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Chapter 19

Transdisciplinary Engineering Systems

NEL WOGNUM , JOHN MO AND JOSIP STJEPANDIĆ

Synopsis

Transdisciplinary processes are aimed at solving problems that cannot be solved by one person nor one discipline, like urban planning, waste treatment facility, or a disruptive innovation. A system view is a good way to describe transdisciplinary processes. Transdisciplinary systems are complex systems. This means that goals of the system may conflict due to the people that act in the system. Transdisciplinary systems are also organisational systems. Inherently, system processes are performed by people, possibly with the help of information systems and other tools. All kinds of arrangements exist to make the processes manageable, like organisational structures, teams, or social norms known as culture. Different levels of transdisciplinary systems exist, while in each level different kinds of people interact. For example, a system aimed at creating a complex service system is different from the complex service system itself. In this paper, we mainly focus on transdisciplinary processes in the engineering domain. The concept of a transdisciplinary system will be explored and defined. Two examples of a two-layer system will be described to illustrate the concept.

Keywords: System, Transdisciplinary System, Systems Engineering

19.1 Introduction

The concept of transdisciplinary processes has been the subject of discourse in the past few decades in the context of large, complex, ill-defined problems, also called wicked problems. Solutions to such problems are not obvious and require long and intensive processes in which many people from many different backgrounds participate. Moreover, the goals of these processes are not fixed but may shift during the course of the process, while also people may leave the processes, enter in a later stage or are replaced by others.

The problems tackled by transdisciplinary processes typically cannot be solved by one person despite the different types of knowledge this person may have. Moreover, such problems can also not be solved by only technical disciplines, because the impact of the solution on society or user communities has to be taken into account. Examples can be found in the development of the autonomously driving car with moral and legal considerations when avoiding collisions with different groups of pedestrians. Another examples is the introduction of 3-D printing, which not only disperses the production to almost any place in the world, but also has an impact on intellectual property protection of designs and processes.

In transdisciplinary processes, knowledge from different scientific communities as well as from practice is needed to reach a solution that is acceptabe to the (often many) stakeholders (see e.g., [Scholz and Steiner, 2015]). Transdisciplinary processes are most often performed in projects with a particular timeline, that may shift over time. Transdisciplinary processes are performed by teams and subteams composed from different disciplines from science (technical as well as social) and practice (both from companies and user or citizen communities). These teams and subteams perform interdependent tasks. The degree of interdependence depends on whether the handling of a specific activity in a working practice infuences or is infuenced by the handling of activities in other tasks. Interdependence may also comprise tasks handled in the past, present tasks and future dimensions of tasks (see [Mathiasen et al., 2017]). Research activities often form an important part of transdisciplinary projects.

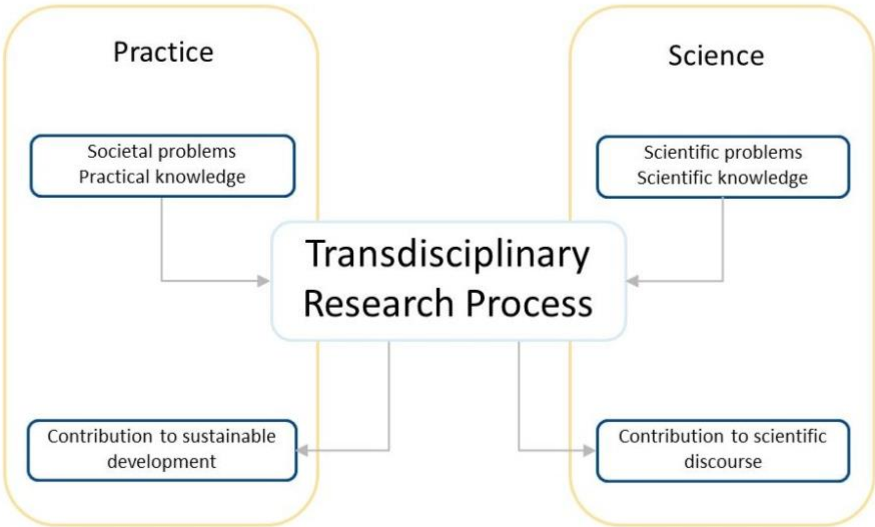

Figure 1. Transdisciplinary Research Process.

In figure 1, the transdisciplinary research process is depicted. As indicated above, both science and practice are involved in the research process. The outcomes should benefit also both research and practice. Moreover, not only technical disciplines need to be involved. Involvement of social science disciplines is deemed essential to achieve solutions that can be used in and valuable and acceptable for the people in the context in which the solution is needed. There are still many challenges to be tackled, though, in transdisciplinary research [Wognum et al., 2019].

In transdisciplinary processes, the old paradigm of scientific discovery (Mode 1) characterized by the hegemony of disciplinary science, with its strong sense of an internal hierarchy between the disciplines and driven by the autonomy of scientists and their host institutions, the universities, is being superseded — although not replaced — by a new paradigm (Mode 2) which is socially distributed, application-oriented, and subject to multiple accountabilities. (Nowotny et al., 2003). Managing a transdisciplinary project is not an easy task. Gaziulusoy et al. [Gaziulusoy et al., 2016] have identified challenges that need to be addressed in managing and participating in transdisciplinary projects. Moreover, as a transdisciplinary project does not necessarily proceed according to preset timelines, budget, and goals, it is characterised by its emergent behaviour and shifting goals. A transdisciplinary project needs to be shaped along its course [Müller and Olleros, 2000] and requires leaders that are visionary and flexible.

In engineering contexts, a transdisciplinary approach has not been studied much yet. Many engineering problems, however, can be characterized as large, complex, and ill-defined with often also unknown outcomes. Especially new innovations, engineering business development, the

adoption of new technology, or the development of a completely new factory, like the smart factory, are examples of such engineering problems. A project approach and multi-disciplinary teams with people from science and practice are needed to achieve an acceptable solution to these problems.
In this paper, we specifically focus on transdisciplinary processes in the engineering domain. We adopt a systems approach for characterizing and describing transdisciplinary engineering processes. We identify challenges that need to be overcome. We state that a system view will help to understand the complexity of transdisciplinary processes and to anticipate the challenges that need attention. Transdisciplinary systems themselves consist of subsystems, which may each be transdisciplinary also. These subsystems consist of different processes, which need different people and knowledge for their execution. Two examples of such multi-layered transdisciplinary systems will be described to illustrate the concept.

The outline of this paper is as follows. In section 1, we describe challenges that exist in managing and performing transdisciplinary projects. In section 2, we introduce the concept of a transdisciplinary system. A transdisciplinary system is a complex system, because many different people are involved with their own possibly conflicting goals. In section 3, multiple interacting layers of a transdisciplinary system, which are themselves (possibly transdisciplinary) systems as well, will be described. In section 4 and section 5, respectively, two examples of a transdisciplinary system with multiple layers are described. In section 6, some concluding remarks are presented.

19.2 Transdisciplinary Engineering Projects

Transdisciplinary processes are typically performed in projects with a more or less defined deadline and that may last several years. Transdisciplinary projects are especially aimed at solving problems that require a vision beyond the immediate engineering task for their solution. In transdisciplinary projects not only technical disciplines need to participate but also disciplines from social sciences. In addition, knowledge is needed from practice and stakeholder communities, including financers, legislators, sponsors, etc. For example, many construction projects can be considered as projects requiring a transdisciplinary approach. Other examples can be found in the medical and in the aeronautics industry.

Transdisciplinary projects are performed by teams of people from research and practice. While the literature refers to arrangements for organizing transdisciplinary teams, Beckett [Beckett et al., 2017] suggest it is more appropriate to think of transdisciplinary networks of autonomous agents and mutual interfaces to enable them to interact. This recognizes the fact that individual actors are also connected to external actors who may indirectly contribute to a transdisciplinary project. This way of thinking recognizes that particular actors may be linked in different ways at different times.
Resarch constitutes a large part of transdisciplinary projects, because standard solutions for the problems addressed do not exist. Collaboration between and coordination of researchers from different disciplines is an important characteristic of transdisciplinary projects. Problems addressed in such projects are practical problems or at least problems that are relevant for practice. This means that people from practice also need to be involved as well as other stakeholders, like financers and legislators. A transdisciplinary project is similar to other types of collaborative (research) projects but differs in three main characteristics [Gaziulusoy et al., 2016]:

1. It is agenda-driven.
2. It aims at integration between and alignment of knowledge from different disciplines, as well as theoretical and methodological transformation of each discipline throughout the process of the research.
3. It involves non-academic participants with significant stakes in the (research) problem and process, as researcher or as informant.

In the literature many challenges haven been described that are faced by transidsciplinary teams. Gaziulusoy et al. [2016] have grouped challenges in transdisciplinary projects as reported in the literature into three groups:

1. Inherent challenges: challenges that directly rise from the characteristics inherent to a transdisciplinary project;
2. Institutional challenges: challenges that arise from the current structures and procedures of knowledge generation and performance evaluation in academic institutions;
3. Teamwork challenges: challenges that stem from the requirement of collaboration of researchers from different expertise background and often from different academic institutions with each each other and with non-academic stakeholders in ways to enable transdisciplinary knowledge generation.

Teamwork challenges, more specifically, have been described in a publication on the longitudinal study of a large transdisciplinary project [Frescoln and Arbuckle, 2015]. Frescoln and Arbuckle have assembled these challenges from the literature on complex projects like TDR projects. These challenges are:

- Communication and language barriers.
- Professional cultures and cognitive cultural differences create subgroups among team members, challenging cross-discipline collaboration.
- Differences in methodologies between disciplines.
- Competition for funds.
- Difficulty in reproducing research.
- Different geographical locations of participants.
- Conflicting goals amont team members.

These challenges are well-known for large distributed projects. Managing such projects is an encompassing task. The Project Management Body of Knowledge (PMBOK) [Project Management Institute, Inc., 2017] has provided guidelines for managing different kinds of projects, from small to large, in various application domains. These guidelines, however, cannot be considered as recipes. Transdisciplinary projects are complex (see section 2.2), goals are shifting during the course of the project, destructive forces may be active, sponsors may loose their interest, etc. [Miller and Lessard, 2000]. Knowledge of and experience with large, complex problems is needed to manage transdisciplinary projects.

The teamwork challenges listed above have also been identified by Gaziulusoy et al. [2016] in a case study of a TDR project. The strict adherence to project deadlines, fixed budgets and reporting requirements does not attend to the evolving characteristics of a TDR project. In addition, an institutional challenge like career development may be hampered, because the development of new scientific knowledge is not often the only priority in a TDR project. Greater emphasis is put on knowledge for practice and targeted on a wider audience. Leaders of TDR projects have to develop adaptive strategies to manage emergent challenges that may compromise scientific validity and social responsibility of the project [Gaziulusoy et al., 2016]. The often large scope of TDR projects also impacts on project management, expertise management and resource management.

In an engineering context, Miller and Lessard [2000] have emphasized that large engineering projects cannot be fully predicted and designed beforehand. A shaping approach is needed depending on task complexity and the degree of development of institutional arrangements. The task complexity requires exploration and testing, while in the development of institutional arrangement strong coalitions need to be formed. The real-options framework is applicable, recognizing that decisions determining project cash flows in conjuction with exogenous events are not all made at the outset of the project [Miller and Lessard, 2000].

Shaping a transdisciplinary engineering project requires several management processes [Miller and Lessard, 2000]:

- Negotiating a project concept or proposition that truly creates value and can be progressively refined in the overarching issue;
- Developing stability for the future of the project;
- Gaining and ensuring legitimacy;
- Achieving shock-absorption capabilities;
- Ensuring capital-cost reduction.

These activities cleary transcend engineering activities. They require the involvement of all relevant actors and disciplines. Below, we explore some projects that require a transdisciplinary engineering (project) approach.

19.2.1 Open Innovation

In the past, many companies performed their innovation processes in a closed way. In the research lab of the company, breakthroughs were sought, products were developed in the company, built in its factory and distributed, financed and serviced from within the four walls [Chesbrough, 2003]. Open innovation, on the other hand, requires collaboration with other companies, because not all new technology can be developed in-house or new technology from the own research lab may not be profitable enough for the own company [Chesbrough, 2003]. The former case requires the buy-in of new techology or close cooperation with the inventing company, often a small company. The latter may result in spin-off companies that are required to collaborate with other, often larger companies. New inventions are not merely given away. Often they are protected by IPR (Intellectual Property Rights), giving a company a means to gain revenues by licensing an invention to other companies to develope and manufacture, or by leasing a name, logo, or slogan to other companies [Jolly, 2010]. Companies may also get an equity stake in companies that further develop and produce their invention [Chesbrough, 2003].

Open innovation requires collaboration between different companies, while involvement of legal people and business people is needed to investigate business opportunities and the legal limits and options. In addition, knowledge of potential markets is necessary to build a viable business model. A true transdisciplinary approach is needed, because the process evolves over time and needs to be shaped. A visionary leader is also needed to buy-in commitment and support. His or her role is to guide, facilitate, manage, and control the innovation process from idea screening to launch (Aas et al., 2015).

19.2.2 Business Development

After a new technology has been developed, a new business may need to be set up, involving possibly the company in which the technology has originated, but more often a new start-up company or spin-off company. The new business may be a technology service provider or a manufacturing company that will produce a new product. A whole new socio-technical system has to be set up in developing the new business.

In setting up a new business or changing an existing one, many different aspects need to be investigated, like economic feasibility, patenting, licensing, location demands, waste disposal, etc. In addition, resource demands and availability are important to consider, in particular financial resources, knowledge and experience of the employees, and management capabilities.
Especially with the demands on sustainability, the 3 Ps need to be taken into account as well: people, planet, profit. The new business needs to provide a good environment for its workforce, it needs to care for the environment with respect to its inputs, outputs and waste during and after the process. A

trade-off needs to be made between investements on the short term and revenues on the longer term (see e.g., [Wognum et al., 2011]).

It is clear that business development requires a transdisciplinary (research) approach, because the process may take some time, goals may shift as insights grow, stakeholder values are at stake, and investments are large. In addition, the process is multi-dimensional, requiring both people from science and practice as well as people from both technical and social-science disciplines. Knowledge exchange needs to be extensive and lead to new knowledge and insights, academically and practically.

19.2.3 Adoption of New Technology

Disruptive technology like 3-D printing leads to many new business opportunities, but also triggers new legislation and copyright and IP protection measures. Ownership of design, printfile or final product need to be redefined.

In setting up a new 3-D printing service all that has been indicated in the previous section needs to be taken into account. In addition, new technology is needed to protect products against plagiarism [Holland et al., 2018]. Although already incorporated in law, e.g., paragraph 54 of the German Copyright Law, counterfeiting and plagiarism are still possible, especially in the B2B area. Holland et al. [2018] have defined four categories of conterfeit protection: internal security, external security, product labelling, and legal safeguard. In their paper, they discuss product labelling more extensively, like visible and invisible tagging and the introduction of marker particles.

This example shows that the adoption of new technology is not only an engineering or technical task, but involved other disciplines as well. The process of new technology adoption may also take quit a long time, because new insights and unexpected consumer or client behaviour may trigger the need for additional protective measures and business redesign.

19.2.4 Towards Industry 4.0

With the development of new technoloy and cloud computing a totally new concept of production facilities has become possible, the so-called smart factory. Smart factories are an instantiation of the Industry 4.0 concept [Rojko, 2017]. The concept Industry 4.0 has been introduced by the German government and is aimed at industrial production systems. Industry 4.0 is the name for the current trend of automation and data exchange in manufacturing technologies. It includes cyber-physical systems (CPS), the Internet of Thing (IoT), cloud computing, and cognitive computing [Hermann et al., 2016; Hermann et al., 2017]. Data are typically stored in the cloud.

In a smart factory, products, processes, and machines have both a real and a virtual presence. They can be called 'smart', because at any point in time their status, progress, activities can be identified, monitored and planned. The data are continuously updated and used during a production process and during product and machine life. Factories are becoming 'smart' and 'adaptive', because of the new intelligence that has been embedded in machines and systems. They are able to share data and support enhanced functionalities at a factory level and include collaborative and flexible systems able to autonomously solve problems that arise during the process [Hermann et al., 2016].
Smart products, processes, and machines can be considered an instance of the IoT. CPSs monitor physical processes and create a virtual copy of the physical world to make decentralized decisions. Over the IoT, CPSs communicate and cooperate with each other and with humans in real time and via cloud computing.

Industry 4.0 is radically changing the way people interact with machines, systems, and interfaces. Many different skills will be required in the new context. Lower-skilled repetetive tasks will be replaced by tasks that require competences in software development, and IT technologies. The Boston Consultancy Group recently reported a set of examples to illustrate the possibilities for deployment and the implications for the workforce in Industry 4.0 contexts [The Boston Consultancy Group, 2018a; The Boston Consultancy Group, 2018b]. For example, companies will need algorithms to analyse real-time or historical quality control data, identifying quality issues and their causes, and pinpointing ways to minimize product failures and waste. The application of big data analysis will reduce the number of workers specialized in quality control, while increasing the demand for industrial data scientists.

Other consequences of adopting Industry 4.0 are:

- Robots will replace humans, because they can be easily trained to take on new tasks, in contrast to humans; A new job may be the robot coordinator;
- Automated transportation systems navigate goods intelligently and independently within the factory; They replace logistics personnel; Increased need will grow for skilled controllers and programmers;
- Production line simulation prior to installation will increase the demand for industrial engineers with production management knowledge and simulation experts;

New jobs will be more cognitive and complex. The business model, in addition, will also change including the markets that can be served, because the range of products and the degree of customization will change. Because production lay-out needs to change frequently, requiring a flexible lay-out. Resource management needs to adapt to the changing situation, because workers need other skills and knowledge. New IT systems, like CPSs, are needed to manage the physical world and interact with the virtual world represented in the cloud. These systems need to be able to cross-organizational borders.

Implementing the Industry 4.0 concept in a company clearly requires a TDER approach. Changing the business is not only a technical task, but involves the whole business as well as sponsors, legislators, and financers. The people in the company as well as existing and potential markets play an important role also. The change process may take many years, with a step-by-step approach, in which the goals to be achieved may shift over time.

19.2.5 Ecosystems

Building on the turbulent experiences of the past decade, global companies have adapted their strategy and structure accordingly. Driven by the increasing complexity of products and processes, as well as the ever-increasing dynamism imposed by the market and the society, companies are increasingly focusing on their core competencies, resulting in much greater flexibility. The additional demand for goods and services resulting from outsourcing is covered by a supplier pool. Together with customers and other partners, this creates a dynamic, flexible network as a new form of corporate culture, sometimes called an ecosystem. This is a specific characteristic of Transdisciplinary Systems Engineering.

Even innovations that are considered to be the biggest drivers of economic development are increasingly emerging in network structures, not only because this type of cooperation enjoys large political support in most countries (Frascati Manual, 2015). As a result, the innovation process also includes the capture and use of existing knowledge, machinery, equipment, infrastructure, training, marketing, design, and software development, thus requiring a transdisciplinary approach.

The increasing importance of services in many areas of economic and public life further underscores this development. In eco-systems, synergies are much easier to raise, because the tayloring of labor among the individual members is part of the self-image of one. Thus, an eco-system provides a first-class means of first establishing innovations, and then marketing them on a long-term and sustainable basis. For an outsider, a functioning eco-system is an important sign that the vendor has created a balance between market dynamics and its range of services.

Ecosystems are particularly widespread in the IT industry. They usually combine (a) a disruptive technological development in a field that is very attractive to customers, (b) the added value created by applying new software or service to existing processes and processes, (c) a broad range of potential users in different fields, and (d) a stable customer base through market knowledge and long-term customer relationships. Thus, ecosystems are typical transdisciplinary systems that include technical, economic and social aspects.

A central component of an ecosystem is often a platform that is built for an economic purpose and depicts complex socio-technical processes. Figure 2 shows the platform OpenDESC.com with its stakeholders in its own ecosystem, which serves as a hub for data communication in the global automotive industry. Arrows show different types of mutual relationships (OpenDESC, 2018).

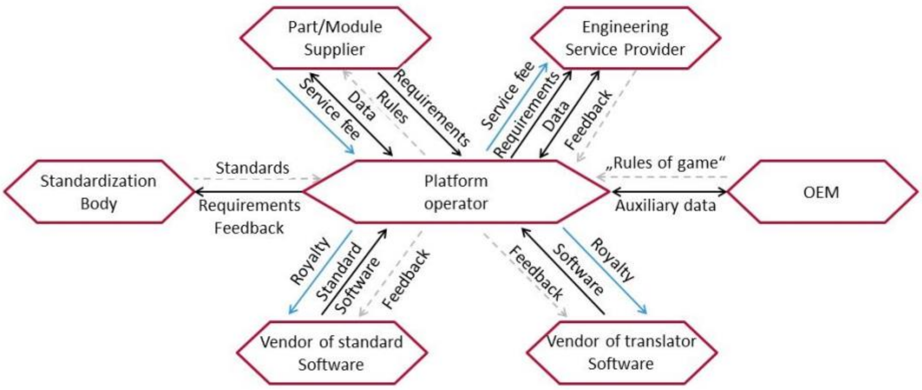

Figure 2. Ecosystem of OpenDESC.com.

It is important to realize, however, that much knowledge from the supply chain and network management domain is needed to properly organize an ecosystem, especially for creating and maintaining the required flexibility, while guaranteering the quality desired by the customer. Flexibility and strict quality management regimes often require conflicting arrangements. A trade-off between flexibility, network procedures, contracts, and the degree of interdependence between parties is needed (see e.g., [Wever et al., 2012]). Proper arrangements are important to make the ecosystem function well.

19.3 Introduction to Transdisciplinary Systems

Systems and systems thinking take a predominant place in current practice and research. The concept of systems of systems is used quite frequently in the literature. Systems are encompassing concepts with different structures, aspects, and layers. It is often not clear, though, what actually is meant with systems and whether the concept is used consequently and consistently in academic and industrial circles. Below, we introduce the system concept into more depth. Then the concept of complex system is defined, after which we describe a transdisciplinary system.

19.3.1 The System Concept

The concept of system is widely used in theory and practice. However, in many cases it is not very clear what really is meant with system. In an attempt to give a formalized account of a fundamental theoretical issue in general systems research Marchal [1975] has given a very elementary definition of a system:

S is a system only if $S = \{E, R\}$, where

(i) E is an element set, and

(ii) $R = \{R_1, \ldots, R_n\}$ is a relation set, i.e., $R_1, \ldots, R_n$ are relations holding among the elements of E.

This definition is a very generic one, but can be given content in any domain and on any level. Even systems of systems can be characterized here, when systems on a lower level are seen as the elements of the higher-level system. Relations between elements of a system can be of any kind, e.g., part-of or functional, but also fixed, like in natural systems, or intentional, i.e., created by somebody and existing as long as needed [Caws, 2015]].

Any object, artifical or natural, can be viewed as a system. Every such system has a function in its context, like a stone, putting weight on the surface it lays upon or storing and disseminating solar heat. A house is a system with many different functions, depending on the context in which the system is considered.
General Systems Theory (GST) [von Bertalanffy, 1951]has emerged in the 1950s and describes a level of theoretical model-building that lies between highly generalized constructions of pure mathematics and specific theories of specialized disciplines [Boulding, 1956]. Mathematics abstracts away from content and context. On the other hand, disciplines, like physics, chemistry, biology, psychology, etc., have their specific theories and correspond to a particular segment of the empirical world.

General Systems Theory is the result of a quest for a systematic theoretical construct that describes the general relationships of the empirical world. It is not a single, self-contained general theory of practically everything that replaces the special theories of particular disciplines [Boulding, 1956]. As Boulding claims, such a theory would be without content. GST seeks a place between the specific without general meaning and the general without specific content. The objectives of GST can be defined with varying degrees of ambition and confidence. At a low level of ambition, but with high degree of confidence, GST can point out similarities between theoretical constructs of the different disciplines. At a higher level of ambition, but with possible lower confidence, it aims to develop a spectrum of theories – a system of systems. Like the periodic table of elements, it may show gaps in theoretical models, which direct research to filling those gaps. This ambition, however, is still not achieved.

The merit of system theory can be found in specifically framing and defining the focus of attention. This can be disciplinary, like a waste treatment model, but also inter-disciplinary, combining two or more different disciplinary systems, like the waste treatment model and the eco system [Nelson, 1976]. Of course, such an integrated model is less acceptable to each of the disciplines, but is a compromise to support communication and the search for trans-disciplinary solutions. Trans-disciplinary systems add a level of analysis, which does not exist on the level of each of the disciplines [Hofkirchner and Schafranek, 2011].

19.3.2 Complex System

Much discussion can be found in the literature on the concept of complex systems. When we simply count the number of elements, systems with a large number of elements may appear to be rather simple, like the solar system [Simon, 1976], because only a limited number of the pairs of interaction appear to be of significance. In addition, systems that occur in nature are mostly hierarchic and nearly decomposable. Approximations on higher levels are often made possible [Simon, 1976]. The weather system, on the other hand, is still hard to simulate and predict. Much of our perception of complexity may be due to the fact that we base our models on wrong assumptions, like in forecasting models to guide economic policy [Simon, 1976].

For the purpose of this paper, system complexity as defined by Nelson [1976] is useful. Nelson defines a complex system as a system having at least two conflicting goals. Such a system always contain human beings, otherwise there would not be goals. Systems functioning without persons have functions to reach the goals of human beings, possibly assembled in societies. The central idea here is intentionality [Nelson, 1976].

In the context of transdisciplinary engineering, complex systems, as defined above, are the organizational systems in which multiple disciplines and multiple organizational roles work together to develop new products or services. Such a system consists of many subsystems, which may not be trans-disciplinary but may still be complex. For example, in developing an electro-mechanic product, the subsystems are the electronic design department and the mechanical design department, each with its own processes, its own goals, people, equipment, and knowledge. In the trans-disciplinary system they have a separate, integrated, process, shared people, shared equipment, shared knowledge, and, above all, shared goals. These goals may possibly conflict, requiring negotiation and possibly adaptation of the goals, process, people, equipment, and knowledge. Other subsystems may not be complex, in the sense defined above, like information systems used to manage product and process information.

In the next section we will explore the concept of a trans-disciplinary system and, in particular, its multi-layered nature.

19.4 Transdisciplinary System

A transdisciplinary system is a complex system as defined above, because people are needed to perform the system processes. Moreover, a transdisciplinary system is an organisational system. People perform processes to achieve a certain goal, which is the attainment of a solution to a problem in the environment of the system, often a market or society. The solution is important for many stakeholders in the environment. The execution of processes is made possible by structure and culture of the system, together called the organisational arrangements or governance. The structure comprises hierarchy between people, including management, operational and support people. Support consists, for example, of the financial administration of the project and creation of project documentation. The culture consists of the norms and rules that together come from the many differen organisations and departments the people originate from. Culture is often a hampering factor in collaboration projects (see e.g., [Wognum et al., 2004]).

In Figure 2, the system of trans-disciplinary engineering is depicted (based on [Wognum et al., 2016]). It shows the transdisciplinary system as the central element of the system. A transdisciplinary system most often consist of multiple subsystems. The development subsystem, shown in figure 1, is aimed at solving the problem that was the trigger of the transdisciplinary project. The development system is a transdisciplinary system in the overall transdisciplinary system, because of the different disciplines, social as well as technical, needed to solve the problem. The solution system, also shown in figure 1, is the outcome of but also input to the development system. The solution system the can be a transdisciplinary system, but does necessarily be one.

The process in the development system is performed by and involves many different disciplines, such as engineers from different disciplines, designers, marketing and sales people, people from social sciences, people from practice. Also people from the solution system are involved. Together these people have a lot of different types of knowledge. Stakeholders, like financial institutions, governments, legal bodies and certification bodies, may have a strong influence on the process, but are often not directly involved. The transdisciplinary process uses technology, like information systems and many different tools, technologies, and methods. The process may also need new technology that has been developed elsewhere.

The outcome of the process is the solution system, a product/service system that performs product and/or service processes with the necessary people, tools and techniques. It is intended to solve the problem. The solution system may itself be a transdisciplinary system. The solution system can be a pre-existing system that needs to be changed to solve the problem. The solutions system consists of the value-adding processes, transforming customer or client wishes into products and/or services.

Input to the solution system consists of the customer or consumer needs. Output of the solution system is the product and/or service desired. Processes in the solution system are performed by people that are often different from those in the development system, because different knowledge is needed. A subset of the people may have participated in or contributed to the development system. Also, the technology used in the solution system is different from the technology used in the development system, although parts may overlap. The solution system is supposed to function independently of the development system after the project has stopped. However, some maintenance and update processes may remain active that can be considered to be part of the development system. It is clear that the system depicted in Figure 3, is a complex system as defined in section 2.2. It is a system in the sense that it is an element set and a relation set as defined above. Many elements, however, are complex systems, while the relationships are many and highly different in nature. Other elements of a trans-disciplinary system need be not complex in the sense defined above, like information systems.

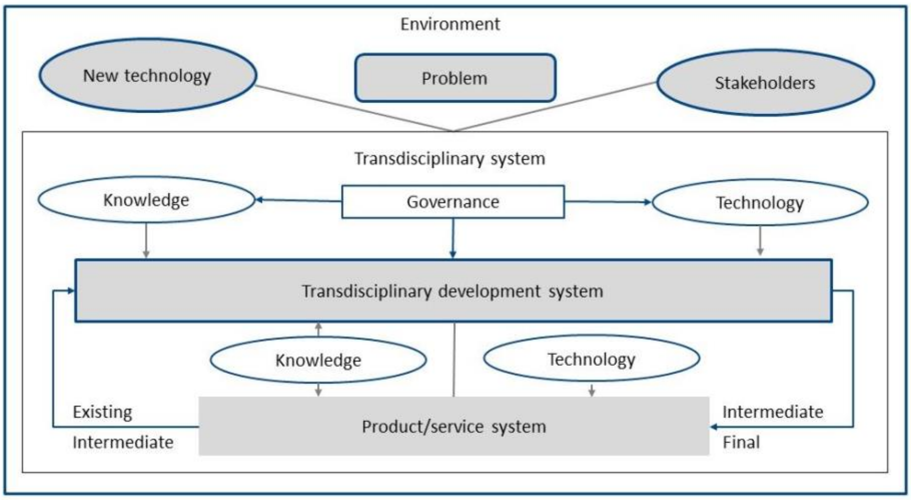

Figure 3. A trans-disciplinary engineering system.

Information systems can be large, with many elements and relationships. They are not complex, however, because output can be predicted from input provided. As soon as humans are involved the system in which the information system is used is complex. Humans may not sufficiently understand the system, this using the system in a way not intended. In addition, the user interface may be difficult to comprehend and use, making users reluctant to use the system in a proper way. Also, users or organizations may have their own goals with the system, like forcing a particular way of working or gaining more power.

There have been attempts to develop frameworks for studying and analyzing complex systems. One example is the soft systems approach by Checkland and Holwell [Checkland and Holwell, 1998]. Another approach is the process model of organizations [Wognum et al., 2004]. Both approaches emphasize that systems thinking supports framing the system of focus. Such models are useful to depict a complex system, to support communication between stakeholders of the system, and to identify problems that require further analysis and definition. The system descriptions are not sufficient for problem solving as such, but help to understand the complexity, structure, and context of the problem. Often, problems concern only a subset of the system under study, but may have an impact on the system as a whole. The systems approach helps to see the relationships between problems and between problems and the behavior of the system. Additional theories and methods are then needed to dive into the problem to come up with ideas for solutions. The context of a system is not depicted in Figure 1, but is very important to consider, because system behavior depends on its context as well as impacts upon and influences its context.

Coming back to trans-disciplinary systems, it is important to clearly distinguish the boundaries of the system at hand in its context as well as the internal structure of the system. For example, one may want to focus on a particular phase of the process, for example, the research phase. In this phase, a subset of stakeholders is involved with a more limited number of functional roles and coming from a more limited number of departments or companies. Still, the system under study is complex. The context of this system are the preceding and subsequent phases and the transdisciplinary system as a whole.

Referring to Figure 3, a transdisciplinary system consists of at least two subsystems:

1. The development system, and
2. The production and/or service system that is the outcome of and input to the development system. It is also the implementation of the solution as aimed for in the development system. The solution system produces the products and/or services desired by customers or consumers. It is the value-adding part of the overall transdisciplinary system.

While the transdisciplinary project stops at a certain point in time, the development system may continue to maintain and update the product/service system. The solution systems is an independent organisation in most cases that produces products and/or services for the environment in which the problem has existed and for which the products and services are meant to be a solution.

In every transdisciplinary process such different layers of subsystems can be distinguished that might require separate attention during the course of a transdisciplinary project. It is important to identify the needs of a subsystem in the context of the overall system, because subsystem actions and outcomes do have an impact on the overarching whole and also on other subsystems.
In the following two section examples of transdisciplinary systems are presented to illustrate the concept of a multi-layered transdisciplinary system.

19.5 Example 1: On-line Hearing Aid Service and Service Development

Mo and Beckett [2018] have studied the development of a service system to provide on-line hearing aid solutions. Traditionally, the most common way of providing hearing support is to have a patient undertake a simple frequency response test at an audiology clinic. The test measures the patient's response to sound at different frequencies, i.e., the hearing profile, which shows where degradation should be compensated for. Then, a hearing aid, tuned to suit this profile, is sold to the patient in a package deal that includes ongoing support and tuning. The hearing aids are produced by specialist manufacturers, and the audiology laboratory clinic acts as their sales agent. The package deal can be quite expensive, hence imposing financial constraints to access of this technology. Also, some patients may have difficulty in attending a clinic for either the initial testing, subsequent fine tuning of the hearing aid or both, due to mobility issues.

Blamey Saunders Hears (BSH) recognised the complexity and inconvenience to patients in the traditional hearing aid packaging process and application pathway. The researcher founders first registered a company in 2007 aiming to develop an alternative system that could offer on-line hearing enhancement solutions. They allocated minimal effort to product promotion in the first few years as the focus was on Beta testing with initial clients in collaboration with the Bionic Hearing Institute in Melbourne, Australia, where the cochlear implant technology was originally developed. The Bionic Hearing Institute is close to an Eye and Ear Hospital and surrounding specialists rooms – a kind of technology cluster precinct. From 2010, BSH moved to its own premises in the same area, maintaining knowledge-sharing connections with expertise from multiple disciplines.

In this case, the process of hearing enhancement was taken as the basis of the new service system. BSH examined the processes in hearing solutions development, including experience with online customer engagement practice with an associated firm, America Hears. It was clear that due to the nature of process, social interaction was an indivisible element in determine the characteristics of the final hearing aid system. Through several years of research, they designed the style of front office engagement and back office support infrastructure. The system comprised steps that were identified, as performed by the initiator and associated partners [Beckett et al, 2016]:

1. *Recognition of hearing impairment*. This step is heavily patient dependent, involving the patient's social and work environment and some form of screening. The new system makes use of the Internet to assist personal decision to seek a more detailed assessment.
2. *Assessment of hearing impairment*. This step involves one or more tests where quantitative and qualitative medical data is collected over the Internet.
3. *Enhancement solution identification.* This considers cost-benefit tradeoffs and some experimentation with options. With the hearing data, the BSH team can assist the patient to select a suitable hearing aid specific to the patient's case.
4. *Enhancement solution implementation.* This step involves fitting and tuning the hearing aid selected at the BSH facility prior to delivering to the patient.
5. *Solution refinement and patient learning.* The patient needs a period of adjustment to use the new hearing aid in a variety of day-to-day situations. This step is to provide support to the patient on a continual basis to assist the patient in this process over the Internet.
6. *Ongoing review and adjustment.* The hearing aid system tends to become a life long device for the patient. This step involves advice from BSH in monitoring patient progress, routine re-assessment, and consideration of technology advances, including upgrading to a different kind of hearing aid.

The solution, as produced by the solution subsystem, to hearing-impaired people is some combination of technology (a hearing aid) and support services. Input conditions are shaped by the patient's perceived hearing capability and associated acoustic environments. The desired output is an enhanced patient sensing and discrimination capability. Practical experience also suggests there are two other possible outcomes: rejection of the opportunity to participate at some point (e.g., on cost grounds) or the abandonment of a particular solution after an initial trial period (e.g., the hearing aid is too difficult to use).

The BSH solution development process is definitely a transdisciplinary system that intertwines between system development and production plus services. It has all characteristics depicted in Figure 2. Within the Environment, identification of requirements of new technology is based on the hearing enhancement process, which works traditionally but with undesirable social difficulties (patient mobility) and supply chain complexity (clinics as the sales agent). It is clear that there are many sources of knowledge required to support the system. Transformation of the traditional clinical-centred process to an online process has many innovative design features of the system's architecture, which makes use of research knowledge of how the Internet-based hearing assessment can be performed accurately and reliably.

In the development process, BSH has identified several strategic partners in development of the solution system. These include the Bionic Hearing Institute, the Eye and Ear Hospital, the specialist rooms around the medical precinct, the Internet developers and the association with American Hears. Involvement of the specialist rooms ensures a range of patients with different levels of hearing impairment to be accessible. The online testing and feedback can be implemented with specialist knowledge. While the development of Internet access is relatively straightforward, installation of information channels and advertisement on the web is critical to delivery of the products (tuned hearing aid) to the customers. It is worth to note that BSH does not manufacture hearing aids, nor is a sales agent of any of the hearing aid brands. This fact helps BSH to be independent when searching for the best solution for the client.

In summary, the process undertaken by BSH is a transdisciplinary system with a development subsystem and an solution subsystem, the production/service system, that are intertwined, as said above. The development subsystem is different from the production/service subsystem with different actors and different knowledge involved. While the development subsystem is a transdisciplinary system, the question is whether the solution subsystem, the product/service system, is a transdisciplinary system also. The answer depends on the degree of involvement of science and practice, and the degree of involvement of the different, not only technical, disciplines.

Several subsystems can be distinguished in the BSH case:

(1) The development subsystem consists of four interacting subsystems:
   a. Development of the online hearing profile assessment subsystem –this subsystem has all features and functional blocks of a transdisciplinary system as shown in Figure 3. New internet-based delivery of the assessment test requires substantial research and development on the capabilities of the equipment under remote control. The sound system needs to be precise, accurate and consistent.
   b. Development of the clinic subsystem – There are some transdisciplinary actions taken in the development of the clinic subsystem, primarily in the social interface during the hearing profile assessment test. The relationship between the clinician and the patients has changed somewhat due to the online test arrangement. However, the delivery and after-post delivery service of the hearing aid involves transdisciplinary actions.
   c. Development of the tuning and adaptation of the hearing aid. This part does not require a transdisciplinary approach, because the existing approach can be used.
   d. Development of the information subsystem. All disciplines including engineering, medical, IT have worked together collaboratively to build the necessary databases and links.

(2) The product/service subsystem consists of four subsystems, that are not transdisciplinary:
   a. Profile assessment subsystem. With this subsystem the patient hearing profile is assessed.
   b. Clinical subsystem. This subsystem provides the interface between clinician and patient.
   c. The tuning and adaptation of hearing aid can be done readily when the hearing profile is known, as before. Not much has changed.
   d. The information subsystem – This subsystem supports the other subsystems.

As will be clear from this example, the development system is different from the solution system. Both systems, though, are mutually dependent. The success of the solution system depends on the vision of the people that have undertaken the development and on the efforts they have spent to, for example, selecting the right people and technology for executing the necessary processes in the solution system. Conversely, the solution system success also depends on the continuous efforts in the development system to maintain and update the solution system. In the end, the solution system is the value-adding part of the whole system.

19.6 Example 2: License Approach for 3-D Printing

In this section, we present a novel approach which overcomes the limitation of the use of 3D printing and builds an ecosystem for the wide exploitation of this production technology anywhere in the world.

19.6.1 Challenges and Legal Background

The rise of the Additive Manufacturing (AM) doesn't only create tremendous chances for a disruptive shift in the area of manufacturing, but also opens the door for many threats by plagiarism and product piracy. Like a bubble-jet printer usage yesterday, the 3D printer becomes typical equipment of almost each engineering office today. The integration of AM procedures into the production process and the complete product life cycle incorporates significant challenges regarding authorized access to product data, assured supply of the agreed quantity, distinction of original parts from counterfeits as well as prevention of intellectual property, product liability and warranty (Stjepandić et al., 2015).

Copyright in the consumer area, according to §53 German Copyright Law, also applies to parts additively manufactured by the end-user and allows copies for private use without the permission of the author. However, a few conditions have to be taken into account: The number of copies must not exceed a maximum 7 copies, which can be passed on to friends and relatives free of charge. Hence, the printer operator may not receive remuneration for the printed pieces, as the parts otherwise would then be sold for profit, being plagiarism. Furthermore, the copy may not originate from an obviously illegal source.

In the field of B2B, it is important to address the need for IP and counterfeit protection for each product and take corresponding protective measures (Chen et al., 2016). Although there will never be a 100% protection, the barrier has to be set as high as economically justifiable for the copyright holder, such that it is not feasible for a pirate to produce counterfeits. The subject of counterfeit protection is bound to a company-wide concept for product and know-how protection. Measures for counterfeit protection require a typical transdisciplinary approach which can be divided in four categories (internal security, external security, product labelling and legal safeguards).

Particular attention has to be paid to the usability in court when selecting the right procedure for an individual application (Holland et al., 2018). Usability in court means recognition and admission of a procedure by the court. This might be a crucial factor in case of a defence against a product liability claim or against unjustified usage warranty claims.

Within the additive manufacturing process chain, the preparation of a geometry, determination of process parameters or manufacturing of components is often done by external partners with whom the copyright questions have to be answered. In the case of a service provider preparing the geometry model for printing and subsequently creating the print template with a slicing software, he may eventually have created a work according to copyright law, §3 section 1 No. 1 or No. 7. The author is then granted protection by preparing the file. Thus, to protect the work, it does not have to be registered.

The conditions required to classify it as authentic work are that it has to be created by a human and also requires to be an “intellectual creation”. In this case, the resulting work must not be copied and distributed without approval of the copyright holder. Public availability needs the approval of the author as well. Furthermore, the original product manufacturer could be restricted by amendments to the prepared geometrical model. Thus, the rules for legal boundary conditions must be defined clearly when entrusting service providers with the creation of a print template, because printing a template means copying it (Holland et al., 2018).

In case the printing file is passed on to a service provider for production, he has no property rights with regard to the protected work. The reason is that in case of the mere process of the printing order the intellectual creation is missing.

For all above mentioned reasons, the success of AM is dependent on a secure procedure to prevent misuse of the original data (Liese et al., 2010). One way is the introduction of a license procedure for a print controlled by a strict procedure called „Chain of Trust“.

19.6.2 Technical Solution

The goal of the envisioned solution is to reduce risks to a minimum by using cryptographic approaches to secure the authenticity of printing data and prevent unauthorized use of it. Encoding and licensing of data by means of Blockchain Technology provides an opportunity. With this technology, the relevant data is encoded and identification of the print template and licensing of the printing process is enabled. Blockchain Technology, however, may be used as well for the application of transactions in terms of franchising. Contrary to Bitcoins, the license allows to print a certain number of a component (Holland et al., 2018).

A so called Smart Contract files the license information in the Blockchain and secures that only the receipient has the permission to update the license, e.g., register a printer part to it. The recipient‘s printer verifies the license before starting to print. Additionally, the serial numbers of the separately printed components can be written into the Blockchain to prove type and quantity having been printed in accordance with the license terms. To ultimately close the Chain of Trust, the machine and automation suppliers have to be taken into account. Similar concepts as those of manufacturing copiers can be realized. In this way, a complete Chain of Trust can be built-up from copyright holder to service provider (Holland et al., 2018). Other ways to improve Trademark Protection are certified partners and the use of trusted printers (“Block-Chain Ready”).

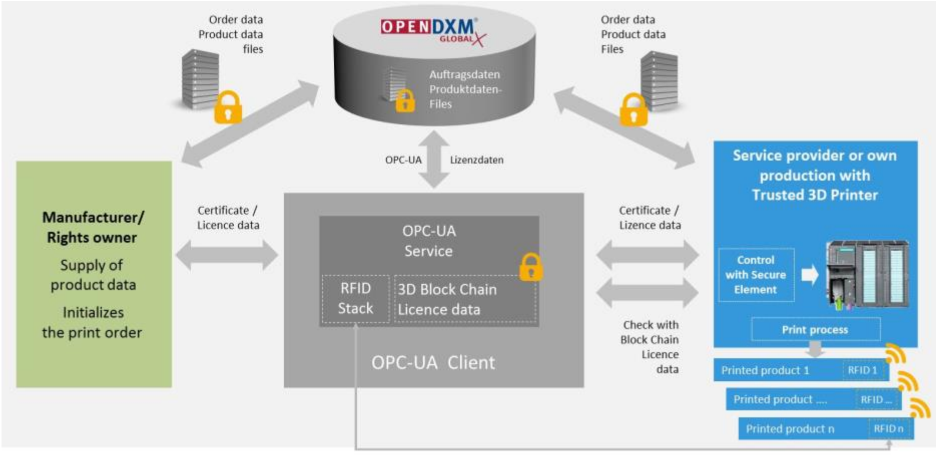

Figure 4. Secure Additive Manufacturing Platform System Architecture.

A consistent Chain of Trust for Additive Manufacturing Procedures for a commercial purpose is realized, from development of digital 3D printing data via the exchange with a service provider of 3D printers trusted by specific secure elements up to labelling of printed components by means of RFID-Chips. In addition to the available encoding mechanisms, a digital license management based on Blockchain Technology is integrated into the data exchange solution OpenDXM GlobalX of PROSTEP AG. The interface for the exchange of certification and license data between copyright holder and receiver is Industry 4.0 Standard OPC-UA. Figure 4 illustrates the System Architecture of SAMPL (Secure Additive Manufacturing Platform).

19.6.3 Business Implementation

After several years of implementation, eight categories of Blockchain projects have been formed (Nussbaum, 2018). The application presented here falls into the category “Shared Data”, which comprises, amongst others, the use of Blockchain in supply chains. Initial Blockchain efforts could have a quick impact by transforming even a small portion of the supply chain, such as the information needed for the individual, decentral, manufacturing of spare parts, which used to gather dust in warehouses waiting to be used. There are many similar possibilities, such as the “open data platform”, which has been a popular startup idea for a few years now with several companies achieving great success with this model. Because business rules and smart contracts can be built into the platform, a Blockchain ecosystem can evolve as it matures to support end-to-end business processes and a wide range of complementary activities.

19.6.4 Transdisciplinary System Model for 3-D Printing

In summary, referring to figure 2, the creation of a 3-D printing service and facility incorporated many different fields and actors.

The development subsystem proceeds in parallel with the development of the 3-D printing service, which is the solution system. When problems are identified in the print service activity, like illegal copying and counterfeit, they require action on the development level. At this level, legal bodies, manufacturers, 3-D print experts, certification bodies at least need to be included in the processes to create a safe and secure 3-D printing service. Business developers and business owners also play a role, while proper external parties need to searched for and selected, which are willing to and capable of providing the necessary technology, material and tools. Moreover, these external actors need to agree on copyright protection measures. In addition, the search for a suitable technology is needed to support the whole supply chain in acting according to the copyright protection agreement, in this case blockchain technology.

It is evident that the development system is a transdisciplinary system, because many different actors from different disciplines need to bring and exchange their knowledge mutually. Moreover, some activities in the system require the input from different sciences, like business and legal disciplines and technical disciplines.
The product/service system in action, the solution system consists of the following actions, actors, agreements, and technology:

1. Preparation of geometry and process parameters is often performed by an external actor. This actor needs to settle the copyright protection matter with the partner(s).
2. Creation of the print template is also often performed by an external partner. This partner automatically is granted protection by the copyright law.
3. Production of the print may be performed by an external actor. This actor does not have propery rights.

It is recommendable to incorporate only certified partners to secure the supply chain from copyright theft and counterfeit. Suitable technology is used to support and secure the supply chain, like the Chain of Trust for Additive Manufacturing based on blockchain technology.

It is not clear yet whether the solution system, the 3-D printing service, is a transdisciplinary system. It is definitely a complex system, but does not necessarily require the input from science for its operation. Though science may not be involved in the solution system itself, it is still involved in the development system to improve or change the solution system.

19.7 Summary

In this paper, a systems view on transdisciplinary engineering has been presented. Transdisciplinary processes are most often performed in large, complex, projects, aimed at creating a solution for a problem, that can not be solved by one person, nor by one discipline alone. Collaboration is needed between science and practice and involves multiple disciplines, not only technical ones. The solution for this problem is expected to have a large impact on the social environment in which the problem exists.

In the system view on transdisciplinary engineering processes, two major intertwined (sub)systems can be distinguished: the development system and the solution system, which is the outcome of and input to the development system. The solution system is often a product/service system offering the desired products and services for the (social) environment that can use or need the products and services. Each subsystem operates with its own set of people, knowledge and technology, and governance. Elements of these sets may overlap.

Both (sub)systems are complex systems, because the people acting in the systems may have their own, often mutually conflicting, goals. Moreover, people are not only acting in these systems, but also in other systems in their own environment, thus bringing different cultures, experiences, knowledge and technology into the subsystem.

Viewing a transdisciplinary process from a systems perspective may help to identify a subsystem or aspect system, that requires specific attention, while taking into account the context in which this system exists. In this way the impact of the system context on the system under consideration as well as the impact of changes made to the system on its context can be better identified and taken into account.

The cases presented above provide an excellent opportunity to study in-depth the transdisciplinary processes and all their aspects, technical as well as social. Methods and tools from different science communities can be used in coherence to create rich knowledge of transdisciplinary processes and their complexities. This knowledge is needed to successfully manage transdisciplinary projects.

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