Transdisciplinary Knowledge Integration

Cases from Integrated Assessment and Vulnerability Assessment

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Abstract

This thesis explores how transdisciplinary knowledge integration can be facilitated in the context of integrated assessments and vulnerability assessments of climate change. Even though knowledge integration is fundamental in such transdisciplinary assessments, the actual process of integrating knowledge is rarely addressed explicitly and methodically. Here, knowledge integration is conceptualised into the 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.

Four cases of knowledge integration are presented. First, the general problem of methodology design is addressed and a graphical framework for representing methodologies is presented. Second, the problem of developing a shared language for speaking about vulnerability to climate change is addressed. A formal mathematical framework of vulnerability and related concepts is presented. Third, a special case of methodology design, the integration of computer models in the context of modular integrated assessment modelling is addressed. A modular approach developed in the PIAM project (Potsdam Integrated Assessment Modules) is presented. Fourth, the integration of computer models, this time in the context of a global assessment of coastal vulnerability to sea-level rise, is addressed. A knowledge integration method, which was developed and applied in the DINAS-COAST project (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise), is presented.

These cases show that semantic ascent is a useful device in those cases in which it is difficult to directly elaborate a shared language at the beginning of the assessment. Formalisation can contribute to the elaboration of a shared language in those cases in which concepts overlap non trivially in their meanings. More emphasis should be placed on the development and application of iterative knowledge integration methods as iteration is crucial in order to benefit from the mutual learning during the course of the assessment.

Keywords: climate change, integrated assessment, knowledge integration, transdisciplinary research, vulnerability, vulnerability assessment.

Foreword

This thesis is motivated by the desire to gain some understanding of the socio-environmental problems the world is facing today, such as, *e.g.*, climate change, and possibly contribute a bit to their alleviation. If one attempts to understand these problems one is confronted with many different opinions. If one then turns towards academia, in the hope that there different opinions are replaced by knowledge, one soon realises that the picture within academia is a quite similar one, only that there the "opinions" come in the forms of scientific disciplines, research fields, paradigms, schools of thought, frameworks and theories. None of these "opinions" offers a comprehensive answer to what is going wrong on this world. The challenge of understanding today's socio-environmental problems is actually the challenge of integrating knowledge from different perspectives. This is the subject matter of this thesis.

I began my academic training at the University of Karlsruhe in Germany with a course of geo-ecology. The course had been advertised as an interdisciplinary one that aims at understanding the "functioning" of human-managed ecosystems as a whole and therefore mixes together perspectives from various bio- and geo-science as well as engineering disciplines.

However, we received a rather disciplinary education. Since we were only 20 students in the course, there were no classes offered particularly for us; we took our chemistry classes at the chemistry department, the biology classes at the biology department and the hydrology classes at the civil engineering department. Each department lived in a universe of its own and it sometimes seemed that the only linkages between them were the students of geo-ecology. In some departments we were even seen as substandard students who were not willing or able to receive the full "disciplination" of a proper scientific discipline. My chemistry professor, for example, made this point very clearly by letting me pass my intermediate examination only after conveying to me that I was certainly not qualified to pursue an academic career.

While we got acquainted with the ways of thinking of different academic disciplines, nobody taught us how to integrate the different perspectives; this we had to find out by ourselves. In the beginning I was struggling with this task, but eventually it turned out to be the most interesting aspect of the course. I more and more adopted a meta-perspective on scientific disciplines and got interested in the questions of why different disciplines had different views and what claims could be made about the certainty of those views. I started taking classes in epistemology and knowledge ethics.

After I had received my university diploma, I was more interested in further pursuing the question of knowledge in general than in working within a specific knowledge domain or scientific discipline, as most of my fellow students did. For a long time I have had an affinity to computer technology, in particular to the free computing platform GNU/Linux. Taking advantage of the rise of the "new economy", I started working as a computer programmer. In various contexts, I was designing databases and programming web-applications for such diverse knowledge domains as car manufacturing, media pedagogy and personnel recruitment.

Writing computer programs, in particular on Linux or other Unix platforms, is, I believe, an excellent school when it comes to handling and integrating knowledge from different domains. Being a good programmer means that one can quickly understand knowledge from different domains and represent it in form of computer programs. Furthermore, the programmer's mission is to abstract commonalities from the different domains and implement them as software modules (*e.g.*, libraries) that can be reused to tackle new problems. In fact, Linux is the result of thousands of people that have, over several decades, collaboratively structured their knowledge into one modular computing system. By working with and increasingly understanding that system one greatly benefits from the experience the many programmers have gained in this huge knowledge integration effort.

After a while, I got bored by programming as an end in itself and wanted to get back into environmental work. I took a position at the Potsdam Institute for Climate Impact Research (PIK). My main task at the institute was to work on the integration of models from various natural and social science disciplines within different collaborate research projects. This work gave me an excellent opportunity to combine what I had learnt at university with my programming know-how. I also encountered a very different intellectual environment from what I knew from university. Interdisciplinarity was not a substandard activity but the desired objective.

However, while integrating knowledge from different disciplinary domains is the daily bread and butter of the climate change scientific community, the actual process of doing so often remains obscure. Methods for or theories about knowledge integration are largely lacking. A review of the literature on inter- and transdisciplinary research in general gave the same picture. The word 'integration' is used frequently, but little is said on what it actually means.

The search for theoretical and methodical support for knowledge integration motivated me to take classes in semiotics at the Technical University of Berlin. Semiotics is the study of sign systems and processes; it includes the study of ordinary language and formal language, but also the study of other "symbolic" languages such as gestures, traffic signs and cultural artifacts in general. The concepts of semiotics have been applied to many natural and social science disciplines as well as to the humanities. In all of these domains signs are used to express and communicate knowledge, whether those signs are mathematical symbols, codes of a programming language, boxes of a chart or words of an ordinary language. Adapting a uniform semiotical perspective on the different domains helps to structure knowledge from these.

Mathematics played a role similar to those of programming and semiotics in the development of my ideas on knowledge integration. Mathematics is paramount in most scientific disciplines and thus acts as a natural bridge between different domains. The mathematical virtues of abstraction and generalisation help to identify commonalities of different knowledge domains. As a member of the scientific computing research group at PIK, I benefited greatly from working closely together with colleagues trained as mathematicians.

I also had the opportunity to dig deeper into fundamental questions of scientific enquiry. In the Cartesian Seminar, a weekly seminar held by a small group of scholars at PIK, we carefully read and discussed literature that dealt with fundamental methodological and epistemological questions, such as, *e.g.*, Descartes' *Regulae ad directionem ingenii*. Since transdisciplinary research lacks canonical procedures for solving problems, it is necessary to take time and discuss fundamental issues that are normally taken for granted in disciplinary research.

The last indispensable element that contributed to my understanding of knowledge integration, was the practise integrating itself. Knowledge integration is a social process, which only works if the participants are open to share and discuss their different perspectives. Within PIK, Wageningen University and the broader climate change scientific community, I found this kind of environment.

This thesis brings together these elements that I have collected over the years in order to handle and integrate knowledge from different domains. It is the attempt to give more meaning to the word 'integration' by explicitly addressing transdisciplinary knowledge integration and by developing methods that can facilitate this process. In my opinion this is a crucial step transdisciplinary research has to take in order to improve its quality and efficiency.

The research for this cumulative thesis was carried out within the following four research projects: (*i*) DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise), a collaborate project funded by the European Commission from 2001 to 2004; (*ii*) EVA (Environmental Vulnerability Assessment), a PIK-internal project that served as a platform for discussing and integrating the findings of a number of externally-funded vulnerability assessment projects including the above mentioned DINAS-COAST project; (*iii*) PIAM (Potsdam Integrated Assessment Modules), also a PIK-internal project exploring the requirements for modular integrated assessment modelling; and (*iv*) FAVAIA (Formal Approaches to Vulnerability that Informs Adaptation), a still ongoing joint research project between PIK and the Stockholm Environmental Institute. Chapters 2 to 6 present individual papers that were produced in the course of the four projects. Chapter 1 develops an overarching language for speaking about transdisciplinary knowledge integration and applies it to synthesise the other chapters.

Writing this thesis was difficult for two reasons. The first reason was that I have never been a "true" PhD student. From the beginning of my work at PIK I held position as a full researcher and was all the time involved in several parallel research projects. After a couple of years, when I then decided to write a PhD thesis, the daily business such as travelling to meetings and writing reports, made it sometimes difficult to find time for concentrating on the thesis.

The second reason was that it was difficult to find the right anchorage within the university system due to the unusual subject matter of this thesis. On the one side there were departments such as environmental science and geography which were interested in the integrated perspective on environmental issues, but not in the process of attaining that integrated perspective, *i.e.* the process of knowledge integration itself. On the other side there were departments such as information science, semiotics, philosophy and sociology of science, which were interested in knowledge integration, but not in the subject matter the knowledge is about, *i.e.* the environmental issues. For me, however, the main point in writing this thesis was to mix together these two perspectives.

In this regard, I am very grateful to have found an anchorage in the environmental system analysis group of Rik Leemans at Wageningen University. From the very beginning, Rik was enthusiastic about the unusual subject matter of the thesis and has been a great help in getting me focused on it. He always made me feel very welcome at the Institute and his home and was very supportive in providing feedback on the manuscripts. Thanks a lot, Rik!

I would also like to thank Rupert Klein and Richard Klein for co-supervising this thesis and collaborating in the research. Rupert and Richard have been great colleagues of mine for many years and were involved in most of the research of the thesis. They always had an open ear for my concerns, encouraged me to further develop my ideas and gave me a truly interdisciplinary home situated between numerical mathematics and human geography.

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Jochen Hinkel
Berlin, September 2, 2007.

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Chapter 1

Synthesis

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Abstract

This chapter 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 chapter 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. Formal-

isation 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.

1.1 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 thesis 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 thesis 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. This first chapter of the thesis is an extended synthesis of the cases. The five chapters that follow present the cases in the necessary detail.

Note, however, that this thesis 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 chapter is organised as follows: Section 1.2 reviews the state of the art of TA in general and IA and VA in particular. Section 1.3 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 thesis. Section 1.4 and 1.5 develop meta-concepts for speaking about scientific knowledge and knowledge integration, respectively. Section 1.6 explores how knowledge integration could be facilitated. Section 1.7 applies the developed concepts to four cases taken from the domains of IA and VA. Section 1.8 comparatively discusses the cases and Section 1.9 concludes the chapter.

1.2 Transdisciplinary assessments

1.2.1 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 1.4 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 thesis 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 thesis.

1.2.2 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 thesis, 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 Chapter 2.

1.2.3 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 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

[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).

"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.

1.3 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.

1.3.1 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 Chapter 2 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

[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).

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

1.3.2 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

[3] `http://unfccc.int/adaptation/sbsta_agenda_item_adaptation/items/3633.php`
[4] `http://www.basic-project.net/`

(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), Füssel and Klein (2006), O'Brien et al. (2006), Füssel (2007), as well as in Chapter 3 of this thesis. A detailed comparison of the methodologies applied in the VAs carried out by the DINAS-COAST and ATEAM projects can be found in the next chapter.

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), Füssel (2007) and Chapter 3 of this thesis. 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]

1.3.3 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.

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

This thesis 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 thesis 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.

1.4 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.

1.4.1 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

[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.

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.

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 1.1 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

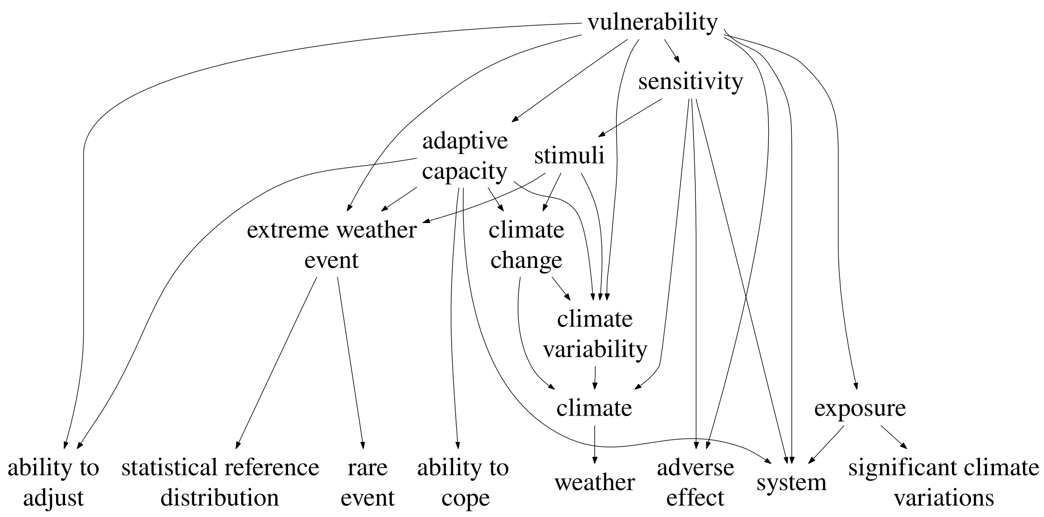

Figure 1.1: The relations between the concept of vulnerability and its defining concepts as given in the Working Group 2 glossary of the IPCC Third Assessment Report. The nodes represent the concepts and the arrows point from the defined concepts to the defining ones.

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 (see Chapter 6).

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). Languages 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*.

1.4.2 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 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)".

[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.

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

1.5 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.

1.5.1 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 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 1.7.2 and in Chapter 3.

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.

1.5.2 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 Chapter 4 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.

1.6 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.

1.6.1 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 1.5.1, "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 1.7.2 and Chapter 3 .

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 1.3.2 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 chapter itself develops a meta-language for speaking about the integration of knowledge.

1.6.2 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 1.4.1), 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 ground-braking 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 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

[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).

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 1.7.2.

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.

1.6.3 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 1.4.2). 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.

1.7 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 meth-

[15]See `http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx`.
[16]See `http://www.ventanasystems.co.uk/vensim.html`.

odologies 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 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.

1.7.1 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 thesis 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 Chapter 2.

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 1.3.1, 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.

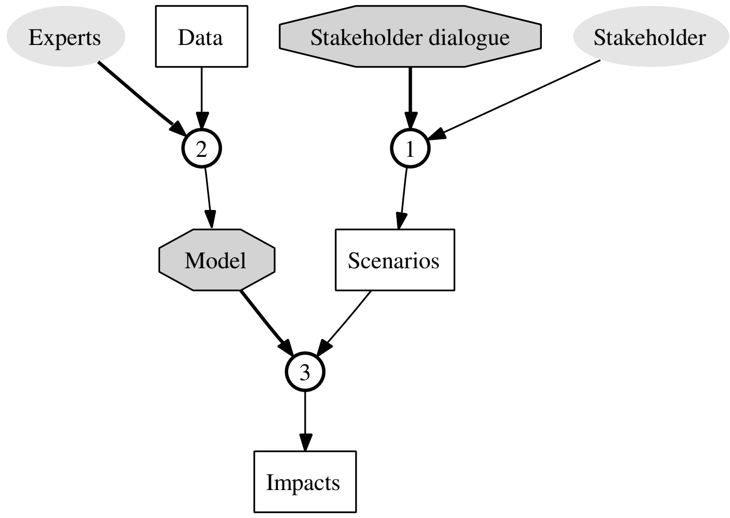

Figure 1.2: Example of a methodology. The octagons represent methods, the rectangles data, the ovals actors and the numbered circles activities.

Figure 1.2 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 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.

1.7.2 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 Chapter 3.

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:

$$f : X \times E \to X, \tag{1.1}$$

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 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

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

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.

1.7.3 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 Chapter 4.

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 Chapter 4 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 1.5.2, 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.

1.7.4 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 Chapter 5 and Chapter 6.

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 chapter.

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 Chapter 5.

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.

1.8 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 1.1), 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 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 1.3) with the IPCC language (Figure 1.1) 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. Chapter 6, for example, shows 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. Vulnerabil-

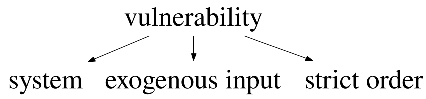

Figure 1.3: The relations between the concept of vulnerability and its defining concepts as given in the FAVAIA language. The nodes represent the concepts and the arrows point from the defined concepts to the defining ones.

ity 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. Chapter 3, for example, shows 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.

1.9 Conclusions and outlook

The main objective of this thesis 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.

Acknowledgements

The author thanks Nicola Botta, Sandy Bisaro, Lorenz Erdmann, Cezar Ionescu, Richard Klein, Rupert Klein, Rik Leemans and Sarah Wolf who commented on earlier versions of this chapter and provided valuable insights.

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

Chapter 2

A framework for analysing methodologies of transdisciplinary assessments

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Abstract

In spite of the lack of a common approach for assessing vulnerability, *i.e.* a multitude of different definitions and methodologies are applied, there is a great need to be able to understand and compare vulnerabilities assessed with different approaches. This need has led to a considerable amount of conceptual literature that analyses and compares different definitions of vulnerability, as well as proposes overarching conceptual frameworks. This chapter shifts the focus, arguing that it is more important to analyse and compare methodologies than definitions, because the definitions put forth are often far away from the methodologies applied; only the methodology defines what vulnerability "really" means in the context of a specific assessment. In addition, there is an increasing need to understand and communicate methodologies of past assessments in order to build upon these in the design of new methodologies. With the aim of facilitating the analysis, comparison and communication of methodologies, this chapter develops a graphical framework for representing methodologies and applies it to compare the methodologies of two recent vulnerability assessments carried out by the DINAS-COAST and ATEAM projects. It is found that the methodologies of the projects differ in three aspects: (*i*) ATEAM delivered data while DINAS-COAST delivered a computer model, (*ii*) ATEAM modelled the environmental system and the human response separately while DINAS-COAST modelled them jointly, and (*iii*) ATEAM involved stakeholders while DINAS-COAST did not. These differences have an influence on the methodologies' products and the way their users perceive them. ATEAM produced simple, aggregate results 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. While the framework developed is specifically beneficial to the field of vulnerability research it can be applied to other fields of transdisciplinary research without any changes.

2.1 Introduction

Vulnerability assessment (VA) has become a widespread activity in global change research. Knowledge about the vulnerabilities of different people, regions or sectors enables scientists and policymakers to anticipate impacts of global change and to develop appropriate responses. The assessment of vulnerability is a transdisciplinary activity, meaning that knowledge from a number of scientific disciplines and also from outside of science (policymakers and other stakeholders) needs to be integrated in order to understand the complex interactions of the human-environment system that determine vulnerability. Being a young and transdisciplinary research field, VA faces terminological and methodological challenges.

There is confusion regarding the meaning of the concept of vulnerability in the global change scientific community. The IPCC Third Assessment Report defined 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. It is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al., 2001, p. 995). The extent to which this definition can be made operational for assessing vulnerability is limited, because the defining concepts themselves are rather vague. Many alternative definitions have been put forward within the global change and related scientific communities.

The diversity in definitions is accompanied by a similar diversity in methodologies for assessing vulnerability. Each problem addressed exhibits unique features and requires the design of its proper approach. To this end, participants from different scientific disciplines and from outside of the science come together and spent a lot of time on discussing which knowledge is relevant and how to configure it into an appropriate methodology. Over the years, approaches have grown in complexity, developing from considering only single stresses to considering multiple stresses, from merely assessing impacts to also taking adaptation into account, and from static approaches to dynamic ones (Füssel and Klein, 2006). Today, methodologies comprise a multitude of participatory and analytical methods.

In spite of the lack of commonly agreed definitions and approaches, there is a great need to be able to compare the results attained with different approaches. In fact, comparability is key to the notion of vulnerability: policymakers often ask which country, region or sector is most vulnerable in order to prioritise efforts that need to be undertaken in order to minimise risks and mitigate possible consequences (Burton et al., 2002; Füssel and Klein, 2006). In addition, there is a need to learn from and build on past assessments for designing new approaches.

Efforts to address these needs have focused upon analysing theoretical definitions of vulnerability and proposing overarching conceptual frameworks (Brooks, 2003; O'Brien et al., 2004; Füssel and Klein, 2006; Füssel, 2007; Ionescu et al., 2005; O'Brien et al., 2006). These analyses, though useful for conceptual clarification, have limited practical relevance for comparing vulnerabilities or learning from past assessments, because in many assessments the theoretical definition put forward is far away from the methodology applied. Here, I approach the abovementioned needs from the other side. Instead of analysing and comparing theoretical definitions, I analyse and compare the methodologies applied for assessing vulnerability. Methodologies are operational definitions of vulnerability, because they define what vulnerability exactly means in the context of the specific assessments. In particular, this paper addresses the following two questions.

The first question addressed is how can the analysis, communication and comparison of methodologies be facilitated? To this end a graphical framework for representing methodologies is developed. By representing methodologies in a graphical and uniform manner, I aim at making complex methodologies quickly accessible to a reader and, as a consequence, at facilitating the analysis, communication and comparison of methodologies, as well as the design of new methodologies. The usefulness of the framework is explored by applying it to analyse and compare the methodologies of two recent VAs. While the approach presented is specifically beneficial to the young field of VA it is not limited to this field and can be applied to other sorts of transdisciplinary research.

The second question addressed is which features of a methodology are useful for which purpose? As pointed out in the Introduction of this book, the primary aim of VAs is to serve the purposes of the users of the assessments results (*e.g.*, stakeholders or decision makers) rather than to advance scientific understanding in its own right. While different purposes, such as to raise awareness, to improve adaptation and to frame the global environmental change mitigation problems are named in the literature (Burton et al., 2002; Füssel and Klein, 2006; O'Brien et al., 2006; Smit and Wandel, 2006), they are rarely related to the design of the assessments' methodologies.

The rest of the chapter is organised as follows. Section 2.2 discusses the concept of a methodology in the context of transdisciplinary research. Section 2.3 develops a graphical framework for analysing methodologies. Section 2.4 applies the framework to analyse the methodologies of two recent VAs carried out by the DINAS-COAST and ATEAM projects and Section 2.5 compares these methodologies. Section 2.6 concludes and gives an outlook.

2.2 Methodologies

The way transdisciplinary assessments in general and vulnerability assessments in particular solve problems differs from the way of disciplinary research. Generally, there is no single or obvious method for solving a given problem, nor are there ready-made methods that can be taken "off-the-shelf". Each problem addressed has unique features and requires the *ad-hoc* design of its proper approach. Relevant knowledge from people of different scientific and non-scientific domains must be identified, selected and configured appropriately. For example, the VA carried out by the ATEAM project (Schröter et al., 2005) involved the development of various scenarios, workshops to identify stakeholders preferences, statistical analysis of socio-economic data and simulation experiments with various hydrological and ecosystem models. For general descriptions of vulnerability assessment approaches see Schröter et al. (2004) and the IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter et al., 1994).

In the context of transdisciplinary assessments, the specific configuration of methods, data and people involved in solving a problem is usually called the *methodology*, *integrated methodology* or *methodological approach* of the assessment. Note that in other contexts the term "methodology" is used in different senses, either to refer to a system of methods followed in a particular discipline or to the branch of philosophy that studies such systems (Wordnet, 2005). In order to not create confusion, I will follow the usage of the term in transdisciplinary research. Note also that methodologies are not methods. A method is a specification of a process that makes the process reproducible by others and applicable to other cases, both of which is generally not possible for a methodology of a transdisciplinary assessment. Methodologies always include elements that are specific to the case addressed.

Methodologies of transdisciplinary assessments 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 of methodologies; methods are transferred from one discipline to another, composed from disciplinary methods, or developed from scratch. Often the problem perception changes during the course of applying the methodology and the methodology must be adjusted accordingly.

Methodologies are operational definitions.[1] Operational definitions define the meaning of a term by giving rules how to measure it, while theoretical definitions define the meaning of a term on the basis of other theoretical concepts (Schnell et al., 1999; Bernard, 2000). This distinction resembles the distinction made in philosophy of science between observable and non-observable or theoretical concepts (Stegmüller, 1974; Carnap, 1995). Vulnerability is a theoretical concept while, for example, income or temperature are observable ones.[2] A theoretical definition tries to capture all relevant dimensions of the introduced concept. For example, the above-mentioned IPCC definition of vulnerability names the dimensions, exposure, sensitivity and adaptive capacity. Making a theoretical concept operational means providing a method (an operation) for mapping it to observable concepts. That method is then called the operational definition.

In this manner, the methodology of a VA is an operational definition of vulnerability; it defines the specific meaning the concept of vulnerability has in the context of the assessment. The results of VAs are statements that declare that or to which extent certain entities are vulnerable. However, how do we interpret these statements? Some idea on the meaning of such statements can be gained by our intuitive understanding of the concept of vulnerability or with the help of the theoretical definitions that are used within the scientific community. However, since different people have different intuitive understandings and use different theoretical definitions, the exact meaning of these statements can only be understood by

[1]A methodology is not a particular "good" operational definition, because, as discussed above, it only holds for a small number of cases.

[2]What observability means differs from discipline to discipline. For example, for a physicist temperature is observable, for a philosopher, however, it is not, because there is no direct sensory perception of it (only the position of a pointer can be observed). This means that observability is a convention: if the members of a discipline have agreed upon a simple or canonical way of measuring a concept, it is said to be observable. See, *e.g.*, Carnap (1995) for a discussion of observability.

looking at the methodology that has generated them.

One motivation for writing this chapter is that while great effort has been made in analysing and comparing theoretical definitions, little effort has been made in analysing and comparing methodologies applied for assessing vulnerability. Furthermore, the work on theoretical definitions is hardly connected to case studies that assess vulnerability. In most case studies, operational definitions are not derived systematically from the theoretical ones and the relation between the two often remains obscure. In my opinion, an improved analysis of methodologies of VAs is more likely to advance the field of vulnerability research and possibly also leads to more robust theoretical definitions than further theoretical work far away from empirical "reality". After all, the primary aim of VAs is to support action in the empirical world.

Another motivation for analysing methodologies is that it is generally the only way of judging the quality of the results of transdisciplinary assessments. Generally, the result statements produced by vulnerability assessments cannot be verified, because the "classical" means of verification, *i.e.* testing results through experiments or *in situ* observations, are lacking due to the large spatial and temporal scales considered. As a consequence, only the quality of the process that generated the statements can be considered and the methodology is the specifications of this process. Similar reasoning underlies, for example, the introduction of the ISO management standards 9000 and 14000, which certify business processes, rather than the products produced (ISO, 2005).

2.3 A framework for analysing methodologies

Building on the intuitive understanding of methodologies developed in the last section, this section introduces a more formal graphical framework for analysing methodologies. The goal of the framework is to present methodologies in a compact and concise manner, which allows for their quick communication and comparison.

A *methodology* of a transdisciplinary assessment is represented as a directed, simple graph[3] with four types of nodes: data, methods, actors and activities. The *actor* nodes denote the people involved in the application (not the design) of the methodology, that is the scientific experts or other stakeholders. The *data* nodes denote data in the widest sense, which includes observed or measured data, as well

[3]In the language of (mathematical) graph theory, a graph is a collection of nodes (or vertexes) and arcs (or edges). A directed graph is a graph with single-headed arrows as arcs. A simple graph is a graph that has at most one arc between two nodes.

as derived data. The *method* nodes denote specifications of activities. Note that this is a very general understanding of what a method is. Whether a specification is widely accepted is not of interest here, as this would normally be the case in scientific discourse. Data and method nodes will be subsumed under the label *knowledge* nodes. The *activity* nodes denote the individual steps of the methodology.

The arcs of the graph connect the activities with their inputs and outputs. Possible inputs to an activity are data, methods or actors. Possible outputs of an activity are data (*e.g.*, the activity is data collection) and methods (*i.e.*, the activity is the development of a method). All paths of the graph end with the final output or the *product* of the methodology.

Each activity has one special input that shall be called its *driver*. The arc between an activity and its driver is printed bold. The driver is either a method or an actor and activities will be called either *method-driven* or *actor-driven*, respectively. Method-driven activities consist in the application of its driving method. Method-driven activities are reproducible by others, while actor-driven activities are not, because no specification is or can be given for them. Instead, an actor or the actor's intention drives the activity. Besides the driver, activities can have any number of further inputs.

Figure 2.1 shows an example 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 is the application of the model on the scenarios to produce data on impacts. Activities 1 and 3 are method-driven activities. Activity 2, the development of the model, is an actor-driven activity, because it cannot be specified in the form of a method and is therefore not reproducible for others.

Activities that do not have any actor as input (no matter whether as driver or normal input) will be called *objective*, while those that do *subjective*. It follows that all actor-driven activities are subjective. Objective activities are deterministic, that is, given the same input, they always yield the same output.[4] Subjective activities are non deterministic, even when driven by a method, because they are social processes that involve actors.

For example, in Figure 2.1, Activity 3 is an objective activity. The application of the model on the scenarios will always produce the same result no matter who runs the model. Therefore this activity does not have an actor as input. Activities 1 and 2 are subjective activities. Activity 1 is method-driven. It is based upon

[4] I disregard stochastic methods, like e.g. the throw of a dice.

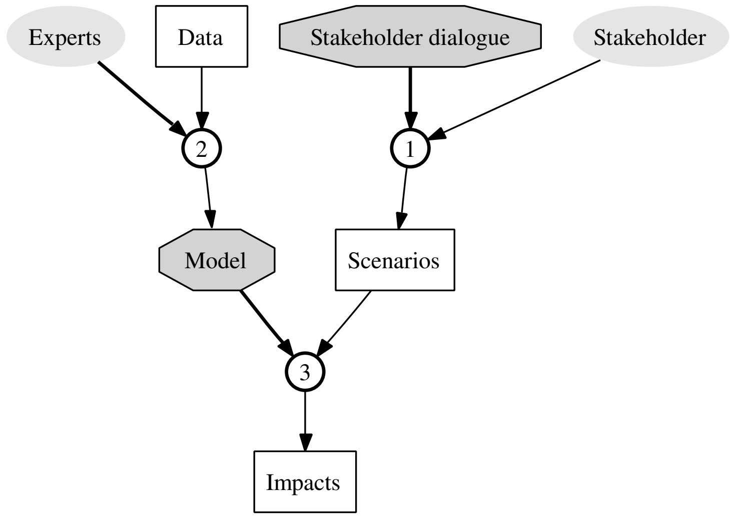

Figure 2.1: Example of a methodology. The octagons represent methods, the rectangles data, the ovals actors and the numbered circles activities.

a method, the stakeholder dialogue, and therefore can be reproduced by others through applying the same method. However, even then the activity will most likely not yield the exact same scenarios. Activity 2 is actor-driven and therefore, per definition, not reproducible; the experts that develop the model represent their own knowledge without being guided by a method.

Note that it is difficult to establish a clear cut between objective and subjective activities. For example, the application of a model most likely involves some value judgements like setting model parameters. However, I am interested in the big picture and most of the time it is quite clear how to categorise an activity.

Knowledge nodes that have an incoming arc shall be called *derived* and those that do not *basic*. Basic knowledge is fed into the methodology from the outside, while derived knowledge is produced within the methodology. For example, in Figure 2.1, the “Data” and “Stakeholder Dialogue” nodes depict basic knowledge, while the “Model”, the “Scenarios” and the “Impacts” nodes depict derived knowledge.

2.4 Two test cases

The objective of this section is to test the practical applicability of the framework by analysing the methodologies of two recent vulnerability assessments carried out by the EU-funded ATEAM and DINAS-COAST projects. The next section will then compare these two methodologies. The choice of these examples is motivated chiefly by the fact that I have first-hand knowledge of the two assessments.

Both projects have operationalised the IPCC definition of vulnerability as given in the Introduction. The vulnerable systems regarded are regions or more specifically the coupled human-environment systems of regions that are exposed to certain climatic and socio-economic changes. In both operationalisations adaptive capacity plays a major role. The way a region is influenced by climatic and socio-economic changes depends not only on the magnitude of the exposure and its sensitivity to it, but also, to a great extent, on the capacity of the region's human system to adapt. Adaptive capacity is defined by the IPCC as the "ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (McCarthy et al., 2001, p. 365).

2.4.1 ATEAM

The project ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) aimed at assessing the vulnerability of European regions relying on ecosystem services such as agriculture, forestry, carbon storage, carbon energy, water, biodiversity and mountains to global change. ATEAM's product is a digital atlas of vulnerability maps. See Schröter et al. (2005) for a detailed account of the project.

Figure 2.2 shows the ATEAM methodology in terms of the framework. In Activity 1, general circulation models (GCMs) and the four emission scenarios of the IPCC Special Report on Emission Scenarios (SRES; Nakicenovic and Swart, 2000) were used to produce climate scenarios. The climate scenarios were regionalised using data of observed patterns of regional climate (Activity 2). Experts of various disciplinary domains developed, also based upon the SRES scenarios, socio-economic, land-use and nitrogen oxides (NO_x) deposition scenarios (Activities 3, 4 and 5, respectively).

After scenario development, the methodology proceeded along two parallel tracks. The first track assessed the potential impacts of the regional climate scenarios on the regions' ecosystem services. Therefore, the scenarios were fed into ecosystem and hydrology models (Activities 6). Stakeholders developed an ecosystem service indicator function that reduces the high dimensional model output to a single dimension for each ecosystem service (Activity 7). The indicator function was applied on all model output to produce the "potential impacts" data (Activity 8). This data was further processed by a so-called stratification method that normalised the regions' potential impact values to a scale between 0 and 1, based on the environmental class the regions belong to (Activity 9).

The second track assessed the regions' adaptive capacities. Detailed socio-economic data of Europe was used to develop a statistical model, the adaptive capacity index, which represents the ability of the social system to adapt (Activity 10). The index was then applied on the socio-economic scenarios to get future projections of the regions' adaptive capacities (Activity 11).

In a last activity, the data on potential impacts and adaptive capacities were combined into vulnerability maps (Activity 12). The maps display different magnitudes of potential impacts as different colours and differences in adaptive capacities as colour saturation.

2.4.2 DINAS-COAST

The EU project DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise) aimed at assessing the vulnerability of coastal regions to sea-level rise. The product of DINAS-COAST is a user-friendly interactive tool called DIVA (Dynamic and Interactive Vulnerability Assessment). At its heart is an integrated model 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 coastal nations. See Chapter 6 for a comprehensive description of the project.

Figure 2.3 shows the DINAS-COAST methodology in terms of the framework. The methodology started with the development of climate and socio-economic scenarios. The climate scenarios were produced with the climate model of intermediate complexity CLIMBER-2 of the Potsdam Institute for Climate Impact Research (Petoukhov et al., 2000) and the SRES scenarios (Activity 3). The climate scenarios were regionalised using the output of a GCM (Activity 4). Also based upon the SRES scenarios, socio-economic scenarios were developed (Activity 5). A consistent global database (Vafeidis et al., under review) containing information on coastal morphology, ecosystems and further socio-economic characteristics was built up (Activity 2).

The main activity in terms of time and actors involved was the construction of an integrated model that represents the coupled human-environment system of the coast (Activity 6). Model development was based on an iterative method (Node "DIVA Method") that enabled experts of different disciplines to integrate their knowledge about coastal subsystems in the form of computer modules (Hinkel, 2005). Since the goal of the project was to give the model directly to users, a graphical user interface (GUI) was constructed (Activity 1).

In a last step, the model, the scenarios and the GUI were combined into the

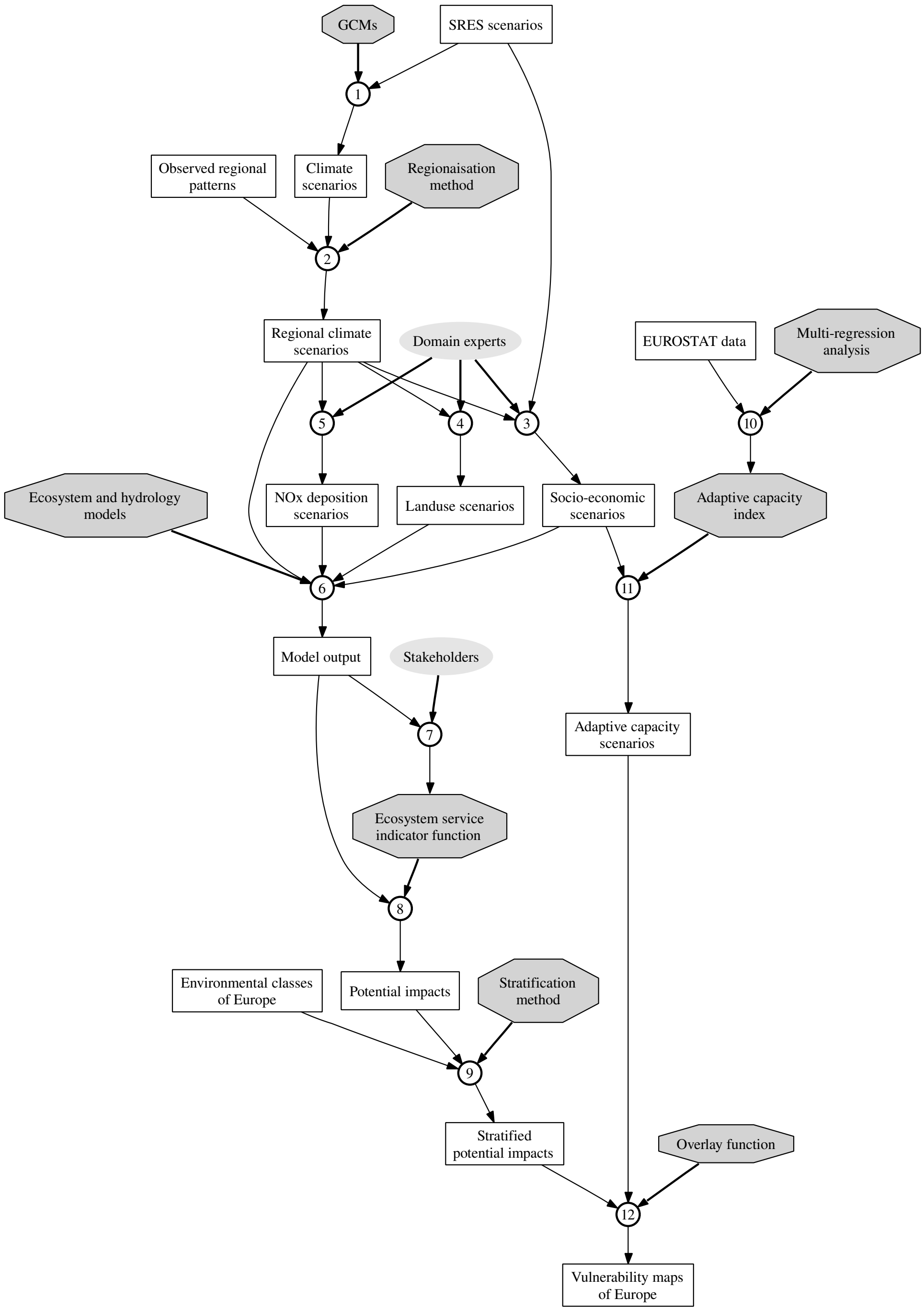

Figure 2.2: The methodology of the ATEAM project. The octagons represent methods, the rectangles data, the ovals actors and the numbered circles activities.

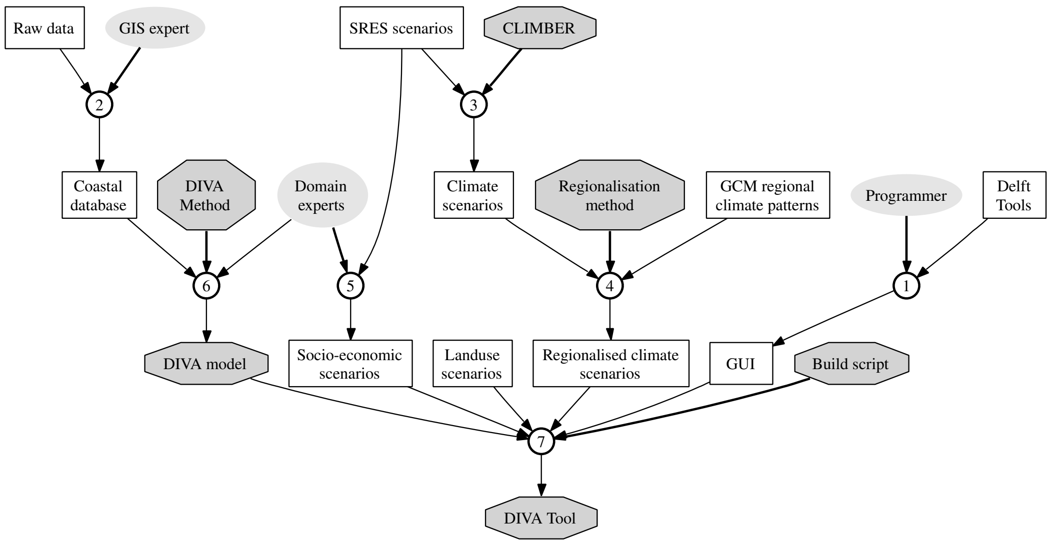

Figure 2.3: The methodology of the DINAS-COAST project. The octagons represent methods, the rectangles data, the ovals actors and the numbered circles activities.

DIVA Tool (Activity 7). The DIVA Tool allows its users to assess the vulnerability of different geographical entities (*i.e.* world regions, countries, administrative units and coast-line segments) by choosing scenarios and adaptation strategies as inputs, running the model and comparing results achieved with different inputs.

2.5 Comparative analysis

This section first compares the methodologies of ATEAM and DINAS-COAST, then compares the methodologies' products, and finally compares the user's perception of these products.

For the comparative analysis, it is important to note that the framework only captures the structure of a methodology and not its interpretation. Each activity of a methodology has a specific interpretation in the context of the assessment. For example, in the cases considered here, the activities stand for the dimensions of the theoretical definition of vulnerability, which are exposure, sensitivity and adaptive capacity (see also Section 2.2). In order to effectively apply the framework for analysing methodologies and especially for comparing them, the structure and its interpretation have to be regarded jointly. In the following, I will use the term "represent" to refer to the interpretation of the methodologies' activities.

2.5.1 Methodologies

In broad terms, the methodologies have a lot of commonalities. Computer models were used to represent the vulnerable systems. Climate and socio-economic scenarios were developed to represent the exposures to which the systems' vulnerabilities were assessed. The models were then applied to scenarios to produce information on potential impacts. Last, model outputs were post-processed and converted in a form adequate for its potential users.

In both cases, the development of climate scenarios was a method-driven and objective activity, while the development of socio-economic scenarios was actor-driven. Existing methods, *i.e.* climate models, were used to produce scenarios of climatic change. However, no standard method existed for the development of socio-economic scenarios and the corresponding activities were driven by domain experts.

The methodologies differ in the way the vulnerable system was represented. In ATEAM two separate models represented the vulnerable entity. Simulation models (Node "Ecosystem and hydrology models" in Figure 2.2) represented the environmental system and some aspects of the human system, like the management of forestry and agriculture. A separate statistical model (Node "Adaptive capacity index" in Figure 2.2) represented another aspect of the human system, namely the ability to respond to undesired impacts on the environmental system. This means that the impacts of the scenarios on the environment and the capacity of the human system to adapt to these impacts were assessed separately, without regarding the feedback between the two processes. In DINAS-COAST one integrated model represented the vulnerable entity. The impacts of the scenarios on the environment and the human system, as well as the human system's adaptation to these impacts, were assessed jointly.

In ATEAM the models that represent the vulnerable entity were, to the greatest extent, basic knowledge while in DINAS-COAST they were derived. ATEAM built upon the knowledge and the resources previously invested by using already existing ecosystem and hydrology models in its methodology. Only the statistical adaptive capacity model had to be built from scratch (Activity 10). DINAS-COAST built a new integrated model (node "DIVA model") as part of the project's methodology (Activity 6), because one important aim of the project was to directly represent the feedback of the human adaptation actions on the coastal systems.

Another difference between the methodologies is that ATEAM involved stakeholders, while DINAS-COAST did not. In ATEAM, stakeholders developed an indicator function that reduces the high dimensional output of the ecosystem models to one dimension for each ecosystem service (Activity 7 in Figure 2.2). This

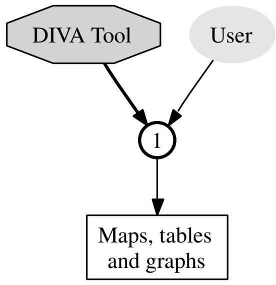

Figure 2.4: The application of the DIVA Tool. The octagons represent methods, the rectangles data, the ovals actors and the numbered circles activities.

point will be picked up again in the next Subsection.

A further difference between the two methodologies is that ATEAM produced data as its product, while DINAS-COAST produced a method. The product of ATEAM are maps that show the magnitudes of the potential impacts on the vulnerable regions and their adaptive capacities. The product of DINAS-COAST is the DIVA Tool, which is a model of the vulnerable regions and a set of possible inputs for that model, *i.e.* a set of scenarios and a set of adaptation strategies.

2.5.2 Methodologies and their products

Differences in methodologies translate into differences in their products, *i.e.* the vulnerability statements produced through the application of the methodologies.

The difference in the type of product, *i.e.* data in the case of ATEAM and a method in the case of DINAS-COAST, is mirrored in the methodologies. While in ATEAM the application of the models that represent the vulnerable entities on the scenarios was part of the methodology (Activity 6 and 11), in DINAS-COAST it is an extra activity to be performed by the user of the methodology's product (see Figure 2.4). Making the model available demands extra resources for tasks like making it platform-independent, documenting it, making it fast and developing an appropriate graphical user interface (Activity 1 in Figure 2.3).

The product of ATEAM, the vulnerability maps of Europe, is data in the form of a graph of a function. Disregarding the spatial and temporal dimensions, the project's methodology maps each of the four SRES scenarios to a scalar indicator representing the region's adaptive capacity and a vector indicator representing the impacts on the region. Symbolising the four SRES scenarios as $e_1, e_2, \ldots, e_4$, the resulting adaptive capacities as $a_1, a_2, \ldots, a_4$, the resulting impacts as $i_1, i_2, \ldots, i_4$, and the methodology as $\mapsto$, the result data of ATEAM can be depicted as the following list of statements:

$$\begin{aligned} e_1 &\mapsto (i_1, a_1) \\ e_2 &\mapsto (i_2, a_2) \\ e_3 &\mapsto (i_3, a_3) \\ e_4 &\mapsto (i_4, a_4) \end{aligned} \tag{2.1}$$

.

Applying the DIVA Tool to all combinations of scenarios and adaptation strategies also yields data in the form of a graph of a function, in which each combination of a scenario with an adaptation strategy is mapped to an impact indicator. Symbolising the scenarios as $e_1, e_2, \ldots, e_4$, the adaptation strategies as $u_1, u_2, \ldots, u_m$, and the impact indicators as $y_{1,1}, \ldots y_{4,m}$, the following matrix of statements is attained:

$$\begin{array}{llll} (e_1, u_1) \mapsto y_{1,1} & (e_1, u_2) \mapsto y_{1,2} & \ldots & (e_1, u_m) \mapsto y_{1,m} \\ (e_2, u_1) \mapsto y_{2,1} & (e_2, u_2) \mapsto y_{2,2} & \ldots & (e_2, u_m) \mapsto y_{2,m} \\ (e_3, u_1) \mapsto y_{3,1} & (e_3, u_2) \mapsto y_{3,2} & \ldots & (e_3, u_m) \mapsto y_{3,m} \\ (e_4, u_1) \mapsto y_{4,1} & (e_4, u_2) \mapsto y_{4,2} & \ldots & (e_4, u_m) \mapsto y_{4,m} \end{array} \tag{2.2}$$

.

In both cases, the result statements are similar in the sense that they relate (*i*) a value that represents a possible exposure (the e's in Formula 2.1 and 2.2), (*ii*) a value that represents the human response action (*i.e.* the a's in Formula 2.1 and the u's in Formula 2.2), and (*iii*) a value that represents impacts (*i.e.* the i's in Formula 2.1 and y's in Formula 2.2).

However, the statements are of different types. Whereas the human action appears on the right-hand side of the $\mapsto$ (*i.e.* as output of the methodology) in the case of ATEAM, it appears on the left-hand side (*i.e.* as input to the methodology) in the case of DINAS-COAST. As a consequence, the interpretations of the two types of statements differ. The interpretation of an ATEAM statement $e \mapsto (i, a)$ is of the form: "When the world evolves according to scenario e, the impact on the vulnerable system will be i, if you don't do anything. At the same time your ability to adapt will be a." The interpretation of a DINAS-COAST statement $(e, u) \mapsto y$ is of the form: "When the world evolves according to scenario e and you adapt according to strategy u, the impact on the vulnerable system will be y."

The difference in the types of statements mirrors the different ways in which the coupled human-environment system was represented in the two methodologies. In ATEAM, the vulnerable system was represented by two separate parts of the methodology; hence, the impacts and the human response appear as separate parts in the result statements. In DINAS-COAST, the vulnerable system was represented by one model; hence, only one impact indicator that, however, already includes the adaptations to the impacts is produced.

A further difference lies in the level of aggregation of the indicators. In ATEAM, the indicators are of low dimensionality (one component for the adaptive capacity plus one component for each ecosystem service) and its components are normalised to a real numbered scale between 0 and 1. In DINAS-COAST, the impact indicator is of high dimensionality and its components are not normalised. The indicator has roughly a hundred real numbered dimensions, each of which stands for one aspect of the impact on a region (e.g. costs of flooding, wetlands lost, damage due to salinity intrusion, etc.). The level of aggregation determines the comparability of indicator values: the indicator values of ATEAM are intuitively easy to compare, while those of DINAS-COAST are not. Indicator values need to be compared for answering questions like which regions are most vulnerable or under which scenario a region is most vulnerable.

The differences in the level of aggregation and, as a consequence, comparability mirrors the different ways in which the preferences of the stakeholders were respected in the methodologies. The intuitive comparability of ATEAM's impact indicators is achieved by letting the stakeholders develop the "ecosystem service indicator function" that reduces the high-dimensional output of the "ecosystem and hydrology models" into one dimension for each ecosystem service (Activity 7 in Figure 2.2). The stakeholders selected and weighted the components of the model output that they valued as important for indicating the state of the ecosystem services. In DINAS-COAST stakeholders were not involved in the methodology. The high-dimensional output of the model is given directly to the users. However, a tool for facilitating the comparative analysis of the output in the form of graphs, tables and maps is also provided.

2.5.3 Products and their users

The previous two Subsections were discussing methodologies and their products from the producer's perspective, that is from the perspective of the scholars designing and applying the methodology. This section considers the methodology from the consumer's perspective, that is from the perspective of the users of the methodologies' products. The discussion is based on published experiences gained from the ATEAM's final stakeholder workshop (Schröter et al., 2004) and on personal experiences gained from conducting user workshops with the DIVA Tool.

One difference between the methodologies was that ATEAM delivered data and DINAS-COAST delivered a model as the product. The advantage of delivering a model is that users have a greater degree of freedom to produce results by manipulating model parameters, running their own scenarios, or even changing the model's code. A possible disadvantage is that users might be over-challenged by this great degree of freedom. In the DINAS-COAST workshops the users were generally positive about having received the model. The fact that the model was delivered to the users was perceived as giving the assessment extra credibility, because this way the users were able to conduct their "own" vulnerability assessments. In particular, the ability to run the model on updated data was welcomed. Many of the users discovered data inconsistencies when they zoomed into the region they knew best (a limitation due to the reliance on global data sources in the DINAS-COAST methodology) and thus appreciated the ability to change the data and rerun the model.

Another difference between the two assessments was the type of result statements produced, *i.e* a measure representing the human system's capacity to adapt being the output of the methodology in the case of ATEAM (the adaptive capacity indicator) and the input to the methodology in the case of DINAS-COAST (the adaption strategy). Stakeholders confronted with the results of ATEAM were less interested in the values of the adaptive capacity indicator, because they felt they could better judge their ability to adapt for themselves (Schröter et al., 2004). In the DIVA workshops, the users had trouble understanding the concept of choosing an adaptation strategy. While choosing a scenario is an accepted practise, choosing a strategy on how to adapt to the impacts of scenarios is not.

A third difference was the level of aggregation of the result statements. ATEAM produced rather simple, aggregate statements containing normalised adaptive capacity and potential impact indicators. These statements made the results accessible to a wide audience and generated a lot of media attention. ATEAM was invited by Science to write a paper (Schröter et al., 2005), which again generated further interest; within the first year after publication, the paper has already been cited 26 times (`www.scopus.com`, 13.6.2007). However, the stakeholders that had been involved in the methodology were less interested in these aggregate statements but rather in particular dimensions of the model output that related to their domain of interest (Schröter et al., 2004). DINAS-COAST produced more complex, less aggregate statements that contain multi-dimensional indicators. At the DIVA workshops, most users were, at first contact, overwhelmed with the many dimensions. However, after having understood how to run the model and analyse the multidimensional results by producing tables, graphs and maps with the GUI, many users expressed interest in having even more detailed information.

2.6 Conclusions and outlook

I argued that an essential part of a transdisciplinary assessment, such as a vulnerability assessment, consists in the *ad-hoc* design of an appropriate methodology, which is a certain configuration of data, methods, actors and activities specifically tailored to the given problem. Supporting the communication and comparison of methodologies of assessments is therefore a crucial step in advancing transdisciplinary assessments. To this end, a graphical framework for representing methodologies of assessments was developed and applied for analysing and comparing the methodologies of two recent vulnerability assessments carried out by the ATEAM and DINAS-COAST projects.

One major difference between the methodologies was that ATEAM produced data, while DINAS-COAST a method, that is a model plus a set of input data. While delivering a model provides the user with more flexibility to produce results, it places an extra burden on the methodology in terms of adjusting the model to the needs of the users and developing a graphical user interface. It also places an extra burden on the users in terms of training required. In the case of DINAS-COAST, the users accepted the extra burden in return for the flexibility to run the model on their own data.

The methodologies also differed in the way the vulnerable system (*i.e.* the coupled human-environment system) was represented and, resulting from that, the type of result statements produced. While in the case of ATEAM different models represented the vulnerable entity without including the feedback of the human adaptation actions on the environment, in the case of DINAS-COAST one integrated model represented the vulnerable entity including the feedback. As a consequence, the ATEAM result statements consist of two indicators per vulnerable system, one indicating potential impacts and the other one indicating the capacity to adapt to these impacts. The DINAS-COAST result statements consist of one impact indicator per vulnerable system, which entails the assumption of a certain way to adapt. The users had trouble with both ways of handling adaptation. Further research is needed on how to handle adaptation methodologically and how to communicate results achieved to the users.

Both methodologies emphasised that the concept of vulnerability cannot be made operational by science alone; its meaning also depends on the preferences that the users of the methodologies' products have on the state of the vulnerable entities. While science provides knowledge in the form of models and data, it is left to the users to compare the model output (*i.e.* the impact indicators) produced.

However, the methodologies differed in the way the preferences of the users were taken into account and, resulting from that, the level of aggregation of the result statements produced. In the ATEAM methodology, stakeholders were involved in weighing the different dimensions of the model output, which led to aggregate result statements. In the DINAS-COAST methodology, no stakeholders were involved and less aggregate statements containing multidimensional indicators were produced. The users of the methodology's product, the DIVA Tool, need to decide for themselves how to weigh the many dimensions of the model output. This activity is, however, supported by a graphical user interface.

Which level of aggregation is more useful depends on the type of user. In both assessments, the broader scientific and policy communities were more interested in aggregate statements, while those that actually make adaptation decisions were more interested in the specific dimensions of the model outputs.

The points made above exhibit a general trade-off between providing bold simple messages and providing detailed information for decision making. In terms of designing an assessment's methodology, this is the trade-off between reducing the complexity of the scientific knowledge to intuitively clear statements and delivering the complexity to the client together with tools to handle the complexity. It is hard to know beforehand which information is useful. The advice that can be given is to identify the users of the assessment's results at an early stage of the assessment and be flexible and able to adjust the methodology as the needs of the users become clearer.

The application of the framework to reconstruct methodologies is not trivial. A lot of people usually participate in an assessment which makes it difficult to exactly reconstruct all the activities involved. The quality of the reconstruction depends on the available information sources in the form of literature and personal interviews. Furthermore, there is a danger in mixing three different views of a project's methodology: (*i*) the methodology originally designed at the beginning of the assessment, (*ii*) the methodology actually applied in the assessment, (*iii*) the methodology to be applied when one would repeat the assessment. Here, the focus lay on the second view.

One important aspect to note is that the granularity by which methodologies are analysed is arbitrary. Activities can be decomposed further into sub-activities or aggregated into super-activities. For example, in the case of DINAS-COAST, the activity of building the integrated model (Activity 6 in Figure 2.3) actually consisted of a series of sub-activities, such as specifying a shared language, programming modules and analysing the linkages between the modules (Hinkel, 2005). Presenting methodologies with different resolutions could be particularly beneficial for communicating and comparing them.

The framework could be extended in two directions. One direction would be to analyse the structure of the data and method nodes further, along the lines started in Subsection 2.5.2. The individual dimensions of the data nodes could be distinguished and described. For such a deeper analysis it would be beneficial to adopt a mathematical notation, in which data are represented as sets, methods as functions or functors and the activities as function applications. The methodology would then be a composition of functions and functors.

Another direction of extension would be to attach information about the process of designing a methodology to the nodes. In a transdisciplinary assessments a lot of time is invested in discussing which methods or data to use. In order to learn from past assessments it would be interesting to know why certain methods or data have been selected. Alternative choices could be listed. Furthermore, methodologies are not static; changes are frequently made to them during the course of the assessment. It would be beneficial to know which changes have been made and why. Another interesting application would be to assess the structural uncertainties of methodologies by exploring how sensitive the methodologies' products are to the usage of other methods or data.

In order to prove its practical usefulness for communicating methodologies of vulnerability assessments, the proposed framework needs to be applied to more cases. Most importantly, the framework should be beneficial to those who design and perform vulnerability assessments. The application to other fields of transdisciplinary research, like sustainability or future research, will be explored.

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Chapter 3

A formal framework of vulnerability to climate change

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Abstract

There is confusion regarding the notion of "vulnerability" in the climate change scientific community. Recent research has identified a need for formalisation, which would support accurate communication and the elimination of misunderstandings that result from the use of ambiguous terminology. Moreover, a formal framework of vulnerability is a prerequisite for computational approaches to its assessment. This paper presents an attempt at developing such a formal framework. We see vulnerability as a relative concept, in the sense that accurate statements about vulnerability are possible only if one clearly specifies (*i*) the entity that is vulnerable, (*ii*) the stimulus to which it is vulnerable and (*iii*) the preference criteria to evaluate the outcome of the interaction between the entity and the stimulus. We relate the resulting framework to the IPCC conceptualisation of vulnerability and two recent vulnerability studies.

3.1 Introduction

Over the past two decades a multitude of studies have been conducted aimed at understanding how climate change might affect a range of natural and social systems, and at identifying and evaluating options to respond to these effects. These studies have highlighted differences between systems in what is termed "vulnerability" to climate change, although without necessarily defining this term. As shown by Füssel and Klein (2006), the meaning of vulnerability within the context of climate change has evolved over time. In the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), vulnerability to climate change was described as "a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity" (McCarthy et al., 2001, p. 995). Straightforward as it may seem, this conceptualisation of vulnerability has proven difficult to make operational in vulnerability assessment studies. Moreover, it appears to be at odds with those conceptualisations developed and used outside the climate change community (*e.g.*, natural hazards, poverty).

It is increasingly argued that many climate change vulnerability studies, whilst effective in alerting policymakers to the potential consequences of climate change, have had limited usefulness in providing local guidance on adaptation (*e.g.*, Smit et al., 2001) and that the climate change community could benefit from experiences gained in food security and natural hazards studies (IISD et al., 2003). As a result, the climate change community is currently engaged in a process of analysing the meaning of vulnerability and redefining it such that assessment results would be more meaningful to those wishing to reduce vulnerability. The clearest preliminary conclusion reached to date is that there is much confusion.

We wish to take up the challenge put forward by O'Brien et al. (2004), who suggested that "one way of resolving the prevailing confusion is to make the differing interpretations of vulnerability more explicit in future assessments, including the IPCC Fourth Assessment Report" (p. 12). We feel that there is an opportunity and indeed a need to cast the discussion in a formal, mathematical framework. By a "formal framework" we mean a framework that defines vulnerability using mathematical concepts that are independent of any knowledge domain and applicable to any system under consideration. The use of mathematics also avoids some of the limitations of natural language. For example, natural language can obscure ambiguities or circularities in definitions (*e.g.*, Copi and Cohen, 1998).

Inspired by conceptual work done by, amongst others, Kates (1985), Jones (2001), Brooks (2003), Luers et al. (2003), Turner et al. (2003), Jaeger (2003), Downing et al. (2005) and Luers (2005) and using vulnerability to climate change as our point of departure, we see this paper as taking a first step towards instilling some rigour and consistency into vulnerability assessment. Building on Suppes' arguments in favour of formalisation in science (Suppes, 1968), our motivation for developing a formal framework of vulnerability is fourfold:

- A formal framework can help to ensure that the process of examining, interpreting and representing vulnerability is carried out in a systematic fashion, thus limiting the potential for analytical inconsistencies.

- A formal framework can improve the clarity of communication of methods and results of vulnerability assessments, thus avoiding misunderstandings amongst researchers and between researchers and stakeholders (especially if the language used for communication is not the native one of all involved).

- By encouraging assessments to be systematic and communication to be clear, a formal framework will help users of assessment results to detect and resolve any inaccuracies and omissions.

- A formal framework is a precondition for any computational approaches to assessing vulnerability and will allow modellers to take advantage of relevant methods in applied mathematics, such as system theory and game theory.

Note that, consistent with Suppes (1968), a formal framework of vulnerability is not the same as a formal framework for vulnerability assessment. We see the latter as being aimed at providing guidance to those conducting vulnerability assessments or measuring the costs and benefits of adaptation (*e.g.*, Carter et al., 1994; Fankhauser et al., 1999; Callaway, 2004). A framework of vulnerability as proposed in this paper would be aimed at understanding the structure of vulnerability and thereby at clarifying statements and resolving disagreements on vulnerability. Also important to note is that the use of mathematics does not require quantitative input, nor does it have to lead to quantitative results. We use mathematical notation as a language in which we can formulate both qualitative and quantitative statements in a concise and precise manner.

We are well aware of two important caveats involved in developing a formal framework of vulnerability. First, the framework could be perceived as being overly prescriptive, limiting the freedom and creativity of researchers to generate and pursue their own ideas on vulnerability. Second, it could be seen as being developed for illicit rhetorical purposes, namely to throw sand in the eyes of those unfamiliar with mathematical notation. In spite of these caveats, we hope that the development of a formal framework of vulnerability will turn out to be a worthy undertaking, offering an opportunity for rigorous interdisciplinary research that can have important academic and social benefits. If this opportunity is seized by many, the risks represented by the two caveats will be minimised.

This paper is organised as follows. Section 3.2 investigates the "grammar" of vulnerability for three cases of increasing complexity; it extracts the building blocks for the actual formalisation of vulnerability and related concepts, which is presented in Section 3.3. Section 3.4 relates the framework thus developed to the approach taken to vulnerability assessment by the IPCC and in two recent studies. Section 3.5 presents conclusions and recommendations for future work.

3.2 Grammatical investigation

Before analysing the current technical usage of the concept of vulnerability within the climate change community, this section starts with an analysis of the everyday meaning of the word. The reason for this is that we consider it likely that the technical usage represents a refinement of the everyday one. In Section 3.3 we then first present definitions that capture the more general meaning of vulnerability and refine them in order to represent the technical meaning.

3.2.1 Oxford Dictionary of English

The latest edition of the Oxford Dictionary of English gives the following definition of "vulnerable" (Soanes and Stevenson, 2003, p. 1977):

1. Exposed to the possibility of being attacked or harmed, either physically or emotionally,
2. Bridge (of a partnership): liable to higher penalties, either by convention or through having won one game towards a rubber.

The Oxford Dictionary of English provides the following example sentence with the first definition: "Small fish are vulnerable to predators".

It follows from the definitions and the example sentence that vulnerability is a relative property: it is vulnerability *of* something *to* something. In addition, both the definitions and the example sentence make it clear that vulnerability has a negative connotation and therefore presupposes a notion of "bad" and "good", or at least "worse" and "better". It also follows that vulnerability refers to a potential event (*e.g.*, of being harmed); not to the realisation of this event.

3.2.2 Vulnerability in context: a non-climate example

In the assumed absence of endogenous controls, the small fish in the Oxford Dictionary of English have no means of defending themselves against predators. They would not be able to respond in any effective way once they realise that a predator has chosen them for lunch, with fatal consequences. Many natural and human systems, however, will be able to react to imminent threats or experience non-fatal consequences. Consider a motorcyclist riding his motorcycle on a winding mountain road, with the mountain to his left and a deep cliff to his right. There is no other traffic, but unbeknownst to the motorcyclist an oil spill covers part of the road ahead of him, just behind a left-hand curve. In natural language we would say that the oil spill represents a hazard and that the motorcyclist is at risk of falling down the cliff and being killed. Expanding on the example sentence of the Oxford Dictionary of English, we would consider that the motorcyclist is vulnerable to the oil spill with respect to falling down the cliff and being killed.

We would normally say that a second motorcyclist who drives more slowly or more carefully is less vulnerable to the oil spill, or that the hazard represents less of a threat to him. One challenge of formalising vulnerability is to account for such comparative statements.

The situation may be considerably more complex if we expand the time horizon. What about a third motorcyclist, who has heard about the oil spill on the road and has been able to prepare for it by buying new tires and improving his driving skills? Can his condition be meaningfully compared to that of the first two, who are confronted with an immediate hazard? What about a fourth motorcyclist, who has been informed but has no money to buy new tires?

Vulnerability to climate change has to account for all these different time scales, and introduces new aspects, such as the ability of the vulnerable entity to act proactively to avoid future hazards (by mitigating climate change or by enhancing adaptive capacity).

3.2.3 Vulnerability to climate change

Climate change will affect many groups and sectors in society, but different groups and sectors will be affected differently, for three important reasons. First, the direct effects of climate change will be different in different locations. Climate models project greater warming at high latitudes than in the tropics, sea-level rise will not be uniform around the globe and precipitation patterns will shift such that some regions will experience more intense rainfall, other regions more prolonged dry periods and again other regions both.

Second, there are differences between regions and between groups and sectors in society, which determine the relative importance of such direct effects of climate change. More intense rainfall in some regions may harm nobody; in other regions it could lead to devastating floods. Increased heat stress can be a minor inconvenience to young people; to the elderly it can be fatal. Extra-tropical storms can lead to thousands of millions of dollars worth of damage in Florida; in Bangladesh they can kill tens of thousands of people.

Third, there are differences in the extent to which regions, groups and sectors are able to prepare for, respond to or otherwise address the effects of climate change. When faced with the prospect of more frequent droughts, some farmers will be able to invest in irrigation technology; others may not be able to afford such technology, lack the skills to operate it or have insufficient knowledge to make an informed decision. The countries around the North Sea have in place advanced technological and institutional systems that enable them to respond proactively to sea-level rise; small island states in the South Pacific may lack the resources to avoid impacts on their land, their people and their livelihoods.

As stated before, the IPCC Third Assessment Report described vulnerability to climate change as "a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity" (McCarthy et al., 2001, p. 995). This is consistent with the explanation above as to why different groups and sectors will be affected differently by climate change. Differences in exposure to the various direct effects of climate change (*e.g.*, changes in temperature, sea level and precipitation) and different sensitivities to these direct effects lead to different potential impacts on the system of interest. The adaptive capacity of this system (*i.e.*, the ability of a system to adjust to climate change to moderate potential damages, to take advantage of opportunities or to cope with the consequences; McCarthy et al., 2001, p. 982) then determines the system's vulnerability to these potential impacts. These relationships are made visible in Figure 3.1.

3.3 Formalisation of vulnerability and related concepts

An important result of the grammatical investigation is that the concept of vulnerability is a relative one: it is the vulnerability of an *entity* to a specific *stimulus* with respect to certain *preference criteria*. We would expect any formalisation of

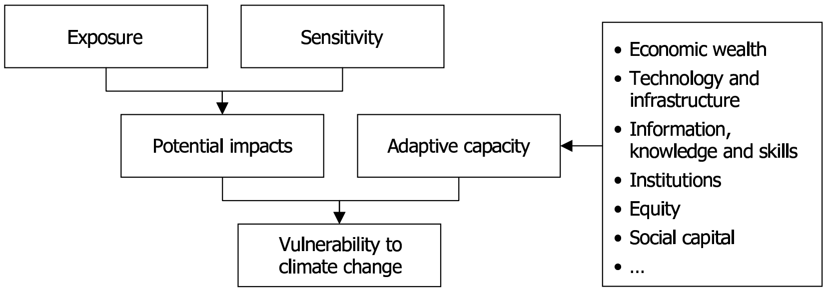

Figure 3.1: Graphical representation of the conceptualisation of vulnerability to climate change in the IPCC Third Assessment Report.

vulnerability to represent these three primitives, which leads us to looking at how the concepts of "entity", "stimulus" and "preference criteria" themselves can be formalised. More complex notions, such as "adaptive capacity", will require the additional formalisation of the entity's ability to act.

This section presents a stepwise formalisation of vulnerability. It uses mathematical notation, with which not every reader may be familiar. For those readers Table 3.1 explains the mathematical symbols used in this section in the order in which they appear.

The mathematical model developed in this section is meant as a clean-room environment, within which statements on vulnerability can be interpreted in isolation from the many real-world "details" that can obscure the issues (whilst, of course, providing the motivation for making such statements in the first place). The definitions are to be read as tentative formulations of vulnerability and related concepts. The reader is encouraged to criticise them and to submit alternatives.

3.3.1 Systems with exogenous input

The mainstream mathematical interpretation of an *entity* is that of a dynamical system in a given state. This is the interpretation we will adopt here. The *stimuli* to which such a system can be subjected are then naturally represented by the exogenous inputs to the system. The simplest kind of dynamical system with exogenous input is a discrete, deterministic one, given by a *transition function* (see Kalman et al., 1969):

$$f : X \times E \to X, \tag{3.1}$$

where X is the set of states of the system and E is the set of exogenous inputs. In systems theory, the state of a system at a given time describes all relevant properties the system has at that time. In physics, when discussing moving particles, the

Symbol	Meaning
$f : X \to Y$	f is a function defined on the set X and taking values into the set Y
$X \times Y$	The set of ordered pairs having as first element an element of X and as second element an element of Y
$x \in X$	x is an element of the set X
$f(x) = y$	The value of f for the element x is y
$x \prec y$	x is worse than y
$X \subseteq Y$	X is a subset of Y
$p \equiv q$	p is equivalent to q (p is true if and only if q is true)
$x \wedge y$	Logical and, *i.e.*, x is true and y is true
$x \notin X$	x is not an element of the set X
iff	if and only if
$x > y$	x is greater than y
$\mathbb{R}_+$	The set of positive real numbers
$\forall\, x : ...$	For all x such that ...
$\exists\, x : ...$	There exists at least one x such that ...

Table 3.1: Mathematical symbols and their meanings.

state of a particle contains not just the position of the particle, but also its speed. Similarly, in Economics, a company would not be described just by its capital, but also by its manufacturing potential, relevant contracts, growth, etc.

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: $f(x,e)$.

Example 1. We can interpret the example sentence from the Oxford Dictionary of English in the context of a simple Lotka-Volterra model (Lotka, 1925; Volterra, 1926), where the state of the system of small fish is given by their number. The exogenous input could be represented by the number of predators in the same environment. Given the present number of small fish and that of predators, the transition function computes the number of small fish in the next time step according to

$$f(x,e) = ax - bx^2 - cxe, \tag{3.2}$$

where x is the number of small fish, e is the number of predators and a, b and c summarise environmental factors (*e.g.*, density of fish population, reproduction rates).

We have chosen this deterministic, discrete dynamical system because of its structural simplicity. The value of this simplicity will become apparent once we start analysing vulnerability. The trained mathematician can extend the formalism so as to cover continuous-time, non-deterministic or stochastic systems and so on, but the presentation of the results would be more difficult to follow.

Preference criteria are used to ascertain whether or not a worsening of the situation (or, in our simple model, of the state) has occurred. They will therefore be represented by a relation on the set of states X. Let us denote this relation by $\prec$, which can be read as "is worse than". We expect $\prec$ to be

1. *transitive*, that is, if $x \prec y$ and $y \prec z$, then $x \prec z$,
2. *anti-reflexive*, that is, no state is worse than itself.

We do not expect $\prec$ to be total, that is, sometimes we might not be able to say whether $x \prec y$ or $y \prec x$ (given anti-reflexivity this question is valid only if $x \neq y$). A relation with these properties is called a *partial strict order*. In spite of $\prec$ representing preference criteria, $\prec$ will usually not be a *preference relation* as used in economics (*e.g.*, Kreps, 1988).

Example 2. Assume $B \subseteq X$ is a non-empty subset of states that can be interpreted as "bad states". Consider the following relation:

$$x \prec x' \equiv x \in B \wedge x' \notin B, \tag{3.3}$$

that is, x is worse than x' iff (if and only if) x is a state in B and x' is a state outside B. This relation is a partial strict order (we cannot compare two states that are both in B, or both outside B).

Example 3. Suppose we have a function $g : X \to \mathbb{R}_+$ that associates to every state a positive real number. This function can be interpreted as an "impact function", where impacts may be represented as costs. If we assume that the bigger the impact, the worse the state, we can define the relation $\prec$ by

$$x \prec x' \equiv g(x) > g(x'). \tag{3.4}$$

Again, $\prec$ is a partial strict order: we cannot compare states to which the same value has been associated by g.

Example 4. As before, assume we have a function $g : X \to \mathbb{R}_+$. We now consider a threshold value $T \in \mathbb{R}_+$ and take $\prec$ to be defined by

$$x \prec x' \equiv g(x) > T > g(x'), \tag{3.5}$$

that is, the impacts observed in state x are considered too high, whilst the impacts observed in x' are acceptable. This example is a special case of Example 2: the "bad" states are those of which the impacts are above the threshold.

3.3.2 Vulnerability: simple, comparative, transitional

In Section 3.2.1 we interpreted the Oxford Dictionary definition to mean that an entity is vulnerable to a stimulus if its situation has the potential to become (noticeably) worse. This can be interpreted mathematically by considering the entity to be a system f in state x, the stimulus to be an exogenous input e and "worsening" to be expressed by a partial strict order $\prec$. Upon the influence of the exogenous input the system makes a transition, resulting in the next state $f(x,e)$. We expect that if the system in state x were vulnerable to e, then $f(x,e)$ would be on the left-hand side of a $\prec$ comparison, that is, it is worse than another state. What could this other state be?

The simplest possible idea, which does not require the introduction of new elements, is to compare the future state to the current one. Accordingly we have:

Definition (simple vulnerability)
A system f in state x is vulnerable to an exogenous input e with respect to the partial strict order $\prec$ if $f(x,e) \prec x$.

Coming back to the system of small fish, we might express the preference criteria along the lines of Example 4 above.

Example 5. For the system of small fish described in Example 1, we consider a partial strict order based on a threshold value T, as follows:

$$x \prec x' \quad \text{iff} \quad x < T \quad \text{and} \quad x' > T, \tag{3.6}$$

that is, the number of fish represented by the state x is below threshold T, whilst in the state x' the number of fish is above T. The system in a given state turns out to be vulnerable to that input if the number of small fish decreases below the threshold in the next time step.

Simple vulnerability fails to account for the *potential* aspect of vulnerability, which was mentioned in Section 3.2.1. As a result, it allows for non-intuitive interpretations. For example, consider a system f in a state x, defined in such a way that for any element of E the state worsens, that is:

$$\forall\, e \in E : f(x,e) \prec x. \tag{3.7}$$

According to the definition of simple vulnerability, this system is vulnerable to any exogenous input. However, a better interpretation would be that the system in state x is not sensitive to the exogenous input (at least as far as the evaluation of states by $\prec$ is concerned) and that simple vulnerability is not a useful notion under these conditions. This can be illustrated by the case of a terminally-ill patient whose situation will deteriorate irrespective of the exogenous input.

The problem here lies with the choice made for the right-hand side of the comparison in Equation (3.7): we are comparing the future state with the current state. In many contexts (and especially within the climate change community) it is more common to compare the effects of one exogenous input with those of another exogenous input representing the evolution "without change", sometimes referred to as the "baseline" or the "reference scenario".

These considerations lead us to the introduction of "comparative" vulnerability:

Definition (comparative vulnerability)
A system f in state x is vulnerable to $e \in E$ compared to $\tilde{e} \in E$ if $f(x,e) \prec f(x,\tilde{e})$.

Comparative vulnerability reduces to simple vulnerability if $f(x,\tilde{e}) = x$.

Example 6. For the system of small fish a baseline could be given by the evolution of the population in the absence of predators. Instead of comparing the future number of small fish as influenced by predators with their present number, we could assess the vulnerability of the small fish to predators by comparing the future numbers of small fish in the presence of predators with those in the absence of predators.

The notion of comparative vulnerability fits the examples considered in the grammatical investigation of Section 3.2 better than simple vulnerability, but it still requires a number of refinements. In particular, we may want to compare *trajectories* of the system instead of just end-points. In the context of climate change it may be important to compare the change between x and $f(x,e)$ to the change resulting from the reference scenario, that is, between x and $f(x,\tilde{e})$. In order to formalise this aspect, we need to consider that the (partial) strict order compares *pairs* of states, not individual states (but as is common in mathematics, we will continue to use the same symbol $\prec$ for the new relation).

Now, assume that we have a program which is capable of assessing simple vulnerability of systems. Is there any way in which one could use it to assess comparative vulnerability? It turns out that there is: the comparative vulnerability of a system can be computed as the simple vulnerability of a related system, as follows.

The system we are going to use as an input to our program is going to have as states *pairs* of states of the initial system:

$$\begin{aligned} F : (X \times X) \times E &\rightarrow (X \times X) \\ F((x_1, x_2), e) &= (f(x_1, e), f(x_1, \tilde{e})) \end{aligned}$$

Consider the case in which both elements of the pair are identical: (x, x). The next state, as given by F, is going to consist of the pair $(f(x, e), f(x, \tilde{e}))$. The first element of the pair is the next state as given by the initial system f under input e, the second element of the pair is the next state as given by f under the "reference" input $\tilde{e}$:

$$F((x, x), e) = (f(x, e), f(x, \tilde{e}))$$

In order to use the definition of simple vulnerability for the system F, we have to have a strict order on the elements of $X \times X$, because they are the states of F. Let us denote this order by $\prec_F$: the subscript F will serve to distinguish it from the order on X used to compare the states of the initial system f. We are going to define $\prec_F$ as in the Example 2 above, by defining what a "bad" pair is. The definition of the system F suggests at once that a pair is bad if the first element is worse than the second (that is, if the transition according to input e is worse than the one given by the reference scenario). We can therefore take the set B as being

$$B = \{(x, x') \mid x \prec x'\}$$

A pair of identical elements is never "bad", because the first element cannot be worse than the second if they are both identical. Moreover, we have that

$$F(x, x) \in B \equiv f(x, e) \prec f(x, \tilde{e})$$

The state $F(x, x)$ is "bad" only if the system f in state x is vulnerable to e compared to $\tilde{e}$. Thus, using the definition of $\prec_F$ resulting from B as in example 2, we have that

$$F(x, x) \prec_F (x, x) \equiv f(x, e) \prec f(x, \tilde{e})$$

and thus, we have proven the following proposition: The system f in state x is vulnerable to e compared to $\tilde{e}$ iff the system F in state (x, x) is simply vulnerable to e with respect to $\prec_F$.

Therefore, comparative vulnerability can be seen as a "variation" on simple vulnerability, one which can fit more naturally the cases in which we have a reference scenario. In what follows, we shall see several such variations on the theme of vulnerability. In all cases, the vulnerability statements can be formulated as simple vulnerability of a related system.

Definition (transitional vulnerability)
A system f in state x is vulnerable to $e \in E$ compared to $\tilde{e} \in E$ if the transition under e is worse than the one under $\tilde{e}$:

$$(x, f(x,e)) \prec (x, f(x,\tilde{e})). \tag{3.8}$$

In the context of climate change the comparison will involve some measure of the difference between aspects of the states that make up the pair: for example, the absolute value of the difference between the temperatures measured or expected in the two states. Since a (partial) strict order is not in general restricted to comparing pairs of states that have a common element, we can also consider extensions of this definition to the case in which the initial state is different. That is, we compare the potential evolution of the system starting in x and subject to e to an evolution that starts in a reference state and is subject to a reference scenario.

3.3.3 Dynamical extensions

In the above definitions we have considered a one-step transition of the system, and in the examples we have interpreted the exogenous inputs as having a "duration", as influencing the system for an extended period of time. In this section we consider the action of a sequence of exogenous inputs: $[e_1, e_2, \ldots, e_n]$. Corresponding to such a sequence, the system will undergo n transitions, $[x_1, x_2, \ldots, x_n]$, where:

$$\begin{aligned} x_0 &= x \\ x_1 &= f(x_0, e_1) \\ x_2 &= f(x_1, e_2) \\ &\cdots \\ x_n &= f(x_{n-1}, e_n). \end{aligned} \tag{3.9}$$

With these considerations we reprise the definitions above.

Definition (simple n-step vulnerability)
A system f in state x_0 is vulnerable to the sequence of exogenous inputs $[e_1, \ldots, e_n]$

with respect to $\prec$ if $x_n \prec x_0$.

Definition (comparative n-step vulnerability)
A system f in state x is vulnerable to a sequence of exogenous inputs $[e_1, \ldots, e_n]$ compared to $[\tilde{e}_1, \ldots, \tilde{e}_n]$ if $x_n \prec \tilde{x}_n$.

These definitions reveal the unsatisfactory aspect of considering only the end-points for our interpretation of "worse", as doing so ignores any worsening of the state before the end-point is reached. Transitional vulnerability takes the entire trajectory into account:

Definition (transitional n-step vulnerability)
A system f in state x is vulnerable to the sequence of exogenous inputs $[e_1, \ldots, e_n]$ compared to $[\tilde{e}_1, \ldots, \tilde{e}_n]$ if $[x, x_1, \ldots, x_n] \prec [x, \tilde{x}_1, \ldots, \tilde{x}_n]$.

Here the comparison is made between sequences of states. The sequences of states always start with the given state of the system, the state x. A further step would be to consider the case when the reference scenario starts from a different state.

Definition (states-comparative vulnerability)
A system f in state x is more vulnerable to the sequence of exogenous inputs $[e_1, \ldots, e_n]$ than in state x' if $[x, x_1, \ldots, x_n] \prec [x', x'_1, \ldots, x'_n]$.

What if the reference scenario is produced not just starting from another state, but by another system, say $f' : X \times E \rightarrow X$? In this case we have the following:

Definition (systems-comparative vulnerability)
A system f in state x is more vulnerable to a sequence of exogenous inputs $[e_1, \ldots, e_n]$ than a system f' in state x' if $[x, x_1, \ldots, x_n] \prec [x', x'_1, \ldots, x'_n]$.

Other variations are, of course possible. We want to underline that not all the definitions given here are useful in all contexts. The choice of the definition and its application must be done carefully, and, most importantly, it must be done explicitly. Since there is an inherent subjectivity in this choice, we can not avoid disagreements, but by making the choices explicit, we can at least hope to avoid misunderstandings.

The point of these somewhat pedantic definitions has been to identify a small set of elements required for making meaningful statements about vulnerability. In addition to the three primitives introduced at the beginning of Section 3.3 (an entity, represented by a dynamical system in an initial state; a stimulus, represented by an exogenous input or sequence of exogenous inputs; preference criteria, expressed by a (partial) strict order), we have proposed a way to account for the potentiality inherent in the notion of vulnerability (*e.g.*, comparative vulnerability).

Which of these definitions is "the right one"? This question assumes that we want to set in the stone of a mathematical formalism the notion of vulnerability, independent of its real-world usage. This is not our intent: what we aim for is to give a mathematical description of the conceptual space in which, in our experience, a wide range of scholarly and practical discussions on vulnerability take place.

3.3.4 Systems with endogenous input

The definitions presented so far capture some important aspects of the concept of vulnerability as used in everyday language. However, they are insufficient to represent terms that apply to more complex systems capable of learning, incorporating feedbacks and developing possibilities of adaptation. To overcome this limitation we need to extend our system by distinguishing endogenous inputs from exogenous ones. Denoting the set of endogenous inputs by U, we have

$$f : X \times E \times U \to X \tag{3.10}$$

and therefore the next state $f(x,e,u)$ depends on the value of $u \in U$. We refer to u alternatively as actions, commands or controls of the system. In most applications the set U will contain a "do nothing" action. The transition function f will, in general, be *partial*: not all actions are possible in every state.

Example 7. The first two motorcyclists of Section 3.2.2 can be modelled as discrete dynamical systems in the following way: the state will contain all (and only) those physical variables necessary for specifying the transition function. The endogenous input is a representation of the manoeuvres the motorcyclist can make when confronted with the oil spill. The exogenous input is represented by the conditions of the road. The transition function will then return the state of the motorcyclist after the encounter with the oil spill.

We can now tackle the definitions of hazards and potential impacts. A hazard is, intuitively, an exogenous input that has the potential to make the situation of the system worse and thus cause potential impacts. As we have seen in the previous section, "worse" can be interpreted in several ways: here we choose the simplest interpretation, not the comparative or the transitional ones. This choice allows for a straightforward presentation and a transparent notation (*e.g.*, we do not need to consider alternative sequences of exogenous inputs). This seems desirable, especially in view of the added complication that the system can react by choosing an action u. The disadvantage is that some of the definitions can appear overly simple. For the sake of clarity we have chosen not to prefix the definitions in the remainder of this section with "simple" (*e.g.*, we provide a definition of a "hazard", not of a "simple hazard"). Reformulating the definitions for the more complex interpretations (*e.g.*, "comparative hazard", "transitional hazard" *etc.*) could be an illuminating exercise for the more mathematically-inclined reader.

We start by defining a relative hazard, that is, one that depends on the action of the system. A hazard then is an exogenous input for which there exists at least one action of the system that would lead to a worsening of the situation.

Definition (relative hazard)
An exogenous input $e \in E$ is a relative hazard for a system f in state x relative to an endogenous action $u \in U$ if $f(x,e,u) \prec x$.

Definition (hazard, potential impact)
An exogenous input $e \in E$ is a hazard for a system f in state x if $\exists\ u \in U : f(x,e,u) \prec x$. In this case, $f(x,e,u)$ is called a potential impact.

Example 8. The oil spill is a hazard for the motorcyclist if there is a possibility of the motorcyclist making a manoeuvre that results in him falling down the cliff.

Definition (unavoidable hazard)
An exogenous input e is an unavoidable hazard for a system f in state x if $\forall\ u \in U : f(x,e,u) \prec x$.

Example 9. The oil spill is an unavoidable hazard for the motorcyclist if, no matter what manoeuvre the motorcyclist would attempt, he will fall down the cliff.

As a final remark, "risk" is usually defined as a measure of the set of potential impacts. This measure could be, for example, the sum of damages associated with the potential impacts weighted by their respective probabilities. In the case of the motorcyclists, the risk could be taken as the probability of them falling down the cliff. However, if we consider the possible outcomes to be injuries and damage instead of alive or dead, we could take the risk as being the expected value of the injuries and damage (the sum of damages weighted by the respective probabilities).

3.3.5 Adaptive capacity

Given a system in state x, subjected to an exogenous input e, we can define a number of problems:

a) **Optimisation**
Choose an action $u \in U$ such that $f(x,e,u)$ is optimal, that is, $\forall\, u' \in U : u' \neq u$ we have *not* $(f(x,e,u) \prec f(x,e,u'))$.

The optimisation problem as stated here does not necessarily have a unique solution (it may have several or none). In addition, in realistic situations we will not have complete knowledge of f, and therefore we will at most be able to solve approximate versions of the problem. A more useful question is therefore:

b) **Adaptation**
Choose an action $u \in U$ such that we have *not* $(f(x,e,u) \prec x)$.

Such an action avoids all potential impacts. We call it effective. For many practical purposes, "effectiveness" is not a clear-cut notion. For example, an action might avoid part of the impact. Future refinements of the framework will consider this aspect.

Definition (effective action)
An action u is effective for a system f in state x subjected to an exogenous input e if *not* $(f(x,e,u) \prec x)$.

As the other definitions in this section, the definition of "effective action" is given in the context of simple vulnerability. In order to obtain, for example, the definition in the context of comparative vulnerability, one has to "invert" the process presented in the previous section in order to reduce comparative vulnerability to simple vulnerability. Replacing f by F, $\prec$ by $\prec_F$ and remembering that the states of F are pairs of states of f, we have: an action u is effective if not $(F((x,x),e,u) \prec_F (x,x))$ which can be transformed as follows:

$$\begin{array}{lll} & F((x,x),e,u) \quad \prec_F \quad (x,x) \\ \equiv & \\ & f(x,e,u) \qquad\quad \prec \quad f(x,\tilde{e},\tilde{u}) \end{array}$$

where $\tilde{u}$ denotes the reference endogenous input (usually a "do nothing" or "business as usual" action).

If there are no effective actions against e, then e is an unavoidable hazard. If e is not unavoidable, then problem b) has at least one solution. The set of effective actions available to the system can be used to interpret the notion of adaptive capacity. For example, we could consider the set itself:

Definition (adaptive capacity as a set)
The adaptive capacity of a system f in state x subjected to an exogenous input e is represented by the set of its effective actions.

Example 10. The adaptive capacity of the motorcyclist is the set of all actions that do not result in the motorcyclist falling down the cliff due to the oil spill. It can be thought of as a measure of, amongst other things, his skill set and the technical specifications of the motorcycle.

If we consider the quality of the actions available to the system, not just their number, we may also define adaptive capacity as a measure of this quality. The complication here is that such a definition would require the additional assumption that actions have "qualities" that can be measured and compared. In this paper we have chosen to make a minimal set of such assumptions, as we aim for generality in our definitions.

3.3.6 Co-evolution of system and environment

One aspect not yet captured by our framework is that vulnerability to climate change is the result of a long-term interaction between the system and its environment. To take this interaction into account, we introduce a model of the environment as a dynamical system, $h : X \times E \times U \to E$, so that the next input from the environment $h(x,e,u)$ depends on the state of the system and on the endogenous action.

As in the previous, static case, given x_0 and e_0 we can define a number of problems. In the static case the problems involved finding an action u with some property (*e.g.*, optimality). In the dynamic case we need to find a policy $\phi : X \times E \to U$, that is, a function that specifies which actions are to be taken, depending on the state of the system and the exogenous input with which it is faced.

Let us consider an initial state of the system, x_0, and an initial input from the environment, e_0. Given a policy ϕ we can consider n-step trajectories, much as in Equation (3.9):

$$\begin{aligned} &u_0 = \phi(x_0,e_0), \quad x_1 = f(x_0,e_0,u_0), \quad e_1 = h(x_0,e_0,u_0) \\ &u_1 = \phi(x_1,e_1), \quad x_2 = f(x_1,e_1,u_1), \quad e_2 = h(x_1,e_1,u_1) \\ &\dots \\ &u_{n-1} = \phi(x_{n-1},e_{n-1}), \quad x_n = f(x_{n-1},e_{n-1},u_{n-1}), \quad e_n = h(x_{n-1},e_{n-1},u_{n-1}). \end{aligned} \tag{3.11}$$

A natural condition on a policy ϕ is that the actions it returns should be effective where possible. Under this assumption we define the following problems:

c) **Optimisation**
Choose a policy ϕ such that the actions taken drive the system along an optimal trajectory. Assuming that $\prec_t$ is a (partial) strict order on sequences of states, we require it to be compatible with the original (partial) strict order $\prec$ in the following way:

$$[x_0,\dots,x_n] \prec_t [x'_0,\dots,x'_n] \Rightarrow \exists\, k : x_k \prec x'_k. \tag{3.12}$$

If a sequence $[x_0,\dots,x_n]$ is worse than a sequence $[x'_0,\dots,x'_n]$, then it must be worse for at least one time step k. An example of such a (partial) strict order is:

$$[x_0,\dots,x_n] \prec_t [x'_0,\dots,x'_n] \quad \text{iff} \quad \forall\, k : x_k \prec x'_k. \tag{3.13}$$

As in the static case, the problem will in most cases have several or no solutions, and for realistic examples only approximate versions of the problem will be solvable.

d) **Mitigation**
Choose a policy ϕ such that for all $k \in \{1,...,n\}$ no $e_{k+1} = h(x_k, e_k, u_k)$ is an unavoidable hazard.

e) **Maintaining adaptive capacity**
Choose a policy ϕ such that for all $k \in \{1,...,n\}$ there exists at least one effective u_k.

Both problems d) and e) can have more than one solution, even when c) has no solution. For stochastic systems problem d) might translate to the reduction of the probability of all unavoidable hazards below a certain threshold. Similarly, for a less abstract notion of effectiveness, problem e) might require, for example, the improvement of the effectiveness of actions available at step k and therefore of adaptive capacity. These and other refinements to the framework are in progress and will be presented separately.

As a final remark, once a policy ϕ has been chosen, the comparative vulnerability of systems in different states can still be assessed using the definitions in Section 3.3.3.

3.3.7 Multiple agents

Owing to the insistence of ascribing vulnerability to an entity, it might seem that our framework cannot represent multiple agents. This is not the case: in this section we show two possible ways of dealing with interacting systems.

For simplicity we consider two systems:

$$\begin{aligned} f_1 &: X_1 \times E \times X_2 \times U_1 \to X_1, \\ f_2 &: X_2 \times E \times X_1 \times U_2 \to X_2. \end{aligned} \tag{3.14}$$

The systems interact with the environment and with each other:

$$\begin{aligned} x_{1,k+1} &= f_1(x_{1,k}, e_k, x_{2,k}, u_{1,k}), \\ x_{2,k+1} &= f_2(x_{2,k}, e_k, x_{1,k}, u_{2,k}). \end{aligned} \tag{3.15}$$

Let us assume we have (partial) strict orders $\prec^1$ and $\prec^2$ on X_1 and X_2, respectively. A first problem would be an assessment of the vulnerability of the combined system:

$$f_{1,2} : X_{1,2} \times E \times U_{1,2} \to X_{1,2}, \tag{3.16}$$

where

$$\begin{aligned} X_{1,2} &= X_1 \times X_2, \\ U_{1,2} &= U_1 \times U_2, \\ f_{1,2}((x_1,x_2), e, (u_1,u_2)) &= (f_1(x_1,e,x_2,u_1), f_2(x_2,e,x_1,u_2)). \end{aligned} \tag{3.17}$$

This assessment requires choosing a (partial) strict order on the set $X_{1,2}$, which would combine the two (partial) strict orders, $\prec^1$ and $\prec^2$. For example, we can choose

$$(x_1,x_2) \prec^{1,2} (x_1',x_2') \quad \text{iff} \quad x_1 \prec^1 x_1' \quad \text{and} \quad x_2 \prec^2 x_2'. \tag{3.18}$$

In this case, the roles of the two systems are symmetrical.

We can give more weight to one of the systems by combining the (partial) strict orders in a lexicographical way:

$$(x_1,x_2) \prec^{1,2} (x_1',x_2') \quad \text{iff} \quad x_1 \prec^1 x_1' \quad \text{or} \quad (x_1 = x_1' \quad \text{and} \quad x_2 \prec^2 x_2'). \tag{3.19}$$

Here the first system is given more importance, because if its output grows worse, the combined system is considered to be worse off, whereas the output of the second system is only relevant if the first one remains unchanged.

A second possible problem is to assess the vulnerability of each system independently. Taking the case of the first system, we would simply consider the environment as including the second system:

$$f_1' : X_1 \times E' \times U_1 \to X_1, \tag{3.20}$$

where

$$\begin{aligned} E' &= E \times X_2, \\ x_{1,k+1} &= f_1'(x_{1,k}, (e_k, x_{2,k}), u_{1,k}). \end{aligned} \tag{3.21}$$

The problems of optimisation, mitigation and maintaining adaptive capacity can now be addressed with respect to the extended environment. Multi-scale analysis becomes important in this case, because the environment will contain a part f_2, which operates at the same scale as the system f_1, and another part, given by the evolution of e, which typically takes place at a much slower pace.

3.4 Preliminary applications

The objective of this section is to relate the framework developed in Section 3.3 to the IPCC conceptualisation of vulnerability (see Figure 3.1) and to two recent vulnerability assessments: ATEAM and DINAS-COAST. It is not the objective to evaluate the IPCC conceptualisation and the two assessments, but rather to test the practical applicability of the framework using real examples. The choice of these examples is motivated chiefly by the fact that we have first-hand knowledge of both the IPCC conceptualisation and the two assessments. Future work will apply the framework to vulnerability assessments that are more qualitative in nature, do not follow the IPCC conceptualisation and do not focus primarily on climate change.

As mentioned earlier and discussed in detail by Füssel and Klein (2006), the meaning of vulnerability within the context of climate change has evolved over time. This is reflected in the respective assessment reports of the IPCC. In our application we use the definition of vulnerability as provided in the glossary of the Working Group II contribution to the Third Assessment Report (McCarthy et al., 2001). The approaches of both ATEAM and DINAS-COAST were developed to be consistent with this definition. An important difference between the two projects is that DINAS-COAST explicitly considered feedback from human action on the natural system.

3.4.1 IPCC

In the glossary of the Working Group II volume of the IPCC Third Assessment Report, vulnerability is defined 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. It is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al., 2001, p. 995). The extent to which this definition can be made operational for assessing vulnerability is limited because the defining elements themselves are not well defined or understood. In addition, vulnerability is said to be a function of exposure, adaptive capacity and sensitivity, but no information is given about the form of this function. As a result, we can only verify whether or not all elements of the IPCC definition are contained in our framework and whether there are any inconsistencies between the two.

There are four defining elements in the IPCC definition, two of which can be mapped directly to primitives used in our definition. The first element, the "degree to which a system is susceptible to, or unable to cope with", is represented in our definition by the (partial) strict order $\prec$. These preference criteria on the set of states X make it possible to assert that the system may end up in an undesirable state, in which it is "unable to cope with" some stimulus. The second element, the "character, magnitude and rate of climate variation to which a system is exposed" describes the (climate) stimulus to which the system is exposed. In our definition this element is the exogenous input e. Since we want to be able to consider non-climatic input as well, we do not limit e to climate stimuli.

The other two defining elements in the IPCC definition, sensitivity and adaptive capacity, have no direct correspondent in the primitives of our framework. We consider both sensitivity and adaptive capacity to be more complex properties of a system , unsuitable as starting points for a formal definition. However, both concepts can be defined using our primitives (see the discussion in 3.3.5) . "Sensitivity" is a well-established concept in system theory, characterising how much a system's state is affected by a change in its input. It requires the differentiability of the transition function f. If this requirement is met, it can be shown that a system cannot be vulnerable to an exogenous input if it is not sensitive to that input, which agrees with the IPCC definition. However, in our framework this requirement and the notion of sensitivity are not necessary to define vulnerability.

The fourth element, adaptive capacity, is defined by us as the set of effective actions available to the system. In our framework it is a more complex notion than vulnerability in that its definition relies on four primitives, not three. In addition to a dynamical system, exogenous input and a (partial) strict order, endogenous input is required to define adaptive capacity (see Section 3.3.5). In contrast to the IPCC conceptualisation, knowledge of adaptive capacity is not required for assessing vulnerability, as is illustrated by the case of simple systems (as in Example 1). However, adaptive capacity will influence the vulnerability of the more complex systems typically considered by the IPCC. As shown in Section 3.3.6, assessments of vulnerability and adaptive capacity are interrelated: their influence on one another depends on the preference criteria chosen.

3.4.2 ATEAM

The project ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) was funded by the Research Directorate-General of the European Commission from 2001 to 2004. It was concerned with the risks that global change poses to the interests of people in Europe relying on the following services provided by ecosystems: agriculture, forestry, carbon storage and energy, water, biodiversity and mountain tourism. It involved thirteen partners and six subcontractors, whose joint activities resulted in the development of a vulnerability mapping tool (Metzger et al., 2004). The project adopted the IPCC conceptualisation of vulnerability, which required combining information on potential impacts with information on adaptive capacity (see Figure 1). Socio-economic data were used to assess adaptive capacity on a sub-national scale, in a way that allowed it to be projected into the future using the same set of scenarios as for the assessment of potential impacts. The information on potential impacts and adaptive capacity was then combined in a series of vulnerability maps (Schröter et al., 2005).

When taking a closer look at ATEAM using the formal framework of Section 3.3, we first need to identify the framework's three primitives. ATEAM aimed "to assess where in Europe people may be vulnerable to the loss of particular ecosystem services, associated with the combined effects of climate change, land use change and atmospheric pollution" (Metzger and Schröter, 2006, p. 3). Thus, the entity is a coupled human-ecological system: the people in Europe who rely on ecosystem services. The system receives both exogenous input (the stimuli) and endogenous input (the human actions). The evolution of such a system can be given by

$$x_{k+1} = f(x_k, e_k, u_k), \tag{3.22}$$

where k denotes the time step and u_k is an element of the set of available endogenous inputs U_k, which are the management actions people can apply to adapt to potential impacts and thus maintain the ecosystem services on which they rely. These actions are usually specific to the ecosystem service considered. For example, a management action for ensuring the ecosystem service “agriculture” could be to irrigate the land.

The second primitive is the stimulus or exogenous input $e \in E$, to which the system’s vulnerability was assessed. This input was given by the scenarios of climate, land use and nitrogen deposition, which represent the possible evolutions of the environment. The scenarios were based on the IPCC SRES storylines (for details see Metzger and Schröter, 2006).

The third primitive notion concerns the preference criteria represented by a (partial) strict order $\prec$, which relate to the loss of ecosystem services. We will discuss the preference criteria in more detail below. Given these three primitive notions, it is now possible to interpret ATEAM as assessing the vulnerability of a region (more accurately: people in a region) in state x_k to an exogenous input e_k with respect to $\prec$. One way of doing so would be to compute the set of possible next states X_{k+1} by evaluating Equation (3.22) for all actions in the set of endogenous inputs U_k and to compare this set to the previous state x_k (simple vulnerability) or to possible next states obtained by a different scenario (comparative vulnerability). Note that for clarity of presentation, we consider only one transition of the system.

However, in the case of ATEAM the transition function of the coupled human-ecological system f in Equation (3.22) was not known. The available knowledge, in the form of ecological and hydrological models, did not consider the feedback from human action to ecosystems. The models can be thought of as simplifying the “real” non-deterministic system into a deterministic one by assuming some average action $\tilde{u}$ that is independent of the exogenous input. This average action represents “management as usual”. The transition function of the deterministic system can then be given by

$$x_{k+1} = f_{\tilde{u}}(x_k, e_k)\,. \tag{3.23}$$

This equation now allows for the computation of possible future states (*i.e.*, x_{k+1}) for the given scenarios. However, to assert that an entity is vulnerable, the third primitive, a (partial) strict order, is needed to compare different states (*e.g.*, future states with present states, states determined by different scenarios or states of different regional sub-systems). In the case of ATEAM the elements of the set of states X are vectors, so it is not trivial to provide an appropriate order relation. The (partial) strict order was therefore developed in consultation with stakeholders in the form of an impact function on the set of states (also referred to as output or indicator function), in a similar way as shown in Example 3. The impact function reduces the thematic components of the state vector to a single real number between 0 and 1 for each ecosystem service. The spatial dimension of the state could be seen as the combined state of several regions (here "combined" is taken as in Section 3.3.7). A benefit of the indicator-based approach is that comparisons could be made between these regions. To allow for such comparisons was one of the main objectives of ATEAM.

Up to this point, the approach was that of a traditional assessment of potential impacts. However, ATEAM also assessed the third element of the IPCC definition: adaptive capacity. Adaptive capacity was modelled as an index that was chosen to be a real number between 0 and 1. It was developed by building a statistical model from observed socio-economic data, which was then applied to the IPCC SRES scenarios to produce future projections of adaptive capacity.

The adaptive capacity index can be seen within our framework as an estimate of the size of the set of available actions U_k. The socio-economic data used to derive the index (*e.g.*, GDP per capita, literacy rate and labour participation rate of women) indicate the capacity of society to prepare for and respond to impacts of global change by choosing an appropriate action (*i.e.*, ecosystem management strategy). The size of this set of actions can be assumed to be an indication of the size of the set of effective actions, since the latter is a subset of the former.

3.4.3 DINAS-COAST

The project DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise) was also funded by the Research Directorate-General of the European Commission from 2001 to 2004. Five partners and two subcontractors worked together to develop the dynamic, interactive and flexible tool DIVA (Dynamic and Interactive Vulnerability Assessment, DINAS-COAST Consortium, 2006). DIVA enables its users to assess coastal vulnerability to sea-level rise and to explore possible adaptation policies. Whilst also following the IPCC conceptualisation, DINAS-COAST took a somewhat different approach to assessing vulnerability compared to ATEAM in that it included feedback from human action to the environment in the representation of the vulnerable system.

At the core of DIVA is an integrated model of the coupled human-environment coastal system, which itself is composed of modules representing different natural and social coastal subsystems (Hinkel and Klein, 2003, 2007). The model is driven by sea-level and socio-economic scenarios and computes the geodynamic effects of sea-level rise on coastal systems, including direct coastal erosion, erosion within tidal basins, changes in wetlands and the increase of the backwater effect in rivers. Furthermore, it computes socio-economic impacts that are either due directly to sea-level rise or are caused indirectly via the geodynamic effects.

Let us now analyse this model in terms of the three primitives of our framework. The first primitive, the vulnerable entity, is the coastal system. The second primitive, the stimulus or exogenous input to which the entity's vulnerability was assessed, was given in the form of climate, land-use and socio-economic scenarios. Similar to ATEAM, these were developed on the basis of the IPCC SRES storylines.

In contrast to ATEAM, the transition function of the coupled human-environment system was known and has the form of Equation (3.22). In addition to the exogenous input, endogenous input (*i.e.*, adaptation actions) was included in the model. The actions contained in the set of endogenous inputs U were (*i*) do nothing, (*ii*) build dikes, (*iii*) move away and (*iv*) nourish the beach or tidal basins.

Given f, U and a set of scenarios E, the vulnerability of the system could have been assessed by computing the transition of the system for every adaptation action $u \in U$ and comparing the resulting set of possible states X_{k+1} with the previous state x_k. However, doing so would be computationally expensive. Instead, DIVA introduced adaptation policies. An adaptation policy is a function that returns an adaptation action u for every state of the system and input it receives from the environment:

$$\phi : X \times E \to U\,, \qquad \phi(x_k, e_k) = u_k\,. \tag{3.24}$$

The following adaptation policies were considered:

- No adaptation: the model computes only potential impacts.
- Full protection: raise dikes or nourish beaches as much as is necessary to preserve the status quo (*i.e.*, x_0).
- Optimal protection: optimisation based on the comparison of the monetary costs and benefits of adaptation actions and potential impacts.
- User-defined protection: the user defines a flood return period against which to protect.

The composition of the adaptation policy ϕ with the state transition function f transforms the non-deterministic system into a deterministic one:

$$x_{k+1} = f(x_k, e_k, u_k) = f(x_k, e_k, \phi(x_k, e_k)) = f'(x_k, e_k). \tag{3.25}$$

The third primitive, the partial strict order, was given in the form of an impact function on the set of states. The function computes additional diagnostic properties such as people at risk of flooding, land loss, economic damages and the cost of protecting the coast. In contrast to ATEAM, the impact function does not reduce and normalise the dimensions of the state vector. One could say that DINAS-COAST provides a scarcer partial strict order than ATEAM. Only the vector's monetary components can be directly compared, which is also the basis for the optimal protection policy. The comparison of the vector's non-monetary components is left to the individual user. For this purpose the model is provided with a graphical user interface that allows for the visual comparison of the outputs for different regions, time steps, scenarios and adaptation policies in form of graphs, tables and maps.

3.5 Conclusions and outlook

In this paper we presented the contours of a formal framework of vulnerability to climate change. This framework is based on a grammatical investigation that led from the everyday meaning of vulnerability to the technical usage in the context of climate change. The most important result of this investigation is that the definition of vulnerability requires the specification of three primitives: the entity that is vulnerable, the stimulus to which it is vulnerable and a notion of "worse" and "better" with respect to the outcome of the interaction between the entity and the stimulus. Section 3.3 presented a mathematical translation of this result, grounded in system theory. In addition, it introduced refinements that capture the informal concepts of adaptive capacity and mitigation. Section 3.4 served as a first test of the framework by assessing whether or not it can represent concepts used in recent work of which the authors have first-hand knowledge.

Preliminary findings of this test include that the three determinants of vulnerability as identified by the IPCC correspond only in part with the three primitives of our formal framework and that ATEAM and DINAS-COAST have chosen not to specify a single partial strict order on their models' respective outputs. Instead, they specified several orders on components of their outputs, leaving room for interpretation by the user. However, it has not been the purpose of this paper to evaluate these projects, in particular because the current version of the framework is too rudimentary for such a task. A more important finding is that the framework has served as a heuristic device to help scientists from very different disciplines (the authors, workshop participants and formal and informal reviewers of this paper) to communicate clearly about an issue of common interest, thereby enriching each other's understanding of the issue. At the same time, the paper has shown that there is scope for many refinements, specialisations and applications of the framework, which means that much work remains to be done to develop it into a useful tool.

The definitions in this paper aimed at showing that a certain type of mathematical theory can account for a simplified grammar of vulnerability rather than at being of immediate use to researchers in the field. A major part of the work to be done will concern structural refinements: formulating stronger, more precise definitions for more complex systems, in a way that makes it easy to deal with continuous time, stochasticity, fuzziness, multiple scales, *etc*. The problems of optimisation, mitigation and maintaining adaptive capacity must be formulated for these systems in ways that relate them to questions asked in vulnerability assessments. To do so will enable us to incorporate results from the fields of control theory, game theory and decision theory, which was, after all, one of the motivations for developing our framework. These theoretical developments should be accompanied by practical applications that elaborate on those in Section 3.4. The analytical framework must be informed by the large body of results available from past case studies and by the needs of ongoing vulnerability assessments and the users of their results.

As mentioned in Section 3.1, it is increasingly argued that the climate change community could benefit from experiences gained in food security and natural hazards studies. These communities have their own well-developed fields of research on vulnerability, although there are important differences with vulnerability assessment carried out in the context of climate change (O'Brien et al., 2004; Patt et al., 2005). The framework proposed in this paper could be used to analyse approaches to vulnerability assessment in these communities, as well as in the climate change community. This could make more explicit and thus lead to a better understanding of the perceived and real differences between the respective models of vulnerability in use. Moreover, it will serve to test the framework proposed here. It will be a challenge to see whether or not the framework can capture in mathematical terms the complexity and richness of individual communities, sectors and regions, as well as of the factors leading to their vulnerability. In addition, the value of the framework for qualitative approaches to vulnerability assessment needs to be demonstrated, especially in those places where data are scarce.

On a final note, we realise that some may perceive a formal framework as limiting the flexibility required to capture the breadth and diversity of issues relevant to vulnerability assessment. Others may consider the mathematical approach to developing the framework as an impediment to discussion and application. As stated before, the framework is not intended to be prescriptive, nor is it meant to exclude non-mathematical viewpoints on vulnerability. The least we hope to achieve is that our framework makes vulnerability researchers aware of the potential confusion that can arise from not being precise about fundamental concepts underpinning their work. At the most, we hope they will recognise the potential benefits of testing, applying and further developing the framework proposed here. Every attempt has been made to make the formal description of the framework as accessible as possible to the mathematically challenged, a group that includes the second author of this paper.

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Chapter 4

The PIAM approach to modular integrated assessment modelling

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Abstract

The next generation of integrated assessment modelling is envisaged as being organised as a modular process, in which modules encapsulating knowledge from different scientific disciplines are independently developed at distributed institutions and coupled afterwards in accordance with the question raised by the decision maker. Such a modular approach can only be successful if it respects all stages of the modelling process, approaching modularisation and integration on a conceptual, numerical, and technical level. The chapter discusses the challenges at each level and presents partial solutions developed by the PIAM (Potsdam Integrated Assessment Modules) project at the Potsdam Institute for Climate Impact Research (PIK). The challenges at each level differ greatly in character and in the work done addressing them. At the conceptual level, the notion of conceptual consistency of modular integrated models is discussed. At the numerical level, it is

shown how an adequate modularisation of a problem from climate-economy leads to a modular configuration which independently developed climate and economic modules can be plugged into. At the technical level, a software tool is presented which provides a simple consistent interface for data transfer between modules running on distributed and heterogeneous computer platforms.

4.1 Introduction

Integrated modelling, which is the process of combining several sub-models that represent different interacting natural and social systems, is an indispensable element of climate change research. So-called integrated assessment models (IAMs) "integrate knowledge from different disciplines in order to describe as much as possible of the cause-effect relationships between phenomena from a synoptic perspective" (Rotmans and Dowlatabadi, 1998) and are used to explore the consequences of scenarios and policies on the co-evolution of natural and social systems. Integrated modelling is also gaining popularity within other scientific communities, like environmental modelling (Argent, 2003) and decision support (Dolk, 1993).

The development of IAMs has become increasingly more challenging. Over the last two decades, IAMs have grown significantly in complexity; more drivers, processes, subsystems and feedbacks are being respected (Rothman and Robinson, 1997; McCarthy et al., 2001). At the same time, IAMs must be structurally flexible in order to quickly respond to new questions raised. Usually many individuals from different scientific disciplines and institutions are involved in their design and implementation. These challenges have led to the idea of a modular approach to integrated assessment modelling in which expertise from various people is brought together in the form of self-contained pieces of software, called modules, and configured in accordance with the question raised by the decision maker.

To date, modular approaches to integrated modelling have focused on the technical integration of computer models (see Argent, 2003). Though (software) technology is essential, a modular approach can only be successful if it also respects the process of building models rather than only the computer models as the end-points of that process. Model integration has to take place on a conceptual, numerical *and* technical level. Conceptual integration addresses the relationships between the "real-world" issues to be solved and their representations in the form of mathematical problems. Numerical integration addresses the relationships between the mathematical problems and their numerical solutions. Technical integration addresses the interoperability of the software modules that implement the numerical solutions and possibly run on heterogeneous and distributed computer platforms.

This chapter synthesises work addressing conceptual, numerical and technical integration that was carried out at the Potsdam Institute of Climate Impact Research (PIK). The work done at each level differs, because the three types of issues are of different nature. Conceptual integration is a fundamental topic within interdisciplinary or transdisciplinary research in general (see Chapter 1). Here, some general considerations on how to approach the issue in the case of model integration are given. Numerical integration depends on the mathematical structure of the problems regarded and thus has to be addressed on a case-by-case basis. Here, it is shown how the modularisation of a typical problem from climate-economy leads to a flexible modular configuration which independently developed climate and economic modules can be plugged into. Technical integration is a common topic in distributed computing and a wealth of software technology is available to choose from. Here, a philosophy towards choosing the "right" technology and a software tool for transferring data structures between computer modules that are independently developed and run on heterogeneous and distributed platforms are presented.

The rest of the chapter is organised as follows: Section 4.2 reviews the state of the art of integrated assessment modelling and motivates its modularisation. Section 4.3 discusses the concept of modularity and its application to integrated modelling. Section 4.4 reviews the stages of the modelling process that are needed for the considerations in this chapter. Section 4.5 discusses approaches to modular integrated modelling in the literature. Section 4.6 introduces and discusses the PIAM approach and Section 4.7 concludes.

4.2 Integrated assessment modelling

Integrated assessment modelling is part of the wider process of integrated assessment (IA) "that combines, interprets, and communicates knowledge from diverse scientific disciplines from the natural and social sciences to investigate and understand causal relationships within and between complicated systems" (McCarthy et al., 2001). The IA process starts with a question raised by decision makers. Then, relevant knowledge is collected and integrated in respect to the question given. In the case of IA modelling knowledge comes in the form of computer models. Finally, the integrated model is used to simulate the effects of scenarios and policies on the coupled natural and social systems and the results are communicated to the decision makers.

Integrated assessment models (IAMs) "integrate knowledge from different disciplines in order to describe as much as possible of the cause-effect relationships between phenomena from a synoptic perspective" (Rotmans and Dowlatabadi, 1998). They are composed of interacting sub-models that represent various natural and social subsystems.

Ideally, IAMs need to cover all interacting processes that cause a problem. For example, according to McCarthy et al. (2001, p. 118) a full-scale IAM that addresses climate change should include sub-models for (*i*) the activities that give rise to greenhouse gas (GHG) emissions, (*ii*) the carbon cycle and other processes that determine atmospheric GHG concentrations, (*iii*) climate system responses to changes in atmospheric GHG concentrations and (*iv*) environmental and economic system responses to changes in key climate-related variables.

In practise, 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). The sub-models representing social, economic and environmental processes should be well balanced (Rotmans and van Asselt, 1996; Houghton et al., 1997; Rothman and Robinson, 1997; Tol and Vellinga, 1998). A second trade-off between the comprehensiveness of the integrated model and the complexity that can be handled analytically, numerically and computationally has to be found. Representing too much complexity complicates or prohibits the finding of efficient numerical solutions and the calibration of the models. Usually reduced-form or models of intermediate complexity are used for IA (Schellnhuber and Toth, 1999).

Practise also shows that no single configuration of sub-models is the one and only solution to a problem. Different groups prioritise different aspects of the problem, respect different processes or choose different models (*e.g.*, parametrisations) for representing the same process. In some disciplines, such as, *e.g.*, in economics, there also exist alternative modelling paradigms. Furthermore, there is no one configuration that can answer all questions. For each new problem raised, the relevant processes need to be identified and the available sub-models about them selected and configured appropriately.

The first and second generations of IAMs lacked the structural flexibility and transparency required by the ad-hoc question orientation of IA. Little attention was paid to methodological issues (Janssen, 1998). IAMs were mostly developed within a single research group for addressing a single research question. Software-technically, IAMs were often poorly designed and modularised. As a consequence it is hard to understand the model's code, incorporate new knowledge, or reuse parts of it for addressing a new question.

Today, the requirements for advancing the methodology of IA modelling can be summarised by the three concepts: transparency, structural flexibility and inter-institutional collaboration (Jaeger et al., 2002). Transparency is required in order to better understand, compare between and learn from existing IAMs. Every model contains a methodological bias. The adequate interpretation and inter-comparison of model results is only feasible if models communicate their assumptions as transparently as possible (Schneider, 1997; Rotmans and van Asselt, 1996). Structural flexibility is required in order to reuse or replace parts of an IAM. Since building models is a resource-intensive task, the capability to reuse legacy code within new IAMs is necessary to quickly respond to new questions raised by the decision maker (Jaeger et al., 2002). Furthermore, a key uncertainty in IA modelling lies in the model structure. The flexibility to replace a sub-model with an alternative one makes it possible to analyse these structural uncertainties (Tol and Vellinga, 1998; Janssen, 1998). Inter-institutional collaboration is required because no single institution or scientific discipline alone has the expertise to answer the complex socio-environmental problems addressed by IA.

4.3 Modular integrated assessment modelling

Modular integrated assessment modelling is proposed as an answer that addresses the above-mentioned requirements. It is a process in which modules encapsulating knowledge from different scientific domains are independently developed at distributed institutions and coupled afterwards in accordance with the question raised by the decision maker (Jaeger et al., 2002).

Modularity is a central concept in programming. It is abstraction on the highest level of program design (Abelson et al., 1996) and supported by every higher programming language. The most important feature of modularity is encapsulation. A module is a self-contained piece of software that is used in combination with other modules to form larger programs. Modules don't expose their internal complexity, but make their functionality available to the outside world via well-defined interfaces. The user does not have to understand how the module solves the problem, she just has to match the problem with the module's specification. As a consequence modules can be used by non-experts, be reused in different contexts, and be easily replaced by other implementations.

The idea of modularity is to handle complex problems by dividing them into well-defined sub-problems to which solutions are easier to be found or already exist. This involves two steps. First, the problem domain must be modularised. The right problem primitives have to be identified and the corresponding solutions must be implemented as modules. Second, modules must be integrated in respect to a newly given problem. Therefore, the new problem has to be decomposed into the problem primitives and the corresponding modules have to be selected and configured appropriately. Thus, modularity and integration are two flip sides of the same coin.

The modularisation of a problem domain is not a trivial task. The difficulties in this task are illustrated by the ongoing “software crisis”, the unsuccessful attempt to turn software development into an engineering discipline. Domains can be decomposed according to different paradigms. For example, modules can either be functions (functional programming), classes (object-orientated programming) or agents (agent-oriented programming). Furthermore, within paradigms, domains can be decomposed according to different criteria. There is abundant literature discussing software design, different programming paradigms and criteria of modularisation (Abelson et al., 1996). Common criteria named are, for example, that modules should not have overlapping functionalities (orthogonality) and that every piece of knowledge must only be represented once (Raymond, 2004; Meyer, 1997). Prominent examples of modular software design are the Unix software tools (Kernighan and Pike, 1984).

Bringing the idea of modularity to integrated assessment modelling means three things. First, the problem domain to which integrated assessment modelling is applied must be modularised; the right modules that, if configured appropriately, provide answers to the different questions raised need to be identified. Second, a repository of these modules needs to be implemented. Each module needs to be well documented in terms of its conditions of applicability. Third, a mechanism is needed that, given a new research question, allows modellers to select and configure modules from the repository in such a way that they collectively produce the answer to the question given.

Technically, the realisation of the modular approach means that it must be possible to code modules in different programming languages and run them on heterogeneous computer platforms distributed across the Internet. The burden put on the modellers must thereby be low; modellers should be able to use the language and platform of their choice and should not need to invest much extra time for learning new technology or writing additional code. The possibility to run simulations over the Internet ensures that modules can be hosted and kept up to date at the institutions where they are developed. In addition, some institutes, for different reasons, might not want to give their code away.

Socially, the realisation of the modular approach means building a community in which modules can be freely exchanged. Agreements on sharing and publishing code and results need to be reached such that the participating scholars do not run the danger of loosing the scientific recognition for their work done. First steps in this direction have been taken by the *CIAM*^{n} (Community Integrated Assessment Modules) initiative launched by a number of European global change research institutions, including the Potsdam Institute for Climate Impact Research (PIK; Germany), the Tyndall Centre (UK), the National Institute for Public Health and the Environment (RIVM; The Netherlands) and the Centre International de Recherche sur l' Environnement et le Développement (CIRED; France) (Jaeger et al., 2002).

4.4 The modelling process

In order to meaningfully modularise integrated modelling it is necessary to consider the process of building computer models. The modelling process connects the computer model to the question it addresses and therefore determines its meaning. Figure 4.1 shows the steps and the stages of the modelling process that are relevant for the purposes of this chapter. Other essential steps, such as, *e.g.*, model validation, model application, and the interpretation of model results, are not relevant here and therefore disregarded.

The first step in modelling is the formulation of the question to be answered. Obviously, the formulation of the "right" question is crucial for the rest of the modelling process to be meaningful.

The second step is the formalisation of the research question into a mathematical problem. For example, the question "What are the impacts of climate change on coastal wetlands?" could be formalised into a mathematical problem, where the wetlands are represented as a dynamical system driven by a climate signal and the task is to find the system's evolution over time. The most common mathematical problems in IA are initial value problems, boundary value problems and optimisation problems.

The third step is finding a numerical solution. Since most problems raised within IA cannot be solved analytically, solutions must be approximated by applying numerical methods.[1] The result of this step is the numerical solution or the algorithm.

The last step that needs to be considered here is the implementation of the algorithm on a computer. It involves choosing a computer platform, a programming language, a compiler, a design and the actual coding. This step yields the executable computer model.

[1] If it is possible to solve the mathematical problem analytically, there would, in most cases, not be the need to use a computer in the first place. In some cases, however, problems that can be solved analytically are solved numerically for reasons of computational efficiency.

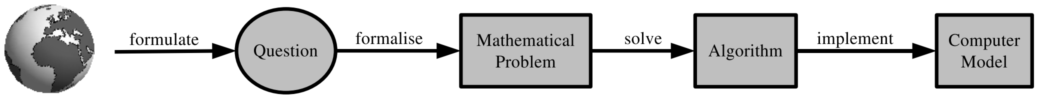

Figure 4.1: The modelling process. Boxes denote its stages and arrows its steps.

Each step is crucial for the computer model to be meaningful. The meaning at each stage is always a reference to the previous stage: the computer model attains its meaning by implementing the algorithm, the algorithm by solving a mathematical problem, and the mathematical problem by representing a research question.

4.5 Approaches to integrated modelling

Approaches to integrated modelling can be distinguished into *problem-driven* and *solution-driven* approaches according to the stage of the modelling process at which the integration takes place. In the former, the integration takes place at the stage of the mathematical problems, while in the latter the integration takes place at the stage of the algorithms or computer models. Other authors have used different terms to refer to this distinction, such as deep versus functional integration (Geoffrion, 1996) and definitional versus procedural integration (Dolk and Kottemann, 1993).[2]

Figure 4.2 illustrates the problem-driven approach. The mathematical subproblems (Problems A and B) are first integrated into one overall problem (Problem C), which then is solved. The resulting "integrated" computer model is a monolithic piece of software. This route is popular within the decision support community; see Dolk (1993) for an overview. Though less frequently, problem-driven approaches can also be found within the environmental modelling community; see, for example, the *declarative modelling* approach put forward by Muetzelfeldt (2004) and the M modelling language (de Bruin and de Vink, 1996).

Figure 4.3 illustrates the solution-driven approach. The mathematical subproblems (Problem A and B) are first solved and implemented individually and

[2]More generally, this is the distinction drawn in programming between declarative and imperative languages. The first category refers to languages in which the code is a specification of the problem to be solved. How the problem is solved is left to the computer to figure out. The second category refers to languages in which the code is the actual algorithm, that is a list of statements which imperatively tell the computer how to solve the problem step by step.

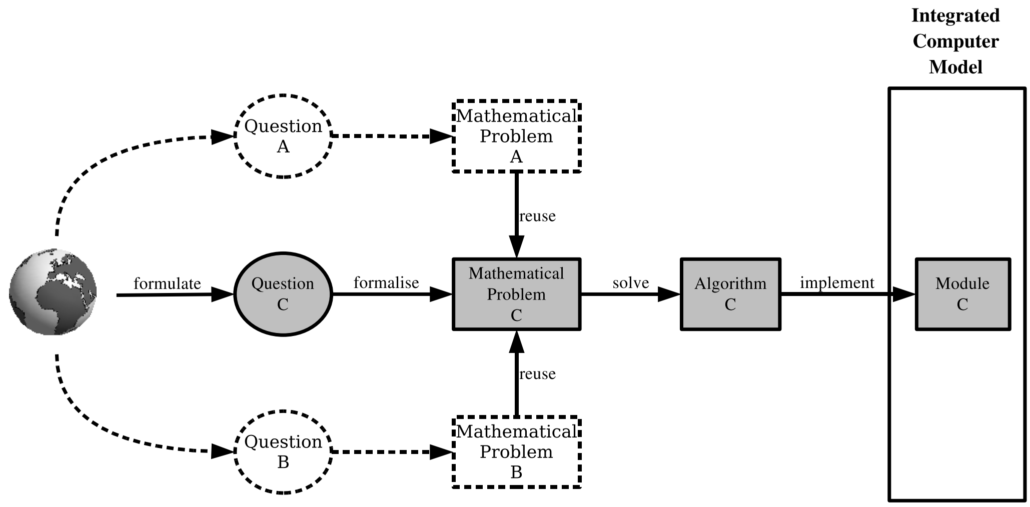

Figure 4.2: *Problem-driven* model integration. The dotted arrows and the transparent boxes refer to the existing models. The drawn through arrows and the shaded boxes denote the steps taken during the integration.

then integrated as pieces of software (Modules A and B). The resulting integrated computer model is composed of various modules. The way the modules are coupled is defined by the question to be answered. The solution-driven approach is popular within the environmental modelling community. An up-to-date overview of approaches is given by Argent (2003).

The problem-driven approach is a good choice, if solving the overall mathematical problem and implementing its solution is relatively easy, or even better, if it can be automated. In this case, only one mathematical problem needs to be solved. The problem-driven approach is not feasible, if the solution and implementation processes cannot be automated and are labour intensive. This is the case for many models used within IA, some of which comprise more than a hundred person-years of work. In these cases, it is desirable to reuse previous solution and implementation work in the form of existing computer code, a fact that has motivated the solution-driven approach.

The solution-driven approach is, in principle, problematic. Integrating computer models by coupling their inputs and outputs without considering the overall mathematical problem may lead to wrong results. Computer models are numerical approximations. Coupling approximations of sub-problem solutions does not necessarily yield a valid approximation of the solution of the overall problem.

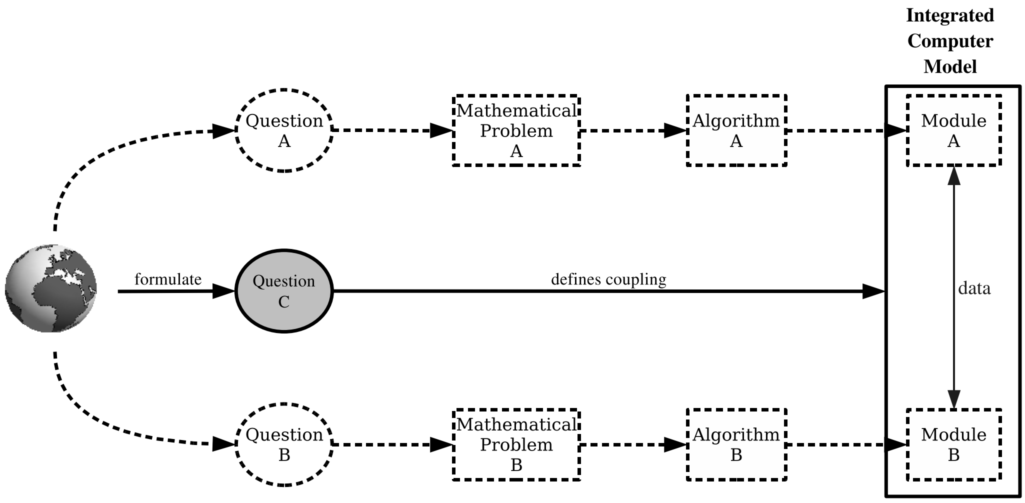

Figure 4.3: *Solution-driven* model integration. The dotted arrows and the transparent boxes refer to the existing models. The drawn through arrows and the shaded boxes denote the steps taken during the integration.

The resulting algorithm might be instable (even though the sub-algorithms are stable) or produce numerical artefacts. This does not mean that the solution-driven approach always produces wrong results. There are cases in which the problem structure trivially maps into the solution structure, like for example when coupling two models that iterate on the same time-step without feedback, the correct results could still be obtained.

4.6 The PIAM approach

4.6.1 Overview

The PIAM approach extends the problem-driven approach with the feasibility to reuse existing computer models for answering new questions. A schematic overview is shown in Figure 4.4. Given a new research question (Question C), an overall mathematical problem is formulated. Thereby, it is attempted to compose parts of the overall problem by sub-problems to which solutions already exist in form of modules (Problems A and B). In other words, the sub-problems A and B are “glued” together by formulating a meta-problem (Problem C). Solving and implementing the overall problem then only consists in solving and implementing

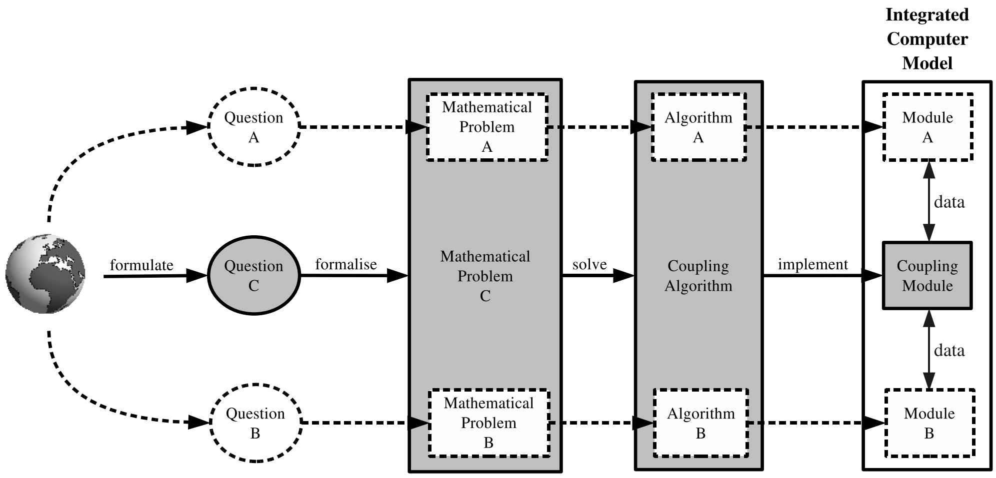

Figure 4.4: The PIAM approach to model integration. The dotted arrows and the transparent boxes refer to the existing models. The drawn through arrows and the shaded boxes denote the steps taken during the integration.

the meta-problem (the "glue"), because the existing modules (Modules A and B) can simply be reused without any changes.

According to the stages of the modelling process, model integration can be separated into the following three subsequent levels, each of which is described in more detail in one of the following subsections:

1. **Conceptual Integration:** First, the concepts of the individual mathematical sub-problems must be integrated. Roughly speaking, this means that the same symbols must represent the same "real-world" phenomena.

2. **Numerical Integration:** Second, the algorithms that solve the mathematical problems must be integrated. It has to be assured that the overall algorithm (the configuration of all sub-algorithms) is an adequate solution to the overall mathematical problem. In some cases, additional coupling algorithms might be needed.

3. **Technical Integration:** Third, the computer modules that implement the algorithms must be integrated. Modules written in different languages, running on heterogeneous platforms or being distributed across the Internet must be able to inter-operate. The product of this step is the modular computer model.

This section regards the modular approach mainly from the point of view of integration, that is from the point of view that there exists a repository of modules, a new question is received and it is attempted to configure the modules in such a way that an answer to the new question is given. However, any modular approach also needs to adopt the modularisation point of view, asking the question of what the modules needed are that could provide the flexibility for such an *ad hoc* integration of modules to answer newly raised questions. Since we are still at the beginning of modular IA modelling this question remains largely unanswered. What can be said is that modularisation is determined by criteria that pertain to all three of the above-mentioned levels of integration. First, modules are defined conceptually, that is by the scientific discipline the represented knowledge belongs to (*e.g.*, an economic module, a climate module). Second, modularisation is constrained by the availability of numerical methods and computational resources; there is no point in modularising in such a way that no or only computationally too expensive numerical solutions can be found. Third, it might make sense to introduce modules just for technical reasons, for example, to control and monitor the execution of other modules.

In the PIAM terminology, modules that represent knowledge of a scientific discipline or domain are called *domain knowledge modules*. Modules that exist for purely numerical reasons, implementing algorithms which are needed to couple or "glue" the former together, are called *numerical coupling modules*. Modules that exist for technical reasons are *job control modules*. A set of modules with defined interfaces and a description of the coupled system's structure is called a *configuration*. An integrated model consists of one or more domain knowledge modules, zero or more numerical coupling modules and one job control module.

4.6.2 Conceptual integration

Before the numerical or technical work can begin, models must be integrated conceptually: it has to be assured that the relationships between the models and the "real-world" phenomena they represent are consistent. The conceptual integration yields a mathematically correct description of the problem to be solved, which then makes it possible to abstract from what the mathematical symbols stand for in the "real-world" and allows the models to be treated as purely mathematical and technical entities on the next two levels.

What are the criteria for an integrated mathematical model composed of various sub-models to be conceptually consistent? The most obvious criterion is one of reference. Syntactically, the integration of models consists in the "coupling" of mathematical equations via common symbols (*e.g.*, variables or parameters). In order for the resulting integrated model to be meaningful, the syntactical operation must also be semantically valid, that is the symbols by which the sub-models are coupled must refer to the same "real-word" phenomena. This implies that they must share the same units. References must also be unique the other way round. The same phenomenon, *e.g.*, a process, should not be represented twice by different symbols.

A further criterion is consistency in the assumptions "behind" the models. The assumptions of one model must not violate the assumptions of another. Assumptions are made during the formulation of the mathematical problem. For example, a certain utility function is chosen or certain processes are neglected. It is problematic that model assumptions are rarely documented and often even made implicitly. Consistency in references and assumptions should also be ensured between models and data or scenarios fed into the models.

In order to assess the semantical consistency of an integrated model, the first necessary step is to document the semantics of each sub-model in terms of references and assumptions. Reference can be documented by annotating the model with meta-data, that is by making meta-statements, such as, *e.g.*, "The symbol 'x' refers to temperature". Documenting assumptions is a more challenging task. Since assumptions are made during the formalisation of the research question, they can be captured by documenting each step of this process. Some assumptions can be captured in the language the model is formulated in by just adding additional equations. Other assumptions need to be captured, similarly to the references, on a meta-level.

In the literature most approaches to conceptual integration focus on references. In the approach of Rahman et al. (2003) meta-data annotation is made directly in the model's code through comments and naming conventions. The meta-data is revealed by introspection and can be used by generic model processing tools. Hinkel (2005) introduces an iterative process for the development of an integrated model by distributed partners, which begins with the elaboration of a joint formal language for referring to the modelled phenomena (see also Chapter 5). Some approaches also address model assumptions. Structured Modelling (Geoffrion, 1987) and Logical Modelling (Kimbrough and Lee, 1988) tackle assumptions by further analysing the structure of the mathematical model. For example, in Structured Modelling a model is represented as a composition of discrete elements. The elements are either primitives, that is their existence is assumed, or complex, that is they are defined upon other primitive or complex elements. This way it is always clear what the model assumes and what it defines upon the assumptions.

4.6.3 Numerical integration

Numerical integration is concerned with the relationships between the mathematical problems and their numerical solutions. The conceptual integration yields a complete mathematical description of the problem, including the new mathematical problem to be solved, the existing sub-problems, and their numerical solutions to be reused. The modular approach is feasible if the following three conditions are met:

1. The specification of the new mathematical problem can be composed from the specifications of the existing sub-problems, to which numerical solutions are already implemented.

2. The new mathematical problem can be solved numerically under the constraint of using existing sub-problem solutions (modules), in the sense of 1. This implies finding a coupling algorithm which, in combination with the existing modules, solves the given overall problem.

3. Sufficient computational resources are available for the solution found.

Since the feasibility of the modular approach depends on the mathematical structure of the problem considered, I proceed by presenting an example from climate-economy which was modularised within the PIAM project. For presentational economy the problem has been simplified; the original one can be found in Leimbach and Jaeger (2004). The research question addressed is to find a CO_2 emission trajectory that maximises economic welfare under the constraint that the global mean temperature (GMT) rise does not exceed a given threshold. The ingredients of the mathematical problem are an economic growth model and a climate model. The economic model consists of a welfare maximising objective function (4.1a), the standard capital stock equation of motion (4.1b), and a budget equation (4.1c). The control variables are investment (I) and emission reduction ($\dot{E}$). C denotes the consumption, u the welfare function, K the capital, δ the depreciation rate, g the production function, and h the cost function of emission reduction.

$$Max \int_0^T u[C(t)]dt \tag{4.1a}$$

$$\dot{K}(t) = I(t) - \delta K(t) \tag{4.1b}$$

$$g(K(t)) = I(t) + C(t) + h(\dot{E}(t)) \tag{4.1c}$$

The climate model is an ordinary differential equation (4.2). W represents the state of the climate system and E the emissions.

$$\dot{W}(t) = \psi[W(t), E(t)] \tag{4.2}$$

The GMT w is a function of the state of the climate system W. The climate goal is to keep the GMT rise Δw below a certain threshold ω:

$$\Delta w \leq \omega \tag{4.3}$$

The monolithic approach to this problem would be to solve the optimal control problem described by the equations (4.1) to (4.3), considering the climate model just as an additional dynamic constraint.

$$Max \int_0^T u[C(t)]dt \tag{4.4a}$$

$$\text{s.t.} \quad \dot{K}(t) = I(t) - \delta K(t) \tag{4.4b}$$

$$g(K(t)) = I(t) + C(t) + h(\dot{E}(t)) \tag{4.4c}$$

$$\dot{W}(t) = \psi[W(t), E(t)] \tag{4.4d}$$

$$\Delta w \leq \omega \tag{4.4e}$$

The numerical solution to the monolithic problem is an algorithm $A_{monolithic}$ mapping a given climate goal ω to an optimal emission trajectory $\hat{E}$.

$$A_{monolithic} : \omega \mapsto \hat{E} \tag{4.5}$$

The disadvantage of the monolithic approach is that neither the climate nor the economic model could be run stand-alone or be replaced by another model of the same type. In order to overcome these limitations, the problem was modularised. The economic optimal control problem and the climate initial value problem were solved individually. Then, it was attempted to find a coupling algorithm, which together with the climate and economy algorithms (*i.e.* the existing solutions to be reused) solves the overall problem.

The solution of the climate problem is an algorithm $A_{climate}$ mapping a given emission trajectory E to a GMT rise Δw.

$$A_{climate} : E \mapsto \Delta w \tag{4.6}$$

The economic sub-problem was posed in a way that it incorporates some information about the state of the climate system. An emission barrier $\bar{E}$ was introduced as an additional constraint in the optimisation, yielding the following problem:

$$Max \int_0^T u[C(t)]dt \tag{4.7a}$$

$$\text{s.t.} \quad \dot{K}(t) = I(t) - \delta K(t) \tag{4.7b}$$

$$g(K(t)) = I(t) + C(t) + h(\dot{E}(t)) \tag{4.7c}$$

$$E(t) \leq \bar{E}(t) \tag{4.7d}$$

The solution to the economic stand-alone problem is an algorithm $A_{economy}$ that takes a given emission barrier $\bar{E}$ as input and outputs an optimal emission trajectory E that does not violate the inputted barrier. For reasons given further below, it was decided to include the welfare gradients μ (which are computed during the optimisation as the Lagrangian Multipliers) as an additional output:

$$A_{economy} : \bar{E} \mapsto (E, \mu) \tag{4.8}$$

Based on these algorithms the meta problem of the modular approach is: Given the economy algorithm $A_{economy}$ and the climate algorithm $A_{climate}$, find the optimal emission barrier, which maximises welfare and meets the climate goal.

The solution to the meta-problem is an iterative coupling algorithm $A_{coupling}$ which takes the GMT rise Δw_k, the emission barrier $\bar{E}_k$, and the welfare gradients μ_k of iteration k and produces a new emission barrier $\bar{E}_{k+1}$.

$$A_{coupling} : (\omega, \Delta w_k, \bar{E}_k, \mu_k) \mapsto \bar{E}_{k+1} \tag{4.9}$$

The three modules are configured according to Figure 4.5. The configuration is iterated until the new emission barrier computed by the coupling module does not significantly differ from the one computed in the last iteration, which means that the optimal solution has been found. The coupling algorithm operates in two phases. If the GMT rise exceeds the climate goal, the emission barrier is lowered. If the GMT rise is below the climate goal, the emission barrier is relaxed at points with high welfare gradients (*i.e.* at points at which a lot of additional welfare can be gained by allowing additional emissions). Convergence of the modular solution and its equivalence to the monolithic solution has been shown in Leimbach and Jaeger (2004). The configuration was run with several climate modules from different institutes.

An important aspect of numerical modularisation in general 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 on a module as

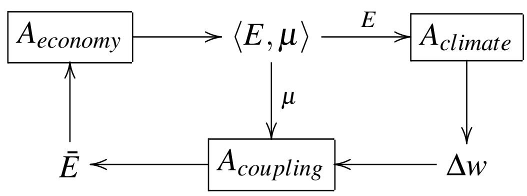

Figure 4.5: The climate-economy configuration. Boxes denote modules, the arrows data flow.

possible, because it minimises the work needed to replace or reuse modules. In the example presented it was decided to make the welfare gradients available to the coupling algorithm, but not the climate gradients, even though this would have enabled a more efficient meta-optimisation. However, the wish was to minimise the work needed to plug existing climate models, which generally do not output the gradients, into the configuration.

4.6.4 Technical integration

On the last level, the computer modules that implement the algorithms produced by the numerical integration must be integrated technically. Modules written in different languages, running on heterogeneous platforms or being distributed across the Internet must be able to inter-operate. Issues to be tackled on the technical level include the transfer of data between distributed computer modules, the conversion of data types and structures, remote execution, job control, and security. In contrast to the conceptual and numerical integration, a lot of work has been done on technical integration.

The problem of integrating software is paramount in distributed computing and a lot of software technology addressing it exists. General purpose component technology, like CORBA, Web Services, GLOBUS, Java-Beans, or .NET, are available for a wide variety of platforms and provide solutions to several of the technical issues at once. There are also software packages specialised to modelling, so called modelling frameworks, that address issues like data management, model versioning, (distributed) simulations monitoring and meta-data and graphical user-interface generation. For an overview of technical approaches see Argent (2003).

In PIAM it was decided not to use any of the existing component technology or modelling frameworks, for a number of reasons. Component technologies are either proprietary (*e.g.*, .NET), involve complicated installation of many software packages (*e.g.*, GLOBUS), or require many adjustments to the model's code and/or extra coding (*e.g.*, CORBA). Most modelling frameworks are also proprietary or based on proprietary component technology. In addition, writing modules within a given modelling framework usually involves a lot of coding which is specific to the framework chosen. Some frameworks even come with their proper language. Given the heterogeneity of modelling languages in use today, the close tie to a specific component technology or modelling framework was perceived as likely to hinder modular integrated assessment modelling as an open community effort.

The approach taken within PIAM aimed at maximising the freedom of implementation, while minimising the additional work needed to convert a computer model into a module. It follows the UNIX philosophy of providing simple solutions for small, well-defined problems. Instead of construing a big software package which takes care of all technical issues at once, the strategy is to create a collection of software tools, addressing one issue at a time. The development is demand-driven. Tools are only implemented when needs for them are formulated by the modellers. If a tool is not picked up by the modellers, little development time has been wasted and whenever better solutions become available, old developments can be replaced. The software tools developed are published under the General Public Licence (GPL; Free Software Foundation, 2006). Since integrated modular modelling is about sharing knowledge between people, institutions and disciplines, we believe that the software supporting this community effort should be "owned" and developed by the community.

The rest of this section presents one software tool developed at PIK to support modular integrated modelling. The tool called TDT (Typed Data Transfer) is a lightweight library for transferring data between distributed pieces of software (see `http://www.pik-potsdam.de/software/tdt`). TDT provides a simple consistent interface for the transfer of data structures between different languages, compilers, and operating systems independent of the actual data transfer protocol used. It takes care of the conversion between different binary representations of data types and structures. Implementations of the library are available for most of the popular C and FORTRAN compiles on Linux, AIX, and Windows. A Python version exists and a Java version is under development. Currently, four data transfer mechanisms are supported: (*i*) file system; (*ii*) Internet (TCP/IP) sockets; (*iii*) shared memory; and (*iv*) the message passing interface (MPI). The library supports all IEEE (Institute of Electrical and Electronics Engineers) simple data types, as well as fixed and dynamically sized arrays, all of which can be recursively nested.

The work needed in order to convert a piece of software into a TDT module consists in two simple steps. First, the input and output (I/O) function calls (*i.e.* open, close, read, and write) that correspond to the data to be transferred, must be

```
// declare a struct
struct {
  double latitude[96];
  double longitude[96];
  int temperature[96];
} temp_struct;

// read the configuration file
TDTConfig tdt_config;
tdt_config = tdt_configure("config.xml");

// open an output channel
TDTState channel;
channel = tdt_open (tdt_config, "channel");

// write some data
tdt_write (&temp_struct, "temp_struct", channel);

// close the output channel
tdt_close (channel);
```

Figure 4.6: C code for writing a simple data structure via the TDT library.

replaced by their TDT equivalents. The signatures of the TDT functions are kept as close as possible to the original ones of the respective language. The C code in Figure 4.6 demonstrates how data of the type “struct” is written via TDT. In the first block of lines the “struct” is declared, then the TDT configuration file is read, the channel to send the data on is opened, the data is written, and finally the channel is closed.

In a second step, the data types and structures transferred between modules must be described in an XML document. This information is needed for the appropriate conversion of platform-specific data representations (*e.g.*, big-endian versus small-endian). Figure 4.7 shows the TDT data description of the C “struct” which is declared in the code of Figure 4.6.

The TDT library has been used for building a variety of modular models at PIK and also other institutes have started using the software. Further software tools for modular integrated modelling are under construction, like web user interfaces for remote execution of modules, module configuration, and monitoring of distributed simulations.

```
<model>
  <decl name="temp_struct">
    <struct>
      <decl name="latitude">
        <array dimension="96">double</array>
      </decl>
      <decl name="longitude">
        <array dimension="96">double</array>
      </decl>
      <decl name="temperature">
        <array dimension="96">int</array>
      </decl>
    </struct>
  </decl>
</model>
```

Figure 4.7: XML code declaring the data structures which are transferred via the TDT library by the C code shown in Figure 4.6.

4.7 Conclusions and outlook

The idea of modular integrated assessment modelling is to reuse expert knowledge wrapped into computer modules in order to be able to quickly respond to questions newly raised by the decision makers. It has been argued that such a modular approach has to respect conceptual, numerical and technical issues at the different stages of the modelling process from the research question to the computer model.

First, integrated models need to be conceptually consistent in terms of the “real-world” phenomena they refer to and in terms of the assumptions “behind” them. To this end, the semantics of each module needs to be documented. References can be captured by annotating meta-data to the model. Model assumptions can be made explicit by documenting the process of formalising the research question.

Second, the mathematical problems addressed need to be modularised in a way that existing solutions to mathematical sub-problems can be reused and numerical coupling algorithms to integrate them can be found. A trade-off between efficiency and flexibility has to be reached. The more information the coupling algorithm receives from the modules, the faster the computation will be; however, the configuration will also be less flexible to include other modules that provide less information. Currently modular models with configurations of three or more modules and multiple feedbacks are being built at PIK. A library of frequently needed coupling algorithms is being developed.

Third, computer models which run on distributed and heterogeneous platforms need to be integrated technically. To this end, modular software tools that address small, well-defined problems are developed at PIK. Given the unclear requirements of the modular approach, small solutions are a good choice, because they can be extended or even be replaced whenever the requirements are better understood or new technology becomes available. The tools must be user-friendly and freely available for a wide variety of platforms in order to minimise the burden put on the modeller who joins the modular approach. Following these lines of thought we have presented a simple library developed at PIK for transferring data between modules written in different languages and running on heterogeneous platforms. Currently, further software tools are under development.

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Chapter 5

The DIVA Method for building modular integrated models

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Abstract

Integrated modelling of global environmental change impacts faces the challenge that knowledge from the domains of Natural and Social Science must be integrated. This is complicated by often incompatible terminology and the fact that the interactions between sub-systems are usually not fully understood at the start of the project. While a modular modelling approach is necessary to address these challenges, it is not sufficient. The remaining question is how the modelled system shall be cut down into modules. While no generic answer can be given to this question, communication tools can be provided to support the process of modularisation and integration. Along those lines of thought a method for building modular integrated models was developed within the EU project DINAS-COAST and applied to construct a first model, which assesses the vulnerability of the world's coasts to climate change and sea-level rise. The method focuses on the development of a common language and offers domain experts an intuitive interface to code their knowledge in the form of modules. However, instead of rigorously defining interfaces between the sub-systems at the project's beginning, an iterative

model development process is defined and tools to facilitate communication and collaboration are provided. This flexible approach has the advantage that increased understanding about sub-system interactions, gained during the project's lifetime, can immediately be reflected in the model.

5.1 Introduction

This chapter presents a method for building modular integrated models. The method was developed and first applied within the EU project DINAS-COAST (Dynamic and Interactive Assessment of National, Regional, and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise). The aim of the three-year project was to develop a dynamic, interactive, and flexible tool that would enable its users to quantitatively assess coastal vulnerability to sea-level rise and explore possible adaptation strategies on national, regional, and global scales covering all coastal nations. This tool is called DIVA, Dynamic and Interactive Vulnerability Assessment, and is centred around an integrated model driven by climatic and socio-economic scenarios.

DINAS-COAST was motivated by the apparent limitations of previous global vulnerability assessments (Hoozemans et al., 1993; Baarse, 1995), including the obsolescence of underlying data sources and the static, one-scenario approach. To overcome these limitations DINAS-COAST combines data, scenarios, and assessment models into an integrated tool, and makes it available to a broad community of end-users on a CD-ROM.

For the development of such a tool expert knowledge from the domains of Natural and Social Science must be integrated, calling for a modular approach to model development. Individual partners independently develop modules representing coastal sub-systems which are then "plugged" together to form one integrated model. While a modular modelling approach is necessary to address these challenges, it is not sufficient. The remaining question is how the modelled system shall be cut down into modules. While no generic answer can be given to this question, communicational and organisational tools can be provided to support the process of modularisation and integration.

Facing these challenges the DIVA Method for modular integrated modelling was created. The method organises the development process and facilitates communication and cooperation. The actual DIVA Tool is currently being built using this method. While the DIVA Tool is specific to DINAS-COAST, the DIVA Method can be reused in other contexts with similar requirements.

The rest of this chapter is organised as follows. Section 5.2 analyses the

DINAS-COAST requirements as perceived from the perspective of model integration and software development. Section 5.3 explicates some concepts of the modelling process needed for the following discussions. Section 5.4 explores the space of solutions to the requirements and Section 5.5 presents the DIVA Method as a possible answer. Finally, Sections 5.6 and 5.7 list some limitations and conclusions, respectively.

5.2 Requirement analysis

The development of an integrated model presents several challenges. Knowledge from the domains of Natural and Social Science must be integrated. This is complicated by the often incompatible terminology, differing model types and modelling styles, and also by the fact that domain experts are distributed over various institutes worldwide. Frequent project meetings are not possible. Most of the model development must be coordinated via email, web-sites, and telephone calls.

While the requirements listed above are common to integrated modelling, some special challenges needed to be addressed in DINAS-COAST. Due to lack of an appropriate data source the model had to be developed simultaneously with its proper world-wide database (Vafeidis et al., 2003, under review). The interactions between sub-systems were not fully understood at the start of the project; instead, such understanding is a major result of the project itself. Both circumstances necessitated a flexible model design that accounts for the incorporation of new knowledge in the form of data, algorithms, or sub-system interactions at any stage during the development process. Finally the DINAS-COAST model, together with the database, is meant to be made available to a broad community of end-users, such as scientists, politicians and coastal planners. This calls for an easy-to-use graphical user interface and an efficient model.

5.3 Modelling process

This section explicates four concepts involved in the modelling process that are needed for the following discussions.

1. **Ontology:** The modelling process starts with some concepts that we have at our disposal with which to perceive the world. It is good practise, especially in integrated modelling, to make this basic conceptualisation explicit. An explicit specification of a conceptualisation shall be called ontology.

2. **Mathematical Problem:** Based on the ontology a mathematical problem is formulated. For example one might have a system of differential equations and be interested in knowing its evolution over time (initial value problem).

3. **Algorithm:** Since in most cases the mathematical problem cannot be solved analytically, its solution must be approximated by applying numerical methods. The result of this step is the numerical solution or the algorithm.

4. **Computer Model:** The last step considered here is the implementation of the algorithm in a programming language. This step yields the executable computer model.

5.4 Modular integrated modelling

An integrated model is composed of various sub-models. It is evident that such a model, like other complex software, should be built in a modular rather than monolithic fashion: all contributors provide their knowledge about sub-systems in the form of self-contained components (modules).

While modularity is a necessary answer for integrated modelling, it is not sufficient. Among others, four questions need to be addressed:

1. At which stage of the modelling process shall the integration take place?

2. What are the modules' interfaces or how shall the system be decomposed into sub-systems?

3. Which technology or software shall be used?

4. How shall the process of model integration be organised?

The following subsections explore possible answers to these questions and motivate the decisions taken in the case of DINAS-COAST.

5.4.1 Integration level

The first question which arises in integrated modelling is at which stage of the modelling process the integration shall take place. Clearly, model integration has to start with a common ontology. Any attempt at it without a common conceptualisation of the system to be modelled is likely to fail. The remaining question is whether to integrate mathematical problems, algorithms, or executable computer models.

From an idealistic point of view models should be integrated at the level of the mathematical problems. Having a complete mathematical formulation of the system allows for careful selection of appropriate numerical methods and leads to stable and efficient algorithms. In practise this route is seldom taken. Reasons for that are: the existence of legacy computer models; the need for a lot of cooperation at an early stage of the project; unclear linkages between sub-systems and that it is uncommon to "think" about integrated modelling in terms of mathematical problem specifications rather than algorithms and computer programs.

From a pragmatic point of view it makes sense to integrate existing computer models. Legacy models, in which a lot of development time was invested, can then be reused. The flip-side of the coin is that the coupling of computer models involves a lot of technical issues, due to the heterogeneity in platforms, computer languages, compilers and data structures involved. A further disadvantage of this approach is that due to the absence of a complete specification of the mathematical problem it often remains unclear whether the numerics of the coupled computer models adequately represent the problem.

In the case of DINAS-COAST an intermediate approach was taken: the models were integrated at the level of the algorithms. Thus the project partners were free to solve their mathematical problem individually, but then had to implement the algorithms as modules in a common programming language. This route could be taken, because there were no legacy models to include.

5.4.2 Module interfaces

An elementary question of any modular approach to integrated modelling is how the modelled system shall be decomposed into sub-systems or, phrased differently: What are the modules' interfaces?

An efficient way of developing an integrated model would be to define specialised interfaces between the modules: each module has its proper interface, specific to the sub-system it represents. That way, the data-flow between the modules is fixed with the definition of the interfaces. The development process would then be straightforward: at the beginning of the project the interfaces are defined, then the developers program their modules concurrently in accordance with the interface specification. At the end of the project the whole model is plugged together.

However, a distinguishing feature of interdisciplinary research is that interactions between sub-systems are usually not fully understood at the start of the project. General interfaces that provide the freedom to define the data-flow between the modules during the course of the project are required. In the approach presented here all the modules have identical interfaces. They share a reference to the model's global state and are allowed to perform any read or write operation on it. Thus the actual data-flow between the modules is not fixed, offering the flexibility to take advantage of the interdisciplinary learning process during the project's lifetime.

The generality of the interfaces has implications on the development process. While specialised interfaces would not require extensive collaboration between partners during module development, general interfaces do so. To organise the collaboration a rigorously defined iterative development process is introduced. Module development takes place in two phases. First, the modules are programmed individually with the freedom to read and write any property of the system's sate. In the second phase, the actual data-flow between the modules is analysed jointly. The two phases are iterated until a satisfactory result is achieved. A detailed description of the iterative development process is found in Section 5.5.2.

5.4.3 Technology

A wealth of methods and technologies from software engineering, like for example object-oriented programming or component technologies, are based on the concept of modularity. The necessity to build complex and integrated models has brought these techniques to the modelling communities and triggered the development of modelling frameworks.

Frameworks provide a conceptual frame, that is an abstract ontology for certain classes of the problems. Frames often support one (or several) modelling paradigms. For example an object-oriented framework for agent-based modelling might provide classes for agents, organisations, and environments. Models implemented in a framework use its basic concepts and specialise them further to their own needs.

An up-to-date overview of modelling frameworks developed within the environmental modelling community is given by Argent (2003). Most approaches, just like the one presented here, tackle model integration at the algorithmic level of the modelling process. Consequently, sub-models must be implemented in a framework-specific language. The route to integrate existing computer models implemented in different languages or on different platforms is taken by Leimbach and Jaeger (2004). Few approaches support model integration at the stage of the mathematical problem specification. Examples are the M software environment (de Bruin and de Vink, 1996) and the declarative modelling approach (Muetzelfeldt, 2004). Other mathematical approaches can be found within the the Decision Support Community. See Dolk (1993) for an introduction.

In the case of DINAS-COAST it was decided to develop a new framework. This was motivated by the will to provide the project partners with a very simple and efficient interface for expressing their knowledge. To this end the framework has to provide the “right” framing. If it frames too little a lot of coding needs to be done to express the specific problem. If it frames too much some aspects of the problem cannot be represented in the frame. A second motivation for developing something new was the aim to tightly couple the framework to tools supporting the actual process of integrated model development.

5.4.4 Organisation

Model integration is an organisationally challenging and communication intensive process. While there is a wealth of modelling frameworks framing model design, there is little framing communication and the process of model development. Model documentation and meta-data are first steps in the right direction (Rahman et al., 2003).

The DIVA Method emphasis and structures the process of integrated modelling. This necessity arose specifically from the requirement that the model must be flexible to account for changes in interfaces, algorithms, and data structures at any stage of model development.

5.5 The DIVA Method

The DIVA Method is a method for building modular integrated models by distributed partners. It consists of a conceptual frame (Section 5.5.1), an iterative development process (Section 5.5.2), a generic model (Section 5.5.3), and a build and documentation tool (Section 5.5.4). The first two sub-sections describe the method from the point of view of the scientists developing the modules, while the last two sections deal with the technical implementation. The DIVA Method was designed to be generic and can be applied to problems with similar requirements as DINAS-COAST.

5.5.1 The frame

The DIVA Method provides, just like any other modelling framework, a conceptual frame for modelling. Only what can be expressed with the frame’s concepts can be modelled by the DIVA Method. For modelling dynamical systems concepts for expressing static information about the system (data model) as well as concepts for representing the system's dynamics are needed.

The statics of the system is represented by a relational-data model consisting of geographic features, properties, and relations. The geographic features represent the real-world entities, like rivers or countries. Properties capture the quantitative information about the features; e.g. a country might have the property area or a river the property length. Finally, relations describe how the features are structured. For example the feature region might contain several country features.

The dynamics of the system is represented by first-order difference equations: the state of the system is a function of the state at the last time-step and the drivers. All properties of the features must be classified according to the role they play in the dynamics into the four categories: driver, state variable, diagnostic variable and parameter. For example the country's area would most likely be static, that is a parameter, while its population might be driving the model.

5.5.2 The development process

The first step of the development process consists in defining the model's ontology: Given the abstract frame the specific features, properties, and relations which constitute the modelled system must be specified. The main part of the ontology is the *list of system properties* which contains the property names, the features they belong to, their type (that is whether they are drivers, parameters, or variables), their data type (e.g float, integer), and some other meta-information. The compilation of the ontology is a joint responsibility of the project consortium.

The ontology is then automatically translated into Java source code by the DIVA build tool (Section 5.5.4). For each feature one class is generated. The class contains public member fields for the feature's properties. Relations between the features are represented by class composition. Figure 5.1 shows generated code for a feature called country. The class has four public member fields: the first three hold the feature's properties (area, population, and GDP) and the last one points to the region the country belongs to.

In the next step the project partners code the algorithms. They express their knowledge about the dynamics of the system in the form of difference equations written in Java and using the generated feature classes. Since now the model's ontology is hard-coded an algorithm will only compile if it is consistent with the ontology. Related algorithms are grouped into modules. Before a module is submitted for inclusion into the integrated model it is run and validated stand-alone.

The last step of the development process consists in the analysis of the modules, their linkages, and the validation of the complete model. Whenever a new

```
public class Country implements Feature {

   public float area;
   public int   population;
   public float GDP;
   public Region region;

   protected readParameters(DataInput in) {
      area       = in.readFloat();
   }

   protected readDrivers(DataInput in) {
      gdpc       = in.readFloat();
      population = in.readInt();
   }

}
```

Figure 5.1: Java class of a geographic feature generated by the DIVA build tool.

version of a module is submitted the build tool automatically updates the project's web-site, which offers documentation and the new model for download. Figure 5.2 shows a generated document which visualises the data-flow between the modules of the DINAS-COAST model. On the basis of this graph the developers analyse the interactions between the modules and decide which changes are to be made in the next iteration of the development process.

Figure 5.3 summarises the work-flow of the development process. It also includes the database and the graphical user interface, which however are discussed elsewhere (`http://www.demis.nl`; Vafeidis et al., under review). Knowledge about the modelled system enters the process via four categories: (*i*) the model's ontology; (*ii*) the modules, which express the functional relationships between the system properties; (*iii*) the data, expressing the actual state of the system and its possible futures in the form of scenarios; (*iv*) the use-cases, which specify the end-user requirements. Those four categories are interrelated: new data may create the need to change existing algorithms or develop new ones with the consequent need to update the ontology. Once the knowledge has entered the development cycle most of the subsequent processes are automated. The development process can be iterated as many times as needed. At any stage a complete model is available. This approach allows for rapid prototyping of new models and their incremental

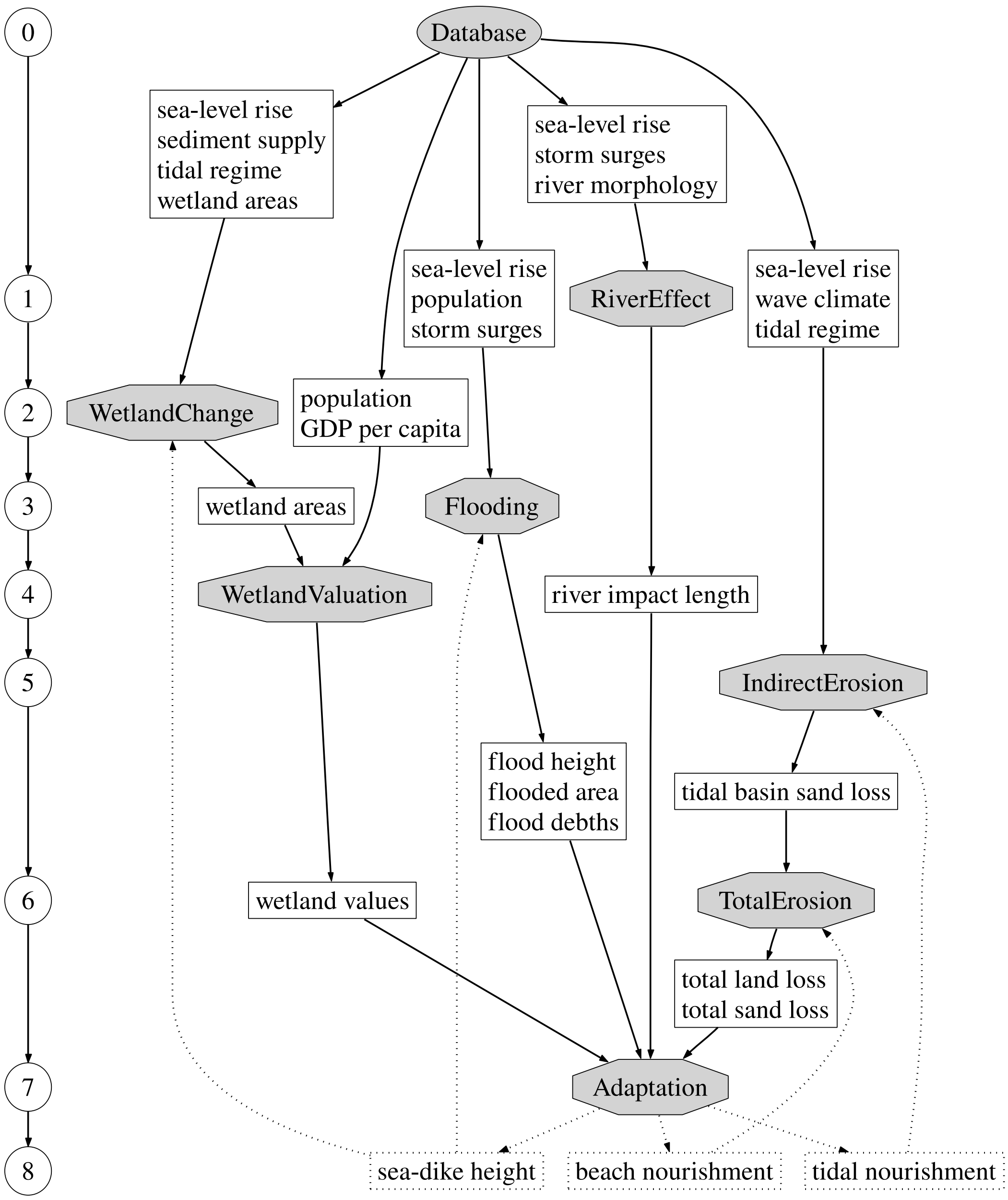

Figure 5.2: Module linkages in the DIVA model version 1.0.1. Octagons represent the modules, rectangles represent data, the drawn through arrows represent the flow of data during one time step, and the dotted arrows represent the data fed into the next time step.

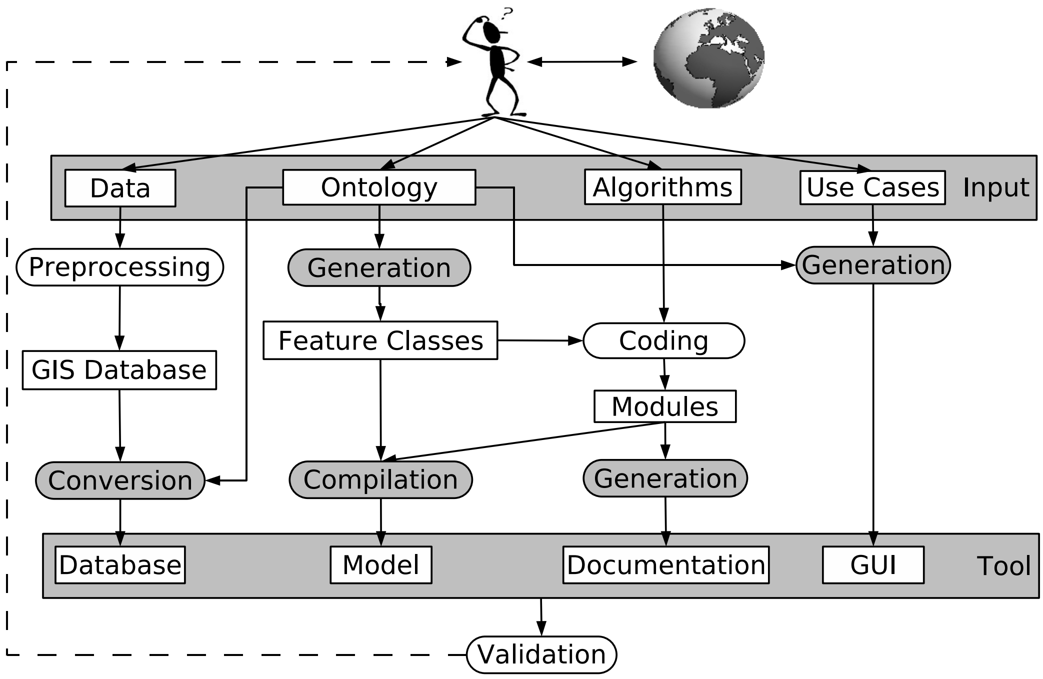

Figure 5.3: The DIVA development process. Boxes denote deliverables, ovals denote processes and shaded ovals denote automated processes.

refinement until a satisfactory result is produced.

5.5.3 The model

The integrated model consists of a generic kernel, a number of modules, and the feature classes. The modules and feature classes are problem specific and developed as described in the last section. All components, as well as the code generator, are completely implemented in Java and thus platform independent. The build tool described in the next section includes some non Java components.

The kernel is responsible for data input, data output, and the time-loop. It dynamically creates the data structures according to the input data, sets the parameters, initialises the state variables, and reads the drivers. The kernel loads the modules at run-time and invokes them sequentially for each time-step. The modules' order of invocation is given in a configuration file. In the case of DINAS-COAST all modules operate on the same time-scale. The model, however, could be easily extended to support multiple time-scales.

Data input and output (I/O) is taken care of by two components: the feature classes and generic adaptors. The feature classes handle the problem specific part of the I/O, that is when to read (write) which properties from (to) which data stream. This logic is specified by the ontology and then taken up by the code generator to produce methods for initialising the feature's parameters, reading its drivers, and outputting its state. For example, in Figure 5.1 the feature country has two drivers: population and GDP. The code generator produces the method `readDrivers()`, which allows reading the drivers from a given data stream. This way model input and output is hard coded and efficient. While the generation of the feature code as described in the last section could be taken care of by any CASE (Computer-Aided Software Engineering) Tools, the generation of the input and output methods could not. The adaptors handle the generic part of the I/O. They take care of reading and writing different file formats. Up to now, only one adaptor for a self describing binary data format developed by Delft Hydraulics exists (`http://www.wldelft.nl/soft/tools/index.html`). However, other formats could be easily implemented.

5.5.4 The build tool

A tool for building, testing, and documenting the model accompanies the development process. It takes the Java modules and the XML ontology as inputs and generates a web-site offering documents in various human- and computer-readable formats (HTML, XML, CSV and PDF). The documents include meta-information about the modules, the model, and the ontology, as well as documents used for the generation of the graphical user interface and input data files. Also included is a diagram that shows the data-flow through the system of modules (Figure 5.2). The whole build and documentation process is fully automated: all documents are always consistent with the current model development status and available on the web.

The DIVA build tool is based on Ant, which is a platform independent build tool developed by the Apache Software Foundation (`http://ant.apache.org`). It is written in Java, open-source, and easy to extended. The build processes and dependencies are specified in an XML language. A couple of other standard open-source tools were used and integrated via *Ant*: The graph visualisation tool Graphviz (`http://www.research.att.com/sw/tools/graphviz`) is deployed to visualise the data-flow between the modules. The XML parser Xerces and the XML processor Xalan (`http://xml.apache.org`) are used for XML parsing and processing. Latex, Latex2html and the postscript utilities Ghostview are used for the generation of the PDF and HTML documents. The DIVA build tool is currently implemented on the GNU/Linux platform (`http://www.gnu.org`).

However, since all the tools mentioned above are also available for a variety of other platforms, it could easily be ported.

5.6 Limitations

The flexibility of the iterative model development process comes at a price. The danger is that model development doesn't come to an end and not enough project time remains for model validation and application. Another drawback of this approach is that no complete specification of the mathematical problem needs to be formulated. This is common to all approaches which integrate models at the algorithmic or computational level. Unintended model dynamics can result from that and more efficient numerical solutions cannot be found.

While the performance of Java has increased significantly, there are still deficiencies compared to languages which are compiled to native binary code. Performance could have been increased by representing the data as arrays of simple types rather then arrays of (feature) classes. However, the primary goal was to make the interface for the module developers as intuitive as possible, rather than to optimise performance. Since all data for one time-step is kept in memory, the model's performance decreases significantly, if the data size exceeds the physical memory of the model's host computer.

5.7 Conclusions and outlook

The DIVA Method is an innovative method for building modular integrated models by distributed partners. Unlike other integrated modelling frameworks it emphasises communication and the organisation of the development process. It provides scientists from different backgrounds with a way to harmonise their conceptualisations of the system to be modelled and an intuitive interface to express their knowledge about it. The process of model development is well defined and automatically documented. As a result, the status quo is constantly available on the web, providing a basis for efficient communication between project partners.

Within the project DINAS-COAST the DIVA Method has been applied to build a tool for assessing the coastal vulnerability to sea-level rise. Meanwhile, application and improvement of both the DIVA Tool and the DIVA Method can go hand in hand. The global scientific and policy relevance of DIVA have already been recognised and collaboration on a range of initiatives is anticipated, including the EU ICZM (Integrated Coastal Zone Management) Strategy, and the new LOICZ (Land Ocean Interactions in the Coastal Zone) Science Plan. Improvements on the current DIVA Tool could include a module for coral reefs and atolls, refining the adaptation module and increasing the spatial resolution of the analysis, thus increasing DIVA's usefulness to coastal management. In addition, it is conceivable to develop regional versions of the DIVA Tool, such as a DIVA-Europe or a DIVA-India.

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Chapter 6

Integrating knowledge for assessing coastal vulnerability

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Abstract

Assessing coastal vulnerability is not a straightforward exercise, not in the least because, vulnerability is not defined consistently in the literature, definitions are difficult to make operational and, as a result, a diversity of methodological approaches are available. Notwithstanding the lack of commonly agreed approaches, there is a great need to compare the vulnerability of regions, countries and sectors; decision-makers are often interested in knowing which entities are most vulnerable, so that they can prioritise their activities. We argue that assessing vulnerability under these circumstances requires two elements. A general *common conceptual framework* is needed to enable unambiguous communication about vulnerability and meaningful comparison between vulnerability assessments. A *well-defined process* is then needed to organise the specialisation of the framework's general concepts for the case of interest, resulting in a case-specific operational definition of vulnerability. We present a recent attempt at developing and applying these two

elements. As an example of the first element we present a formal framework of vulnerability and as one of the second the DIVA Method, a method that organises the iterative integration of knowledge from different domains. We show how these two elements have been applied in the EU-funded project DINAS-COAST to develop the coastal vulnerability assessment tool DIVA. Both elements are generic and thus easily extensible and transferable to address new challenges including non-coastal ones.

6.1 Introduction

In view of the high natural and socio-economic values that are threatened and might be lost in coastal zones, it can be important to identify the types and magnitude of changes to which coastal systems are exposed, as well as the options that are available to minimise risks and reduce possible adverse consequences. However, assessing coastal vulnerability is not a straightforward exercise, not in the least because there is confusion concerning the precise meaning of the term "vulnerability". Vulnerability is specific to a given location or group or sector. There is therefore no single recipe for assessing vulnerability to climate change or any other type of change. Different scholarly communities have developed different conceptualisations of vulnerability, and different conceptualisations exist even within these communities.

Existing conceptualisations are often found to be imprecise when attempting to make them operational for assessment. For example, the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) defined 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. It is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al., 2001). The extent to which this "definition" of vulnerability can be made operational is limited because its constituent concepts are either very general or remain undefined. In addition, it does not explain the functional relationships between these concepts.

The diversity in conceptualisations and their being imprecise have led to a diversity in methodological approaches for assessing vulnerability (Brooks, 2003; O'Brien et al., 2004; Adger, 2006). In addition to this methodological diversity, methodologies have grown in complexity over the past two decades: they now consider multiple stimuli rather than a single stimulus, they allow for dynamic rather than static analysis, they have become interdisciplinary and they have moved from a predominant emphasis on impacts to a stronger focus on adaptation and adaptive capacity (Füssel and Klein, 2006).

Notwithstanding the lack of commonly agreed definitions and approaches, there is a great need to be able to assess and compare the vulnerability of regions, countries and sectors. Knowledge of vulnerability would enable scientists and decision-makers to anticipate and act on the adverse consequences of current and future changes, including those resulting from sea-level rise and other effects of climate change. Comparability is key to the notion of vulnerability: decision-makers are often interested in knowing which countries, regions, communities or sectors are most vulnerable, so that they can prioritise their activities.

How could a methodology for assessing vulnerability be specific enough to consider the unique circumstances of a given system whilst being generic enough to ensure that the vulnerability of this system can be compared with that of other systems, possibly assessed using different methodologies? In this chapter we argue that this would require two elements: (*i*) a common domain-independent conceptual framework of vulnerability and (*ii*) a well-defined process that specifies how the framework's general concepts can be specialised to accommodate the specific case of the assessment.

A *common conceptual framework* is needed to enable unambiguous communication about vulnerability and meaningful comparison between vulnerability assessments. Given the diversity of types of natural and social systems under study, this common framework must be very general indeed: the definition of vulnerability should only include those elements that are absolutely necessary for avoiding ambiguity and it must be independent from a specific domain of application. A *well-defined process* is then needed to organise the specialisation of the framework's general concepts for the system of interest, resulting in a case-specific operational definition of vulnerability. This step requires detailed system understanding and the integration of expertise from different knowledge domains. Case-specific definitions of vulnerability cannot be prescribed, but the process of deriving them from the general concepts can be structured and facilitated.

This chapter presents a recent attempt at developing and applying these two elements. First we present a general domain-independent formal framework of vulnerability proposed by Ionescu et al. (2005) as an example of the first element. The framework is also described in Chapter 3. As an example of the second element we then present the DIVA Method: a method developed by Hinkel (2005) to organise the iterative integration of knowledge and thus develop a case-specific operational definition of vulnerability. The method is also described in Chapter 5. Finally we show how the formal framework and the DIVA Method have been applied in 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) to develop the coastal vulnerability assessment tool DIVA (Dynamic and Interactive Vulnerability Assessment; DINAS-COAST Consortium, 2004). Note that the chapter does not present results produced by the application of DIVA; these can be found in Hinkel and Klein (in prep.) and Nicholls et al. (2006).

6.2 The evolution of methodologies for assessing coastal vulnerability

Before climate change emerged as an academic focus, vulnerability as such was not an important concept in coastal research. Traditionally, research in coastal zones has been conducted mainly by geologists, ecologists and engineers, roughly as follows (Klein, 2002):

- Geologists study coastal sedimentation patterns and the consequent dynamic processes of erosion and accretion over different spatial and temporal scales;
- Ecologists study the occurrence, diversity and functioning of coastal flora and fauna from the species to the ecosystem level;
- Engineers take a risk-based approach, assessing the probability of occurrence of storm surges and other extreme events that could jeopardise the integrity of the coast and the safety of coastal communities.

The challenge of climate change has spurred the collaboration between these three groups of coastal scientists; vulnerability has become an integrating focus of this research collaboration. Since 1990 a number of major efforts have been made to develop guidelines and methodologies for assessing coastal vulnerability to climate change, which combined the expertise of the three disciplines, complemented with economics.[1]

In 1991 the Coastal Zone Management Subgroup of the IPCC published its Common Methodology for Assessing the Vulnerability of Coastal Areas to Sea-Level Rise (IPCC CZMS, 1991). It comprises seven consecutive analytical steps

[1]Many involved in these efforts were unaware of the long history of vulnerability assessment in other disciplines, particularly the social sciences. In social-science research on poverty, food security and natural hazards, vulnerability is also interpreted in terms of potential harm and capacity to cope, but studies tend to focus in more depth on particular groups and communities within a society. In so doing, they take a quite different (*i.e.*, bottom-up) approach to vulnerability assessment. This approach is typically place-based and cognisant of the rich variety of social, cultural, economic, institutional and other factors that define vulnerability. It does not rely on global or regional models to inform the analysis; instead the major source of information is the vulnerable community itself (Klein, 2002).

Indicator	Description
People affected	The people living in the hazard zone affected by sea-level rise.
People at risk	The average annual number of people flooded by storm surge.
Capital value at loss	The market value of infrastructure which could be lost due to sea-level rise.
Land at loss	The area of land that would be lost due to sea-level rise.
Wetland at loss	The area of wetland that would be lost due to sea-level rise.
Adaptation costs	The costs of adapting to sea-level rise, with an overwhelming emphasis on protection.
People at risk	The average annual number of people flooded by storm surge, assuming the adaptation to be in place.

Table 6.1: The vulnerability indicators of the IPCC Common Methodology.

that allow for the identification of populations and physical and natural resources at risk, and of the costs and feasibility of possible responses to adverse impacts. Results can be presented for the seven vulnerability indicators listed in Table 6.1.

The Common Methodology has been used as the basis of assessments in at least 46 countries; quantitative results were produced in 22 country case studies and eight sub-national studies (for an overview see Nicholls, 1995). Hoozemans et al. (1993) applied the Common Methodology on a global scale. Studies that used the Common Methodology were meant to serve as preparatory assessments, identifying priority regions and priority sectors and providing an initial screening of the feasibility and effect of coastal protection measures. They have been successful in raising awareness of the potential magnitude of climate change and its possible consequences in coastal zones. They have thus provided a motivation for implementing policies and measures to control greenhouse gas emissions. In addition, they have encouraged long-term thinking and they have triggered more detailed local coastal studies in areas identified as particularly vulnerable, the results of which have contributed to coastal planning and management.

Nonetheless, a number of problems with the Common Methodology have been identified, which mainly concern its data intensity and its simplified approach to assessing bio-geophysical and socio-economic system response (for a more detailed discussion see Klein and Nicholls, 1999). Alternative assessment methodologies have been proposed, but they have generally not been applied by anyone other than their developers. A semi-quantitative methodology proposed Kay and Hay (1993) was applied in a number of South Pacific island countries, where it was felt that the Common Methodology put too much emphasis on market-based impacts. An index-based approach proposed by Gornitz et al. (1994) included the risk of hurricanes and was developed for use along the east coast of the United States. However, it did not consider socio-economic factors.

The relative success of the Common Methodology led the IPCC to adopt its approach as a model for assessing the vulnerability of other, non-coastal systems to climate change. The top-down approach of the Common Methodology was intuitively attractive to the wider climate change community, whose work has been strongly model-orientated. In 1994 the IPCC published its Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter et al., 1994), which provide system-independent guidance to countries that wish to assess their vulnerability to climate change. The Technical Guidelines are outlined in a similar fashion to the Common Methodology, but fewer analytical steps are implied and less prior knowledge is assumed. In addition, the Technical Guidelines are not prescriptive in the choice of scenarios, tools and techniques to conduct the analysis. The United Nations Environment Programme (UNEP) Handbook on Methods for Climate Change Impact Assessments and Adaptation Strategies (Feenstra et al., 1998) offers a detailed elaboration of the IPCC Technical Guidelines for a range of socio-economic and physiographic systems, including coastal zones (Klein and Nicholls, 1998). The UNEP Handbook has been used in a number of developing countries under the UNEP Country Studies Programme and in the first phase of the Netherlands Climate Change Studies Assistance Programme. The United States Country Studies Program used similar guidance provided by (Benioff et al., 1996).

In the late 1990s the EU-funded project SURVAS (Synthesis and Upscaling of Sea-Level Rise Vulnerability Assessment Studies) aimed to synthesise and upscale all available coastal vulnerability studies and to develop standardised data sets for coastal impact indicators suitable for regional and global analysis (de la Vega-Leinert et al., 2000a,b).[2] However, this effort was only partially successful: synthesis and upscaling was impeded by the fact that studies had used different methodologies, scenarios and assumptions. As a result, until the publication of DIVA (DINAS-COAST Consortium, 2006) the global assessments by Hoozemans et al. (1993) and its updates by Baarse (1995) and Nicholls (2002, 2004) remained the only sources of global information on coastal vulnerability to sea-level rise.

[2]See also `http://www.survas.mdx.ac.uk/`

6.3 A formal framework of vulnerability to climate change

The first element required to assess vulnerability is a conceptualisation of vulnerability. We want this *a priori* conceptualisation to be as general as possible so that it can be applied to a variety of natural and social systems and it ensures comparability with others approaches. The formal framework proposed by Ionescu et al. (2005) serves these purposes. Their definition of vulnerability differs from most definitions in the literature in that it is independent from specific knowledge domains (*i.e.*, scientific disciplines) and from the system of interest (*e.g.*, a biological or social system). Vulnerability is defined on the basis of domain-independent mathematical concepts. In this chapter we only give a brief overview of the framework; for a full account see Chapter 3.

The formal framework requires one to specify (*i*) the *entity* of which the vulnerability is assessed, (*ii*) the *stimulus* to which the entity would be vulnerable, and *(iii)* the *preference criteria* that are used to evaluate the outcome of the interaction between the entity and the stimulus (*e.g.*, an adverse or undesirable outcome). In other words, it is the vulnerability of an entity to a specific stimulus with respect to certain preference criteria. Examples in coastal zones include the vulnerability of Bangladesh to sea-level rise with respect to the number of people affected by coastal flooding, the vulnerability of tourist resorts in Florida to an increased intensity of hurricanes with respect to economic losses, the vulnerability of the Great Barrier Reef to increased sea-surface temperatures with respect to the degradation of coral ecosystems, and the vulnerability of a fishing community in Vietnam to the conversion of mangroves into fishponds with respect to the loss of traditional livelihoods. Any definition of vulnerability must thus contain the three primitive concepts of entity, stimulus and preference criteria in order to convey meaningful information, and in fact most approaches described in the literature do (Brooks, 2003).

In the framework proposed by Ionescu et al. (2005), the entity of which the vulnerability is assessed is represented as a discrete dynamical system and the stimulus to which it is exposed is the system's exogenous input. The system's "reaction" to the exogenous input is given by:

$$x^{k+1} = f(x^k, e^k) \tag{6.1}$$

where

$f : X \times E \to X$ is called the transition function of the system,
X is the set of states of the system,
E is the set of exogenous inputs to the system and
k is the time step (we consider a discrete system).

The system's output is given by:

$$y^k = g(x^k) \tag{6.2}$$

where

$g : X \to Y$ is called the output function of the system and
Y is the set of outputs.

These outputs can be thought of as indicators of the state and are in general considered measurable or observable quantities. The preference criteria are represented as a (partial) strict order $\prec$ on the set of outputs Y. A strict order is a anti-reflexive and transitive relation and thus a very general mathematical model to represent preference criteria. The notation $y^k \prec y'^k$ means that the system that produces output y^k is considered to be "worse off" compared to the system that produces output y'^k.

The concepts introduced here now allow us to define vulnerability: a system is vulnerable to an exogenous input if it ends up "worse off" than it was before, or more formally:

Definition 1.
A system (f, g) in state x^k is vulnerable to an exogenous input e^k with respect to $\prec$ if and only if (iff) $y^{k+1} \prec y^k$.

In addition, it is possible to compare the vulnerability of one entity under different circumstances (*i.e.*, in different states) or to another entity receiving the same exogenous input.

Definition 2.
A system (f, g) is more vulnerable in state x^k than in state x'^k to an exogenous input e^k with respect to $\prec$ iff

i) the system in state x^k is vulnerable to exogenous input e^k with respect to $\prec$ and

ii) $y^{k+1} \prec y'^{k+1}$.

Definition 3.
A system (f,g) in state x^k is more vulnerable to an exogenous input e^k than a system (f',g') in state x'^k is to an exogenous input e'^k with respect to $\prec$ iff

i) it is vulnerable to e^k with respect to $\prec$ and

ii) $y^{k+1} \prec y'^{k+1}$.

Whilst the concepts introduced so far have allowed us to define vulnerability, a further primitive concept is needed to include the notion of adaptation. Adaptation requires that the vulnerable entity has actions at its disposal to respond to the exogenous inputs it receives. To represent these actions, the dynamical system's transition function must be extended to include endogenous inputs:

$$x^{k+1} = f(x^k, e^k, u^k) \tag{6.3}$$

where u^k is an element of $U^k = U(x^k, e^k)$, the set of available endogenous inputs (or adaptation actions).

Adaptation involves choosing an *effective* action that will prevent the system from being worse off in the next time step (*i.e.*, choose an action $u^k \in U^k$ such that *not* $(y^{k+1} \prec y^k)$). The size of the set of effective actions available to the system can be interpreted as the system's *adaptive capacity*.

Finally, we can define an *adaptation strategy* as a function that returns an adaptation action u^k for every state x^k of the system and for every exogenous input e^k it receives:

$$u^k = \phi(x^k, e^k) \tag{6.4}$$

where

$$\phi : X \times E \rightarrow U.$$

A more elaborate description of the framework, along with examples, can be found in Ionescu et al. (2005).

6.4 The DIVA Method

The second element required to assess vulnerability is a well-defined process that organises how the formal framework's general concepts can be specialised to accommodate a specific case. This process involves two tasks. First, the mathematical concepts must be interpreted, that is, they must be mapped to components of the "real-world" system of interest (*i.e.*, the vulnerable entity, the stimuli and the preference criteria). Second, the mathematical concepts must be specialised to represent their "real-world" counterparts. The mathematical forms of the state transition function (Equation 1 or 6.3), the output function (Equation 6.2) and the adaptation strategies (Equation 6.4) have to be specified in order to apply the framework's formal definitions. The product of this task is the operational definition.

The challenge of this process lies in the interdisciplinary nature of the two tasks, especially the second one. Knowledge from both the natural and the social sciences must be identified and integrated into a complete mathematical description of the system of interest. There is no single possible outcome when integrating knowledge into an operational definition of vulnerability. Different groups of experts tackling the same problem will inevitably come up with different specialisations and therefore with different definitions. Moreover, the definition of vulnerability evolves within a group of experts over the course of the assessment. The interactions between the various parts of the system are usually not fully understood at the start of an assessment; instead, such understanding is a result of the assessment itself.

How can an assessment methodology be designed to deal with the fact that the operational definition of vulnerability is almost certain to change as system knowledge develops over the course of the assessment? One way of dealing with vulnerability being a moving target is to design a methodology that allows for the development and refinement of operational definitions during the assessment. In other words, rather than to settle on *the* definition of vulnerability at the outset, an iterative process is agreed to develop and refine *good* definitions of vulnerability in response to the development of new, integrated knowledge.

Integrating knowledge can be particularly challenging when the participants in the assessment represent different scientific disciplines, use incompatible terminology and lack the time or funding for frequent face-to-face meetings. These challenges create a need for methods that foster the communication, collaboration and mutual learning between participants and thus lead to a better interdisciplinary understanding of the issues at hand and to a more adequate definition of vulnerability.

In DINAS-COAST the DIVA Method was developed specifically to facilitate the integration of knowledge from distributed experts with different disciplinary backgrounds. The DIVA Method was then applied to build the DIVA Tool (see Section 6.5). However, the DIVA Method is a generic method for building modular integrated models by distributed partners and could be applied to any problem with similar requirements. For a detailed technical description of the DIVA Method see Chapter 5.

The DIVA Method consists of a modelling framework and a semi-automated development process. The modelling framework addresses the integration of knowledge at the product level: it frames the product (*i.e.*, the DIVA Tool) by providing a general *a priori* conceptualisation of the system to be modelled based on the formal framework presented in Section 6.3. It does so by providing concepts for expressing static information about the system, as well as for representing the system's dynamics. The static information of the system is represented by a relational-data model consisting of geographical features, properties and relations. The geographical features represent the real-world phenomena such as rivers or countries. Properties capture the quantitative information about the features. For example, a country might have the property "area" or a river the property "length". Finally, relations describe how the features are structured. For example, a region might contain several countries. The dynamics of the system are represented in the form of difference equations, in accordance with the formal framework.

The development process then addresses the integration of knowledge at the process level. It organises the iterative specialising of the framework's general concepts to the needs of the specific problem addressed, thereby structuring the integration of knowledge from the various experts. Knowledge enters the process as four categories (see Figure 6.1):

- The system's ontology, which is a formal vocabulary for referring to properties of the modelled system;
- The algorithms, which implement the system's state transition function, output function and adaptation strategies;
- The data, which express the initial state of the system and the inputs to which its vulnerability is being assessed (in the form of scenarios);
- The use-cases, which specify how the user can interact with the model via a graphical user interface (GUI).

The four categories of knowledge are interrelated; for example, new data may create the need to change existing algorithms or develop new ones with the consequent need to update the ontology. Once knowledge has entered the development process, most subsequent processes are automated. The development process can be iterated as many times as needed and whilst at any stage new knowledge can be incorporated, there is always a complete model available.

The first step of each iteration of the development process is the elaboration of a common formal vocabulary or ontology. The specific features, properties and relations that constitute the modelled system must be specified. All properties of

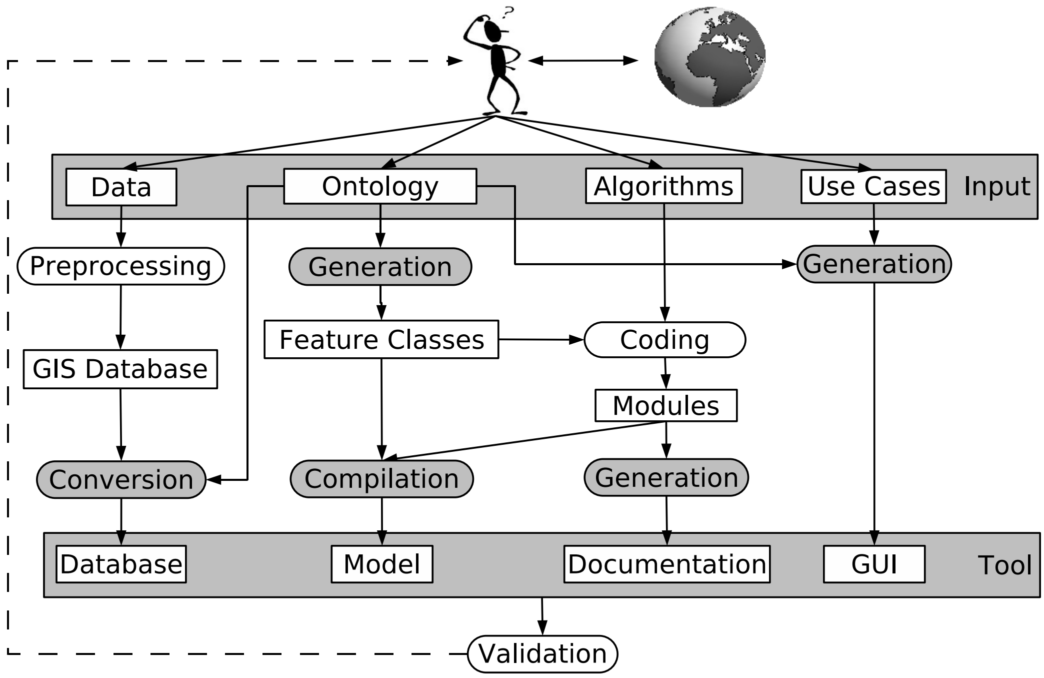

Figure 6.1: The DIVA development process. Boxes denote deliverables, ovals denote processes and shaded ovals denote automated processes.

the features must be classified into four categories according to the part they play in the system's dynamics: driver, state variable, diagnostic variable and parameter. For example, the country's area would most likely be static (a parameter), whereas its population might be driving the model. The compilation of the ontology is a joint responsibility of the project team.

In the next step the ontology is automatically translated into Java source code, which is then used by the project partners to code the algorithms. The hard-coding in Java ensures that an algorithm only compiles if it is consistent with the ontology. Related algorithms are grouped into modules. For example, a social scientist could write a module called "CountryDynamics", which simulates how the properties of the feature "country" evolve over time. Before a module is submitted for inclusion into the integrated model it is run and validated in stand-alone mode.

The last step of each iteration of the development process consists of the analysis of the modules and their linkages, and the validation of the integrated model. The project website is automatically updated with every new submission of a module, offering documentation and the new model to download. An important document that is automatically generated is a graph visualising the data flow through the modules (Figure 6.2). With this graph the project team can analyse the interactions between the modules and decide whether any changes need to be made in the next iteration of the development process.

The main advantage of the iterative approach is that the specification of subsystem interfaces is not required before one can begin to develop and code the algorithms. This allows the module developers to take advantage of the interdisciplinary learning process that takes place over the course of the assessment.

6.5 The case of DINAS-COAST

This section illustrates the methodological issues presented above with the help of an example. It shows how the formal framework and the DIVA Method have been applied for the assessment of vulnerability of the world's coastal zone to sea-level rise within the project DINAS-COAST.

6.5.1 The conceptualisation of vulnerability

The vulnerable *entity* studied in DINAS-COAST is the world's coastline, or more specifically segments of it. To reflect its large natural and socio-economic diversity, the coastline was decomposed into segments that are assumed to be homogeneous in terms of vulnerability to sea-level rise but which vary in length, with

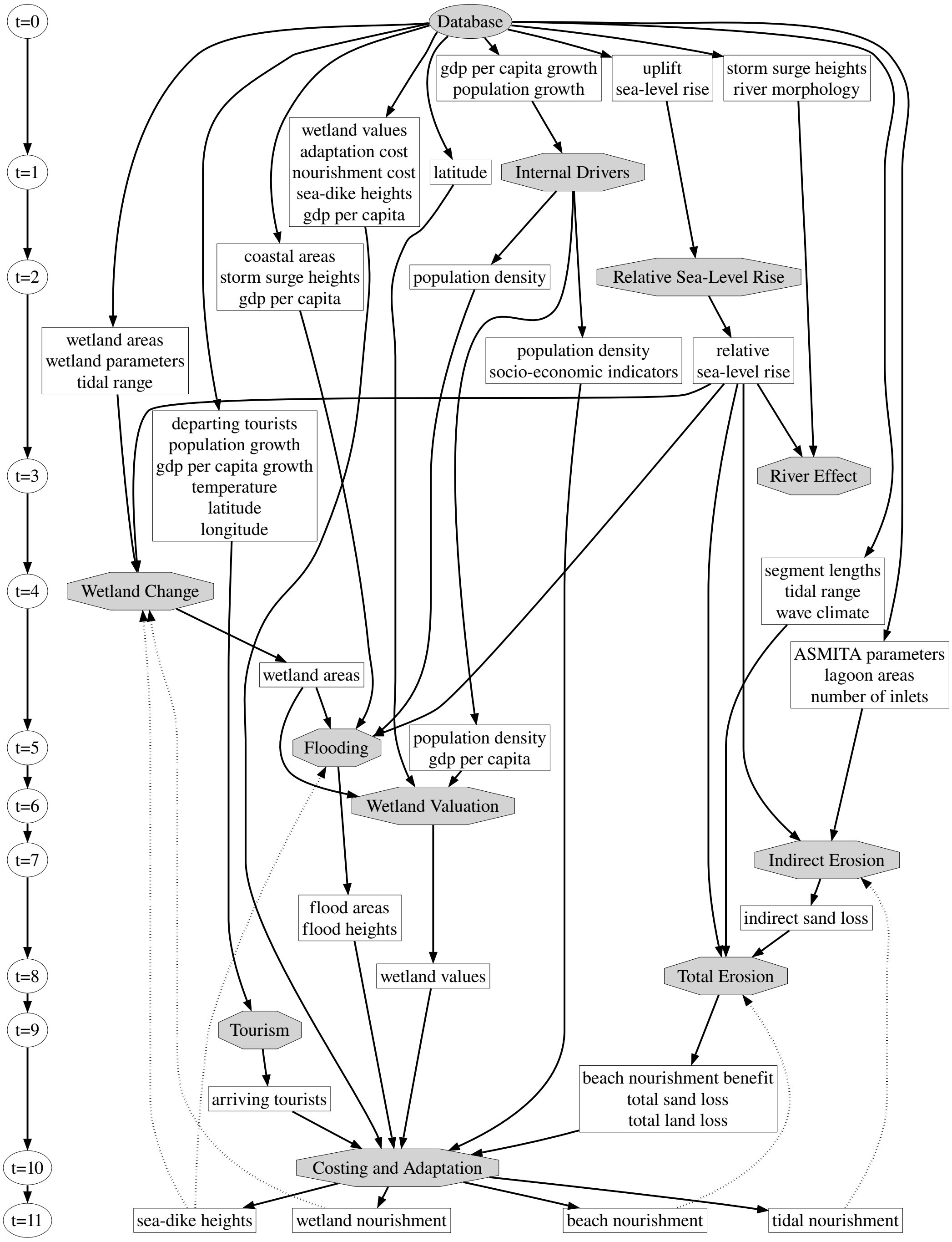

Figure 6.2: Module linkages in the DIVA model version 1.5.5. Octagons represent the modules, rectangles represent data, the drawn through arrows represent the flow of data during one time step, and the dotted arrows represent the data fed into the next time step.

an average length of 70 km. This segmentation was performed on the basis of physical, administrative and socio-economic criteria, producing 12,148 coastline segments in total (McFadden et al., 2007). Data on coastal characteristics needed for the calculation of potential impacts, such as coastal topography, population and protection status, are attributed to the coastline segments (Vafeidis et al., under review, see also Section 6.5.2).

Characterising the vulnerable entity also includes identifying its potential adaptation actions and strategies. As will be discussed in more detail in Section 6.5.2, four different adaptation strategies are considered. The project team's choice for these four strategies was motivated by a desire to provide users with the possibility to explore differences and trade-offs between strategies, as well as with the flexibility to define their own coastal protection standards. However, the coarse geographical scale of the analysis limits the usefulness of these results for coastal management.

The *stimuli* in DINAS-COAST that drive the assessment of vulnerability are scenarios of sea level, temperature, precipitation, coastal population and gross domestic product per capita. These scenarios are based on the four storylines of the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic and Swart, 2000), which have been the standard source of scenarios for climate impact and vulnerability assessment for the past five years. More recently there has been increased interest in using scenarios of stabilising atmospheric greenhouse gas concentrations, but they were not available in time for use in DINAS-COAST.

The *preference criteria* relate to the output variables of the assessment. These largely correspond with the indicators used by the IPCC Common Methodology, listed in Table 6.1. This choice of output variables reflects both the desire to be able to compare between previous and current assessments and the fact that coastal research has focused strongly on these types of impact over the past decade. As a result of the latter factor, the assessment of impacts in the current version of the DIVA Tool is considerably more sophisticated than the assessments carried out by Hoozemans et al. (1993), Baarse (1995) and Nicholls (2002, 2004). New output variables include effects on tourism arrivals and world heritage sites, as well as more detailed assessments of the costs of adaptation and the loss of wetlands, including their valuation.

6.5.2 The operational definition: the DIVA Tool

The conceptualisation of vulnerability above was developed into an operational definition of vulnerability by applying the DIVA Method (Section 6.4). The product of this step is the DIVA Tool, which consist of a global coastal database, a model, a set of scenarios and a GUI. The tool enables its users to simulate the effects of climate and socio-economic change and of adaptation on natural and human coastal systems on national, regional and global scales.

The vulnerable *entity* is represented by a computer model that implements and recursively applies the three functions of the formal framework: the state transition function f (Equation 6.3), the output function g (Equation 6.2) and the adaptation strategy ϕ (Equation 6.4): The complete model is a function h that, given an initial state x^0, takes a sequence of inputs $(e^1, e^2, \ldots, e^K)$ representing the evolution of the environment from time 1 to K and produces a sequence of outputs $(y^1, y^2, \ldots, y^K)$ representing the evolution of the coastal system:

$$(y^1, y^2, \ldots, y^K) = h(x^0, (e^1, e^2, \ldots, e^K), \phi) \tag{6.5}$$

where

$h : X \times E^K \times \Phi \to Y^K$,
X is the set of states of the system,
E is the set of exogenous inputs,
Φ is the set of adaptation strategies and
Y is the set of outputs of the system.

The transition function f and the output function g are unique, whereas the adaptation strategy ϕ can be selected from a set of possible strategies. As mentioned earlier, an adaptation strategy is a function that returns an adaptation action for each state of the system and for each input it receives (see Equation 6.4). The adaptation actions contained in the set of endogenous inputs U are (*i*) do nothing, (*ii*) build dikes, (*iii*) move away, (*iv*) nourish the beach, (*v*) nourish the tidal basins and (*vi*) nourish the wetlands. Some combinations of these actions are possible as well. For each time step (corresponding with model input) the DIVA model selects an adaptation action according to the following four adaptation strategies:

- No adaptation: the model only computes potential impacts;
- Full protection: raise dikes or nourish beaches as much as is necessary to preserve the status quo (*i.e.*, x^0);
- Optimal protection: optimisation based on the comparison of the monetary costs and benefits of adaptation actions and potential impacts;
- User-defined protection: the user defines a return period against which to protect.

The functions f, g and ϕ are distributed across various modules. Each module represents a specific coastal subsystem and encapsulates the knowledge of one or more experts. Table 6.2 lists all the modules of the current version of the DIVA model (1.0) and Figure 6.2 shows the flow of data through the modules. The first modules to be invoked compute geo-dynamic effects of sea-level rise on coastal systems, including direct coastal erosion, erosion within tidal basins, changes in wetlands and the increase of the backwater effect in rivers. This is followed by an assessment of socio-economic impacts, either directly due to sea-level rise or indirectly via the geo-dynamic effects. The last module is the costing and adaptation module, which implements adaptation actions according to the user-selected strategy. These actions influence the calculations of the geo-dynamic effects and socio-economic impacts of the next time step.

The *stimuli* are represented by sea-level rise and socio-economic scenarios. Both sets of scenarios were developed to be mutually consistent on the basis of the four IPCC SRES storylines (Nakicenovic and Swart, 2000). The climate scenarios were produced with the climate model of intermediate complexity CLIMBER-2 of the Potsdam Institute for Climate Impact Research (Petoukhov et al., 2000; Ganopolski et al., 2001), whilst the socio-economic scenarios were produced by Hamburg University. The climate and socio-economic scenarios have been regionalised so as to allow for more realistic assessments. The climate scenarios have been made available for low, medium and high climate sensitivities, which allows users to assess the range of possible impacts and their sensitivity to the climate scenarios. Although scenarios of temperature and precipitation have been developed, DIVA 1.0 makes limited use of them. This largely reflects the uncertainty surrounding the contribution of these climate variables to coastal vulnerability.

The *preference criteria* on the model's output have only partially been implemented. The DIVA model does not produce a scalar indicator of vulnerability. The model's output (Table 6.3) has many components and no strict order is given on the set of outputs Y. However, since the output is quantitative, a strict order (*i.e.*, a total order) is given naturally on each component of the output. The monetary components are directly comparable and are used to calculate the "optimal protection" adaptation strategy. The non-monetary components have not been made comparable through normalisation. Rather, it is left to the user to explore and compare the outputs that are produced by choosing different adaptation strategies and scenarios. This is facilitated by the GUI, which allows for the visual comparison of the outputs for different regions, time steps, scenarios and adaptation strategies in form of graphs, tables and maps.

Module Name	Author(s)	Description
Internal Drivers	Richard Tol	Produces socio-economic scenarios.
Relative Sea-Level Rise	Robert Nicholls, Loraine McFadden, Jochen Hinkel	Creates relative sea-level rise scenarios by adding vertical land movement to the climate-induced sea-level scenarios.
River Effect	Rob Maaten	Calculates the distance from the river mouth over which variations in sea level are noticeable.
Wetland Change	Loraine McFadden, Jochen Hinkel	Calculates area change due to sea-level rise for six types of wetlands, taking into account the effect of flood defences.
Flooding	Robert Nicholls, Jochen Hinkel	Calculates flooding due to sea-level rise and storm surges, taking into account the effect of flood defences.
Wetland Valuation	Luke Brander, Onno Kuik, Jan Vermaat	Calculates the value of different wetland types as a function of GDP, population density and wetland area.
Indirect Erosion	Luc Bijsterbosch, Zheng Bing Wang, Gerben Boot	Calculates the loss of land, the loss of sand and the demand for nourishment due to indirect erosion in tidal basins. This is a reduced version of the Delft Hydraulics ASMITA model (Stive et al., 1998).
Total Erosion	Robert Nicholls	Calculates direct erosion on the open coast based on the Bruun rule. Adds up direct erosion and indirect erosion for the open coast, including the effects of nourishment where applied.
Tourism	Richard Tol	Calculates number of tourists per country.
Costing and Adaptation	Richard Tol, Gerben Boot, Poul Grashoff, Jacqueline Hamilton, Jochen Hinkel, Loraine McFadden, Robert Nicholls	Calculates socio-economic impacts and either user-defined or optimal adaptation.

Table 6.2: The modules of the DIVA model version 1.5.5.

Issue	Indicator
Erosion	Land lost, sand lost in tidal basins.
Flooding	Dike height, people at risk, people actually flooded.
Saltwater intrusion	Area influenced by seawater intrusion into rivers.
Wetlands	Area of six different types of wetlands, monetary value of wetlands.
Costs	Adaptation cost, cost of nourishment, cost of building dikes, cost of saltwater intrusion, cost of migration, residual damage.

Table 6.3: Selected output of the DIVA model version 1.5.5.

6.6 Conclusions and outlook

This chapter has argued that the methodological advancement of vulnerability assessment would benefit from the development of two elements: (*i*) a domain-independent conceptual framework of vulnerability to enable unambiguous communication about vulnerability and meaningful comparison between vulnerability assessments and (*ii*) a process to organise the specialisation of the framework's general concepts into operational, system-specific definitions so as to facilitate the integration of knowledge from different experts and disciplines.

The formal framework proposed by Ionescu et al. (2005) is an example of the first element. The general conceptualisation can be applied to any system whose components can be mapped to the three primitive mathematical concepts of entity, stimulus and preference criteria. This is particularly useful when knowledge about natural and social systems needs to be integrated, as is the case when assessing coastal vulnerability. To take the same general starting points for different assessments ensures comparability. In addition, a formal framework is a prerequisite for computational approaches such as the one taken by DINAS-COAST.

The DIVA Method is an example of the second element, a process that specifies how general concepts can be specialised into an operational definition to accommodate a specific case. It is an innovative method for developing an integrated model by geographically distributed partners, providing scientists with different backgrounds with a methodological procedure to harmonise their conceptualisations of the system of interest and with an intuitive interface to express and integrate their knowledge about it. The process of model development is well defined and automatically documented. As a result, the status quo is always available on the Internet, providing a basis for efficient communication and collaboration between project partners.

The generic nature of both the formal framework and the DIVA Method makes them easily extensible and transferable to address new challenges, including non-coastal ones. Improvements on the current version of the DIVA model could include developing a module for coral reefs and atolls, considering consequences of climate change other than sea-level rise (including extreme events), focusing more strongly on river-coast interactions, refining the adaptation module and increasing the spatial resolution of the model, thus increasing DIVA's usefulness to coastal management. In addition, it is conceivable to develop regional versions of the DIVA Tool, such as a DIVA-Europe or a DIVA-South Asia.

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Summary

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 on designing and implementing 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.

Transdisciplinary problem solving differs from that of disciplinary research in that it is facing specific conceptual and methodological challenges. The first challenge encountered is that it is not exactly clear what the problem to be solved is; participants and contributing disciplines use alternative and sometimes incompatible concepts to describe the problem and its solution. Furthermore, in contrast to disciplinary problem solving, no standard "off-the-shelf" methods are available. Each problem addressed has unique features and requires the integration of knowledge from various scientific disciplines and from outside of science into an appropriate methodology.

Even though this integration of knowledge is *the* crucial step in transdisciplinary problem solving, it is rarely addressed explicitly; the participants of a transdisciplinary problem-solving efforts come together and *somehow* put together what they know. Concepts for speaking about the integration of knowledge are lacking.

This thesis takes first steps in filling this gap. It addresses the questions 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. In the first chapter meta-concepts for speaking about knowledge integration are developed and applied to discuss four cases of knowledge integration from the domains of IA and VA. In the following chapters the individual cases are

presented in greater detail.

Knowledge integration is differentiated into two subsequent phases. First, the participants of the assessment need to elaborate a *shared language* which is applicable for describing the problem and discussing potential solutions. Second, the participants must, based upon the shared language, design an appropriate 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.

In the first case of the "Framework for Analysing Methodologies of Transdisciplinary Assessments" (FORMETA) the general problem of methodology design was addressed. In TAs, a lot of time is spent on discussing methodologies of past assessments and the design of methodologies for new assessment. FORMETA aimed at facilitating these discussions and the design of new methodologies by providing a language to better communicate about and compare between methodologies of past assessment.

The first step in addressing this problem was to analyse the usage of the term 'methodology'. In the context of TAs the term is used to refer to the specific configuration of data, methods, actors and activities involved in solving the problem addressed. The second step taken was to translate (*i.e.* formalise) the results of the analysis into the language of mathematical graph theory: a methodology is represented as a directed simple graph. The nodes of the graph represent the involved 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 output of the methodology's last activity is called *product* of the methodology.

The graphical framework developed was tested by analysing and comparing the methodologies of two recent VAs carried out by the DINAS-COAST and the ATEAM projects. It was found that the methodologies 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 did this jointly, and (*iii*) ATEAM involved stakeholders while DINAS-COAST did not. These differences have an influence on the type of result statement produced by the methodologies and the way users perceive them. ATEAM produced simple, aggregate results 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.

In the second case of the project "Formal Approaches to Vulnerability that Informs Adaptation" (FAVAIA) the problem of developing a shared language for speaking about vulnerability to climate change and related concepts such as risk, hazard and adaptive capacity was addressed. Even though the concept of vulnerability is widely used within the climate change scientific community it is not defined consistently through the literature and often used without definition.

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. The analysis revealed that vulnerability is a relative concept, in the sense that accurate statements about vulnerability are only possible if one clearly specifies (*i*) the *entity* that is vulnerable, (*ii*) the *stimulus* to which it is vulnerable and (*iii*) the *preference criteria* to evaluate the outcome of the interaction between the entity and the stimulus.

In a next step, the three basic concepts identified were formalised (*i.e.* translated) into three mathematical primitives. The entity was mapped to a discrete dynamical system ($f : X \times E \to X$; f is the system's transfer function, X the set of states and E the set of exogenous inputs), the stimulus to the system's exogenous input ($e \in E$) and the preference criteria to a partial strict order relation on the systems set of states ($\prec \in X \times X$).

In a third step, vulnerability and related concepts were defined upon the mathematical primitives. For the simplest case of a one-step transition of a discrete dynamical system, vulnerability was defined as:

> 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 was generalised to more complex cases in which, *e.g.*, whole trajectories instead of one-step transitions are considered, the vulnerability of a system relative to a given reference scenario is considered and the entity reacts or adapts to the *stimuli*. Finally, the resulting framework was related to the IPCC definition of vulnerability and to those operational definitions applied in the aforementioned ATEAM and DINAS-COAST projects.

In the third case of the project "Potsdam Integrated Assessment Modules" (PIAM), an important special case of methodology design, the integration of computer models in the context of modular IA modelling was addressed. In the past, IA models were hardly modularised, which made it difficult to reuse parts of them in order to be able to quickly 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.

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, was trivial in the example case considered because 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. It is important to note that it generally does not suffice to just couple the input and output of the computer models. Computer models are approximate (*i.e.* numerical) solutions of mathematical problems; coupling the approximate solutions of several individual problems does not necessarily give an adequate solution of the overall problem; additional coupling algorithms might be needed.

In the example case considered, finding an efficient coupling algorithm was, in fact, a major challenge. A trade-off between computational efficiency and placing little requirements on the output of the models had to be reached. 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.

In the fourth case of the EU-funded project "Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise" (DINAS-COAST), a further case of integrating computer models, this time in the context of a global assessment of vulnerability to sea-level rise, was addressed. The task was to integrate computer models of different coastal sub-systems that are built by distributed participants and to make the integrated model available in the form of the user-friendly tool DIVA (Dynamic and Interactive Vulnerability Assessment), which allows the simulation of the effects of climate scenarios and adaptation strategies on all coastal nations.

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. This challenge was addressed by the introduction of a formal meta-language consisting of the concepts of geographical feature (*i.e.*, the "real world" entities; *e.g.* rivers or countries), property (*i.e.* the quantitative information about the features; *e.g.* a river length) and relation (*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, also turned out to be a challenge. It was not possible to define the linkages between the models to be integrated at the beginning of the assessment, because at this point the interactions between sub-systems were not fully understood; instead they were a result of the interdisciplinary learning process during the course of the assessment. This second challenge triggered the development of the DIVA method. The method consists of the above-mentioned meta-language and a development process that allows for iteratively refining the shared language and the linkages between the individual models. The DIVA method was then applied to develop the DIVA Tool.

From the cases considered, 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, the usage of a meta-language for representing methodologies of TAs improved the communication about methodologies of assessments and made important differences between the methodologies of ATEAM and DINAS-COAST transparent. In the case of DINAS-COAST, the introduction of a meta-language resolved the difficulties that the participants could not agree on a shared language and the model linkages at the beginning of the assessment.

Second, formalisation can contribute to the development of shared languages, in particular in those cases which involve complex relations between concepts and in which concepts overlap non-trivially in meaning. The formal mathematical language developed in the FAVAIA case 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.

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 through knowledge integration methods. This is particularly true 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. The DIVA method developed in the DINAS-COAST project has helped the participants of the assessment to iteratively elaborate a shared language and the linkages between models and thus to take advantage of the mutual learning process during the course of the assessment.

Samenvatting

Dit proefschrift verkent hoe een transdisciplinaire kennisintegratie de context van integrale kwetsbaarheid assessments voor klimaatverandering bepaalt. Ook al is kennisintegratie fundamenteel in zulke transdisciplinaire assessments, toch wordt het eigenlijke kennisintegratieproces slechts sporadisch op een expliciete en methodologische wijze geadresseerd. Kennisintegratie wordt hier genterpreteerd als de uitwerking van een gemeenschappelijk begrippenkader (of taal), gevolgd door het ontwerpen en gebruik van een relevante methodiek. Drie specifieke stappen voor het faciliteren van zon kennisintegratie worden gentroduceerd. Stap 1 is de semantische aanpak of de verschuiving van spreken in een gewone taal naar spreken in een meta-taal, die de eigenlijke taal eenduidig beschrijft. Stap 2 formaliseert de noodzakelijke vertaling van verklaringen, die worden gemaakt in de gewone of technische taal, naar de formele meta-taal. Tenslotte wordt in stap 3 de kennisintegratie methode voor de meta-taal ontwikkeld. Zon methode is noodzakelijk voor een heldere opzet met een eenduidig taalgebruik, die vervolgens moet worden gebruikt in het integratieproces.

Vier verschillende voorbeelden van kennisintegratie worden gepresenteerd en geanalyseerd. Als eerste wordt het algemene probleem van het methodiekontwerp besproken. Hiervoor is een grafisch visualisatiekader ontwikkeld. Als tweede worden de verschillende problemen bij het ontwikkelen van een gedeeld kwetsbaarheid begrippenkader voor klimaatverandering geadresseerd. Daarna wordt een bijzonder voorbeeld van methodologisch ontwerp behandeld en bediscussieerd. Dit ontwerp behelst een modulaire integratie van computer modellen in de context van de integrale assessment modelering, zoals die ontwikkeld is binnen het PIAM project (Potsdam Integrated Assessment Modules). Tenslotte wordt de integratie van computer modellen in de context van een mondiale kwetsbaarheid assessment van kustgebieden voor zeeniveaustijging behandeld. Deze kennisintegratie methodiek, die was ontwikkeld voor en toegepast in het DINAS-COAST project (Dynamic and Interactive Assessment of National, Regional and Global Vulnera-

bility of Coastal Zones to Climate Change and Sea-Level Rise), wordt beschreven en gevalueerd.

Deze vier voorbeelden laten zien dat de semantische aanpak bruikbaar is in alle gevallen waarbij het moeilijk is om direct een gemeenschappelijk en gedeeld begrippenkader uit te werken aan het begin van de assessment. Het verder formaliseren kan bijdragen aan de uitwerking van een gedeeld begrippenkader in die gevallen waar begrippen duidelijk overlappen in hun betekenis. Meer nadruk zal echter gelegd moeten worden op de verdere ontwikkeling en toepassing van iteratieve kennisintegratie methodieken, waarbij de verschillende iteraties doorslaggevend zijn voor het nuttige wederzijdse leerproces tijdens de kwetsbaarheid assessment.

Trefwoorden: klimaatverandering, integrale assessment, kennisintegratie, transdisciplinair onderzoek, kwetsbaarheid, kwetsbaarheid assessment.

List of Abbreviations

ADAM	Adaptation and Mitigation Strategies; a project currently being funded by the European Commission under the Sixth Framework Programme.
ATEAM	Advanced Terrestrial Ecosystem Analysis and Modelling; a project funded by the European Commission from 2001 to 2004 under the Fifth Framework Programme.
DINAS-COAST	Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise; a project funded by the European Commission from 2001 to 2005 under the Fifth Framework Programme.
DIVA	Dynamic and Interactive Vulnerability Assessment; a software tool for assessing coastal vulnerability developed by the DINAS-COAST project.
EVA	Environmental Vulnerability Assessment; a former PIK project.
FAVAIA	Formal Approaches to Vulnerability that Informs Adaptation; an ongoing, joint research project between PIK and the Stockholm Environmental Institute.
FORMETA	Framework for analysing methodologies of transdisciplinary assessments.
GCM	General circulation model.
IA	Integrated assessment.
IAM	Integrated assessment model.
IPCC	Intergovernmental Panel on Climate Change.
NEWATER	New Approaches to Adaptive Water Management under Uncertainty; a project currently being funded by the European Commission under the Sixth Framework Programme.
PIAM	Potsdam Integrated Assessment Modules; a former PIK project.

PIK	Potsdam Institute for Climate Impact Research.
SRES	Special Report on Emission Scenarios; IPCC report.
TA	Transdisciplinary assessment.
VA	Vulnerability assessment.

Curriculum Vitae

Jochen Hinkel was born on March 26 1970 in Böblingen, Germany and grew up in various places including Angermund (near Düsseldorf, Germany), Greenwich (Connecticut, United States) and Herrenberg (near Tübingen, Germany). From an early age until today two things have fascinated him: the diversity of cultures and collective, self-organised forms of living. After high school, he spent a couple of years travelling through Southern Europe, Africa and South America, gaining experiences in working on organic farms in Portugal, canoeing on the Congo River in former Zaire and harvesting coconuts in the Tairona National Park in Columbia. Currently he is living in a collective house in Berlin together with 24 others, both kids and grown-ups.

Jochen studied geo-ecology at the University of Karlsruhe (Germany), with the major subjects being landscape ecology, geo-chemistry, water management, agricultural engineering and hydro-geology. In his master thesis he developed geographic information system (GIS) and digital image processing methods for analysing aerial views of river beds in order to capture the correlation between river bed geometry, river works and sediment dynamics.

During his university education Jochen has done social work, supervising handicapped people, and development work for the German Agency for Technical Cooperation (GTZ) in Santa Cruz, Bolivia. After university he worked as a freelancer programming web-applications and as an information technology consultant for a personnel recruitment agency in Hamburg.

Since mid 2000, Jochen holds a position as a researcher at the Potsdam Institute for Climate Impact Research (PIK) in Germany and has worked on issues of scientific data management, model integration, integrated assessment and vulnerability to climate change within both internal and international research projects. A major contribution to his PhD thesis was the work within the European-funded DINAS-COAST project, in which he coordinated the development of the DIVA Tool, an interactive software tool that allows its user to assess coastal vulnerability from sub-national to global levels.

Currently, Jochen is leading PIK's FAVAIA research group, which aims at advancing the state of the art of vulnerability and adaptation assessments by providing and applying mathematical formalisations of the main concepts involved. The group belongs to PIK's research domain *Transdisciplinary Concepts & Methods* and currently contributes to the European-funded ADAM and NEWATER projects.

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