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Abstract

This paper explores how transdisciplinary knowledge integration can be facilitated in the context of integrated assessments (IAs) and vulnerability assessments (VAs) of climate change. Even though knowledge from a wide range of natural and social science disciplines must be integrated in such transdisciplinary assessments (TAs), the actual process of integration is rarely addressed explicitly and methodically. This paper reviews the methodological *status quo* of IAs, VAs and TAs in general, develops concepts for speaking about knowledge integration, suggests how knowledge integration could be facilitated and then applies these considerations to four cases taken from the domains of IA and VA. Knowledge integration is conceptualised into the two subsequent phases of the *elaboration of a shared language* and the *design of a methodology.* Three devices for facilitating knowledge integration are put forward: (*i*) *semantic ascent* or the shift from speaking in a language to speaking in a meta-language about the former, (*ii*) *formalisation* or the translation of statements made in ordinary or technical language into a formal language, and (*iii*) *knowledge integration methods*, which are methods that provide a meta-language for speaking about the knowledge to be integrated and organise the process of integration. It is found that semantic ascent is a useful device in those assessments in which it is difficult to directly elaborate a shared language. Formalisation can also contribute to the elaboration of a shared language, in particular in those cases in which concepts overlap non trivially in their meanings, as it is the case for vulnerability and related concepts. More emphasis should be placed on the development of iterative knowledge integration methods as iteration is crucial in order to benefit from the mutual learning during the course of the assessment.

1 Introduction

Transdisciplinary assessments (TAs) address problems that cannot be solved by a single scientific discipline, nor by science alone. People from different disciplines and from outside of science all possess unique knowledge about distinct aspects of the problem and need to collaborate to design and implement effective solutions. Integrated assessment (IA) and vulnerability assessment (VA) are two variants of TA which are prominent in the context of problems associated with climate change, such as how to mitigate greenhouse gas emissions and how to adapt to climate impacts.

TAs are facing conceptual and methodological challenges. The first challenge usually encountered is that it is not exactly clear what the problem to be solved is (Funtowicz and Ravetz, 1993; Scholz and Tietje, 2002). Participants and contributing disciplines use alternative and sometimes incompatible concepts to describe the problem and its solution. The problems are difficult to understand, because they are rooted in the complex interactions between the human and the environmental systems. In contrast to disciplinary problem solving, no standard "off-the-shelf" methods are available. Each problem addressed has unique features and requires the development of its proper approach; knowledge from various scientific disciplines and from outside of science must be integrated into an appropriate methodology.

VAs in particular are facing additional conceptual and methodological challenges. Within the climate change scientific community the concept of vulnerability is used in a variety of different meanings, often not defined properly or even used without definition (Brooks, 2003; Ionescu *et al.*, 2005). As a result, a considerable diversity of methodologies is applied for assessing vulnerability (Füssel and Klein, 2006; Adger, 2006; Eakin and Luers, 2006). Within the related scientific communities of food security, natural hazards, poverty and development, the concept is also used yet in a variety of other meanings (*e.g.*, Birkmann, 2006).

In order to address these challenges, scholars involved in TAs are increasingly adopting a meta-perspective on their own work. Not only the "real world" is subject matter of scientific analysis but also the concepts and methodologies used for studying it. A growing body of literature reviews, compares and classifies methodologies applied in the IA of climate change (*e.g.*, Weyant *et al.*, 1996; Rothman and Robinson, 1997; Schneider, 1997; Tol and Fankhauser, 1998; Toth and Hizsnyik, 1998; Edenhofer *et al.*, 2006). The diverging definitions of vulnerability are analysed, methodologies for assessing it compared, compendia of methods compiled and overarching frameworks proposed (*e.g.*, Brooks, 2003; O'Brien *et al.*, 2004; Ionescu *et al.*, 2005; Füssel and Klein, 2006; Füssel, 2007; O'Brien *et al.*, 2006).

While the work carried out from the meta-perspective has provided useful overviews of the methodological state of the art of IA and VA, it exhibits two shortcomings. First, the meta-perspective itself is suffering from conceptual difficulties; concepts for speaking about and comparing between methodologies of TAs are lacking. Second, the work has focused on analysing methodologies of past assessments and not addressed the problem of integrating knowledge for designing new methodologies, which is, I believe, *the* crucial step in transdisciplinary problem solving. The actual process of integrating knowledge is hardly addressed explicitly; the participants of transdisciplinary problem-solving efforts usually come together and *somehow* put together what they know. Concepts for speaking about the integration of knowledge into a methodology adequate for solving the given problem are lacking.

This paper aims at extending the shift towards the meta-perspective by providing a more robust conceptual basis for transdisciplinary knowledge integration. It addresses the question of how scholars from different disciplines can effectively integrate their knowledge for solving a given problem and what methods could be applied for facilitating this process. Based upon disciplines that study knowledge and knowledge representation, such as philosophy of science, linguistics, semiotics, computer science and cognitive science, this paper develops *meta-concepts* for speaking about transdisciplinary knowledge integration. These meta-concepts are then be applied to discuss four cases of knowledge integration from the domains of IA and VA.

Note, however, that this paper does not aim at contributing to the above-mentioned disciplines, nor does it aim at unifying scientific disciplines. Its goal is a pragmatic one, namely to support the practitioners of TAs in the process of integrating knowledge for solving "real world" problems. I am not concerned with the long-term evolution of the scientific system, but with the short-term collaboration between members of different disciplines to solve a common problem. The hypothesis is that this collaboration can be facilitated and some of the conceptual and methodological challenges TA is facing today can be resolved by providing a sound conceptual and methodological basis for transdisciplinary knowledge integration.

The rest of the paper is organised as follows: Section 2 reviews the state of the art of TA in general and IA and VA in particular. Section 3 takes a closer look at the challenges involved in designing methodologies, reviews the work carried out from the meta-perspective and motivates the approach taken in this paper. Section 4 and 5 develop meta-concepts for speaking about scientific knowledge and knowledge integration, respectively. Section 6 explores how knowledge integration could be facilitated. Section 7 applies the developed concepts to four cases taken from the domains of IA and VA. Section 8 comparatively discusses the cases and Section 9 concludes the paper.

2 Transdisciplinary assessments

2.1 From disciplinary research to transdisciplinary assessment

A number of labels such as multidisciplinary, interdisciplinary, transdisciplinary or problem-orientated have been attached to research that does not take place within a single scientific discipline. To understand these labels, first some notion of a scientific discipline has to be gained. There are many diverging definitions in the literature, most of which define the concept on a social and a cognitive dimension. On the social dimension, scientific disciplines are defined in respect of the existence of institutions such as university departments, education programmes, conferences and journals. On the cognitive dimension, scientific disciplines are defined in respect of their members sharing certain cognitive structures, such as concepts, theories, methods and problem definitions. Section 4 will discuss some of these shared cognitive structures in more detail. Note that other concepts, like research field, community, paradigm (Kuhn, 1970) or research programme (Lakatos, 1970) are also used to refer to the organisational units of science. Here, I will use the term discipline because it is intuitively the clearest notion. For a more comprehensive discussion on scientific disciplines and associated concepts see, for example, Klein (1990) and Bechtel (1986).

The organisation of science into disciplines is not static, but a living product of the two antithetic processes of differentiation and integration (Klein, 1990, p. 43). Disciplines have emerged historically (Mittelstraß, 2005). The differentiation of science into today's disciplines began in the 19th century and has been key to the rapid technological advancement of modern society (Stichweh, 1994). Highly specialised terminology and methodology makes communication and problem solving within the realm of a discipline efficient. Despite the success of disciplinary research, there has always been the urge and the need to overcome the disciplinary organisation of science (Klein, 1990, pp. 40–54). For one reason, cooperation between disciplines is an important source of innovation for advancing individual disciplines. For another reason, some problems cannot be solved by the knowledge of one discipline alone.

Here, I am not concerned with the long-term evolution of the scientific system, but with the short-term collaboration between members of different disciplines as it takes place, for example, within a joint research project. Since the 1970s this heterogeneous collaboration itself has been studied conceptually (Klein, 1990) and, in recent years, also empirically (*e.g.,* Conrad, 2002; Röbbecke *et al.*, 2005). The labels multidisciplinary, interdisciplinary and transdisciplinary have been used for referring to different forms of collaboration, albeit by different authors differently. See Klein (1990, pp. 55–73) and Balsiger (2004) for overviews.

The simplest form of collaboration between disciplines is often called multidisciplinary. Thereby, an issue is regarded from the perspectives of various disciplines, but each discipline produces its own results (Heckhausen, 1987). Multidisciplinary research "is essentially additive not integrative" (Klein, 1990, p. 56). A more elaborate form of collaboration is interdisciplinary research, in which a common problem is solved jointly by different disciplines; knowledge from several disciplines is not simply added up but integrated. Interdisciplinary research produces one common result, rather than segregated disciplinary perspectives.

Collaboration that not only integrates disciplinary knowledge, but, at the same time, aims at transcending disciplinary boundaries, has been coined transdisciplinary research by Mittelstraß (1987). Mittelstraß sees transdisciplinarity as the "true form" of interdisciplinarity. It is a research principle that aims at overcoming disciplinary insularity in those cases in which disciplinary concepts and methods do not match the problems to be solved (Mittelstraß, 2005). This is particularly true for problems that are raised outside of the scientific system, such as, *e.g.*, for problems associated with climate change or environmental change in general. Transdisciplinarity is, however, not seen as substitute to disciplinarity, but as a complementary *problem-orientated* research principle; it means lateral thinking against established disciplines, methods and institutions without however aiming at creating new disciplines.

The concept of transdisciplinarity is also used in a wider sense to refer to the collaboration between scientific and non-scientific participants (Balsiger, 2004). In this understanding knowledge integration also needs to respect traditional or tacit knowledge (Komiyama and Takeuchi, 2006). Since enabling extra-scientific stakeholders to participate in the research process is a major issue, transdisciplinary research is sometimes also called participatory research. This wider understanding of transdisciplinarity is also mirrored in the concepts "mode 2" and "post-normal" science. The concept "mode 2" was introduced by Gibbons *et al.* (1994) to express that knowledge for solving societal problems is not produced by science alone, but co-produced by science, policy and the private sector. The concept "post-normal" science was introduced by Funtowicz and Ravetz (1993) in opposition to the classical "unexciting, indeed anti-intellectual routine" way of scientific problem solving coined 'normal science' by Kuhn (1970).

Transdisciplinary problem-solving in the wider sense is frequently also labelled *assessment* instead of research. Examples are integrated assessment, vulnerability assessment, environmental impact assessment, technology assessment and sustainability assessment. The term 'research' is reserved for the intra-scientific practise of problem-solving whereas the term 'assessment' refers to the joint problem solving amongst science and other stakeholders. In assessments, problem-solving is driven by the purpose "to inform policy and decision-making, rather than to advance knowledge for its intrinsic value" (Weyant *et al.*, 1996, p. 374). However, scientific interests also contribute to the agenda setting (Rothman and Robinson, 1997; Jahn, 2005).

This paper focuses on integrated assessment and vulnerability assessment as two particular kinds of transdisciplinary assessments. The concept of transdisciplinarity is used in the sense of Mittelstraß (1987). The focus lies on the intra-scientific aspects of the assessments, in particular on knowledge integration. The extra-scientific aspects, though essential, fall outside the scope of this paper.

2.2 Integrated assessment

The label integrated assessment appears in the context of environmental research since the 1970s and has become popular in the context of climate change since the early 1990s (Rotmans and van Asselt, 1996). There are many definitions of IA in the literature, most of which share the features that were discussed in the last Subsection, such as problem-orientation, participation and transdisciplinary knowledge integration. For example, Rotmans and Dowlatabadi (1998) define IA as "an interdisciplinary process of combining, interpreting and communicating knowledge from diverse scientific disciplines". The Integrated Assessment Society (TIAS) sees IA as a "meta-discipline" that organises the integration of knowledge from heterogeneous domains (TIAS, 2005). For further definitions and discussion on these, see, *e.g.*, Parson (1995); Rotmans and van Asselt (1996); Rothman and Robinson (1997) and Tol and Vellinga (1998).

In this paper, I will use IA in the very wide sense of being a TA for addressing problems associated with climate change. The United Nations Framework Convention on Climate Change (UNFCCC) names mitigation and adaptation as the two generic options for achieving its "ultimate objective", that is, the "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (Article 2). Mitigation refers to any "anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases" (McCarthy *et al.*, 2001, p. 990). Adaptation refers to "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (McCarthy *et al.*, 2001, p. 982).

While in the 1990s the academic and policy focus lay on mitigation (Kates, 1997), in the last couple of years, interest in adaptation has increased significantly (Burton *et al.*, 2002). This is due to the fact that climate change is being observed and evidence is strong that humans are, to a significant extent, responsible for the change (IPCC, 2007). Furthermore, due to the delayed response of the climate system, the climate will continue to change for decades to centuries, no matter how strong the mitigation efforts are. However, it is also understood that adaptation will not suffice (Burton *et al.*, 2002) or only be possible at high social and economic costs (Stern, 2007). Today, it is widely agreed that adaptation and mitigation are complementary strategies (Klein *et al.*, 1995).

Within IA a wide range of analytical and participatory methods are applied. Analytical methods include modelling, scenario analysis and risk analysis. Participatory methods include expert panels, focus groups, and the Delphi method. Here, I will focus on the analytical methods, in particular on modelling.

Computer models are important methods in the IA of climate change. Due to the large temporal and spatial scales of the problems considered, it is often not possible to conduct experiments or to measure *in situ*. So called integrated assessment models (IAMs) are composed of interacting sub-models that represent various natural and social subsystems and aim “to describe as much as possible of the cause-effect relationships between phenomena from a synoptic perspective” (Rotmans and Dowlatabadi, 1998). This means that, ideally, IAMs should cover all interacting processes that cause a problem. In practise however, the causal structure with its many feedbacks has to be simplified depending on the specific perspective taken and the resources available. A “trade-off between breadth and depth in any specific assessment” must be reached (Rothman and Robinson, 1997, p. 26). Thereby, the sub-models representing social, economic and environmental processes should be well balanced (Rotmans and van Asselt, 1996; Houghton *et al.*, 1997; Tol and Vellinga, 1998). Usually reduced-form models or models of intermediate complexity are used as components of IAMs (Schellnhuber and Toth, 1999). See Rotmans and Dowlatabadi (1998) for a recent overview of IAMs built in the climate change context.

There is no single configuration of sub-models that is *the* solution to a problem. Different groups prioritise different aspects of the problem, take into account different processes or choose different models (or parametrisations) for representing the same process. A “complete understanding” in the sense of traditional natural science does not exist (Rothman and Robinson, 1997). For each new problem raised, the relevant processes need to be identified and the available models about them selected and configured appropriately.

So far, IA modelling has focused on mitigation, and taking adaptation into account remains a key challenge (McCarthy *et al.*, 2001, p. 120). First steps towards this end have been taken by the two recent EU projects ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling; Schröter *et al.*, 2005) and DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise; Hinkel and Klein, 2007). A comparison of the methodologies of both projects is given in Hinkel (in press).

2.3 Vulnerability assessment

Another special kind of transdisciplinary assessment popular in the climate change scientific community is vulnerability assessment. The concept of vulnerability was introduced to capture why different systems (*e.g.*, regions, sectors or groups of people) are affected differently by climate change (Turner *et al.*, 2003). The differences are due to two broad reasons. First, changes in key climate variables are unequally distributed across the globe, that is, different systems are exposed differently. For example, temperature rise is projected to be greater in higher latitudes than in lower latitudes (Houghton *et al.*, 2001). Second, systems differ in their internal responses to changes in climate variables. For example, a coastal community in the Netherlands might have sufficient financial and technical means to respond to sea-level rise by building dikes, while a coastal community in Bangladesh might not be able to do so. The internal responses are more difficult to understand and many concepts related to vulnerability such as, *e.g.*, sensitivity, coping capacity, adaptive capacity and resilience, have been introduced for analysing these.

Even though vulnerability and related concepts are widely used, they are not defined consistently in the literature. The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes" (McCarthy *et al.*, 2001, p. 995). This definition, however, is rather vague and therefore difficult to make operational, in particular because the defining concepts themselves are vague. As a consequence, many alternative definitions have been but forward.[1] Other scientific communities such as food security, natural hazards, poverty and development, use the concept in their own meanings. For recent summaries on the state of the art of VAs see Adger (2006) and Eakin and Luers (2006).

One source of the conceptual diversity is that VAs are actually carried out for very different purposes (Burton *et al.*, 2002; Füssel and Klein, 2006; Smit and Wandel, 2006; Patt *et al.*, in prep.). From the mitigation perspective, VAs are carried out to inform policy makers about the potential impacts and to establish targets and policies to prevent "dangerous" climate change. The problem addressed is how much mitigation is needed to avoid major vulnerabilities. Most of the vulnerability work synthesised by the IPCC was carried out from this perspective (Burton *et al.*, 2002). From the adaptation perspective VAs are carried out to prioritise resource allocation to particularly vulnerable groups or regions, to recommend adaptation measures or to develop concrete adaptation policies. The problems addressed are which systems are particularly vulnerable and what can be done to reduce these vulnerabilities.

While so far the different scientific communities have been mostly working in isolation (Thomalla *et al.*, 2006) an increasing need to bridge between approaches and scientific communities is recognised. On one hand, reducing the vulnerability of local communities to poverty, food insecurity and natural hazards needs to take into account the changing climate (UNDP, 2002; ISDR, 2005). On the other hand, the design of climate change adaptation policies needs to build upon local experiences, because the most efficient vulnerability reduction often takes place locally (IISD *et al.*, 2003; Sperling and Szekely, 2005; IATF/DR, 2006; Schipper and Pelling, 2006). Furthermore, vulnerabilities to climate change greatly depend upon, and are related to, vulnerabilities to other kinds of environmental and also socio-economic changes, like for example, changes in world market prices (O'Brien and Leichenko, 2000).

A great methodological diversity can also be found in VAs, which is not surprising given

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[1] Brooks (2003, p. 5) notes that there are even inconsistencies within the TAR, *i.e.* between the above cited definition and the definition given in Chapter 18 (Smit *et al.*, 2001).

the diversity of definitions and the involvement of several scientific communities, as well as the different purposes, scales and types of systems considered. Roughly, methodologies can be distinguished into “top-down” approaches carried out more from the mitigation perspective and “bottom-up” approaches carried out more from the adaptation perspective (Dessai and Hulme, 2004). Similar distinctions have also been made by other authors, such as “biophysical” versus “social vulnerability” assessments (Brooks, 2003), “first generation” versus “second generation” assessments (Burton *et al.*, 2002), “end-point” versus “starting-point” assessments (Kelly and Adger, 2000) and “outcome” versus “context” vulnerability assessments (O’Brien *et al.*, 2006). These distinctions are increasingly blurred; hybrid approaches are becoming more frequent (UNFCCC, 2006; Eakin and Luers, 2006).

The top-down methodologies have their roots in the fields of climate change and climate impact assessment. The focus lies on the biophysical aspects of vulnerability. Generally, methodologies consist in the development of climate scenarios, which then are fed into models of biophysical systems followed by a socio-economic impact and adaptation assessment. Indicator based approaches are also popular (UNEP, 2001; Brooks *et al.*, 2004). See Kates (1985) and the IPCC technical guidelines (Carter *et al.*, 1994) for systematic overviews of these methodologies.

The bottom-up methodologies have their roots in the fields of natural hazards, food security and poverty. The focus lies on the social aspects of vulnerability. Generally, methodologies consist in conducting case studies on the level of local communities; social conditions, institutions and the perception of vulnerability are thereby emphasised.

3 Transdisciplinary methodology

This section takes a closer look at the challenges involved in designing methodologies of TAs, current efforts to address these challenges by adopting a meta-perspective on transdisciplinary work and the general problem of transdisciplinary integration.

3.1 Methodologies of transdisciplinary assessments

The process of transdisciplinary problem solving differs from that used in disciplinary research and involves some unique conceptual and methodological challenges. In the literature there are many general descriptions of this process; see, *e.g.*, Rotmans and Dowlatabadi (1998) for one from an IA point of view, Schröter *et al.* (2004) for one from a VA point of view, and Klein (1990, pp. 188–195), Burger and Kamber (2003, pp. 65–67) and Jahn (2005) for ones from a general TA point of view. Here, I list some of the features that are common to these descriptions.

The very first challenge encountered in the problem-solving process is that it is usually not clear what exactly the problem is. Generally, it is not obvious how the complexity of the “real world” can be reduced and structured into a scientific problem. Different participants of the problem-solving process conceptualise the problem differently, because they come from different disciplinary backgrounds or hold different stakes. Funtowicz and Ravetz (1993) name high stakes and high uncertainty as the characteristic properties of TAs. Since it is disputable what exactly the problem is, Funtowicz and Ravetz

(1993) speak of societal issues rather than problems and Scholz and Tietje (2002) of ill-defined problems.

Even when the problem has been identified, there is no single method nor are there ready-made methods that can be taken off the shelf. Each problem addressed has unique features and requires its proper approach. Problem solving begins with the selection and configuration of methods from distinct knowledge domains. For example, the assessment of the vulnerability of ecosystem services to global change carried out by the ATEAM project (Schröter *et al.*, 2005) consisted in the development of various scenarios, workshops to identify stakeholders' preferences, statistical analysis of socio-economic data and simulation experiments with various ecosystem models. The particular configuration of methods, data, people, *etc.*, that are involved in solving the problem is usually called *methodological approach*, *integrated methodology*, or just *methodology*[2] of the assessment. See Hinkel (in press) for a more detailed analysis of methodologies of TAs.

Methodologies are not methods. A method is a specification of a general problem-solving process that is applicable to several cases and makes problem solving reproducible. Contrary to this, a methodology is specific to the problem addressed; it is generally not possible to transfer a methodology to another case.

Methodologies are generated reflexively, that is, they are developed, applied and evaluated in parallel (Euler, 2005). A significant amount of time is usually spent on the design and re-design of the methodology. Methods are transferred from one discipline to another, composed from disciplinary ones, or developed from scratch. Since the problem perception is bound to change during the course of the project, it is usually necessary to iterate between problem definition, development of the methodology and its application several times.

Generally, it is difficult, often impossible, to verify methodologies and the results produced, because the classical means of verification, *i.e.* doing experiments in the lab or measuring *in situ*, are lacking. The results produced are statements that can only be verified in the far future or are of statistical nature, which means that they are in principle not verifiable. Because of these limitations, there is an ongoing debate on quality criteria for methodologies of TAs (Gibbons *et al.*, 1994; Funtowicz and Ravetz, 1993; Cash and Clark, 2001; Cash *et al.*, 2003).

In the histories of IA and VA, methodologies have grown in complexity in that increasing numbers of subsystems, processes, drivers, feedbacks and types of impacts are taken into account. Rothman and Robinson (1997) summarise that IAs have evolved from linear to complex chains of analysis that include various feedbacks, from considering non-adaptive to adaptive human behaviour and from single to multiple development paths. The IPCC TAR opens with the observation that assessments generally move from focusing on climate change as the only driver to also taking into account other global environmental and socio-economic changes and considering a number of cross-cutting issues, such as uncertainties (McCarthy *et al.*, 2001, p. ix). Füssel and Klein (2006) distinguish four stages of increasing complexity in the methodological evolution of VAs, ranging from the assessment of multiple effects caused by the single climatic

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[2] Note that the term methodology is normally used in different senses, either as being the branch of philosophy that studies methods or as a general system of methods followed in a discipline or research field (Wordnet, 2005).

stressor (impact assessment) to minimising the risk caused by multiple stresses (adaptation policy assessment).

3.2 An emerging meta-perspective

The diversity and complexity of existing methodologies together with the ongoing need to design new ones has pushed scholars to adopt a meta-perspective on their own work. Not only the "real systems" are the subject matter of study, but also the concepts and methods applied to analyse and argue about these "real systems". Roughly, three types of activities can be distinguished.

The first type of activity is the collection of methodologies. In the domain of VA, prominent examples are the UNFCCC's "compendium on methods and tools to evaluate impacts of, vulnerability and adaptation to climate change", which focuses on top-down methodologies (UNFCCC, 2006), and the community level risk assessment toolkit maintained by the Provention Consortium (Provention Consortium, 2006), which focuses on bottom-up methodologies. Two ongoing efforts to collect methodologies of VAs are the "Nairobi work programme on impacts, vulnerability and adaptation to climate change" carried out by the UNFCCC secretariat[3] and the BASIC project[4] funded by the European Commission. Similar efforts are undertaken in other fields of transdisciplinary research (see, *e.g.*, Scholz and Tietje, 2002).

The second type of activity is the comparison and classification of methodologies. IAs are compared, for example, in Weyant *et al.* (1996), Rothman and Robinson (1997), Schneider (1997), Tol and Fankhauser (1998), Toth and Hizsnyik (1998) and Edenhofer *et al.* (2006). Diverging definitions of vulnerability are analysed and methodologies for assessing it compared, *e.g.*, in Brooks (2003), O'Brien *et al.* (2004), Ionescu *et al.* (2005), Füssel and Klein (2006), O'Brien *et al.* (2006) and Füssel (2007). A detailed comparison of the methodologies applied in the VAs carried out by the DINAS-COAST and ATEAM projects can be found in Hinkel (in press).

A third type of activity is the development of conceptual and methodological frameworks. Frameworks usually come in the form of box and arrow diagrams; their interpretations, however, differ greatly, lying somewhere between semantic networks (Minsky, 1968), influence diagrams (Howard and Matheson, 2005) and causal loop diagrams (Forrester, 1961). They aim at guiding the assessment without however prescribing the specific concepts and methods to be used. In the domain VA conceptual frameworks have been proposed, for example, by Kates (1985), Turner *et al.* (2003), Brooks (2003), O'Brien *et al.* (2004), Ionescu *et al.* (2005), Füssel and Klein (2006), O'Brien *et al.* (2006) and Füssel (2007). Methodological frameworks can be found in Carter *et al.* (1994), Jones (2001), UNDP (2002), Schröter *et al.* (2004) and Lim *et al.* (2005). Despite these numerous efforts, developing frameworks still remains a high priority on the research agenda; ongoing efforts can be found in the form of the "Policy Appraisal Framework" (PAF) of the ADAM (Adaptation and Mitigation Strategies) project and the "Management and Transition Framework" (MTF) of the NEWATER (New Approaches to Adaptive Water Management under Uncertainty) project.[5]

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[3] `http://unfccc.int/adaptation/sbsta_agenda_item_adaptation/items/3633.php`

[4] `http://www.basic-project.net/`

[5] See `http://www.adamproject.eu` and `http://www.newater.info`.

3.3 Transdisciplinary integration

While the meta-perspective activities listed above provide useful overviews of existing approaches, they have not substantially addressed the conceptual and methodological challenges of TAs, mainly due to two reasons. First, the meta-perspective activities themselves suffer from conceptual difficulties. The comparisons of different definitions of vulnerability, for example, are carried out without having well established *meta-concepts* for speaking about the different definitions; the meta-concepts used, such as 'interpretation', 'language', 'discourse' and 'meaning', are hardly defined. Second, the meta-perspective activities provide little help on how to design methodologies for new assessments. Most collections of methodologies, for example, consist in long and flat enumerations without much information on which methodology is applicable in which case. Frameworks often overgeneralise and lack guidance on how to interpret or apply them. The actual process of selecting or deriving adequate frameworks is not addressed.

This paper extends the shift towards the meta-perspective on TAs by abstracting further from the specific scientific content of the assessment. It addresses the general (meta-) problem faced in TAs, which is *integration*: assessing a transdisciplinary problem means integrating people, knowledge and artefacts that pertain to different scientific and non-scientific knowledge domains. According to these three "pieces", three dimensions of integration can be distinguished (Becker *et al.*, 2000):

Social integration is about integrating the participants of a project. A TA is a social activity, in which researchers, policy makers, and other stakeholders meet and work together. Different interests, motivations and goals are present and need to be considered and, if possible, harmonised.

Cognitive or knowledge integration is about integrating the knowledge of the project's participants. Heterogeneous knowledge from various domains in the form of concepts to perceive the world, theories to explain, as well as methods to operate on it must be configured into an adequate methodology.

Technical integration is about integrating the artefacts the participants have produced or are producing during the course of the assessment. Experiments might have to be set up jointly, joint papers have to be written, data or computer systems have to be integrated.

Social integration is a prerequisite for the success of integration on the other two dimensions. Only if the participants of an assessment are socially integrated, that is they respect each other and share common goals, can the integration of their problem-solving knowledge can be successful. Also, cognitive integration is a prerequisite for the technical integration. In order to meaningfully integrate artefacts, shared concepts for speaking about them are needed.

There are already efforts made to address social and technical integration methodically within TAs. Social integration methods focus on the integration of extra-scientific participants (*e.g.*, policy makers and other stakeholders) and are often called participation methods. Social integration methods that address the integration of intra-scientific participants, *i.e.* the scholars pertaining to different disciplines and having different interests, are, however, rare. Technical integration methods are readily available. The technical dimension of integration is the most tangible one and the problems appearing there are not specific to transdisciplinary research.

Cognitive integration is, however, hardly addressed explicitly; cognitive or knowledge integration methods are rare. This paper aims at taking first steps in filling that gap. To this end, the next Section analyses the subject matter of cognitive integration, that is (scientific) knowledge.

4 Scientific knowledge

This section develops meta-concepts for speaking about scientific knowledge, or rather *represented* scientific knowledge. Knowledge is a mental category that refers to the relationship between an individual's belief and the external world. Here, I will avoid epistemological questions and not worry about the nature or certainty of this relationship[6]. Instead, I consider external representations of knowledge, that is the linguistic expressions produced by knowing individuals.[7] A substantial quality of scientific knowledge is that it can be represented and communicated orally or in written forms, such as papers, tables, graphs, mathematical formulae, diagrams and computer programs. Meta-concepts will be developed based on disciplines that explicitly study knowledge and knowledge representation, such as philosophy of science, computing science, cognitive science, semiotics and linguistics.

4.1 Concepts and languages

Knowledge representation requires a language to represent the knowledge in. The basic building blocks of languages are concepts. Concepts[8] are linguistic signs[9] and consist of two inseparable parts (de Saussure, 1916):[10] (*i*) the *expression*, that is, its "material" part, *e.g.* the string of characters on a paper or the sound waves produced by a speaker, and *ii*) the *meaning*, that is, what the material part stands for, represents or denotes.[11] In ordinary languages the expression part of a sign is called *word*, in a technical or scientific language *term*. An *interpretation* is a map from expressions to meanings. Usually, when we produce expressions the recipient (*e.g.*, you as you are currently reading this text) automatically interprets the expressions. In the cases in which I want to refer to the linguistic expression itself, it will be enclosed in single quotes.

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[6] For a prominent discussion on the nature of this relationship see the dialogue held between Socrates, Theaetetus and Theodorus in Plato's Theaetetus in which knowledge is characterised as belief that is true and justified (Plato, 1921).

[7] For a motivation of this perspective, see Carnap (1938) on the logical foundations of the units of science.

[8] The literature is not consistent. In some cases, the term 'concept' is used synonymously to the term 'idea' to refer only to the meaning part of a linguistic sign. In other cases it is used synonymously to the term 'term' to refer to the material part of a linguistic sign. Again in other cases it is used for only special kind of terms, *i.e.*, general terms or predicates. See, *e.g.*, Siegwart (1999) for a discussion on the different usages.

[9] The term 'sign' is used in many different ways. See Eco (1984) for an overview.

[10] The original terms used by de Saussure (1916) for the two parts are 'signifier' (french 'signifiant') and the 'signified' (french 'signifié').

[11] There are many different theories about what constitutes meaning, ranging from meaning being what an expression references in the "real world", to it being the effect an expression produces in the recipient's mind. For the purposes here, however, it only matters that an expression stands for something else, whatever this might be.

A *language* is a collection of concepts (the language's *lexicon*) and relations that hold among them. There are very different kinds of languages, such as ordinary languages, *i.e.* the collections of concepts that we use in every day situations (*e.g.*, German or English), technical languages (*e.g.*, the jargons of scientific disciplines), graphical languages (*e.g.* a chart or a graph), programming languages and mathematical language. Other terms used similar to what is called language here are conceptualisation, conceptual model, vocabulary, terminology, taxonomy, thesaurus, ontology (Gruber, 1993) or "domain of discourse" (Jaeger, 2003).

Due to the dyadic nature of signs, languages are systems with a double structure. The syntactical or grammatical structure relates the terms of the language and the semantical structure relates the terms' meanings.

Technical languages are usually introduced as a system of definitions. Definitions establish the meaning of a new term (the term to be defined or *definiendum*) on the basis of other terms whose meanings are already established (the defining terms or *definies*) (Suppes, 1999). The introduction of a technical language starts with some undefined or *basic concepts* (also called categories or primitives). Then, more *abstract* concepts are defined upon the basic ones. The basic concepts must be intuitively clear to the users of a language, otherwise the defined concepts cannot be understood.

As an example of a technical language, Figure 1 shows a section of the language defined in the Working Group 2 glossary of the IPCC TAR (McCarthy *et al.*, 2001). The system of definitions is shown in the form of a directed graph; the nodes represent the concepts and the arrows show how the concepts are defined upon each other, that is they point from the defined concepts to the defining ones. The concepts at the bottom of the figure are the basic concepts, the ones above these are the defined concepts. Moving from bottom to top, the level of abstraction increases. In order to understand the abstract concept of vulnerability, one has to understand all the basic concepts at the bottom of the figure.

Technical languages enable their users, *e.g.* members of a scientific discipline, to communicate efficiently about a domain of interest. Abstract concepts such as vulnerability compactly express complex states of affairs for which lengthy descriptions in ordinary language would be required. In science, such technical languages form the "contexts needed for reasonably coherent exchange of logical arguments" (Jaeger, 2003, p. 4).

Languages differ in their degree of generality and are frequently nested. A *conceptual framework* is a language that "frames" a more specific language. For example, the IPCC language can be used as a conceptual framework for the development of a more specialised language to speak about the vulnerability of ecosystem services as done in the ATEAM project (Schröter *et al.*, 2005) or to speak about the vulnerability of coastal systems as done in the DINAS-COAST project (Hinkel and Klein, 2007).

Languages can be either conventional or artificial. Conventional languages, such as ordinary and technical languages, are social institutions that have emerged through the interaction of individuals over time and are changing steadily. In science, many concepts are continuously "contested in a struggle about their meaning" (Hajer and Versteeg, 2005, p. 176). Artificial languages, such as programming languages, are designed.

Languages form our potential for speaking about the world. We cannot reason or communicate about the world independently from language (Runggaldier, 1990). Lan-

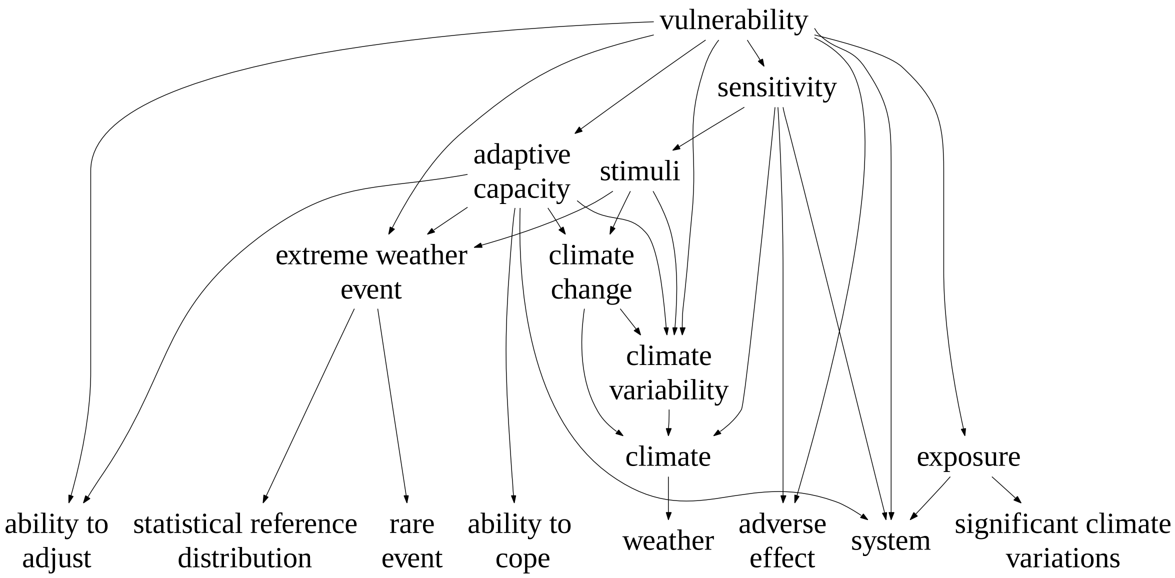

Figure 1: The relations between the concept of vulnerability and its defining concepts as given in the Working Group 2 glossary of the IPCC Third Assessment Report. The nodes represent the concepts and the arrows point from the defined concepts to the defining ones.

guages always offer a simplified view of the world. They reduce the ultimate complexity of the "real world" by only capturing some aspects and leaving (many) others away. The complete collection of languages an individual has is sometimes called *world-view*.

4.2 Theories and methods

While languages define what can potentially be said, theories and methods are actual statements that express our knowledge about the world.

A *theory* consists of a language and a collection of general statements (called laws) formulated in the language. For example, the theory of gravity includes the concepts particle, mass, gravitational force, distance and Newton's law of universal gravitation. Laws are general statements, that is they are true for many instances in space and time. The singular counterparts of laws are data, which are particular statements made about singular instances in space and time (Balzer, 1997). Note that here the concept of theory is used in a very wide sense that includes, for example, what is called model[12] in other contexts, that is collections of statements that are much less general, certain, or socially accepted than the theory of gravity.

A *method* consists of a language and statements that specify a problem-solving process. Methods are based upon theories and can be seen as theories in action. For example, the theory of gravity can be applied as a method for calculating the trajectory of a falling body. The difference between a method and a theory is one of purpose. While

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[12] The term 'model' is used in many different senses (Stachowiak, 1973). To avoid confusion, I will only use the term to speak about computer models, which are, in the terminology applied here, methods. See the next paragraph.

a theory aims at describing or explaining a phenomenon, a method aims at using a theory for deriving new insights. One of the main principles of scientific methods is reproducibility, which roughly means that the same method applied by others gives "equal" results.[13]

The characterisation of scientific knowledge given here is not meant to be comprehensive. There are less obvious cognitive structures or tacit knowledge involved in scientific enquiry. In Kuhn's seminal book the concept of paradigm is introduced to emphasise that members of a scientific discipline do not simply share concepts, methods and theories but also implicit rules on how to apply these in paradigmatic cases, and that an important part of disciplinary education consists in learning these rules (Kuhn, 1970). A similar idea is expressed by Lakatos (1970, p. 132) with the concepts of positive and negative heuristics, which are sets of not necessarily explicit methodological rules, some of which "tell us what paths of research to avoid (negative heuristics), and others what parts to pursue (positive heuristics)".

5 Transdisciplinary knowledge integration

Based on the meta-concepts developed in the last section, this section discusses what it means to integrate knowledge (*i.e.* languages, methods and theories) within TAs. Two subsequent phases of knowledge integration are distinguished: (*i*) the elaboration of a shared language, and (*ii*) the design of a methodology.

Note that transdisciplinary knowledge integration is not to be confused with the unsuccessful attempts, most prominently the ones by logical empiricism (Neurath, 1938) and general system theory (Bertalanffy, 1968), to (re-)establish the unity of science, that is to establish an all-encompassing scientific theory of the world. The difficulties faced in these and other attempts lay in the fact that languages, theories and methods of different disciplines do not fit together like the pieces of a puzzle (Kitcher, 1999). Each discipline abstracts differently from the "real world", thereby selecting some aspects and neglecting all others (Jaeger, 2003). In fact, placing the focus on only a small number of aspects is an essential means of solving problems in a complex world. Languages and theories, by their very nature, aim at simplifying the "real world" for a specific purpose, and thus always have a limited scope. See Bechtel and Hamilton (2007) for a historic account of the unity of science. In contrast to the unity of science, transdisciplinary problem solving aims at pragmatic and problem-specific local integration of knowledge. The failure to derive a global theory does not mean that it is impossible to integrate knowledge locally, as the practise of transdisciplinary research shows.

5.1 Elaboration of a shared language

The first phase of integrating knowledge for solving a transdisciplinary problem is *language integration* or the elaboration of a *shared language*, which is applicable for describing the problem and discussing potential solutions, amongst the participants of the problem-solving effort. Note that in some cases, one shared language might be hard to

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[13] The meaning of "equal" differs depending on the disciplinary context.

attain and it might be necessary to live with differing, but complementary views of the problem.

The starting points for language integration are *bridging concepts* (Becker *et al.*, 2000), which are concepts that are shared by languages of different disciplines. The most important bridging concepts are those of ordinary language. Another important body of bridging concepts is provided by mathematics (Jaeger, 2003). Besides the basic mathematical concepts, like sets and functions, concepts of mathematical system theory (Kalman *et al.*, 1969) and its numerous derivatives such as system dynamics (Forrester, 1961), system analysis (Miser and Quade, 1985) and earth system analysis (Schellnhuber, 1998) are applied in many disciplines. See Olsson (2004) for an overview of the different "schools of system thinking".

Languages can be extended by introducing new concepts through *concept definition*. An important role in transdisciplinary research is played by *integrated concepts*, which are concepts that are defined upon concepts that pertain to the languages of several disciplines. For example, the concept sustainability is usually defined in ecological, social and economic terms (WCED, 1987). The goal of concept definition in the elaboration of a shared language is to abstract new concepts that allow the participants of a problem-solving effort to express integrated ideas more economically.

The inverse operation to concept definition is *concept analysis*. While concept definition composes a new concept out of established ones, concept analysis decomposes concepts into less abstract ones. Concept analysis can be thought of as being the answer to the question: "What do you mean by . . . ?". For example, what does one mean when stating that Bangladesh is vulnerable to sea-level rise. A possible answer could be that Bangladesh might be damaged adversely when the sea level rises. The goal of concept analysis in the elaboration of a shared language is to reduce the level of abstraction to a shared one, that is to decompose technical concepts that are not understood by all participants into bridging concepts that are understood by all.

Concept analysis and concept definition are often applied in combination in order to refine an existing concept for a more technical usage; first, a concept is analysed, and then, based on the outcome of the analysis, it is redefined. This combined operation is called *concept explication* (von Kutschera and Breitkopf, 2002). The idea of concept explication is that a redefined concept should be as close as possible to its meaning in the existing discourse. As an example, see the explication of the concept of vulnerability in Section 7.2 and in Ionescu *et al.* (under review) .

After having explored possible operations on languages the subsequent question is what the "right" operations to perform are? What makes a language a good one? In principle, the decision in favour of or against a certain language is a normative one. However, since languages are social institutions with their own history, there is a living system of meanings that needs to be respected.

From an ideal point of view, Peirce (1983), for example, lists the following rules: New terms should only be introduced when necessary, *i.e.* when no existing term expresses the desired meaning. Synonyms, *i.e.* terms that have the same meaning, should be avoided (see also Newell *et al.*, 2005). Terms should only be used in their original meaning. To avoid confusion, words of ordinary language should not be used as technical terms. From the point of view of programming language design the following prominent principles can be added: (*i*) orthogonality, *i.e.* concepts should not overlap in meanings, and (*ii*) compactness, *i.e.* as few terms as possible should be used to express the desired meaning (Raymond, 2004).

From a pragmatic point of view, other rules that partially contradict the ones listed above can be formulated. Different scientific communities might have different histories of using a term, each of which should be obeyed. In some cases, it also makes sense to introduce a new term for a concept that already exists in order to get rid of unwanted connotations that are associated with the existing concept. Or as Abelson *et al.* (1996, p. 359) note: "We can often enhance our ability to deal with a complex problem by adopting a new language that enables us to describe (and hence think about) the problem in a different way". Furthermore, when introducing a new technical term, it is often beneficial to take a term of ordinary language and refine its meaning because it enables "outsiders" to quickly comprehend the refined meaning. In the end, given the pragmatic aim of TAs, the most important criterion should be: If a language is effective for communicating amongst the participants of a problem-solving effort, it is a good one.

5.2 Methodology design

The second phase of knowledge integration is - based upon the shared language elaborated - *methodology design*, that is the integration of methods and theories into an appropriate methodology.

Methods can be integrated by coupling their outputs to inputs of other methods. A precondition for this activity is that the output concepts of the foregoing method are identical with the input concepts of the subsequent one. For example, an economic model that produces carbon-dioxide emissions can be coupled to a climate model that is driven by such emissions. Generally, the input-output integration of methods is problematic because only some of the concepts of the methods' languages (the input and output ones) are considered. There could be inconsistencies between the methods' disregarded "internal" concepts or the theories sustaining the methods could contain conflicting assumptions.

The *numerical integration* of computer models is a special case of method integration that deserves additional attention here. The point to note is that it generally does not suffice to just couple the inputs and outputs of the computer models; additional coupling algorithms might be needed. Computer models are approximate (numerical) solutions to mathematical problems. Coupling the solutions does not necessarily yield a solution to the overall problem; numerical instabilities may result. See Hinkel (submitted) for a more elaborate discussion of this point.

The integration of theories is a more challenging task than the integration of methods, because in this case all concepts, not only the input and output ones, plus the laws of the corresponding theories need to be considered. Theory integration was the aim of the above-mentioned unity of science movement. The main device applied was theory reduction, that is the attempt to reduce theories of higher level sciences such as biology to lower level ones such as physics (Dupre, 1983; Bechtel and Hamilton, 2007).

In the practise of TAs the input-output integration of methods is more abundant than theory integration. The result of method integration is not one unified theory, but a patchwork of methods that are connected via some shared concepts. Heckhausen (1987) illustrates this kind of integration by calling it "chimera interdisciplinarity" in the sense that knowledge of one discipline is engrafted onto knowledge of another discipline. Theory integration rarely takes place within one problem-solving effort. Rather, it is part of a longer term transformation of an interdisciplinary research field into a proper scientific discipline.

Finally, it shall be noted that cognitive integration is driven by social processes and institutional hierarchies. Zandvoort (1995) empirically studied cognitive integration within several research projects and identified different styles of integration. He concludes that a "demand-and-supply" style, in which one discipline dictates which and how knowledge shall be supplied by another discipline, dominates transdisciplinary research.

6 Facilitating transdisciplinary knowledge integration

While the last section gave an account on how knowledge can be integrated in principle, this section asks how knowledge integration can be facilitated in practise.

6.1 Semantic ascent

An important device for facilitating knowledge integration is what Quine labels *semantic ascent* or the "shift from talk in certain terms to talking about them" (Quine, 1960, p. 271). Phrased in Carnap's terminology, semantic ascent means changing from talk in an *object-language* about some subject matter to talk in a *meta-language* about linguistic expressions formulated in the object-language (Carnap, 1934).

An example illustrates this idea. Taking the object-language statement analysed in Section 5.1, "Bangladesh is vulnerable to sea-level rise," a meta-language statement would be: "The term 'vulnerable' appears as part of the expression 'something is vulnerable to something else'." For a continuation of the analysis of vulnerability expressions see Section 7.2 and Ionescu *et al.* (under review).

These types of analysis are called syntactical or grammatical analysis. Instead of analysing a statement merely from within the language it is formulated in, one ascends to a meta-language and analyses the form of the statement. The attention is shifted from the meaning of the terms to the syntactical relations between the terms. This is why in a meta-language statement the terms of the object language appear in single quotes (*i.e.* they are not meant to be interpreted).

Semantic ascent is also the basis for pragmatic or discourse analysis, that is the study of who uses concepts in which context for which purpose (Hajer and Versteeg, 2005). For example, an interesting pragmatic analysis has been undertaken by Janssen *et al.* (2006) on co-author and citation relations of publications that used the terms 'vulnerability', 'adaptation' and 'resilience'. The study revealed that the three terms were originally used independently by three disparate communities with an increasing number of cross citations appearing over the last years.

What is the role of semantic ascent in TAs? "The strategy of semantic ascent is that it carries the discussion into a domain where both parties are better agreed [...] on the main terms" (Quine, 1960, p. 272). For example, if a group of scholars cannot agree on the meaning of the term 'vulnerability', they might still be able to agree on a meta-language to talk about the different meanings of the term. Having left the Babylonian confusion present in the object language, the scholars can take stock of the different usages that are present and then agree on a common usage. Finally, they can descend back to the object language and communicate more efficiently.

The ascent to meta-languages is already popular in the context of TAs. The comparisons of definitions and methodologies of IAs and VAs discussed in Section 3.2 make use of meta-languages. Meta-data, that is, statements formulated in a meta-language, are attributed to data, that is, statements formulated in an object-language. This paper itself develops a meta-language for speaking about the integration of knowledge.

6.2 Formalisation

A second important device for facilitating knowledge integration is formalisation. Formalisation is the translation of statements made in a non-formal language (*e.g.*, ordinary or technical language) into a formal language.

The term 'formal' is used in a weak and in a strong sense. In ordinary discourse the term is used in the weak sense of pertaining to form or structure. From this point of view, any expression written in mathematical or other artificial symbolic notation is considered to be formal. In mathematical discourse the term is used in the strong sense of pertaining to a special kind of mathematical entity called a *formal system* (Curry, 1958). From this point of view, mathematical expressions generally are not formal; only those formulated within a formal system, are considered to be formal.

A formal system is a formal language together with transformation rules that specify how expressions of the formal language can be transformed.[14] A formal language, in turn, is a set of primitive expressions (*e.g.*, symbols) and formation rules that specify how complex expressions can be constructed from the primitive ones. A transformation rule is, for example, what a pocket calculator applies when evaluating the expression '12/2' into the simpler expression '6'. In opposition to ordinary or technical language (as defined in Section 4.1), a formal language (in the strong sense) is a purely syntactical structure consisting of expressions without meanings. See Hofstadter's famous book for an accessible introduction to formal systems (Hofstadter, 1979). Here, I will use 'formal', unless otherwise said, in its weak sense.

Formalisation into a formal system is only feasible in some cases. One of the groundbraking events in the history of mathematics was Gödel's proof that even the relatively simple mathematical theory of arithmetic could not be formalised (Gödel, 1931).

However, formalisation into (informal) mathematics is common practise in science or even said to be the usual process in the evolution of scientific fields or disciplines (Suppes, 1968; Bertalanffy, 1968). Such formalisation can be seen as a gradual process that includes the extension of the ordinary language lexicon through the introduction of technical terms, the standardisation of the syntax of the language, the replacement of

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[14] In the context of logic these rules are also called rules of inference (Copi and Cohen, 1998) and in the context of computing science operational semantics (Mitchell, 1996).

some technical language expressions through artificial symbols and finally, the complete translation into mathematics or into a formal system (Posner, 1997).

Suppes (1968, p. 654) notes that “one broad aim of formalisation is to make communication easier across scientific disciplines”. Formal languages offer a compact notation, which allows complex subject matters to be expressed, communicated and reasoned about efficiently. They have a rigorously defined syntax which means that the relations between concepts are unambiguously given. Differences and commonalities between different languages are easily identified. Circularities and contradictions in the language’s definitions can be avoided. When formulating statements in a formal language one is forced to be exact and, as a consequence, to reveal assumptions that would otherwise remain implicit.

A further motivation for formalising statements is to analyse the consequences of these statements. As Einstein and Infeld (1966) note, the laws of physics are easy to understand, what is difficult to understand is what follows from them. When a theory is expressed in a formal system, the transformation rules can be applied to the initial statements (*i.e.* axioms and laws) to produce new statements (*i.e.* theorems) that follow from them. Mathematical modelling or computer simulation are variants of this procedure. For example, having represented a “real world” phenomenon in the form of mathematical equations allows the application of mathematical transformation rules (analytical or numerical methods) for solving these equations. The solution statements attained can then be translated or interpreted back into terms of the modelled “real world” phenomenon.

A common misunderstanding is that formalisation means quantification (in the sense that everything is expressed in terms of real numbers) and leaves no room for representing qualitative knowledge. However, there are also qualitative mathematical concepts. In fact, quantitative mathematical concepts are defined upon, that is, presuppose qualitative ones (see, for example, the introduction of real numbers in mathematical text books). An example of how the concept of vulnerability is formalised into qualitative mathematical concepts can be found in Section 7.2.

Another common misunderstanding is that formalisation means that essential aspects of a problem are disregarded. It is of course true that nothing about the “real world” can be said exclusively by mathematical statements. In order to do so, an interpretation, that is a map from the mathematical concepts to the natural language concepts they represent, is necessary. Formalisation is the process of establishing that map and, if one does not throw away the map afterwards, nothing is lost when formalising.

The question is not whether natural or formal language are better in principle, but what the right mix between the two types of languages is for solving a given problem. The advantage of ordinary language over the mathematical one is that in mathematical language one cannot express everything that can be expressed in ordinary language. The advantage of mathematical language is that once one has arrived at the point of being able to express what’s at stake in mathematics, then unambiguous further exploration is possible in a way that is not achievable in ordinary language.

6.3 Knowledge integration methods

The third device I want to put forward for facilitating knowledge integration is the notion of a *knowledge integration method*, *i.e.* a method that organises the process of integrating knowledge. Previously, a method was said to consist of two parts: a language and a specification of a problem-solving process using that language (see Section 4.2). A knowledge integration method consists of a meta-language, that is a language for speaking about knowledge to be integrated, and a specification of the knowledge integration process.

Note that a distinction between *integrated methods* and *integration methods* is made. An integrated method addresses a transdisciplinary problem (a problem that cannot be addressed by disciplinary methods) and is the product of knowledge integration. For example, an integrated (assessment) model is an integrated method. In contrast, an integration method addresses the process of knowledge integration itself, such as, for example, the construction of an integrated (assessment) model. The latter are the ones considered here.

In the literature there are a lot of techniques that can be applied to facilitate knowledge integration. There are, for example, general purpose knowledge representation languages such as Topic Maps (Biezunski *et al.*, 1999) and the Unified Modelling Language (UML; Fowler and Scott, 1997), which can be used to make relations between concepts explicit. Another interesting technique for language integration that has been applied in transdisciplinary research is formal concept analysis (Wille, 1982, 2005), which is a branch of applied mathematics that analyses conceptual hierarchies. There are also a bunch of software packages that support the construction and integration of system dynamics models, such as Stella[15], Vensim[16] and Simile (Muetzelfeldt and Massheder, 2003).

However, most of these techniques are not integration methods in the sense defined above, because they only provide a meta-language and do not support the process of integrating knowledge. Furthermore, the meta-languages provided are often too general. In order to effectively facilitate the knowledge integration process, meta-languages must be specifically targeted at the problem given; coming up with an adequate meta-language is often a main challenge in transdisciplinary knowledge integration. These and related aspects will be explored with the help of several examples in the next section.

7 Cases

This section presents four cases of knowledge integration from the domains of IA and VA. The first case addresses the problem of methodology design in general, that is how to facilitate the development, communication and comparison of methodologies of TAs in general and VAs in particular. The second case addresses the problem of developing a shared language for speaking about vulnerability to climate change. The third case addresses a more specific problem of methodology design, that is the problem

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[15] See `http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx`.

[16] See `http://www.ventanasystems.co.uk/vensim.html`.

of integrating computer models in the context of the broader vision to modularise IA modelling. The fourth case also addresses the integration of computer models but in the context of a global assessment of coastal vulnerability to sea-level rise. I was directly involved in all four cases albeit with differing contributions.

7.1 FORMETA: a framework for analysing methodologies of transdisciplinary assessments

The "framework for analysing methodologies of transdisciplinary assessments" (FORMETA) was developed by myself in the context of this paper and the EVA (Environmental Vulnerability Assessment) project at the Potsdam Institute for Climate Impact Research (PIK). EVA served as a platform for discussing and integrating the findings of a number of collaborative, externally-funded VA projects including the DINAS-COAST and ATEAM projects. The members of the EVA group were struggling with the above-mentioned diversity and complexity in methodologies for assessing vulnerability; a lot of time was spent on trying to understand and compare methodologies of different assessments. For a detailed presentation of this case please refer to (Hinkel, in press).

FORMETA exclusively addressed the second phase of knowledge integration, *i.e.* methodology design. The problem was how to facilitate the communication, comparison and the design of methodologies of TAs.

The first step in addressing this problem was to ascent to a meta-language, because it was difficult to directly communicate about methodologies. The usage of the term 'methodology' within the context of VAs and other TAs was analysed. In this context, as detailed in Section 3.1, the term refers to a configuration of both analytical and participatory methods that are involved in solving a given problem. Furthermore, methodologies also include "non-methodical" activities, *i.e.* activities which do not follow a clear specification, as well as the data on which the methods have been applied.

The second step taken was to translate (*i.e.* formalise) the results of the analysis into the language of mathematical graph theory. It was chosen to represent a methodology as a directed simple graph with four types of nodes: data, methods, actors and activities. The arcs of the graph connect the activities of the methodology with their inputs and outputs, *i.e.* they show the flow of data between the activities. The final output of the methodology is called its product.

Figure 2 shows, as an example, a methodology consisting of three activities. The octagons represent methods, the rectangles data, the ovals actors and the numbered circles activities. Activity 1 is the development of scenarios, Activity 2 is the development of a model and Activity 3 the application of the model on the scenarios to produce data on impacts. Activities 1 and 3 are method-driven activities, that is they consist in the application of a method. The difference between the two is that in the first case a participatory method is applied, while in the second case it is an analytical one. Analytical methods do not have, by definition, any actor as input. Activity 2, the development of the model, is an actor-driven activity, because it can not be specified in the form of a method and is therefore not reproducible by others.

In order to test the framework it was applied to analyse the methodologies of two recent

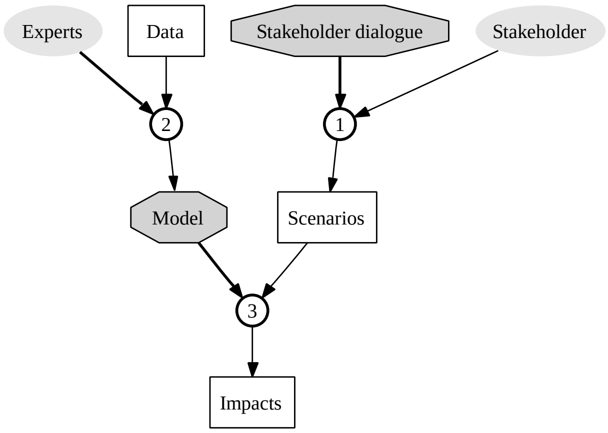

Figure 2: Example of a methodology. The octagons represent methods, the rectangles data, the ovals actors and the numbered circles activities.

VAs carried out by the DINAS-COAST and the ATEAM projects. It was found that the methodologies of the projects differ in three aspects: (*i*) the product of ATEAM was data while that of DINAS-COAST was a method, *i.e.* a computer model, (*ii*) ATEAM modelled the environment and the human response separately while DINAS-COAST modelled them jointly, and (*iii*) ATEAM involved stakeholders while DINAS-COAST did not. These differences have influences on the type of result statement produced by the methodologies and the way users perceive them. ATEAM produced simple, aggregate result statements which have been recognised by a wide audience while DINAS-COAST produced more complex, less aggregate statements which did not receive such a wide recognition but were welcomed by users confronted with concrete decisions.

7.2 FAVAIA: a formal framework of vulnerability to climate change

FAVAIA (Formal Approaches to Vulnerability that Informs Adaptation; `http://www.pik-potsdam.de/favaia`) is a joint research project between PIK and the Stockholm Environment Institute (SEI) which also emerged out of the above-mentioned EVA project. FAVAIA aims at alleviating some of the conceptual difficulties present in the field of vulnerability today by formalising vulnerability and related concepts. The main product of FAVAIA is a formal framework of vulnerability to climate change. For a detailed presentation of this framework please refer to (Ionescu *et al.*, under review).

FAVAIA addressed only the first phase of knowledge integration, the elaboration of a shared language. The problem was to develop a shared language that enables a more precise dialogue between researchers following different definitions of vulnerability and related concepts such as risk, hazard and adaptive capacity.

The first step taken to address the problem was to analyse vulnerability statements made within ordinary language and the technical language of the climate change scientific community. Given the diversity of disciplines involved and types of systems considered, the language to be developed must be very general, because only then can it be used to highlight the commonalities and differences of the more specific languages used by different scholars. The best starting point for developing such a general language is ordinary language.

The syntactical analysis of statements made in ordinary and technical languages showed that the concept usually appears as part of the expression ‘something is vulnerable to something else’. The semantical analysis showed that the first ‘something’ usually refers to the *entity* that is considered to be vulnerable (*e.g.*, a group of people, region or sector) and the ‘something else’ to a *stimulus* (*i.e.* perturbation or stress) the entity is exposed to. Further analysis of the context vulnerability statements are made in shows that the term is used with a negative connotation. The Oxford Dictionary of English speaks of entities that are “attacked or harmed” (Soanes and Stevenson, 2003) and the above-mentioned IPCC definition of “adverse effects” (McCarthy *et al.*, 2001, p. 995). Hence, speaking of vulnerability presupposes *preference criteria*, that is a notion of “good” and ”bad”, or at least “better” and “worse”.

The conclusion of the concept analysis was that meaningful statements about vulnerability are only possible if they can be cast in the following canonical form that involves the three basic concepts identified in the analysis: *An entity is vulnerable to a specific stimulus with respect to certain preference criteria.*[17] An example would be: Bangladesh is vulnerable to sea-level rise with respect to preferring a small number of people affected by coastal flooding over a large number.

In a next step, the three ordinary language basic concepts identified are formalised into three mathematical basic concepts (primitives). The entity is mapped to a dynamical system, the stimulus to the system’s exogenous input and the preference criteria to a (partial strict) order relation on the systems set of states. In the simplest case of a discrete dynamical system the evolution of the system is given by a transition function:

$$f : X \times E \to X, \tag{1}$$

where X is the set of states of the system and E is the set of exogenous inputs.

Given the current state of the system x (an element of X; $x \in X$) and an exogenous input e ($e \in E$), the transition function tells us which element of X will be the next state of the system: $f(x, e)$. The order relation $\prec$ on the systems set of states allows us to compare different states the system is in; $x_1 \prec x_2$ means that the system in state x_1 is considered to be “worse off” compared to it being in state x_2.

In a third step, vulnerability and related concepts are defined upon the mathematical primitives. The first definition given, the one of simple vulnerability, states that a system in a certain state is vulnerable to an exogenous input if it ends up “worse off” than before, or more formally:

> A system f in state x is vulnerable to an exogenous input e with respect to $\prec$ if and only if $f(x, e) \prec x$.

This simple definition is not powerful enough to capture the meaning of vulnerability in statements made about the more complex entities that are normally considered in

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[17] The necessity of explicitly naming the entity and the stimulus has been highlighted before by, *e.g.*, Brooks (2003, p. 6).

climate change research, in particular the social-ecological (Gallopin, 2006) or coupled human-environment (Turner *et al.*, 2003) systems. Especially one important aspect is missing, namely the notion that entities react or adapt to the *stimuli.* To capture this notion, the simple system is extended to also include endogenous input that represents the entity's actions. This extension allows the mathematical definition of terms like 'hazard', 'potential impact', 'adaptation' and 'adaptive capacity'. Furthermore, the definition of simple vulnerability given above is generalised to *transitional vulnerability*, which is applicable to cases in which whole trajectories instead of one-step transitions are considered, and *comparative vulnerability*, which is applicable to cases in which the vulnerability of a system relative to a given reference scenario is considered.

7.3 PIAM: a modular approach to integrated assessment modelling

The PIAM (Potsdam Integrated Assessment Modules) project hosted at PIK aimed at taking first steps towards modularising integrated assessment models (IAMs). In the past, IAMs were mostly developed within a single research group for addressing specific problems. Little attention was paid to methodological issues; software-technologically, IAMs were often poorly designed (Janssen, 1998). As a consequence it was hard to understand the model's code or reuse parts of IAMs for addressing new problems. In order to be able to better respond to new questions raised by the decision makers, the next generation of IA modelling is envisaged as a modular process, in which modules are developed independently by different institutes and plugged together afterwards in accordance with the questions raised (Jaeger *et al.*, 2002). For a detailed presentation of this case please refer to Hinkel (submitted).

PIAM addressed both phases of knowledge integration. The problem was to integrate computer models that are developed and maintained independently by different research groups. PIAM also addressed some aspects of technical integration, such as the transfer of data between heterogeneous systems and the conversion of data structures, which, however, will not be discussed here. For a description of PIAM's technical solution see Hinkel (submitted) and the TDT (Typed Data Transfer) web-site (`http://www.pik-potsdam.de/software/tdt`).

PIAM considered this problem by means of an example case: the integration of an economic model that optimises inter-temporal welfare and thereby outputs an emission trajectory and a climate model that is driven by an emission trajectory and computes the resulting global mean temperature rise. The task was to find the optimal emission trajectory while keeping temperature rise below a certain threshold.

The first phase of knowledge integration, the elaboration of a shared language, means, in the context of model integration, that the individual models must be represented in a shared language; the same terms (here, mathematical symbols) must have the same meaning (here, represent the same "real world" phenomenon). In the example case considered language integration was trivial, since the models were only connected via two shared concepts: the emissions trajectories and the temperature rise.

The second phase of knowledge integration, methodology design, means, in the context of model integration, that the models formulated in the shared language must be integrated numerically. As pointed out in Section 5.2, it generally does not suffice to just couple the input and output of the computer models; additional coupling algorithms might be needed. An important aspect thereby is to reach a trade-off between computational efficiency and encapsulation. On one hand it is desirable to provide the coupling algorithm with all information that helps to speed it up. On the other hand it is desirable to place as few requirements in terms of information output on a model as possible, because it minimises the work needed to replace or reuse it.

In the example case considered, finding an efficient coupling algorithm whilst placing low information requirements on the climate model was the major challenge (for the details see Leimbach and Jaeger, 2004). It was decided to make the welfare gradients of the economic model available to the coupling algorithm, but not the gradients of the climate model, even though this would have enabled a more efficient coupling algorithm. However, the wish was to minimise the work needed to be able to (re-)use existing climate models, which generally do not output the gradients.

7.4 DINAS-COAST: a global assessment of vulnerability to sea-level rise

The EU-funded project DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise; `http://www.dinas-coast.net`) aimed at assessing the vulnerability of coastal zones to sea-level rise. The final product of DINAS-COAST was an interactive tool called DIVA (Dynamic and Interactive Vulnerability Assessment) that enables its user to simulate the impacts of selected climatic and socio-economic scenarios as well as adaptation strategies on the coastal regions of all nations. DINAS-COAST involved participants from several European research institutes. My responsibility in the project was to organise the integration of the computer models that represent different coastal sub-systems and were written by the distributed project participants. For a detailed presentation of this case please refer to Hinkel (2005) and Hinkel and Klein (2007).

DINAS-COAST addressed both phases of knowledge integration. The problem was the integration of computer models that are built by distributed participants which pertain to several natural and social science disciplines. DINAS-COAST also addressed technical integration, which, however, falls outside of the scope of this paper.

The first phase of knowledge integration, the elaboration of a shared language, turned out to be a challenge due to the fact that ten models and around 200 concepts needed to be respected. The same terms were used for different meanings (*e.g.*, the term ‘land loss’ was used to denote a rate, a relative value and an absolute value) and the spatial references of the concepts were often unclear (*e.g.*, land loss per unit coast-line or per unit coastal area?). Different terms were also used for the same meaning.

This challenge was addressed by the introduction of a formal meta-language that then could be used to facilitate the process of elaborating a shared language. An analysis of the individual languages of the participants revealed that all information could be expressed as instances of the three meta-concepts: geographical feature, property and relation. The geographical features represent the “real world” entities (*e.g.*, rivers or countries), properties capture the quantitative information about the features (*e.g.*, a river might have the property length or slope) and relations describe how the features are structured (*e.g.*, a river might belong to several countries). With the help of these meta-concepts, the project participants were able to elaborate a shared language, that is a list of geographic features, properties and relations that make up the coastal world modelled by DINAS-COAST.

The second phase of knowledge integration, the methodology design, meant that the linkages between the sub-models, which are represented in terms of the shared language, needed to be defined and a coupling algorithm found. It turned out that the coupling algorithm was simple: all models could be represented as first order difference equations iterating sequentially on a common time step.

However, a second challenge arose: it was impossible to define the linkages between the models at the beginning of the project. As is frequently the case in TAs, the interactions between subsystems were not fully understood at the start of the assessment; instead they were a result of the interdisciplinary learning process during the course of the assessment. The shared language and the linkages between the models were thus steadily changing.

This second challenge triggered the development of the DIVA Method, an integration method for iteratively building modular integrated models by distributed participants. The method consists of the above-mentioned meta-language and a development process that allows for iteratively refining the shared language, the individual models and the linkages between them. Roughly, model development takes place in three phases. First, a shared language is elaborated with the help of the meta-language. Second, the modules are programmed individually in terms of the shared language. In the third phase, the actual linkages between the modules that resulted are analysed jointly by all participants. In order to facilitate the analysis, the DIVA Method includes a web based tool that automatically generates documentation of the models and their linkages. The three phases are iterated until a satisfactory result is achieved. A detailed description of the DIVA Method is given in Hinkel (2005).

Even though the DIVA Method was specifically designed and applied to build the DINAS-COAST model, it is generic and can be applied to cases with similar requirements, *i.e.* the models' algorithms must be representable in terms of first-order difference equations operating on the same time step and data must be representable in terms of geographic features, properties and relations.

8 Discussion

The four cases presented in the last Section differed in the phases of knowledge integration that were addressed and in the generality of doing so.

FAVAIA only addressed the first phase of knowledge integration, *i.e.* the elaboration of a shared language. A formal, mathematical language for speaking about vulnerability to climate change was developed. Formalisation seemed adequate for three reasons. First, existing languages, such as, *e.g.*, the IPCC one, are already rather complex in that they include many concepts (see Figure 1), some of which overlap non trivially in their meanings (Gallopin, 2006). Mathematical language is more apt to unambiguously express the complex relations between such concepts. Second, formal definitions can better be connected to those related concepts that have already been formalised, such as, for example, risk, sensitivity and resilience. Third, formal definitions are required

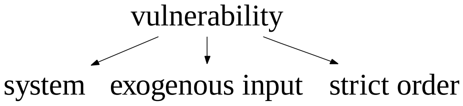

Figure 3: The relations between the concept of vulnerability and its defining concepts as given in the FAVAIA language. The nodes represent the concepts and the arrows point from the defined concepts to the defining ones.

in those cases in which VAs rely on formal methods (*e.g.*, computer models), which is frequently the case.

A comparison of the FAVAIA language (Figure 3) with the IPCC language (Figure 1) illustrates some of its advantages. While the former defines vulnerability directly upon three basic concepts, the latter makes use of eight basic concepts and several intermediate ones. In the former, the relations between the basic concepts and the defined concept of vulnerability are exact due to the usage of mathematics. As a consequence, making the FAVAIA definition operational is a more straightforward exercise; it suffices to map the three basic mathematical concepts to the "real world" situation considered. Hinkel and Klein (2007), for example, show how this has been done in the DINAS-COAST project in order to assess coastal vulnerability.

Another advantage of the FAVAIA language is the clear separation of normative from other aspects. One difficulty in making the IPCC definition operational is that several of its basic concepts such as "adverse effect", "significant climate variations" and "rare event" contain a strongly normative component. Vulnerability statements made using the IPCC definition are vague, because these normative components are usually not made explicit. In the FAVAIA definition the normative aspects are exclusively represented by a single basic concept: the order relation on the state of the vulnerable entity. Vulnerability statements are only "permitted" if the speaker explicitly specifies this order relation.

Due to its generality, the FAVAIA language can also be applied for analysing and relating already existing definitions of vulnerability. Ionescu *et al.* (2005), for example, show how the IPCC definition and the operational definitions used by the DINAS-COAST and ATEAM projects can be represented as special cases of the FAVAIA one. Since the framework is independent from climate related concepts it can also be applied for analysing definitions used in other scientific fields. For an application in the field of poverty see Kumar *et al.* (2007).

While formalisation can improve the precision in communication, there are two important limitations. First, in some cases the vagueness of ordinary language might be desirable in order to extend languages for speaking about new phenomena for which concepts are not yet available (Wittgenstein, 1969; Eco, 1984). However, as soon as new concepts have been established, formalisation can contribute to further developing them into a more precise language. Second, even when mathematical formalisation is useful in principle, in practise there is a danger of excluding the non mathematically trained. Such exclusion would be counterproductive in the context of VAs, in which scholars with varying levels of mathematical training need to collaborate. In the case of FAVAIA, it was found that if sufficient time was invested in carefully introducing the formal language even the mathematically challenged could benefit from the formalisation exercise.

In the case of DINAS-COAST, the elaboration of a shared language was also central, albeit differing from the case of FAVAIA in several aspects. Since DINAS-COAST integrated formal methods, *i.e.* computer models, language development needed to be formal right from the start. Furthermore, the structure of the involved languages differed. In opposition to FAVAIA, DINAS-COAST involved many more concepts; the overlap of concepts was, however, not such an issue. The cases also differed in the way the languages were developed. The DINAS-COAST language was developed collaboratively amongst the participants of the assessment, while the FAVAIA language was developed independently from a particular assessment. In the former case the challenge lay in the impossibility to agree on a shared language at the beginning of the project. This challenge was addressed by semantic ascent: a meta-language was developed and then applied to elaborate the required problem-specific language during the course of the project. In the latter case, the challenge lay (and still lies) in the social dimension of integration, since not only a project-wide harmonisation of languages, but a community-wide one is desirable.

In the cases of FORMETA, PIAM and DINAS-COAST, the second phase of knowledge integration, methodology design, was addressed, with an increasing level of specificity. The FORMETA case was the most general one in that it addressed methodology design in general. PIAM addressed the more specific case of computer model integration, thereby considering both optimisation and simulation models. DINAS-COAST addressed a still more specific case of computer model integration, considering only simulation models in the form of first-order difference equations that iterate on the same time step.

In the case of FORMETA, a meta-language for representing methodologies was developed in order to support the process of communicating and comparing methodologies of past assessments and designing new methodologies. The framework was tested by applying it to compare the methodologies of two recent VAs carried out by the ATEAM and DINAS-COAST projects. Whether the framework is useful to scholars in the design of new methodologies has yet to be seen in practise.

The first phase of integrating computer models, the development of a shared language, was, in the case of PIAM, not such an issue, because models were only coupled via relatively few shared concepts. In the DINAS-COAST case the development of a shared language was of particular importance, because models were coupled via many shared concepts.

The second phase of integrating computer models, the numerical integration, was challenging in both projects, but for different reasons. In the case of PIAM, the derivation of an appropriate coupling algorithm was the major task of the project. In the case of DINAS-COAST, this task was straightforward, because all of the models involved were first-order difference equations iterating on the same time step. However, while in the case of PIAM, the linkages between the models were few and clear at the beginning of the project, in the case of DINAS-COAST they were not; iteratively establishing those linkages was in fact the major task of the project.

In the case of DINAS-COAST, a knowledge integration method, the DIVA Method, was developed, because neither the shared language nor the model linkages could be fixed at the beginning of the project but were bound to frequently change during the course of the project. The DIVA Method organises and supports the iterative development and refinement of language and linkages during the course of the project. The usefulness of iteration for knowledge integration has been recognised generally for TAs (Klein, 1990, p. 190). In the case of PIAM no knowledge integration method was developed; language and linkages could easily be established at the beginning of the project. The challenge lay in the numerical integration, a process that cannot generally be organised by an integration method, but needs to be taken care of manually by the numerical mathematician.

In the case of PIAM, the social dimension of integration was more challenging than in the case of DINAS-COAST. PIAM aimed at a community-wide integration of models in the form of establishing a community in which modules for IA can be freely exchanged. The social aspects were addressed as part of a wider, still ongoing, European initiative called CIAM (Community Integrated Assessment Modules) that aims at building a community of institutions in which modules for IA can be freely exchanged (Jaeger *et al.*, 2002). In the case of DINAS-COAST, the social dimension was less challenging; not a community-wide but only a project-wide integration was aimed at.

9 Conclusions and outlook

The main objective of this paper was to show that and how TAs can benefit from addressing knowledge integration explicitly and methodically. Towards this end, I developed a framework of transdisciplinary knowledge integration and applied it to four cases. Knowledge integration was differentiated into two subsequent phases: (*i*) the elaboration of a shared language amongst the participants of the assessment, and (*ii*) the design of a problem-specific methodology.

Three devices for supporting knowledge integration were put forward: semantic ascent, formalisation and knowledge integration methods. Semantic ascent means shifting from speaking in a language about some subject matter to speaking in a meta-language, about the former language. The meta-language makes it easier for the participants to elaborate a shared language that is adequate for the problem to be solved. Formalisation means translating statements made in ordinary or technical language into formal language. It forces the participants to make underlying assumptions and relations between concepts explicit and therefore allows them to communicate more precisely about the problem to be solved. A knowledge integration method is a method that consists of a meta-language for talking about the knowledge to be integrated, and a specification of the knowledge integration process, *i.e.* the process of applying the meta-language in order to elaborate the shared language and to design the assessment's methodology.

With the help of this framework, I analysed four cases of knowledge integration from the domains of IA and VA. In the first case of FORMETA, the general problem of methodology design was addressed. In the second case of FAVAIA, the problem of developing a shared language for speaking about vulnerability to climate change was addressed. In the third and fourth cases of PIAM and DINAS-COAST, a frequent special case of methodology design, the integration of computer models, was addressed on differing levels of generality.

Three general conclusions are drawn. First, semantic ascent is a useful device in those cases of transdisciplinary knowledge integration in which no direct agreement on a shared language or a methodology for solving the problem can be reached. In the case of FORMETA, a meta-language for representing methodologies of TAs was developed in order to support the communication, comparison and design of methodologies. In the case of DINAS-COAST, a more specific meta-language for speaking about the integration of a particular kind of computer model was developed and applied to facilitate the elaboration of a shared language and the design of a the methodology.

Second, formalisation can significantly contribute to the development of shared languages. In the FAVAIA case, a formal mathematical language for speaking about vulnerability to climate change was developed. This language has helped researchers at PIK, members of the FAVAIA project, workshop participants, and members of the ADAM and NEWATER projects to communicate more precisely about the common issue of vulnerability to climate change. Crucial to the success of formalisation is a careful communication of the approach in order to not exclude the non mathematically trained as well as to prevent the common misunderstanding that formalisation means quantification.

Third, it is important not only to support knowledge integration by providing adequate languages through semantic ascent and formalisation, but also to organise the actual process of integrating knowledge. This is particularly important in cases in which many participants, concepts and methods are involved and the shared language and methodology are bound to change during the course of the assessment. Thereby, iteration plays a pivotal role. In the case of DINAS-COAST, a knowledge integration method, the DIVA Method, was developed in order to organise the process of elaborating a shared language and the linkages between models of distributed participants.

The presented approaches are being further developed and applied. The definitions of the FAVAIA framework are currently being generalised to continuous-time, stochastic and fuzzy systems, as well as to systems of several interacting agents.[18] Both the FAVAIA and the FORMETA frameworks are tested and further developed in a meta-analysis of case studies that is carried out within the above-mentioned ADAM project. The two frameworks are used to code, compare and synthesise about 200 impact, vulnerability and adaptation assessments that have been conducted in Europe. The PIAM approach is currently being extended to cases of more than two interacting models; libraries of frequently needed coupling algorithms are being developed. The application of the DIVA Method to build tools for the assessment of coastal vulnerability of several world regions such as Europe, the Caribbean and Southeast Asia is currently being explored.

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[18] See the FAVAIA web-site for more information: `http://www.pik-potsdam.de/favaia`.

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