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The real type and ideal type of transdisciplinary processes: part I—theoretical foundations

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Abstract Transdisciplinarity integrates or relates different epistemics from science and practice (Mode 2 transdisciplinarity) or from branches of disciplines if interdisciplinary integration is impossible (Mode 1 transdisciplinarity). The paper explains, based on an analysis of the historical development of the Mode 2 transdisciplinarity concept, how transdisciplinary processes link interdisciplinary applied research and multi-stakeholder discourses by facilitating methods. We elaborate on what type of problems may be managed using what knowledge, how this might be accomplished, what types of objectives are desired, and by what organizational means. Thus the paper presents ontology, epistemology, methodology, functionality, and organization of an ideal type of transdisciplinary process. Socially robust orientations are the expected outcomes of this process. These orientations provide science-based, state-of-the-art, socially accepted options of solutions which acknowledge uncertainties and the incompleteness of different forms of epistemics (i.e., of knowing or thought), in particular within the sustainable transitioning of complex real-world problems.

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History and conceptions of transdisciplinarity

Societal changes, crises or transformations can lead to new ways of generating, utilizing, and transferring knowledge. Transdisciplinarity has emerged in this context. At the end of the nineteen-sixties, developed Western countries were facing rapid economic and technological development. Traditional values as well as educational and research systems called for innovation and university structures for renewal.

The concept of transdisciplinarity became a subject of thorough intellectual discourse in nineteen seventy (see "Appendix"). Piaget (1972) recognized that interdisciplinarity is possible only among neighboring disciplines such as physics and chemistry. He was looking for a joint kernel or cognitive-epistemological structure by which all disciplinary languages and specific types of causation could be unified. He was aspiring to develop "full transdisciplinarity" that should provide a system of knowledge which includes the interactions and reciprocities of physics, biology and psychology and other disciplines, without boundaries and in a consistent manner. Thus, a kind of meta-structure that allows for an integration of disciplines and a basis for a unity of knowledge was aspired. Instead of full transdisciplinarity, we call this notion Mode 1 transdisciplinarity as it refers to mere inner science (Gibbons et al. 1994). Jantsch (1970, 1972) countered this inner-science, structuralist view with a functionalist, societal perspective. He saw societal needs as the creative force for directing, shaping, and organizing research and education.

He suggested a transdisciplinary university that would include system-design laboratories nurtured by both discipline-oriented and function-oriented departments for building capacities for the self-renewal of societies (1970).

A quarter of a century later, bolstered by the environmental problems of the nineteen-eighties and various crises, a new type of collaboration between science and society became practiced which was called Mode 2 research (Gibbons et al. 1994). In the following, the unspecified term transdisciplinarity (Td) means Mode 2 transdisciplinarity as we focus on this notion of the concept. At some universities, "experiential knowledge" and "scientific knowledge" (Scholz 1995a) became integrated in case study-based research and education, as a reality of transdisciplinarity. This was followed by large-scale funding in some Central European countries (Häberli and Grossenbacher-Mansuy 1998) and the development of an extensive practice of transdisciplinarity (Klein et al. 2001). Case studies are of special importance for transdisciplinary processes as they embody the complexity, multi-layeredness of tradeoffs and conflicts, uncertainty, and incompleteness, which relate to any form of scientific knowledge for which real-word contexts and -structures are the underlying basis.

Today, the societal complexity and—presumably—vulnerability of societies have increased again. Challenges such as adaptation to climate change, transition of energy systems, human and environmental health management—but also quandaries such as stock market dynamics or antagonisms between religions—call for an increased effort not only to collaborate across various disciplines but also to incorporate the great abundance of creative and innovative capabilities in society itself in the coping with these challenges (European Commission 2012; OECD 2012; Scholz 2011; Steiner 2008, 2011, 2013). All these big societal transitions are of ill-defined nature. This holds true for the environmental-biophysical and technological layers of these problems. But a major challenge is the ambiguity of what we call the social design, i.e., "the rules, mechanisms, and preferences that govern the interaction of humans with material (including technical) and social environments" (Scholz et al. forthcoming). Historically, transdisciplinarity developed much when dealing with human-environment relations. However, we may see also a high potential for transdisciplinarity in intercultural mitigation, given some liberal habits for coexisting cultures and lifestyles. This paper elaborates first how transdisciplinarity may contribute in societal sustainability learning. We present the history and an ideal type of transdisciplinarity, i.e., the Zurich 2000 conception, then report and discuss the challenges of transdisciplinarity and report, based on more than 20 years of experience related to 41 studies, what obstacles transdisciplinary processes are facing and how the reality of transdisciplinary processes is shaped. The discussion focuses on basic questions on the future of sustainability.

The emerging concept and practice of transdisciplinarity

In Europe, over the past two decades, Mode 2 transdisciplinarity (Td) has become *a third way of utilizing and doing science* supplementing disciplinarity and interdisciplinarity (Klein et al. 2001). This holds true, at least, for some disciplines such as the environmental sciences (Scholz et al. 2006), landscape management (Naveh 2005), and the emerging sustainability sciences (Lang et al. 2012; Yarime et al. 2012). Recently, Td has become an issue of corporate sustainability in management sciences (Schaltegger et al. 2013) and of agro-sciences (Francis et al. 2013). *Mutual learning* among scientists and practitioners about a complex, societally relevant problem may be seen as the kernel of transdisciplinary processes (Scholz 2000; Scholz et al. 2000).

In the US and other parts of the world, the term transdisciplinarity has not been widely used for long. But we find similar approaches, such as *community-based participatory research* (Fals Borda and Rahman 1991; Leung et al. 2004) or variants of *action research* (Kemmis et al. 2004). Here, Kurt Lewin's *experimental action research* (Lewin 1946) may be seen as a precursor of transdisciplinarity. The term transdisciplinarity in North-America has been often used in health and community science and often is commonly understood as a team-based interdisciplinary problem solving (Kessel and Rosenfield 2008; Stokols et al. 2003).

There are different definitions and notions of transdisciplinarity. In the following, we refer to the *Zurich 2000 definition*, which was elaborated on at a large-scale conference including 800 people, with 300 practitioners among them (Häberli et al. 2000; Klein et al. 2001; Scholz et al. 2000). The essence here is that transdisciplinarity aspires to the efficient use of knowledge by relating different epistemics (i.e., ways of knowing) when dealing with a complex, societally relevant real-world problem (Häberli and Grossenbacher-Mansuy 1998; Scholz 1995b). This is done by launching mutual learning among science and key stakeholders from society "including local knowledge, scientific knowledge, and the knowledge of concerned industries, businesses, and non-governmental organizations" (Häberli et al. 2001, p. 7). A transdisciplinary process calls for relating both knowledge and values from practice in science as well as for developing and utilizing science knowledge in and for practice (Scholz 1995a; Scholz et al. 2000a, b). The goal is the production of "socially robust knowledge" (Gibbons and Nowotny 2001; Häberli et al. 2001). This definition of transdisciplinarity reflects the complexity and multidimensionality of sustainability (Martens and Rotmans 2005) and has been seen as an appropriate methodology of sustainable transitioning (Scholz and Marks 2001). Thus, transdisciplinarity is based genuinely on systems theory and is theoretically nourished by key concepts such as complexity, vulnerability, and resilience or more specific concepts such as tipping points, rebound effects, etc.

Along with the Zurich 2000 conception, we may distinguish between a *normal* and a *post-normal science* approach. The normal scientific view postulates that—though the boundaries between science and practice have become blurred—scientists and practitioners have different primary objectives and reference systems. Simplified, the primary *goal of normal science* (Kuhn 1996) is to contribute to more-realistic descriptions of the objects and processes of the material and immaterial world (i.e., to approach 'truth' and/or to produce knowledge that can be validated). This goal differs from the main conventional goals of practitioners, which are, e.g., to operate successfully on the market, to become re-elected, or to contribute to their institutional or personal objectives. This position differs from the post-normal scientific view (Funtowicz and Ravetz 2003, 1993), which—in complex, real-world situations where facts are uncertain and values and interests form perceptions and decisions—does not distinguish between science and practice knowledge. Thus, in this approach, science becomes one (stakeholder) voice, and a valid description according to disciplinary standards becomes obsolete. This approach can be also contrasted to the (normal-science) vision that we need "*disciplined* (i.e., discipline-grounded) *interdisciplinarity*" in *transdisciplinary* (i.e., theory–practice-based) *processes* to cope successfully with the challenging… problems of the twenty-first century (Scholz 2011, p. xv). As presented in Fig. 1, this conception suggests that transdisciplinary processes relate interdisciplinary research with knowledge of multi-stakeholder discourses (see Fig. 1).

Interdisciplinarity may be defined as the merging of concepts and knowledge from different disciplines. This is presented in the upper lens of Fig. 1 for the example of sustainable phosphorus management. The challenge here is the sustainable transitioning of global anthropogenic phosphorus flows. The description of the phosphorus flows, the losses and efficiencies of their use, as well as a description of the economic, social, and environmental impacts, calls for knowledge from a wide range of disciplines. But transdisciplinary processes relate scientific knowledge and rigor to experiential knowledge (in its ideal form, to "experiential wisdom" about the real-world system). This holds true if we think, for instance, about the construction and evaluation of scenarios of future use of phosphorus. Thus, in the case of the global phosphorus flows, a transdisciplinary process has to include all the key stakeholder groups of global phosphorus management (lower lens of Fig. 1).

Transdisciplinary processes may be viewed as a *means of sustainability learning*. They require a socially robust orientation on how to cope with a "complex situation

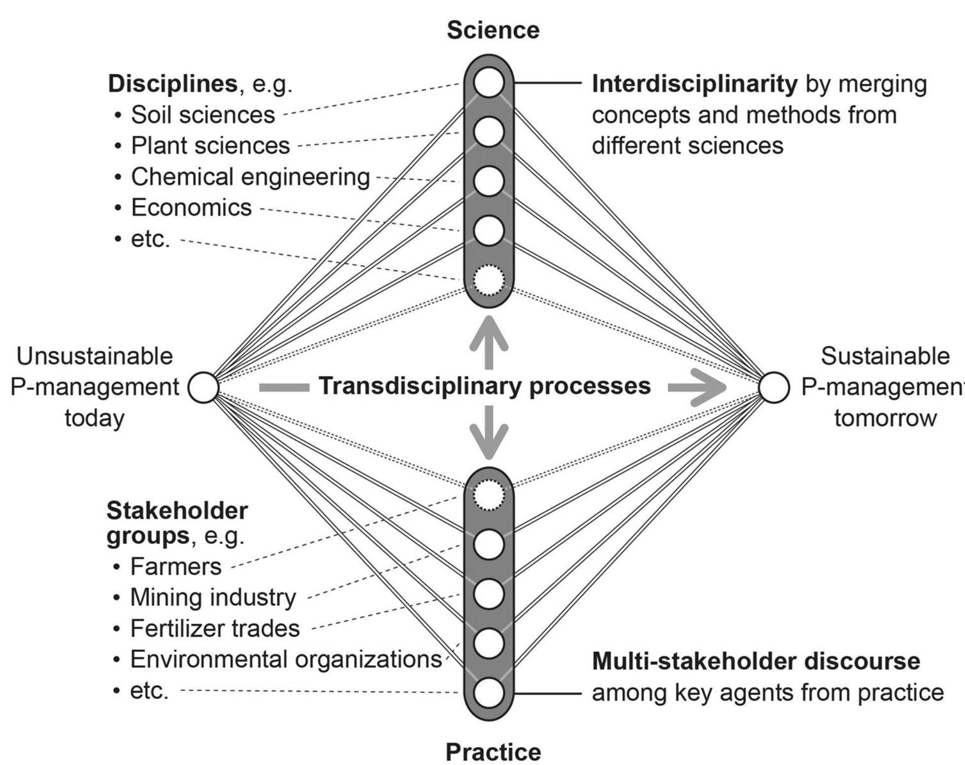

Fig. 1 The components of transdisciplinary processes: interdisciplinary applied research and a multi-stakeholder discourse (for the case of sustainable phosphorus management; figure after Scholz and Le 2014, p. 120)

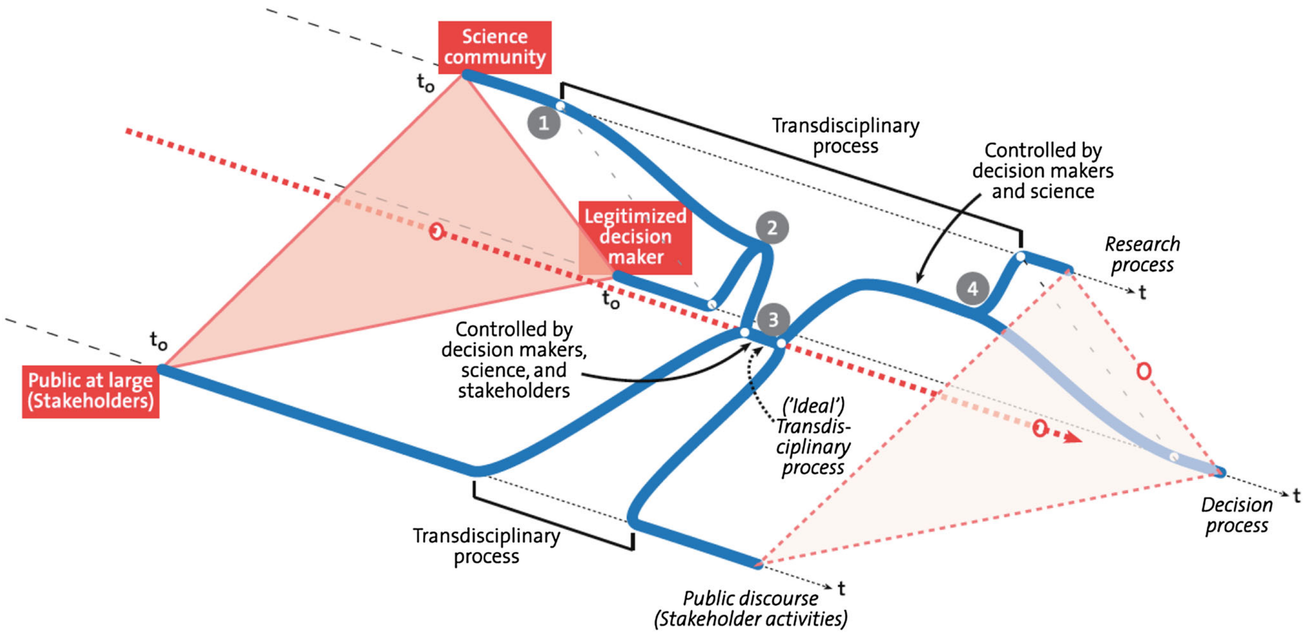

Fig. 2 The dynamics and stages of a transdisciplinary project (figure after Scholz 2011, p. 375)

where many uncertainties remain to be resolved" (Gibbons et al. 1994, p. 148). Research conducted on the subject of transdisciplinary processes assesses them not only by their disciplinary standards and validity but also by their potential societal impact. Research is "carried out in application" (Gibbons et al. 1994, p. 3), "created in broader, … social and economic contexts" (p. 1) and also includes the criteria of whether the solution found in praxis will "be competitive on the market, … cost effective" or "socially acceptable" (p. 8). This has led to the view that "the modern university has become a hybrid institution with multiple and sometimes incommensurable missions" (Scott 2007, p. 214).

Transdisciplinarity and other forms of theory–practice collaboration

Transdisciplinarity (a) may be distinguished from other forms of theory–practice collaboration such as (b) *consultancy* (c) *participatory research* or (d) (shallow) *action research* and (e) *public participation* (Scholz 2011). If we look at the sustainable transition of a system or process, we may—simplified and idealized—distinguish among three types of actors (see Fig. 2). First, there is someone from practice or from the scientific community who recognizes that both science and society may join forces, for instance, to better understand the obstacles involved in the transition of systems of joint interest. For main aspects of this system transitioning, second one can often identify a democratically legitimized decision maker (such as an owner of a brownfield area). And, third, we can identify stakeholders from the public at large.

Figure 2 presents how a transdisciplinary discourse may develop. In a first step (1), members from the scientific or the practitioner community recognize that they have joint interests in a complex, relevant phenomenon that can be better understood and dealt with if knowledge from practice and from science is integrated. Step (2) is the *building of partnership* and may include an agreement by both parties to launch a mutual learning forum on an *equal footing*. Scientists and practitioners may take co-leadership (or joint responsibility) and *initiate* a process that includes representatives from the key stakeholder groups (3). The participants need to jointly define a guiding question, the system boundaries, the time frame and specific goals, and other important aspects of a *core phase* of a transdisciplinary process. After that, post-processing takes place until the legitimized decision maker can leave the learning area and scientists can return to their labs (4).

In *consultancy* (b), scientists usually conduct contract-based research, whereas transdisciplinary research that gives (formal) freedom to researchers should be the ideal model. The goals, desired outcomes, accessibility of the data, etc. remain under the control of the principal, and the scientist becomes an agent who is compensated by a salary. In (c) *participatory research,* we are facing the opposite relationship. Scientists employ a practitioner, for instance a CEO of a company that has become successful because of its flat-organization management, to provide them with background information about how certain processes function in practice. After some compensation, the scientists continue with their research. In general, participatory research is part of a transdisciplinary process. Finally, (d), we often face the situation where scientists become personally motivated to change a certain concrete phenomenon. They combine their scientific activities with a stakeholder perspective and do not utilize the scientific potential of various forms of action research such as launching a "circle of planning, action and fact-finding" and evaluation (Lewin 1946, p. 38). A pure actionist approach which does not utilize the theoretical potential may be called *action research.* We want to mention that we talk about (e) *public participation* if there is a publicly legitimized decision maker (e.g., a lord mayor) who decides that certain stakeholders may contribute to the decision-making process. Here, as in consultancy, the legitimized decision maker retains control over the process.

Transdisciplinarity differs fundamentally from *applied research* or *unidirectional knowledge transfer*. Transdisciplinarity is based on knowledge integration from science and practice (Scholz and Marks 2001). The terms *co-design, co-production*, *co-creation or co-construction of knowledge* (Gibbons et al. 1994; Nowotny 1993) and the objective of *producing socially robust knowledge* (Nowotny et al. 2001) have been introduced to characterize this process. A question of theoretical and also societal relevance asks in what way the collaboration between science and practice takes place. That is, what roles do scientists and practitioners take?

Transdisciplinarity differs from the *Triple Helix* approach (Leydesdorff and Etzkowitz 1996; Leydesdorff and Meyer 2006) which conceptualizes the interaction of science, industry, and politics. In many triple helix processes, science becomes one voice among others. Thus the complementarity between science and practice disappears; scientists would become one element of the multi-stakeholder discourse represented in the lower lens of Fig. 1. And the upper lens of Fig. 1 would be dissolved. Science receives the status of an interest and opinion-driven stakeholder group in an agora of views of interests. This is done mostly in contrast with the ideas that science is a public good which has to serve all stakeholders. Here science often follows a genuine subjectivist conception and departs from the objective to approach descriptions of reality which may become subject of validation. The Triple Helix conception, such as the conception of the "*real experiment*" takes a societal top-down view of innovation. The "real experiment," a concept developed in Germany, promotes the interaction of sociologists/scientists with actors involved in the practice of societal innovation (Gross et al. 2003); but it does not clarify what roles the different stakeholders should take. The *team science approach*, however, which has been developed in the context of the health sciences, includes community stakeholders (Stokols et al. 2010) and transdisciplinary integration, and thus it seems to be similar to the presented Mode 2 transdisciplinarity.

Ideal type and real type of transdisciplinary processes

The distinction between the ideal and the conception of the "maximum of perfection" as a subject of the "intelligible world" of an idea and the sensible, empirical reality ("the creation of all perfection") was first elaborated in Immanuel Kant's (Kant 1770, §9) inaugural dissertation. Later, in Max Weber's work, *The Methodology of the Social Sciences* (Weber 1949) the concept of an (holistic) *ideal type* was developed. The ideal type of a transdisciplinary process is a general conception that, "free from the detailed complexity of actuality" (Watkins 1952), provides a simplified description of what constitutes transdisciplinarity. In this sense, an ideal type provides the essential narrative of this form of theory practice collaboration, which allows to distinguish it from other forms.

A description of the ideal type should include the following aspects: (1) the type of problem for which transdisciplinary processes may take place (the *ontology* of transdisciplinarity); (2) the type of knowledge produced in a transdisciplinary process and transdisciplinary research (*epistemology*); (3) the processes, techniques, and methods upon which a Td process is built (*methodology*); (4) the outcomes and purpose of a Td process (*functionality*); and (5) its main organizational traits (*organization*).

Box: Mode 2 Transdisciplinarity[1] in a nutshell

Mode 2 Transdisciplinarity has become a third mode of doing and utilizing science, supplementing disciplinarity and interdisciplinary. Hence, transdisciplinarity is conceived 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*[2] for developing *socially robust orientations*[3] about a specific real-world issue (either a problem or a case).[4]

Transdisciplinarity processes may serve *capacity building* among all participants; *consensus building* about what the main problems are, including their genesis and transformation, *strategies for mitigating emerging conflicts* (i.e., analytic mediation) in a process

[1] This box synthesizes the ontology and the main features of the proposed ideal type of transdisciplinarity that is based on the Zurich 2000 definition and on the discourses in the ITdNet. Mode 1 transdisciplinarity differs from Mode 2 transdisciplinarity (see text and "Appendix").

[2] See Fig. 1.

[3] See the definition in "Outcomes of transdisciplinarity".

[4] Historically, the emergence of transdisciplinarity has been strongly related to applications for sustainable transitions.

of sustainable transformation, and as a means for *legitimizing policy options* (if representatives of all relevant stakeholder groups have been included and properly considered).

Science and practice collaborate on an equal footing, and both collaborate throughout the course of the entire process, including defining the problem, representing the problem, and developing strategies for transforming the problem.[5] In the ideal form of transdisciplinarity, there is co-leadership of a science leader or spokesperson (or a group of scientists that acquires and generates relevant scientific knowledge) and a (democratically or morally) legitimized decision maker (or a group of stakeholders) who serves as a spokesperson and representative of the multi-stakeholder discourse. Accepting the otherness of the other is seen as a prerequisite for mutual learning. This includes the otherness of other scientific disciplines,[6] the otherness of different stakeholders' roles and interests of the various stakeholder groups as well as the otherness of the epistemics and modes of causation between forms of science and practice.

Science is conceived as a public good[7] that must serve all stakeholder groups (as long as they follow the rules of human rights and democratic constitutions). A main role of science is to develop knowledge and theories that allow for more clearly describing the processes in social, technical, and biophysical systems[8] and their interactions.[9] By contrast, practitioners may follow their interests. However, all participants are expected to make some level of commitment to sustainability.[10]

[5] Thus, preparing for sustainable decisions and not the decisions and actions that are considered to be objectives of the legally legitimized stakeholders is the subject of a transdisciplinary process. (For sustainable decision see Footnote 9).

[6] This calls for the search of a meta-level that allows for relating different types of reasoning or validation and the search for Mode 1 transdisciplinarity (see "Appendix" or Scholz et al. (2015)). Transdisciplinarity in philosophy and science: approaches, problems, and prospects. Moscow: Navigator).

[7] This excludes scientific work provided as contract research and implies that the results—eventually followed by a double peer-review—are publicly available.

[8] Here scientists are challenged to distinguish between rigorous data and evidence-based descriptive statements (e.g., about estimates of negative impacts of technologies), to explicate personal, and value- and norm-based components of judgments (e.g., what is a safeguard object and what not or what level of risk is considered as acceptable). A special challenge here is to openly communicate the uncertainty and incompleteness related to evidence based knowledge.

[9] This calls for a realist stance and may not be shared by certain radical constructivist or post-modern conceptions of science.

[10] Here, something such as a minimum definition or a consensus that sustainable development calls for system-limit management (i.e., avoiding system collapse) in the frame of intra- and intergenerational justice may be taken (Laws et al. 2004).

Ideal type: ontology, epistemology, methodology, functionality, and organization of transdisciplinary processes

For what types of problems are Td processes meaningful? (ontology)

In the late nineteen-eighties, environmental accidents such as Chernobyl (1986) and Schweizerhalle (1987) challenged the emerging environmental sciences to search not only for abstracted theories and strategies but also for the contexts of specific cases. In the emerging department of environmental sciences at the Swiss Federal Institute of Technology Zurich (ETH), for instance, it became evident that the complexity of "open, concrete, real, societal relevant problems" (Scholz 1995b, p. 42) has to be investigated on a case level. And the idea of "transdisciplinary courses" was born (Frischknecht and Imboden 1995, p. 57). This challenged researchers to understand the relationship between the specific and the generic and to develop strategies for how to cope with complex and specific contexts. Science had to learn to cope with "ill-defined problems." And, because the genesis of the problem as well as its transformation is related to stakeholders and their interests, a typical transdisciplinary problem includes normative issues. This is part of the nature of an "ill-defined" problem.

Whereas in a common problem the initial state and the target state, as well as, in general, the type of barrier that must be overcome, are known, this is not the case for ill-defined problems (Simon 1973). In a sustainable transition, what the target state looks like is not exactly known, and neither is how sustainable or unsustainable the present (initial) state is—or sometimes even the type of barrier.

Knowledge integration as the core of transdisciplinarity (epistemology)

The main added value of transdisciplinarity compared to other forms of conducting science or theory–practice is the integration or relationship of different forms of epistemics (i.e., ways of knowing). Whereas disciplines are brilliant at explaining specific aspects in a theoretical form, the major asset of transdisciplinarity is the merging and relating of different types of perception, knowledge, and valuations in an integrated manner.

Transdisciplinarity is challenged to demonstrate that this asset is a real one. Here also science and its disciplines are challenged. If science is not able to show its specific capacity, it might be well substituted by professional non-science experts. This has been suggested by Mieg (2006),

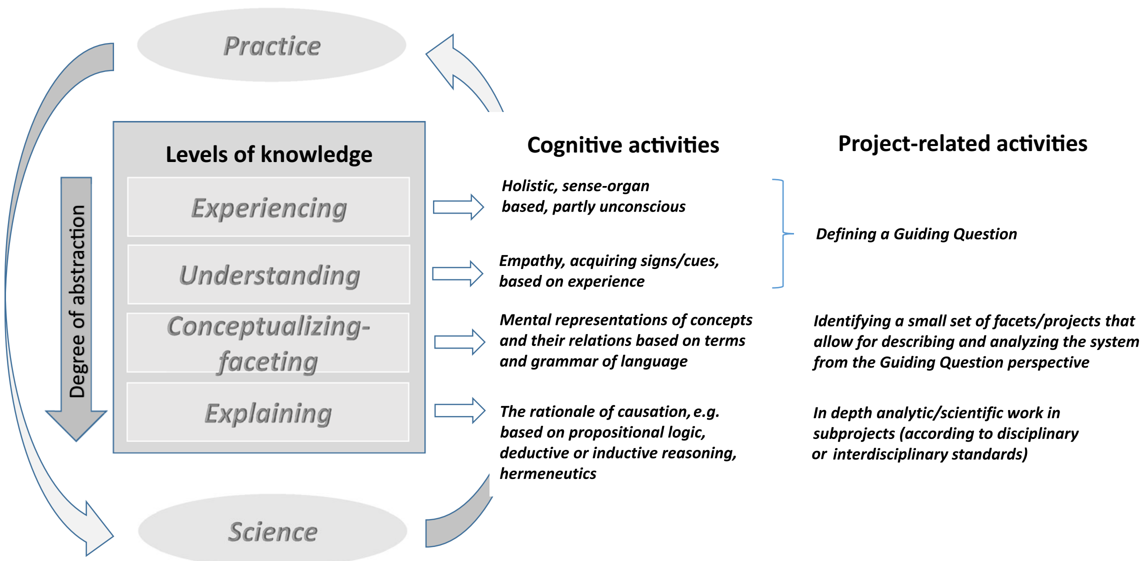

Fig. 3 The architecture of knowledge (from cognition to transdisciplinary processes)

who differentiates between different forms of expertise. The scientists' roles are seen in system analysis, diagnosis, and the designing of synthesis. We have to acknowledge that certain knowledge may become professionalized (and thus a matter of practice) and may appear in the form of planning consultancy. This is also in line with arguments by Abbot, who states that inference as a form of decision consulting is "purely a professional act" (Abbott 1988, p. 42).

Given the theoretical importance of knowledge integration and mutual learning, we approach this issue from three perspectives. We first present forms of epistemics on the level of the individual. Second, we look at what types of knowledge integration we can distinguish related to different systems. Third, we briefly sketch the idea of Egon Brunswik's Theory of Probabilistic Functionalism, which may serve to understand different processes of knowledge integration.

1. Forms of epistemics: the architecture of knowledge

The presented concept of the architecture of knowledge was first introduced by Scholz (2000). We distinguish four forms of knowing and knowledge integration.

Experience is considered a primary means of knowledge. It is considered direct, sense organ- and perception-based knowing, and it has a holistic nature, as major parts of this knowledge are unconscious and may not be singled out (Chadha 2010; Kolb 1984; Polanyi 1966; Wellek 1953). This position claims that a direct experiential (sensation- and perception-based) knowledge may be only partly substituted. This is due, among other reasons, to the complexity and multi-layeredness of real-world problems. People living or acting with a system on an extended or even daily base are considered the case or system experts. Experiential system knowledge is one main aspect of distinguishing practitioners from scientists.

Understanding is based on experiencing (see Fig. 3). It may relate to the material–biophysical and to the social–epistemic–cultural environment. If we relate understanding to the other's mind or to human agency, empathy is an important means (Stueber 2013). Mutual understanding of the other's intention and thinking is supported by the perceptual system as the recent research on mirror neurons reveals (Giacomo et al. 2008). The value of an experiential case encounter as a prerequisite of understanding (e.g., of certain climatic conditions) also refers to the natural, built or technological environment. From a theoretical perspective, it may be important that understanding is based on cues (Brunswik 1952) and signs (Atkin 2010; Peirce 1991), i.e., on signifying elements that provide meaning to something, and not on (digital) information.

Conceptualizing is based on relating concepts, the "constituents of thought" (Margiolis and Laurence 2011). Concepts may be represented and described by natural and scientific language. We consider concepts to be mental representations and conceptualizations by relating these concepts to rules or grammar (Chomsky 1975). The conceptualization of something may be represented by mental maps. Conceptualization is a basic means of communication (Steiner 2009, 2011). Thus, we may ask what language and relations are applied between concepts. The language and the process of conceptualization should support creativity and innovation (Steiner 2009). We assume that the conceptual level is most important in transdisciplinary discourses (Habermas 1987) and for understanding the rationales of mutual learning between science and practice and among stakeholders (Scholz 2011). Conceptualization is a key level of discourse among stakeholders.

Explaining serves to make things comprehensible by understanding past, present, and future cause and impact (if–then) relationships. Explanation can be conceived simply as communicating causation. Scientific explanation must refer to logical, scientific, and empirical data or issues in which a certain phenomena or issue (i.e., the explanandum) is explained by certain arguments and reasons (i.e., the explanans). Though we may consider propositional logic to be a major reference of logic that is accepted in all sciences, we have to acknowledge that there are different modes of logic and reasoning. In the natural sciences, we may distinguish deductive–nomological reasoning (Popper 1935/2005) and inductive–empirical reasoning (Hempel and Oppenheim 1948). In the humanities, hermeneutics is an important means applied to the humanities (Malpass 2014). However, we also encounter patterns of explaining by non-classical scientific reasoning in layperson's everyday reasoning, religions and cultures.

2. Types of knowledge integration

Figure 4 presents five types of knowledge integration that may be identified in transdisciplinary processes (see Fig. 1).

The first type is called the modes of thought/epistemics and is closely related to the architecture of knowledge and strongly refers to knowledge acquisition. A primary distinction of cognitive psychology is that between intuitive and analytical thinking (Hammond et al. 1983; Kahneman 2011; Scholz 1987). The intuitive mode of thought is based on personal experience and pictorial metaphors, is widely preconscious, includes emotion, and is holistic, as it consists of instantaneous parallel processing of data from a global field of knowledge. It is characterized by low cognitive control, and there is a feeling of uncertainty with respect to the method but of certainty with respect to the result. Experiencing and understanding are linked mostly to intuition.

However, the inventions of (advanced) scientists are also based on experience and intuition. In their daily work with symbols, formulas, and highly abstract knowledge, these may become directly accessible (whereas other concerns of daily life may become alien). Dreyfus and Dreyfus (2005) and Fischbein (1987), for instance, stress that only understanding-based experience allows access to the

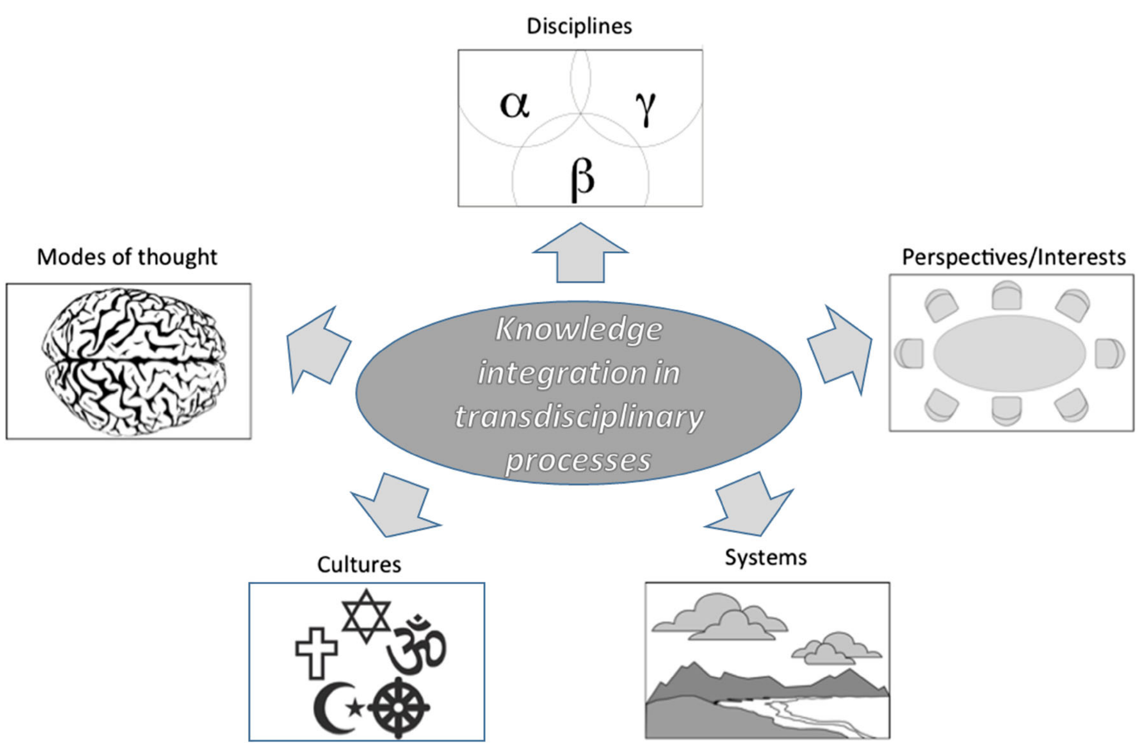

Fig. 4 Knowledge integration in transdisciplinary processes refers to modes of thought, (inter-)disciplinary (related to humanities, natural and social sciences), perspectives/interests, systems, and cultures

solution of scientific problems. By contrast, analytic thought is based on abstract, conceptual, or numerical patterns; pure intellect and logical reasoning; and widely conscious and emotion-free discrete details. Furthermore, it is independent of personal experience and performed with a high level of cognitive control. Often, one may find high certainty with respect to the method and uncertainty with respect to the result (Scholz 1987). In transdisciplinary processes, the intuitive mode is prevalent on the side of practitioners, whereas the analytic mode dominates the (common) work of scientists (Scholz 2011; Slovic et al. 1995).

The second mode of knowledge integration relates to interdisciplinarity. The icons present the humanities (α sciences), natural sciences (β science), and social sciences (γ sciences). The historically developed separation of academic disciplines is even more differentiated in the academic agenda of the United States, where science is commonly distinguished from the humanities, social sciences, arts, law, and, not least, engineering and applied sciences. However, various initiatives increasingly attempt to bridge the various academic disciplines and strengthen the position of society as expressed in programs of "Science, Technology, and Society" (STS) at Harvard's Kennedy School (http://sts.hks.harvard.edu/), Stanford University (https://sts.stanford.edu/), and MIT (http://web.mit.edu/sts/), for example, or by the Center for Science, Technology, Medicine and Society (CSTMS) at UC Berkeley (http://cstms.berkeley.edu/research/sts/). This search for a common culture could be interpreted as a call for increased interdisciplinarity and transdisciplinarity to manage society's future challenges.

Each of the different scientific subsystems includes different modes of representation (e.g., conceptual or symbolic systems), types of reasoning, and verification. Interdisciplinarity may be seen as a merging of concepts and methods from different sciences, and it becomes apparent when concepts (from the theoretical core, see Sneed 1971) and methods from different disciplines are integrated. Generally, this works only for neighboring disciplines or in cases where a common language (e.g., the representation of concepts by mathematical variables and the relationship by integrated modeling) is possible (here we may speak about a cross-disciplinary structure). Mode I transdisciplinarity aspires to consistent relationships between sciences without a cross-disciplinary language and where interdisciplinary seems unfeasible (see Fig. 4, Disciplines).

Third, we can look at the framing of knowledge by different cultures. We consider culture as the set of implicit and explicit societal rules, (spiritual) belief systems, symbols and processes of valuation that underlie human interaction and the valuation of human, biotic, and abiotic entities. The icon in Fig. 4 indicates that the world's predominant cultures have been shaped by their religions (Geertz 1966). History and major political conflicts have demonstrated a tremendous need for us to contribute to a better understanding of strategies that enable peaceful relations among cultures (such as the Islamic and the Jewish religions). Cultures differ with respect to the rules of causation that are accepted. Whereas one may (more or less successfully) translate from one language to another, the same is not possible for cultures. This has been shown in an extraordinary intercultural project on the conception of cancer among the Maya of Guatemala and leading oncologists (Scholz 2012). Whereas the Maya explained the etiology of disease as an individual's state of disharmony with the natural, social, and spiritual world, Western oncologists take a cell-based genetic view. The anthropological concept of the emic/etic principle (Harris 1976), which states that the fundamental rules of one culture remain inaccessible to another, illuminates why we should not talk about integrating cultures but rather on relating cultures.

From a sociology of science perspective (Pickering 1992), we may also talk about cultures in science. Some cultures are "non-integratable" or "non-relatable" in the science system. For instance, communities of hermeneuts, neo-positivistic evidence-based epidemiologists, and chemical pharmacists follow different styles of validation, reasoning, language, communication, dressing, and behavior. We may even consider Nicolescu's approach of looking for a spiritual-philosophical meta-level to which seemingly incompatible disciplinary models may be integrated under the perspective of culture. Nicolescu is concerned with "recherches et etudes transdisciplinaire" (Nicolescu 2000) and thus relates modes of thought and cultures. Against the challenge of mastering the complexity of pressing, multi-layered real-world problems, Mode I transdisciplinarity (see "Appendix") may receive more attention in the future.

Fourth, different human systems such as individuals, groups, organizations, nations, etc. have different perspectives, values, and preferences. Two factors may be important here. On the one hand, we have to distinguish between a value-related and an epistemic perspective. The conflict of values leads to different preferences that may call for mediation (Susskind et al. 1999). If we look at the level of the human individual, conflicts may arise depending on social role, gender, personal history, and personality factors. This induces selective perception and different representations of one and the same world. Interest-based selective perception (Postman et al. 1948) notes that human systems (such as scientific disciplines) represent one and the same world with different data (Werner and Scholz 2002). On the other hand, we have to acknowledge that an understanding of conflict in transdisciplinary processes calls for going beyond the level of the individual. We have to take into account the interests of the whole hierarchy of human systems, ranging from the individual via the group, organization, or institution up to nations and supranational systems (such as the EU). One and the same person may show different interests, depending on his or her role. In other words, a mental model is an internal representation (i.e., a model) of a real-world situation that requires either verbal or non-verbal language to be communicated or shared with others and which can be neither objectively true nor fully accurate (Forrester 2009; Steiner 2013; Werner 2005). As pointed out by Steiner (2013), mental models are dynamic representations of a particular system or a specific problem. They evolve and change over time, and they differ from individual to individual, even among members of the same problem-solving team (Van Boven and Thompson 2003). Forrester (2009) and Gentner (2002) stress that mental models usually have serious shortcomings; they are based on incomplete information and include incoherence (i.e., internal contradictions). The challenge of a transdisciplinary process is to mediate between different mental representations as well as values in order to provide socially robust orientations (see below) (Environmental System Sciences 2006; Steiner 2008).

Fifth, transdisciplinary processes ask us to look at systems in an integrated, holistic way. The icon in Fig. 4 for systems represents water, air, and soil systems that must be integrated if we are to think about a sustainable transformation of an environmental system. Likewise, in medicine, specialized knowledge was historically segregated, at least to some extent by the organs (heart, vascular system, lungs, etc.), but current medical approaches call for a holistic view of the patient. This is strongly related to developing a substantiated, thorough understanding (the architecture of knowledge; see Fig. 3) that allows for sustainable action for all participants.

3. Egon Brunswik's Theory of Probabilistic Functionalism: how the architecture of knowledge might unfold in transdisciplinary processes?

The "supposed core of transdisciplinary processes" is knowledge integration. Hence, important questions to be considered are: What does it mean? How does it work? And how might we invoke it in an efficient and proper way? To answer these questions, we have to acknowledge where—i.e., for what systems—knowledge integration might take place. If we look at sustainable transitioning of societal systems, such as adaptation to climate change, it is clear that, at its best, the whole entity of social or human systems from the individual to human society must be considered.

From a development of science perspective, one may state that transdisciplinary processes call for new branches of knowledge or even disciplinary knowledge that may answer how knowledge integration, mutual learning, etc. may be described, analyzed, and—perhaps at least for some salient processes—measured.

We will briefly sketch two lines of research that may contribute to answering the above questions. One is Egon Brunswik's theory of probabilistic functionalism. The other consists of the emerging research on coupled human–environment interactions. Here the hierarchy—which assumes that biological and socio-anthropological evolution induce hierarchical levels of interacting human systems by upward and downward causation—allows for relating learning on a wide scope of human systems such as individuals, organizations, or societies.

Brunswik (1903–1953), a student of the physicist Moritz Schlick and the psychologist Karl Bühler, who both belonged to the Vienna Circle, was interested in the history of science and philosophy (Fischer and Stadler 1997; Hammond and Stewart 2001). He demonstrated his theory when working on visual perception (Brunswik 1952) to answer questions such as: How must an organism successfully function in an environment in which it may apprehend information only with high uncertainty? How does the visual system with seemingly poor physiological properties (including few cones and rods, a slow velocity of transfer of electro-chemical impulses, a blind spot, etc.) manage to construct a sufficiently reliable image of environmental objects? Brunswik took a functionalist perspective, including that a human system acquires only that information needed for successful performance, and followed the principle of evolutionary stabilization, which means that only those processes of knowledge production that are beneficial in a probabilist feedback system will be used in the long run (i.e., assuming that errors may be sometimes rewarded and proper actions penalized).

He acknowledged that any organismic human system has genuinely incomplete access to the uncertainty geared ("causal texture" of the) to a complex environment. Thus, his theory postulated that information acquisition is probabilistic and has to be stabilized or mediated by contextual or other cognized entities to provide representations that are good enough (satisfactory) to meet the needs of an organism. This principle of information acquisition was called vicarious mediation. Goldstein (2006) nicely described that Brunswik distinguished two levels of mediation: one, micromediation, is applied when specific information is missing (e.g., a specific precept is not accessible, e.g., as hidden by a blind spot) and has to be substituted by information from other cues. The other is macromediation, which becomes necessary, for instance, if all details may be seen well, but perspective, distance, or other constraints do not allow for a reliable image, and the very properties have to be derived from context variables.

Naturally, technical means (such as a microscope) may also help to provide better access to specific information.

For understanding and conceptualizing how organisms and human systems cope with a complex environment, Brunswik referred to the cue concept (Heider 1930; von Uexküll 1931). This concept goes beyond information or stimuli, as it refers to entities that are perceivable. Thus, a cue includes some meaning and can be considered a sign or signal that may be processed by an organism. The immune system might process information from cancer cells that include danger signals and that might induce activation (Gallucci and Matzinger 2001).

The distinction between proximal and distal cues is important when conceptualizing knowledge integration in transdisciplinary processes. When studying, for instance, barriers of sustainable transitions, the various stakeholders and representatives from different disciplines have varying access to partly overt and covert distal cues. The exchange of these proximal cues and reassessing the relationship (e.g., the causality) of these cues with respect to a "focal target variable" is of importance. Brunswik was aware that the acquisition and processing of cues depend on constraints under which information may be sampled. Thus, the organism is challenged to show context-sensitive adaptive functional cognition. Thus, we may hypothesize that local experts have specific strategies for acquiring and utilizing cues.

The sketched principles of the theory of probabilistic functionalism have been applied to judgment and (clinical) decision-making (Hammond 1954), aviation decisions (Kirlik 2006), group decision-making, nursing, etc. Scholz and Tietje (2002) presented a set of 11 methods that may be used to facilitate transdisciplinary processes in system representation, system evaluation, and system transition when using Brunswik's conception. The paper by Scholz et al. (forthcoming) elaborates why and how certain forms of knowledge integration of a study team or of a group of stakeholders and scientists who are participating in a transdisciplinary study can be conceptualized. This may be evident if salient system properties or criteria for evaluation can be represented by variables.

To the best of our knowledge, there are only a few studies that have actually measured in what form capacity building takes place in a transdisciplinary process. Hansmann et al. (2003) applied a pre/post experimental design to show that junior scientists (i.e., students at a master's degree level) get closer to local experts' judgments on the importance of different impact variables in a course of 4 months' participation in a transdisciplinary process. Discussions among the junior scientists and the (indirect) interaction with case experts clearly improved the cue validity, if the experts' knowledge is seen as a benchmark. The second study is the above-mentioned Walter et al. (2007) study that showed that participation in a case study improved knowledge about transdisciplinary transitions. Thus, there are methods that may prove effective for transdisciplinary processes by normal science means. Naturally, many stakeholders and scientists suppose that certain single events are caused by transdisciplinary processes. But given the multi-causality in complex environments, there are no (objective) methods that may prove to what extent the transdisciplinary process factually contributed.

Mode 1 and Mode 2 transdisciplinarity show similarities and dissimilarities. Both aspire to integrate knowledge and reasoning with respect to a meta-level, but the reference systems differ fundamentally (if we take a normal science perspective). Mode 2 refers to the successful development of a given human system. The issue is whether a company or the human species may have a good future or if humans can successfully adapt to a rapidly changing environment. Surviving in the market or avoiding collapse are typical valuation standards. The integration of intuitive understanding, concept-driven analyses (e.g., in presentation or public media), or experience- or data-based causation (explanation; see Fig. 4) and the triangulation of perspectives for capacity and consensus building, strategies for mitigation (mediation), and legitimization of key decision makers can be launched by multi-stakeholder discourses. Mode 1, by contrast, aspires to develop a meta-structure that allows for a more realistic description of material–biophysical and socio-cultural, epistemic structures, which are currently dealt with separately in a myriad of disciplines in the natural and social sciences, engineering, health sciences, and the humanities (see "Appendix"). The dream of a unity of science may remain a dream forever. Yet science may take up the challenge of striving to go beyond interdisciplinary by creating bridges between non-neighboring disciplines. The current approaches to conceptualizing and investigating inextricably coupled human–environment systems (Ostrom 2009; Scholz 2011) that—finally—call for integrated rationales from natural, social, and humanities reasoning may be viewed as a promising step in this direction. Linking Mode 1 and Mode 2 type research may become a serious challenge for sustainability research.

Methods of transdisciplinarity (methodology)

If transdisciplinarity is considered a methodology (of sustainable transitions), we may ask what methods should be included in the course of a transdisciplinary process. Scholz and Tietje (2002) distinguish between methods of (1) representing a system, problem or issue of interest, including methods of projection, i.e., methods that portray future states; (2) evaluating systems; and (3) transforming systems. The three clusters relate to phases of a transdisciplinary process. Since many transdisciplinary processes may be conceived as strategic means of sustainability management, it is not surprising that the main methods that may be applied and adapted to the practice of a transdisciplinary process have their origins in decision research, operations research, and planning sciences. Thus, the main comprehensive texts that describe methods for the three phases also include sections on problem definition and structuring, assessing performance measures for evaluation, or managing and conceptualizing uncertainty or risk (Friend and Hickling 2005; Gregory et al. 2012; Scholz and Tietje 2002).

With respect to complex real-world problems, the difference between symptoms and 'real' problems is often not obvious. Steiner (2011, 2014) outlined a method-based, collaborative, creative search for identifying (frequently) hidden 'real' problems. The method should be applied "… if innovation aims at comprehensive system improvements and changes in thinking paradigms, rather than simple, incremental changes" and supports problem definition and representation.

When we look at the system presentation, one challenge is joint problem representations. Often, the stakeholders (including the public at large) may well understand semi-quantitative methods such as material flowcharts, supply chains, or (impact variable-based) scenario analysis. However, representation may also be done by simple iconic representations such as with "rich pictures" (Bell and Morse 2013). For the evaluation, we may utilize various methods from multi-attribute utility theory (MAUT) or risk assessment. However, good semi-quantitative methods for assessing vulnerability or resilience are missing (Scholz et al. 2012). This is important, as it is not the assessment of a threat, i.e., risk, that is at the core of sustainability evaluation but an assessment of adaptive capacity after a negative event has happened. With respect to the transformation of systems, it is important to include the stakeholders from the very beginning, i.e., in the initiation phase. Ideally, the methods should become formative, in the sense that the process of applying the method improves the system's design and performance.

Figure 5 presents exemplarily how different methods may be integrated and how stakeholders may be involved in a transdisciplinary process. The different steps of defining (0) the guiding question and (1) system boundaries; constructing a (2) system model [based on different impact variables collected in a multi-stakeholder process (Hansmann et al. 2009)] and (3) variants of future development using, e.g., the method of formative scenario analysis; (4) sampling multi-attribute evaluations from different stakeholder groups (MAUT II) and from science

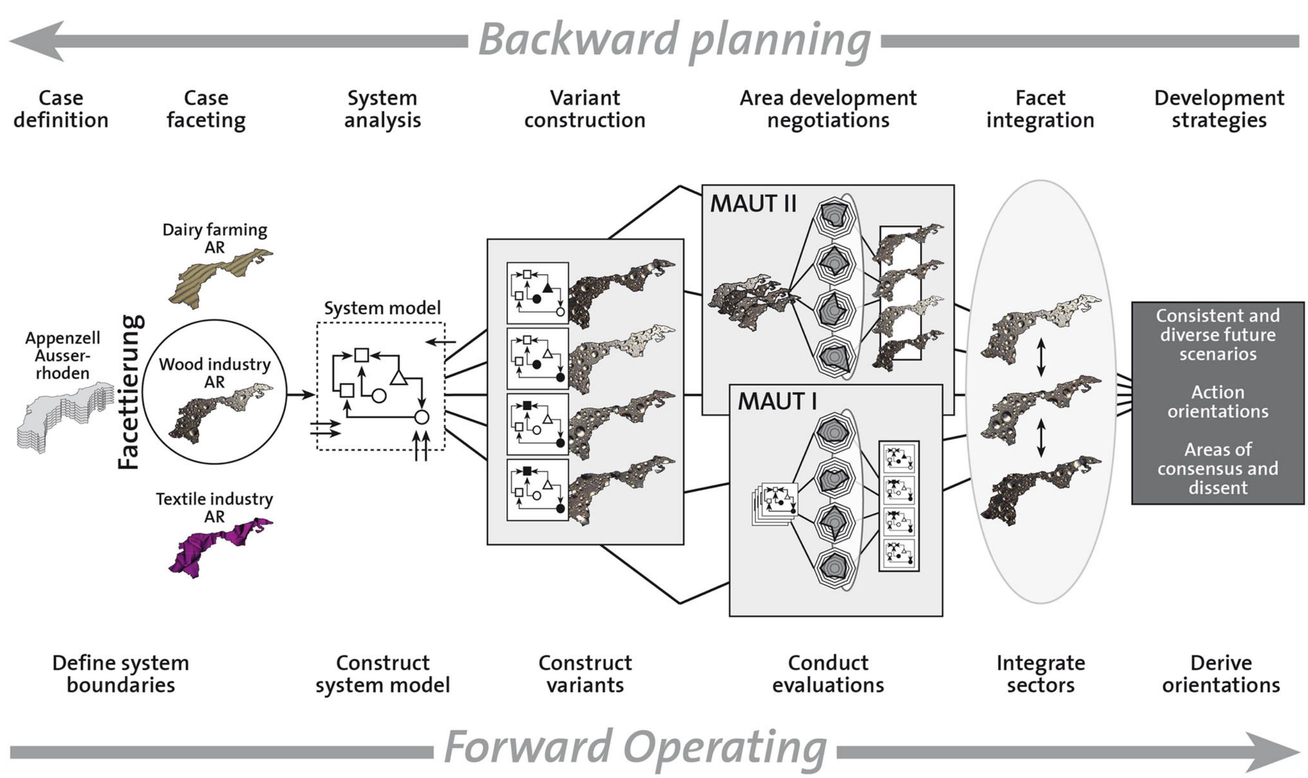

Fig. 5 Knowledge integration by methods of system representation and system evaluations (the area development negotiation method, adapted from Scholz and Tietje 2002, p. 265)

(MAUT I); (5) looking for integration of the different facets (Wiek and Walter 2009); and (6) deriving robust orientations are conducted jointly with the stakeholders (see Fig. 1). Figure 5 stresses that transdisciplinary processes have to follow a backward planning principle. This means that the questions regarding which evaluation criteria, stakeholders, scenarios, system and system boundaries are taken into consideration depend on the guiding question and on what scientists and practitioners aim to achieve as a result of the process. If the core objective is, for instance, the assessment of consent and dissent among stakeholders, then the scenarios must be constructed according to a hypothesis formulated according to this perspective. This may be seen as an example of applying hypothesis testing as experimental action research usually does. We also should mention that it is often open to debate whether scientific (data- and method-based) MAUT I or (judgment-based) MAUT II is correct or superior.

Functions of transdisciplinary processes (functionality)

Scholz (2011, p. 385) distinguishes four functions of transdisciplinary processes as follows: (1) societal capacity building as a basis for sustainable transitions; (2) consensus building; (3) analytic mediation as a policy process and alternative to expensive litigation or administratively focused arbitration, where scientists serve as facilitators; and (4) legitimizing by informal power, which reveals the involvement of science knowledge in policy processes.

Societal capacity building, which may be considered the primary goal, is operationalized by constructing socially robust knowledge. Consensus building is related to the normative side as group norms or societal norms are formed. Both analytic mediation and legitimization can be seen as variants of an instrumental function.

Outcomes of transdisciplinarity

As transdisciplinarity differs from consultancy, recommendations are not seen as the ideal product of a transdisciplinary process. We instead aim to generate socially robust orientations (Gibbons and Nowotny 2001; Nowotny et al. 2001). Whereas the nature of recommendations involves a “you should”, orientations provide patterns of causation of the kind “if you do this, a main impact/rebound effect will be this.” The stakeholders who collaborated with the scientists in constructing the orientations may adapt and utilize the orientations in their decision-making process.

A socially robust orientation (1) enables state-of-the-art scientific knowledge for robust actions and decisions; (2) provides a basis for consensus, thus it must be understandable, acceptable, and communicable by all stakeholder groups; (3) acknowledges the uncertainties and incompleteness inherent in any type of knowledge about processes of the universe; (4) generates processes of knowledge integration of different types of epistemics (e.g., scientific and experiential knowledge, utilizing and relating disciplinary knowledge from the social, natural, and engineering sciences); and (5) considers the constraints resulting from the context for both generating and utilizing knowledge.

This implies that it is not the decisions and actions but rather the new knowledge which is integrated in processes of mutual learning and consented orientations for making sustainable decisions that is the main outcome of a transdisciplinary process. We should note that, in contrast to a problem-solving approach (e.g., “We have solved a problem and found a solution; consequently, we need to find an implementation strategy!”), an ideal transdisciplinary process does not call for implementation. The outcome for practice is the improved decision-making capacity as a form of empowerment (Walter et al. 2007). In its ideal, this capacity is built during the transdisciplinary process and does not require a post hoc implementation.

But what are the outcomes for science of a transdisciplinary process? What type of new scientific knowledge may emerge from interacting with practitioners that is not likely to arise otherwise, ideally? Our answer is that this depends on the type of sciences. Let us look at what we may call interface sciences. These sciences have to consider how human systems react and interact with technological, human-made systems. Health sciences or the myriad of planning sciences can serve as examples. We may find conceptions similar to those found in transdisciplinarity in these disciplines. Examples are community-based participatory action research (Leung et al. 2004) or the planning cell approach (Dienel 1970/1991; Renn et al. 1993). The latter is at the interface of public participation. The presented ideal type of transdisciplinarity may be seen as a theoretically elaborated extension of these approaches.

When we consider applied sciences such as business sciences or system-based (natural) sciences such as agriculture, applied ecology, energy, or risk research, research conducted in a transdisciplinary process might produce contributions to the subject field. A characteristic of transdisciplinarity is that it promotes new links among disciplines because it starts from a real-world problem and thus turns the scientific process upside down. We can take the paper “Technical safety vs. public involvement” (Krutli et al. 2010) as an example. This paper emerged from relating a classical case of safety-based risk assessment (Junker et al. 2008) to social science research on perceiving the threats and benefits of nuclear energy (Krütli et al. 2012). The latter stresses the need for public participation if societally accepted solutions for nuclear waste proposals are wanted. This idea emerged from a Swiss–Swedish transdisciplinary multiple case study (the stakeholder oriented publications are Scholz et al. 2007; Schori et al. 2009).

But transdisciplinary processes might also contribute to groundbreaking innovation and perhaps even to a reorganization of science. The conception of coupled human–environment systems (HES) can be taken as an example. After about 15 years of running "interface case studies" at the ETH–Zurich, it became clear that such studies need a conceptualization of inextricably coupled HES. A challenge here was that the impacts of different human systems such as an individual, group, organization (e.g., a company or NGO), national agency/institution, etc. had to be described. Interacting with natural environmental systems, for instance, these systems (e.g., a CEO representing his/her company or an individual arguing as a parent) have different rationales. To understand and describe these interactions, a framework of coupled systems was developed, and to work with a coherent conception of environment and the interactions among the hierarchy levels of human systems, a new cell-based definition of human systems was invented (Scholz 2011). A human system was defined as the activities of all living cells which emerged from the zygote and their interactions that may be assigned to a human system; thus, the environment may be defined simply as the universe minus these cells. Naturally, such a conception might also have developed without transdisciplinarity, but the history and the multitude of case studies presented in Table 1 of Part 2 of this paper document how close practice and the development of theory was connected in developing the HES framework.

Organizational constraints of an ideal transdisciplinarity process

A transdisciplinary process needs not only social and scientific goals but also personal and financial resources. A basic issue is that transdisciplinary processes hardly allow for restrictive consultancy as does contract-based research. The project should be designed in such a way that scientists maintain their independence. This holds true, in particular, if scientists work on highly value-loaded, societally contested issues. Let us consider as an example the case of nuclear waste disposal. A multi-stakeholder process requires that the facilitators and co-leaders of the process receive acceptance from all stakeholders, ranging from nuclear industry advocates and representatives to leaders of the anti-nuclear movement. Thus, the only way to accept funding from the nuclear power industry has been for the research topic to be formulated in a way that was non-competitive in nature and that allowed sponsorship to be applied without endangering the independence of the scientific research team.

Outlook

After presenting the historical development of transdisciplinarity, we introduced the Zurich 2000 Mode 2-related conception of transdisciplinarity. Within this paper (Part I), we focused on the ideal type of transdisciplinarity. The theoretical foundation of transdisciplinarity offered in Part I provides the basis for discussing the obstacles, challenges, and constraints encountered in real-world applications of transdisciplinary processes. Part II deals with the constraints and obstacles that are encountered when running transdisciplinary processes. Part II will outline the specifics of this real type of transdisciplinarity based on the experiences of 41 mid- and large-scale transdisciplinary studies on sustainable transitions of urban and regional systems, organizations, and policy processes, which were conducted by seven universities as members that have participated in a discourse on transdisciplinarity for teaching and research since 1993. Based on this survey, we present a comprehensive discussion about the strengths and weaknesses of the theoretical foundations as the practice and the relation and of the ideal and the real at the end of Part II. Seven propositions that highlight research needs and identify deficiencies and priorities for future research on transdisciplinarity will conclude the second part.

Appendix

From interdisciplinarity to Mode 1 and Mode 2 transdisciplinarity

The discussion on the dysfunctionality of closed disciplinary boundaries and the role of society began at the 1970 conference on interdisciplinarity (Apostel et al. 1972). At that time, it became evident that the increasing sociotechnical complexity in developed Western countries called for new knowledge and values. The traditional academic system and prevailing concepts such as "man as rationale being" became obsolete and were replaced by the conception of "man as bounded rational being" (Scholz 1983; Selten 1990; Shulman and Carey 1984; Simon 1982). The societal prestige and reputation of universities diminished, as expressed by the saying, "Society has problems, whereas universities have departments" (Lind 1999). Student and academic activists demanded social leadership and a fundamental transformation of universities. Those who considered the university an organization "producing scholars and scientists" and who staunchly defended "the discipline as a cornerstone of intellectual training" (Gass 1972) were severely criticized. Students and critical academic minds wanted to take on social leadership.

Erich Jantsch, a visionary Austrian physicist and system theorist, stated, "the university has to become a political institution in the broadest sense, interacting with government … and industry in the planning and design of society's system" (Jantsch 1972, p. 102). Jantsch criticized the narrow technological approach that sciences suggested using to cope with social crises and noted, "the classical single-track and [linear] sequential problem-solving approach itself becomes meaningless" (Jantsch 1972, p. 99). His critique also included the autonomy of the sciences, the cultivation of science for science's sake, and the tendency of some major sciences (such as physics and mathematics) toward imperialism. Jantsch considered "science, education and innovation, above all, as general instances of purposeful human activity" that have "dominant influence in the development of society and its environment" (Jantsch 1972, p. 99). These societal trajectories were seen as the major drivers for "co-ordination in the education/innovation system" to be called "*transdisciplinarity*" (p. 105).

An opposite and inner-science notion of transdisciplinarity was provided by epistemologist, biologist, and cognitive developmental psychologist Jean Piaget's (Piaget 1972) view on the epistemology of interdisciplinary relationships. Piaget was acknowledging that an integration (or merging) of concepts and methods from different disciplines works only between neighboring disciplines that have similar structures, data, and methods and modes of validation. In line with finding a unity of knowledge, Piaget considered "full transdisciplinarity"to be a meta-(system) knowledge that includes operating and regulating structures of systems in a general way.

The physicist Basarab Nicolescu (see text) aligns with Piaget, but postulates a spiritual super-level as an integrating entity (Nicolescu 2002, 2006, 2014). Inspired by his insights into quantum physics and theories such as multiple-world theory (Nicolescu 2014) and the "superposition of quantum 'yes' and 'no' states'" (Nicolescu 2006, p. 143), he stressed the difficulty of integrating the theory of relativity and the theory of quantum mechanics, as this is in contrast to the principle of the excluded middle (his approach to Mode 1) with the principle of the included middle. Nicolescu states that it is difficult for him "to understand why 'joint problem solving' must be the unique aim of transdisciplinarity" (Nicolescu 2006). Instead, he focuses on the need for knowledge integration in science. He considers "classical" logic (which operates with binary "true/false" states, i.e., the axiom of the excluded middle) incompatible with the findings of quantum physics. When referring to what is presumably the most important theorem related to the philosophy of science—Gödel's incompleteness theorem—he is looking for a unity of knowledge. Here, he suggests a "spiritual meta-level" which, at its core, postulates a God-like entity, as a unifying meta-level.

Today, we may better acknowledge the differences in roles and functions of the different modes of doing science. The future will show what roles disciplinarity (Abbott 2002), interdisciplinarity, and transdisciplinarity might find, and whether a delta science (which supplements alpha science [i.e., humanities], beta sciences [i.e., natural sciences] or gamma sciences [i.e., social sciences]) or transdisciplinarity colleges or transdisciplinary universities might develop (Scholz and Marks 2001).

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