methodology and results of the workshops see Horwath et al. (2018), Horwath & Terhechte (2018)).

To dismantle barriers of lay people regarding their participation in transdisciplinary exchange with engineers and scientists, we applied the principles of openness and communication (Bohnsack, 2008; Rosenthal, 2018) deduced from the requirements and quality criteria established in qualitative research methodology, which we transferred to our particular workshop settings as follows: we addressed participants as experts in their area of practise and experience, pointed out that their experience and expertise are crucial for scientists to fully comprehend the problem and that science or technology skills are not necessary to make meaningful contributions to the workshops discussion. In addition, through the appreciative moderation of the discussions we ensured an open, respectful and non-hierarchical discussion climate. To encourage and structure the discussions, we asked three basic questions in each workshop:

1. What are the biggest challenges you currently perceive in your professional field?
2. What would good solutions to these problems look like?
3. What could science and engineering contribute to solve these problems?

b) Rescue and security services

At the Rescue and Security Workshop, ten participants from rescue and security organisations, i.e. fire service, medical emergency service, and from research institutions attended. The main challenges they discussed were related to the rescue of people, i.e. the location and exploration of areas, rescue and transport of vic-

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2 The following section sums up empirical findings and results presented in Horwath et al. 2018. In favour of the readability of sections a) to e) we refrain from pointing out identical wording as direct quotes. Instead, we aim to state here that the main content of section a) to e) can also be found in more detail in Horwath et al. 2018.
tims from collapsed buildings, natural disasters, and – most frequently – transport of adipose people or victims of car accidents.

Participants described the main challenge of such scenarios in keeping the required rescue time short: victims have to be located and provided with first aid, have to be stabilised and kept alive, and they have to get prepared for the transport from a site of accident or disaster. Ironically, the issue of the rescue time is also caused by advances in vehicle engineering and the construction of cars such as improved material strength or a myriad of electronic features, which increase the time required to reach victims of car accidents (see Case Study III). As a consequence, complex rescue strategies have to be performed, tailored to the particular on-site conditions and the technologies that are available and can be applied in the particular environment. Thereby, first responders have to proceed with great caution and care in order to avoid putting victims, members of the rescue teams or the public at any further risk. Another challenge participants discussed was the weight of the rescue equipment itself. Paradoxically, despite significant technical progress and new options available through lightweight technologies, rescue tools and vehicles tend to become even heavier. For instance, in many cases a fully equipped fire truck actually exceeds its legally permitted weight limits.

Discussing solutions, participants perceived that lightweight technologies could contribute to develop lighter rescue equipment and optimise tools and vehicles for rescue and emergency operations. However, reflecting on the above-mentioned paradoxical situation and the fact that technological advancement always entails new challenges or downsides, they also pointed out that lighter and optimised technologies may not necessarily lead to better solutions for rescue services. Importantly, responding to emergencies or disasters and the rescue of those affected requires rescue teams to perform an integration of organisational, technological, medical, and other procedures necessary to achieve their tasks. Hence, the development of rescue and security technologies has to take the complexity of such processes into account in order to develop applicable solutions. Specifically, in the case of firefighters (and technological rescue services), any approaches to optimise tools have to take the significance of a frequent “misuse” of tools into account: As each rescue scenario poses different challenges, firefighters need to be creative and often use the available tools in ways that quite diverge from their originally intended functions (Hanses & Horwath, 2021; Hanses & Horwath, 2022, Hanses et al., 2020); for a general discussion of how tools and their use relate to gender and diversity in firefighting organisations see also Horwath (2013), Horwath et al. (2021a), Horwath et al. (2021b), Kastein et al. (2022); for insights into the intimate but also gendered relationship between firefighters and their tools see Harrison & Olofsson (2016).

To address these issues, two (then) associated FK-LEM members explored the potential of lightweight design for firefighting and rescue technology under
consideration of important practises of “misuse” (Neuser, 2019), and the potential to optimise tools and practises for the case of rescue scenarios in car accidents (Hanses, 2019). Therefore, both candidates were trained and supported to apply expert interviews and participant observation. Thus, empirical findings on user practises enriched their technological and material analysis. As a result, we were able to identify a range of tools with a high potential to be optimised in line with the practical experience, needs and requirements of practitioners in the field. In a later research phase, the transfer of expert knowledge for the optimisation of firefighting rescue tools was also supported by the master thesis of the associated FK-LEM member Kathiri (2022).

However, participants also researched creative solutions in our workshop. Regarding the question of how to reduce rescue time, one antagonist in the struggle against time that first responders face is the prevalence of ever more complex materials and structures in the design of modern cars, which ironically often serve the purpose of making the vehicle safer (see Case Study III). In order to tackle this problem, the participants discussed the implementation of predetermined and standardised “breaking points” in the construction of new cars: “Optimised for a quick rescue”, a “breaking point” would allow first responders to open cars more easily, e.g. by lifting the roof. A standardisation of predetermined “breaking points” independent of particular car models, companies or branches was seen as a potential path to ensure that first responders can start their operation quickly. Another suggestion was to extend standard crash tests by developing and including indicators for rescue features and test results on rescue time for frequent rescue scenarios. Finally, participants stressed that new evaluation systems should be designed to promote such rescue features in cars, i.e. data which help to assess additional costs of such features but also to explain their potentially lifesaving value.

Reflecting on challenges related to international disaster control, participants encouraged the development of a further innovation: lightweight rescue tools for lay people. In the face of catastrophic events, increasingly due to the effects of climate change, the involvement of lay people and untrained volunteers can be crucial to saving lives. Therefore, rescue tools that are lightweight enough to facilitate easy transport and simple enough to enable lay people to handle them safely would be of immense value. The availability of such tools would allow people who are affected and volunteers to rescue themselves and others.

Participants made several suggestions on how research and development should contribute to solving the discussed challenges: vehicle engineers, some claimed, should actively promote rescue features, extend crash test scenarios and elaborate on new rescue-related safety standards. They should actively promote the use of lighter and safer materials for the construction of cars, and get actively involved so as to change standardised priorities of the vehicle industry and mar-
keting, i.e. push for the establishment of new standards, norms and marketing concepts regarding material and structure-related rescue and safety features. Concerning rescue and safety equipment more generally, participants concluded that for any new solution to be practicable and potentially established within rescue and security organisations, it has to match the complexity of emergency realities and facilitate emergency rescue strategies. Consequently, the optimisation of rescue tools by means of lightweight design in the FK-LEM research cluster started with an empirical analysis of organisational contexts, practical demands and experience with particular rescue scenarios and tools. Based on the results, crucial criteria to link practical, functional and technological improvements for a safe performance could be identified and addressed.

c) Nursing care, mobility, and assisted living

At the workshop dedicated to nursing care, mobility & assisted living, fourteen participants from public and private care homes, various health institutions, hospitals, medical technology companies, civil society and people with care needs attended.

Against the background of the demographic development towards an aging society, the major challenge perceived by practitioners was how to provide increasing numbers of people with sufficient care facilities and services. Ideally, “people should be provided with as much technology as necessary – but not necessarily more technology than actually required” (participant, public health institution) in order to enable them to live as independently as possible within their chosen social and/or family environment. Practitioners criticised the current trend to compromise elderly or disabled people’s autonomy by sending them to care homes instead of prioritising options for a more autonomous assisted living. Assisting technologies could change such practices and support the normative establishment of a care-at-home-priority. However, assisting technologies come with further challenges.

Smart assisting technologies, for instance, hold a huge potential to enhance the freedom and autonomy of individuals in need of care and assistance – but also for surveillance, control, and violation of privacy. For a detailed analysis of the fundamental change of the priorities guiding privacy policies of assisted care settings see also Zuboff (2019). She describes the shift from the initial principle that the rights to access and use the data created in such environments belong exclusively to the people who live in the house, and should serve exclusively to improve their own lives. This principle has been reflected in early assisted living concepts, such as the famous Georgia Tech “Aware Home” from the year 2000. However, two decades later the now exploding market for smart homes, devices and data extraction in the U.S. has fundamentally limited data scarcity and privacy protecting approaches to assisting technologies (Zuboff, 2019, 5-7; Zuboff, 2019, 233-234; Zuboff, 2019, 246).
lack of trustworthiness of technologies and their providers. Another problem causing barriers to the acceptance of new technologies is limited technological affinity and understanding on the side of potential users, resulting in a lack of confidence or motivation with respect to becoming skilled enough to learn how to use assisting technologies efficiently. Workshop participants cautioned that social acceptance and practical applicability of highly effective technologies in care contexts cannot be taken for granted, even if these technologies would bring about a great degree of improvement to people’s daily lives.

Some participants suggested that certain gaps between existing technologies and their social acceptance, desirability and applicability are also related to prevailing funding terms and to typical procedures of research and development in engineering: funding policies tend to foster research practices which focus on highly specialised topics and deal with abstract problem definitions. As a consequence, the process of technology development unfolds rather isolated from the social contexts, needs and practical expectations of future users. Instead of analysing the particular social preconditions and how they can be used to improve both technology and its social embedding in the user context, engineers are expected to focus on the production of new technology in terms of models or prototypes. Usually, funding for technological research does not allow for an exhaustive analysis of social environments, user’s needs, for comprehensive usability tests, or the development of socio-technological strategies for the transfer of assisting technologies into living environments.

In stark contrast, practitioners stressed the importance of acknowledging individuals and their particular needs as the appropriate starting point for a definition of the requirements for socially sustainable assisting and care technologies. Even though the effort to analyse such needs may be challenging for all people involved – researchers, engineers, elderly and/or disabled persons as well as their caregivers – the process was considered crucial to determine “which support is really needed, and (how) could it be realised by technological means” (participant, caregiver). Eventually, the results of a thorough analysis would justify the investment as they allow for the construction of socially relevant and suitable technologies. The example of an individualised cutlery set (Hemme, 2018) and substantial previous work from Schramm et al. (2017, 2018) served to highlight the potential of lightweight solutions and additive manufacturing designed from individual needs.

However, in the experience of our workshop participants, effective norms, laws and standards often undermine their aims to exhaust the enormous potential of additive manufacturing to provide individualised assisted living solutions swiftly. Although the current state of 3D printing technologies allows engineers to produce various artefacts or products at relatively low cost and effort, the inherent risk is their legal liability for such devices. Producers of such 3D items can be held accountable for any damage potentially related to their technology,
i.e. accidents or defective materials. While norms and standards are recognised as important means to make technologies safe, participants find it increasingly challenging to deal with areas where (legal) standards lag behind technological advancement. As a consequence, many existing technologies for assisted living, care and mobility cannot be provided to those who would benefit immediately; instead they remain what participants called “drawer solutions” or “technologies for the drawer”, respectively.

Public health institutions and private insurance companies play a crucial role in the development and transfer of assisting technologies. Individuals in need of assistance have to apply for support in official procedures, and public health institutions have the power to allow or refuse these applications for assistance regarding both technological assistance and human assistance by a caregiver. For each case, they grant permission and financial support or deny them. Practitioners heavily criticised the quality and length of the administrative procedures to assess care needs and to authorise entitlement to receive the assisting technology. Public health institutions as cost objectives also decide on the materials and standard components used for the production of assisting technologies, such as wheelchairs, for instance. Hence, institutional decisions determine the potential as well as the limits and the quality of assisting and care technologies to a large degree – sometimes with severe consequences for the people affected.

Conflicting values and competing norms have also been pointed out as a further challenge. Various disadvantaged social groups, their needs as well as their legitimate values and social norms are perceived to be played off against each other, for instance the needs related to individual mobility of disabled people vs. the requirements of fire protection norms, privacy vs. mobility needs related to the use of smart wheelchairs, cheap materials to provide more people with assisting technologies vs. exploitation of humans and resources in globalised production chains culminated in the metaphor of “wheelchairs made by children’s hands” (participant).

Regarding solutions, participants stressed the need to improve transparency, exchange of information, technology transfer, administrative procedures, education, and awareness of professionals. Solutions to improve technology transfer should include changes of funding policies in a way that would enable researchers to take future application contexts, individual needs, and issues of technology transfer into account. Participants emphasised that such requirements should be promoted as important dimensions of care and assisting technology development if transfer and applicability are to be successful. In addition, case studies to focus on the topic of technology transfer into care contexts would be helpful in order to design effective strategies. Another approach to enhance transferability of technological innovations was to form syndicates for technology development involving researchers, cost objectives, stakeholders, civil society, and engineers. This way “drawer solutions” could be avoided by a collaborative development and
decision-making based on the consolidation of relevant proficiencies and responsibilities.

Generally, participants described a lack of transparency regarding the range of currently available technologies and trends in technological development. Although a myriad of information on care and assisting technologies can be found online, user-friendly, understandable explanations that include assessment of risks and benefit or details on availability are hard to find. Hence, participants suggested the creation of specific information platforms for the people affected. This way, their particular questions, interests and needs could be better addressed. Participants also suggested that more “objective” information on assisting technologies should be provided. By objective, they referred to information independent of the specific interests and corporate perspectives of technology providers, companies, and health institutions.

Practitioners urgently called for measures to improve the administrative procedures and current practises of health institutions that serve to assess the care needs of individuals. Significantly, they point out that changes also need to be made within the educational systems of health care professionals and engineers of assisting technologies. In the opinion of our participants, health care professionals and engineers should be trained in a way that would enable them to critically reflect on the impact of the decisions they make concerning assisting technology, be it the decision on applications to receive assistance, or a decision on which materials to use, or a decision on the data policy of smart assisting items.

Participants see the path to advance the (social) acceptability of assisting technologies in an open dialogue among stakeholders. Such a dialogue should also address the ambiguities inherent to technologies and take the concerns of users and caregivers seriously. Ambiguities of smart technologies, i.e. autonomy vs. coercion and surveillance, are important issues as elderly and disabled people are particularly vulnerable to privacy violations and patronising treatment. Hence, ambiguities as well as the above competing needs and values should be actively reflected upon, balanced, and dealt with. Such aspects – ambiguity and values – should also form part of standard information on technology for lay people as a basic understanding of how a technology works and transparency provided on related risks contribute to create trust and acceptance.

Participants expected researchers and developers to get involved in the establishment of a continuous open dialogue, to pay attention to concerns related to the ambiguities of technologies, and to provide understandable and transparent information on care and assisting technologies.

Importantly, researchers and developers should be accountable to members of civil society, receptive to their criticism and concerns, and reflective on the social dimensions and impact of technologies. To achieve this, participants considered interdisciplinary and transdisciplinary research essential to grasp the complexity
of care and assisting technologies within their particular social and institutional contexts of application.

d) Sustainable resources & climate protection

Twenty participants from a variety of public and private institutions, politics, civil society, and industry attended the workshop Sustainable Resources & Climate Protection. Climate protection and progress toward sustainable resources require changes in individual behaviour that often appear inconvenient. Accordingly, participants started by discussing the challenge of how to gain broader acceptance for sustainable behaviours and technologies. However, they also pointed out that sustainability is not only a question of (dis)comfort but also of social class – not everyone is able to afford new technologies or behavioural changes.

The second challenge was described as a “competition of materials”, where more often costs and economic interests rather than the best or most sustainable material available to solve a given problem determine whether materials are used and standardised. Once established, norms and standards in turn determine which materials prevail in engineering and construction. As effective standards and norms tend to favour conventional materials and practises, new approaches are difficult to establish, and innovative engineers have to make greater efforts to ensure their competitiveness.

In the private sector, insecure market developments resulting in high development pressure were perceived as another major challenge. For example, the future of mobility could take several directions as various trends concerning materials, energy and construction can be observed in different markets. Companies respond with high investments in order to be prepared for changes in unknown directions. Such practises result in a huge waste of resources for research and development with potentially no outcome or progress toward environment protection. Hence, participants raised questions about responsibility.

Related to the challenge of how to bring about change, the question of responsibility was perceived as a major challenge. “Market rules”, “customers”, “providers/engineers” and “politics” appeared to be entangled in a way that each group assigned “responsibility” for changes to the other group, thus inhibiting progress and improvements.

Yet, even where commitment to sustainability and climate protection existed, participants still found it challenging to decide what sustainability actually is. For instance, the lightweight construction industry uses and creates a variety of materials to reduce the weight of conventional products in order to save energy. But little is known about decomposition and recycling possibilities of such combined materials. Generally, participants criticised a lack of transparent evaluations and specifically evaluations that cover the whole life cycle and all components of a particular technology or product.
Finally, participants discussed a perceived change that technologies that are prevalent in everyday life, such as washing machines, were designed to last for as long as possible in former decades, whereas today opportunities for updates or replacement through advanced models are guiding principles.

Participants suggested a number of approaches for solutions. The trend to short life cycles should be addressed by new combinations of re-use and recycling models.

To bring about meaningful changes for climate protection and resource efficiency, solutions and areas “where small changes have huge effects” (participant, public service) must be identified and promoted. Such areas are not only found in everyday practices, but also in agricultural and industrial processes. The increasing availability of suitable technologies, such as e-bikes, may help to boost sustainable behaviour. In addition, new business models need to be developed and promoted in order to demonstrate that sustainability and economic success are not mutually exclusive. Consequently, new sales and marketing strategies should be implemented to generate awareness for actual product costs as opposed to the market price, i.e. the costs of a product drawing on the whole life cycle from resource mining to decomposition. Awareness and comparability of market prices and the actual costs which individuals and society have to pay for a product or technology may make sustainable products more attractive for costumers.

Finally, participants called for politics to take responsibility for future generations. Strategies need to be implemented top down (by laws and incentives) as well as bottom up (by engineer's attitudes and decisions). Importantly, politics should also draw on current trends to foster sustainable practices instead of forcing solutions which may not be practicable, i.e. reinforce current trends to use public transport instead of individual mobility with cars.

To achieve the outlined solutions, participants made the following suggestions about what research and development could contribute: researchers should be encouraged to keep the “the bigger picture” in mind. In a profession characterised by highly specialised expert profiles and research topics, it is easier to lose the social and ecological embedding and consequences of technologies; they become out of sight. Participants called for research and development to actively create that “bigger picture” by reflecting on the social impact of engineering topics, strategies, and practices. According to the participants, a systematic reflection should take place routinely at the beginning of every research project. Also, researchers were prompted not to hide behind catch phrases like “the costumers’ expectation and needs” to legitimate decisions in engineering processes. Rather, they were expected to critically reflect and question such assumptions and arguments, as “expectations and needs” are socially constructed, and they are heterogeneous among diverse social groups.

A topic intensely discussed was education for sustainability. Here, more basic research is needed to develop technologies in line with social values instead of in-
sisting on a dubious “market orientation” as the guiding norm. Sustainability issues and social values need to be included in education as well as in the training of engineers in order to create a generation of engineers that is professionally capable of reflecting on social and ecological values and developing technologies from there.

Researchers should acknowledge the need for transparency and information and develop new concepts to illustrate the complexity of production and life cycles. There was a strong need for scientific models to demonstrate that and how sustainability and economic success are not mutually exclusive. The promotion of such models should not only motivate individuals but also create incentives for companies to apply them. Finally, participants argued for the development of new combined recycling and re-use strategies: the life cycle of some products could be extended by designs that allow broken components to be fixed; products designed to be updated or to have a short life cycle should be re-usable, at least their particular components if recycling of the whole product is not possible. Therefore, norms and standards for elements and for groups of components to be re-used in further products (by customers or companies) need to be implemented.

e) General Conclusions

In addition to the empirical findings and the problem descriptions from the societal areas of interest, the methodology developed for the Thought School 2017 also enabled us to derive some general conclusions for our transdisciplinary work, in particular from the discussion about societies’ expectations and needs with respect to sustainable and responsible science and engineering:

- The need for transparency and exchange of information between science and society
- The need for new models and strategies
- The need to respond to challenges resulting from complex and competing norms and values, and to reflect upon the impact for the social groups affected
- The need to recognise the ambiguity inherent to technologies and to find strategies to deal with it
- The need to take responsibility and act on that base – also in science and engineering

Thus, we could take a variety of interests, needs and value orientations from different societal and scientific actors into account and formulate our research questions and strategies accordingly. Didactically, we found that the intense discussion with a variety of actors and exchange of various forms of knowledge, of experience, ideas and practices, the process of documenting and analysing the discussions, and reflection upon results and implications for engineering during the internal workshop of the Thought School enabled our PhD candidates and the participating FK-LEM profes-
sors to gain deep insights with respect to the complex entanglement of apparently abstract engineering topics with social welfare and justice (Horwath et al., 2018).

The results in terms of research and development approaches as well as research partners and networks served as a base to advance the establishment of sustainable mobility initiatives at the Faculty of Engineering. The Thought School proved to be of immense importance for the development of a common problem definition and supported us in finding research partners and strengthening the transdisciplinary network. With the progress of our research, the Thought School not only served to exchange ideas with the public but increasingly created a framework for the production of new knowledge and the establishment and institutionalisation of new topics. For instance, the Thought School 2018 was dedicated to “New Approaches for Sustainable Mobility”, providing a keynote and three workshops on “Transdisciplinary Mobility Projects”, “Mobility Support through Additive Manufacturing” and “Sustainable Mobility and the Reduction of CO$_2$-Emissions”. The discussion of a variety of innovative approaches to sustainable mobility, in particular with various external partners like the Wissenschaftszentrum Berlin für Sozialforschung (WZB), inspired the development of further research and development initiatives, such as “NeMo Paderborn – Neue Mobilität, die verbindet” (https://nemo-paderborn.de/). In addition, newly designed projects at the Faculty of Mechanical Engineering, such as HyOpt – Optimierungs- basierte Entwicklung von Hybridwerkstoffen (NW-2-2-008a), started to include comprehensive interdisciplinary research not only on acceptance of hybrid materials among various stakeholder groups but also on the influence of societal and economic conditions on the establishment of specific norms of construction and materials in automotive design (see also Triebus et al., 2022). Another example is the new Re2Pli project, which is about establishing a sustainable production process for lightweight components using only renewable energies. Our work at the FK-LEM also sparked a successful constitution of further initiatives, i.e. Engineers without Borders Paderborn, the elaboration of a data base on re-use and recycling materials as a teaching resource for lecturers of our faculty, or the newly established emphasis on responsible and sustainable engineering, including lectures and the focus of development of the faculty itself. However, it should be mentioned that the rise of the climate protection movement was an unexpected external force which helped to legitimate and boost the faculties’ engagement with more sustainable approaches to engineering, materials and design.

In 2019, the Thought School focused on “Sustainable and Responsible Engineering”. In close cooperation with members of the Fridays4Future movement, we developed a list of demands for a sustainable Paderborn University. The list of demands was presented at the Thought School where we also discussed how climate protection could be put into practise within our everyday work environments. After the public discussion, we handed the list over to the Executive Board of Paderborn University. In addition, we also provided a workshop for members (pupils,
parents, teachers) of the Fridays4Future movement to reflect on privilege and how it enables or hampers active commitment, participation, and societal change.

Production of new knowledge

As a next step, within the FK-LEM research team, the internal part of the Thought School served to integrate results from the workshops with scientists and the public and to derive new knowledge with respect to the constituting research topics (Table 1). Therefore, we translated the insights gained in the public part of the Thought School into research questions and revised the concepts for our research clusters iteratively. In doing so, we also connected the cluster research to the individual PhD topics. Thus, we were able to link the topics to their societal relevance (see Pohl et al., 2017) and to identify multiple societal and industrial stakeholders for transdisciplinary cooperation. FK-LEM PhD candidates, associate members and professors worked together to examine the following questions for the individual PhD topics and each of the three research clusters:

General question: How can lightweight design contribute to solutions for the “Big Societal Challenges”?

Detailed questions:
1. Which disciplinary knowledge and which methods could enable the development of the individual PhD thesis in a way that contributes to solve the general question?
2. What can the three research clusters contribute to solve the general question?
3. What knowledge and which methods are missing? Which societal (and industrial) actors do we need to involve into the research processes?

The results were adjusted (disciplinary) research plans for the individual PhD projects and for their coordination within each of the three research clusters (Table 1).

The examination and subsequent discussion of the research strategies was guided by the 10-Step Approach to render research socially relevant (Pohl et al., 2017). A further result was a clear picture of the methodologies, epistemologies and theories necessary to enable FK-LEM participants to realise their envisioned research plans, in other words: the programme to be provided in our Research Seminar.

Transdisciplinary research partners and the formation of boundary objects

In the next step we established stakeholder networks and invited selected members of society/practitioners to participate in each cluster. In line with the strategy of the MIWF (2013), one criterion for the selection was the potential to contribute to the formation of new networks and infrastructure to promote lightweight design as an approach to solve the “Big Societal Challenges”.
The Re-Use and Recycling Cluster started to cooperate with “Lippe zirkulär”, a regional network of stakeholders from political, societal and industrial/economic sectors working together to develop, promote and implement new models of circular economy in the district Lippe. Through this involvement, the contact with the company Hebie GmbH & Co.KG arose and the common research object could be designed. The Rescue Cluster cooperated with the German Network of Female Firefighters and the Weber-Hydraulik GmbH. The Medicine Cluster found its cooperation partners

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4 https://www.lippe-zirkulaer.de/
5 https://www.feuerwehrfrauen.de/english/
mainly through being accountable for enquiries from society and health professionals and responded to more immediate needs of the public, for instance by producing shields to protect health professionals at the beginning of the pandemic.

Bringing people from various areas of society into the research process and knowledge productions entails a contextualisation as researchers move into the context of application and think about the implications of what they are doing, of formulating problems in particular ways and of legitimate ways to conceptualise the position of the people in transdisciplinary research (Gibbons & Nowotny, 2001, p. 75). There are many ways to conceptualise that position, for instance people as a statistical aggregate (e.g. the survey study of the Rescue Cluster), as active agents (e.g. addressed through participating observation, the Thought School or the research cooperation of the Re-Use and Recycling Cluster), or as participating observers in research activities (e.g. Case Study I). However, we reflected upon and modified the “place of the people” in our research continuously rather than reducing the participatory potential by prescribing it through our research design.

Together with our societal partners, we envisioned which artefacts and services, according to their practical experience, would be appropriate to be created or optimised in a way that also contributes to solving a real-world problem and to integrating the knowledge from science and practise (Bergmann et al., 2010, p. 64f), in other words: the “boundary objects” we aimed to co-design, co-construct or co-produce by joining forces from science and practise. The Re-Use and Recycling Cluster decided to design a bicycle stand, the Rescue Cluster focused on the optimisation of two selected standard tools for rescue operations, and the Medicine Cluster started to examine the legal and (inter)disciplinary requirements for the production of 3D printed products.

As Bergmann et al. (2012, p. 108) point out, artefacts, “(...) due to their nature as materialized focal points of research and some specific properties, are well suited as boundary objects within transdisciplinary problem-solving processes”. The concept of “boundary objects” stems from science and technology studies (Star & Grisemer 1989; Star, 2010), where it serves to highlight that objects such as tools, information, prototypes, demonstrators or research objects can have different meanings for different communities, i.e. scientists, engineers, practitioners, etc. Boundary objects are

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7 Due to our confidentiality agreement with Weber-Hydraulik GmbH, we cannot give any details about the particular tools and the criteria applied for the optimisation. However, we aim to provide insights into research methods, processes and empirical findings from the field that form the transdisciplinary approach to derive technologically and socially relevant criteria for technology optimisation.
“both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. [...] (Star & Griesemer, 1989, p. 393).

This interpretive flexibility is a main characteristic of boundary objects: They have different meanings in different social worlds but their structure is common enough to more than one world to make them recognisable (Star & Griesemer, 1989, p. 393). Thus, boundary objects enable action and cooperation among various actors and across various social sites. The creation and management of boundary objects is considered a key process in developing and maintaining coherence across intersecting social worlds (Star & Griesemer, 1989, p. 393).

Two further “boundary objects” emerged during the research process: the “Big Societal Challenges” and “the transmission electron microscope (TEM)”. “Big Societal Challenges”– as outlined above – is a complex of challenges that also come with interpretive flexibility, have different meanings in different social worlds and are intended to stimulate action and collaboration. Therefore, by examining the challenges, perceptions and interpretations empirically, differentiating between social worlds and actors, and by exploring and discussing related concepts, such as the 17 Sustainable Development Goals, defined and adopted by all United Nations Member States in 2015, we transformed the “Big Societal Challenges” into an epistemic object.

The transmission electron microscope (TEM) as a scientific object attracted much interest within our research group. However, a conclusive strategy to include it into the work of the research clusters, or the question of how this object could be used for transdisciplinary research was hard to discover. Therefore, we turned the latter question into the research question (see Case Study I).

**Transdisciplinary Integration**

During the research process, multiple actors bring an essential heterogeneity of skills and expertise to the problem-solving process (Gibbons & Nowotny, 2001, p. 69). This sort of interdisciplinary and transdisciplinary research, as a consequence, requires dealing with different knowledge bases (e.g. theoretical knowledge, tacit knowledge, practical experience, etc.), thought styles, and communities.

The integration of different forms of knowing and knowledge (Bergmann et al., 2012) took place in the Thought School and the Research Seminar primarily. A first step was the empirical examination described above and an explication of interpretations regarding the big societal challenges, transdisciplinary research, and the expectations of the public towards science and engineering, as well as the

8 [https://sdgs.un.org/goals](https://sdgs.un.org/goals)
development of common definitions for the research process, first with the wider public (joint formulation of relevant research topics in lightweight design, see also Horwath et al. (2018)), then transferred and elaborated on within the FK-LEM and the contributing disciplines (integration through interdisciplinary conceptual work, see Bergmann et al. (2012)).

In this phase, the Research Seminar also served as a research forum for screening, introducing, discussing, advancing, applying and integrating appropriate interdisciplinary and transdisciplinary methods for each cluster; it allowed data collection, analysis, continuous reflection of the collaborative process and technology development towards our boundary objects. Importantly, it also served as a forum to develop a transdisciplinary research and collaboration culture which differed from the prevailing (highly competitive, discipline-focused and gendered) scientific cultures (Cech, 2013; Cech, 2014; see also Horwath et al., 2018). Importantly, this culture includes accountability

“(...) to different stakeholders, to different users, that the way to understanding how scientific knowledge is produced opens up. Once there is awareness, which has to penetrate even to curricula and the way we educate future scientists and engineers – once you open this up – then accountability becomes a way to broaden the horizon of those for whom you are producing knowledge” (Gibbons & Nowotny, 2001, p. 71). To foster transdisciplinary integration, we emphasised education and mutual learning processes both among the members of FK-LEM and between researchers and practitioners. Education is a key approach of transdisciplinarity. It is linked to the idea of changing the role of science in society through changing higher education and its relationship to society (Thompson Klein, 2008, p. 399). In order to provide a research environment which allows – at least to a certain degree – overcoming the constraints of the narrowly defined competition and practise in science collaboratively, we provided formats such as the Research Seminar and the PhD colloquium to ensure that both transdisciplinary and interdisciplinary research of the PhD candidates receives professional support. This proved to be essential for the commitment to contribute to both streams of research. As Jahn et al. (2012, p. 8) describe:

“Transdisciplinarity requires an uncommon willingness of individual scientists to learn and to think outside the disciplinary box. This willingness, in return, crucially depends on the extent to which individual interests are recognised and supported.”

Processes of quality assurance are vital for transdisciplinary research. As stated above, quality control in transdisciplinary research goes beyond scientific excellence (which, of course, remains one criterion). In that it should also integrate so-
societal value in the definition of “good science” (Gibbons & Nowotny, 2001, p. 71), it aims to produce not only reliable but also socially more robust knowledge and thus better technological solutions as well. Although to this date, we are not able to provide a full evaluation of the quality of our work, we can point to the evaluation of the Re-Use and Recycling Cluster (see Case Study II), to a multitude of disciplinary (peer reviewed and thus quality-controlled) publications of our PhD candidates, and to the successful collaborations established within and between cluster groups. The FK-LEM allowed us to practise collaborative learning, which goes beyond cooperation:

“Cooperative learning typically entails divisions of labor, with each participant being responsible for part of a shared goal. In contrast, collaboration is a coordinated synchronous activity resulting from continued attempts to construct and maintain a shared conception of a particular problem. Cooperation helps facilitate collaboration. However, collaboration assumes a high degree of joint attention, communication, interaction, mutual engagement, and co-elaboration of knowledge.” (Klein, 2018, p. 15).

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MIWF – Ministerium für Innovation, Wissenschaft und Forschung des Landes


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Introduction


