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Scaling in Integrated Assessment: Problem or Challenge?

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ABSTRACT

Scaling is an important issue in Integrated Assessment, because Integrated Assessment tries to synthesize different knowledge patterns that operate on a variety of scales. But we miss a unifying theory that describes and explains the dynamic behaviour of interfering patterns at various scales in time and space. In this article, we explore some ideas about how to deal with the geographical scaling dimension in Integrated Assessment, giving some examples of heuristic methods that could be used, in absence of a sound theoretical basis. In addition, a third dimension of scale becomes more and more important, that goes beyond the geographical scale dimension. That dimension demarcates the functional relationships between agents, both collective (institutions and organizations) and individual agents (human beings). In this article, we discuss the functional scaling dimension, giving some preliminary ideas how to deal with that third scale level in Integrated Assessment.

Keywords: scaling, integrated assessment modeling, IPCC SRES scenarios, emergent properties.

1. INTRODUCTION

It is increasingly recognized that scale is a core methodological problem in many scientific fields. This is particularly true for Integrated Assessment, which operates by definition on multiple scales, both in time and space. Thus, the European Forum for Integrated Environmental Assessment (EFIEA) workshop on scaling organized by the International Centre for Integrative Studies (ICIS) in Maastricht, aimed at collecting state-of-the-art knowledge on scales from a variety of angles, was quite timely. Based on this state-of-the-art representation, the building blocks for a potential research agenda for scaling in Integrated Assessment can be defined.

Regarding the state-of-the-art, much scaling ‘‘handwork’’ has been done in Integrated Assessment (IA) modelling. But it mainly concerns statistical up- and down-scaling techniques to move from a lower spatial scale level to a higher one and vice versa. Notwithstanding the usefulness of these statistical techniques, we now realize that much more is needed to represent multiple scales in IA-modelling. Furthermore, other tools commonly used in IA, such as scenario building, are in need of innovative multiple scale methods. Finally, a largely unexplored field is the relation between scaling and uncertainty.

In general, this paper gives a portfolio of ideas how to deal with scaling in IA-tools and methods. Rather than discussing in-depth the relation between scaling and a particular IA-instrument, we touch upon a number of scaling issues and present some ideas how to incorporate multiple scales in IA-tools & methods. First of all we address the overall methodological problem behind scaling in Integrated Assessment. Then we discuss scaling in IA-modelling, treating three different heuristic scaling-methods that are currently used. Next, we sketch scaling in IA-scenarios, giving two recent examples of multiple-scale scenario assessments. We then discuss scaling in relation to the representation of agents, followed by a brief discussion of scaling and uncertainty. We finish with a set of recommendations for future IA-research.

2. WHAT IS THE PROBLEM?

To illustrate the problem of scaling we start with a phrase of van der Veen, an economist at the Twente University: ‘‘Economists are not used to thinking in terms of geographical space.’’ He indicates that key elements of economic science, such as information flows, money, prices and virtual markets, do not have explicit geographical components. However, he argues, economic phenomena, e.g. the diffusion of information and technology and the transport of goods and materials (both intentional and unintentional), are spatial by nature. Paradoxically, economists feel most comfortable in an administrative space rather than in a geographical space [1].

In general terms, scale is the dimension used to measure or assess a phenomenon [2]. Usually, we distinguish between

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two different types of scale: the geographical or spatial scale, and the temporal scale. As we will see in this paper, there is also a third important scale, which we refer to as functional scale. Each scale has an extent and a resolution. The extent is the overall size or magnitude of the spatial or temporal dimension. The resolution is the precision used in measurement or assessment. For example, a model may have a spatial extent of a country and a resolution of 1 km by 1 km. Similarly it may have a temporal extent of 50 years with a resolution of 5 year (i.e., results are determined for every 5 year increment). Levels are then defined as units of assessment that are located at the same position on a scale, referring to location along a scale. Spatial levels we can distinguish are micro-, meso-, and macro, whereas common temporal levels are short, medium and long-term.

Science is the search for and the explanation of observed patterns. The act of identifying particular patterns means that choices about scale, extent and resolution have to be employed. Patterns may appear at one level and be lost at another [3]. A cellular biologist for example, identifies patterns at the level of an individual cell, whereas a doctor works with organs that are clusters of cells. Whereas the natural sciences have since long understood the importance of scale and have relatively well-defined hierarchical systems of analysis, the social sciences have long worked with scales of less precision and greater variety and have not worked with well-defined conceptions of scale.

Scale is at the heart of Integrated Assessment because the complex societal problems that it tries to address involve multiple scales in time and space. The different knowledge patterns that IA tries to combine, interpret and communicate involve a priori a variety of scales. Scale matters for IA for various reasons. First of all the driving forces of complex societal problems arise from different domains with their own scale characteristics. But on the other hand the impacts of complex problems play also out differently in different domains. The response mechanisms (including institutional structures) differ also along different scales. And, following the definition of IA of Rotmans [4], scales are important to combine, interpret and communicate different knowledge patterns to make a sound and comprehensive IA.

There are three major problems involving scale in Integrated Assessment. The first is how to combine a variety of processes which differ by nature in time, i.e., how to order unlike processes in time? The second is how to do so in a spatially explicit way, i.e., how to order and allocate unlike processes in space? And the third is that we need to go beyond the traditional scale dimensions to represent human behaviour: next to the temporal and spatial scale we need a third dimension that demarcates the functional relationships between agents.

The deeper problem is that no unifying theory exists that is capable of describing and explaining much of the dynamic behaviour at various scales of social, economic and ecological activity of interest to IA practitioners. This is in contrast to, for example, the unifying theory of mechanics explaining the acceleration of small bodies in free fall as well as the orbit of large planetary bodies. Thus, improving our knowledge base of the interlinkages between large-scale and small-scale processes within and across scientific disciplines is one of the daunting challenges of our time.

In the absence of an overarching scaling theory we mostly use heuristic methods in the IA-field. In the sections hereafter we present some of these heuristics as used and applied in the field of IA-modelling, IA-scenarios, agent-based IA-representations and uncertainty.

3. SCALING IN IA-MODELS

Integrated Assessment models are frameworks that structure the nature of a problem in terms of causalities. These frameworks are generally computer-based models, which quantitatively describing the cause-effect relationships of a particular problem or issue, also in relation with other problems or issues. Most current IA-models are rooted in systems analysis and global modelling, a tradition that started in the early seventies with the Club of Rome [5]. The second generation of IA-models more explicitly addressed environmental issues such as acid rain and global climate change. The third and current generation of IA-models is focusing on sustainable development, also covering non-environmental issues like human health, city development, water, transport and tourism. IA-models are intended to be flexible and rapid assessment tools, enabling the exploration of interactions and feedback, and which can be used for communication with a broad group of stakeholders. Still, many IA-models face some limitations and drawbacks, including their abstract level of representation, deterministic character, and inadequate treatment of the various types and sources of uncertainty. Here we will focus more particularly on how spatial scale is addressed in a number of IA-models.

The great majority of IA-models operate on one particular spatial scale level. Many IA-models operate on the global scale level, with only a minority on the regional and local scale level. In terms of temporal scale, most IA-models act on a long time scale, of 50 years or even longer. Hardly any model operates on multiple scale levels. Quite a few IA-models, however, do try to use heuristics and simple algorithms for tackling the issue of allocating the spatial distribution of certain types of environmental change, notably land use. In general, we can distinguish three of these techniques:

grid-cell based modelling;
cellular automata modelling;
multiple-scale regression modelling.

3.1. Grid-cell Based Modelling

Grid-cell IA-models make use of a grid-pattern that is laid over the global functions taken up in these models. Usually, these IA-models are modular by structure, where different modules (submodels) could have different grid-cell resolutions. There is a certain imbalance in the grid-cell representation of the processes represented in these models. Overlooking the temporal disaggregation in the various modules, the time horizon is common, but the time steps of the various modules vary considerably, from one day to five years. In terms of spatial disaggregation, the situation is more imbalanced. The major social, economic, demographic and technological driving forces are represented in a highly aggregated manner, and not at the grid-cell level. The physical modules, such as the atmosphere-ocean or terrestrial-aquatic modules, however, do act on the grid-cell level. So the states and impact modules are often represented at a fairly detailed grid-cell level, e.g., on a grid scale of 0.5 latitude and 0.5 longitude. And finally, the response functions, if involved anyhow, are not grid-cell based. So we see a serious flaw between major driving forces as determinants of long-term change, which operate at the global or world regional level, and physical processes that are modelled at a fairly detailed grid-cell level. For instance, in the IMAGE 2.1 model, one of the more advanced IA-models of global climate change, there is a laudable attempt to simulate in geographic detail the transformation of land cover as a result of changes in land use, climate, demography and economy [6]. However, a major determining factor behind land cover is the land management parameter, which is specified at the world regional level, where there are 13 world regions distinguished in the model.

A final comment is that there is no dynamic interaction among the grid cells in the models. So the representation of dynamic processes in the model is identical for each grid cell, without dynamically influencing each other just as is the case with cellular automata models. So the overall conclusion is that the grid-cell presentation of IA-models suggests much more precision than can be fulfilled, and could even be misleading for non-modellers.

3.2. Cellular Automata Modelling

Cellular automata models are based on grid-cells that communicate with each other in an intelligent manner. The dynamic state of each cell depends on the state of the surrounding cells, the characteristics of the cells, and the distance to the core cell. Usually, these types of models operate at two different scale levels: the local level (micro-level) and the regional level (macro-level). For example, see the cellular automata models as developed by Engelen et al. [7]. In the case of dynamic land use representation, at the local level the suitability for land use types is determined for each cell. At the regional level the amount of land needed is calculated and allocated. An integrated model integrates social, economic and ecological processes based upon the amount of land is estimated and allocated. The term cellular automata model suggests that local dynamics determines the ultimate land use. But the real dynamics is determined by macroscopic trends rather than by suitability on the micro-scale. Other drawbacks are that the rules for determining the suitability are rather controversial, and the rules behind the ‘clustering mechanism’ are not well known. Further, the relations between cells are dependent on the scale levels themselves.

So the overall conclusion is that cellular automata model seems more suitable for micro-scale level on a relatively short time scale. The reliability of cellular automata models on the macro-scale level seems rather low, just as the reliability on the longer time scale. So the presentation of geographically-explicit results on both the macro- and micro-level may be misleading.

3.3. Multiple-scale Regression Modelling

Multiple-scale regression models are models that include two or more spatially-explicit scales at which land use is allocated. An example of a multiple-scale regression model is the CLUE-model as described in [8]. On a relatively coarse scale general land use trends and the land use driving mechanisms that act over a longer distance are calculated. On a relatively fine scale local land use patterns are calculated, taking local constraints into account. The land is allocated on the two levels (coarse and fine) based on complex interactions among socio-economic, biophysical and land use constraints. The dynamics of changing land use is based on correlations (regression analysis) and not on causal mechanisms. Because these correlations are assumed to be constant, the time scale is relatively short (5–10 years). So the overall conclusion is that multiple-scale modelling seems a promising method, but is more directed towards the spatial component than the temporal component. The correlation basis makes it a quasi-static method rather than a dynamic method.

All heuristic scaling modelling methods presented above have their pros and cons. It is hard to judge whether one scaling method is to be preferred to another one. Further, these methods are not mutually exclusive at all. But unfortunately they represent different schools that hardly communicate with each other [8]. But blending the cellular automata approach with the multiple scale, where correlations are replaced by causalities, would already mean a tremendous step forward.

4. SCALING IN IA-SCENARIOS

Scenarios are descriptions of journeys to possible futures that reflect different perspectives on past, present and future developments with a view to anticipating the future [9]. Scenario analysis has evolved significantly over the past decades. In their early days, scenarios were used primarily as planning and forecasting tools, displaying a rather mechanistic and deterministic worldview. Later, scenario analysis moved beyond merely fulfilling a decision-support function to one that also supports a more open form of exploration. Nowadays, scenarios have evolved into powerful exploratory tools: they do not predict the future, but rather paint pictures of possible futures and explore the various outcomes that might result if certain basic assumptions are changed. So currently, scenarios are often used to broaden, deepen and sharpen the mindset of stakeholders involved in a process of exploring possible futures [10].

In the field of scenario development, scaling is an underdeveloped issue. A screening of 40 existing scenarios on sustainable development indicated that almost all scenarios were developed at one scale level [11]. This mono-scale level orientation is surprising but also worrysome, with only a few exceptions. A few exceptions concern the latest IPCC-scenarios [12], the so-called SRES-scenarios, and the scenarios developed for the 3rd Global Environmental Outlook [13].

The IPCC SRES-scenarios focus on changes in economic, technological and demographic trends and energy use as major drivers for global climate change. Specifically, the scenarios explore the global and regional dynamics that may result from changes at a political, economic, demographic, technological and social level, see Figure 1. The distinction between classes of scenarios was broadly structured by defining them *ex ante* along two dimensions. The first dimension relates to the extent both of economic convergence and of social ands cultural interactions across regions; the second has to do with the balance between economic objectives and environmental and equity objectives. This

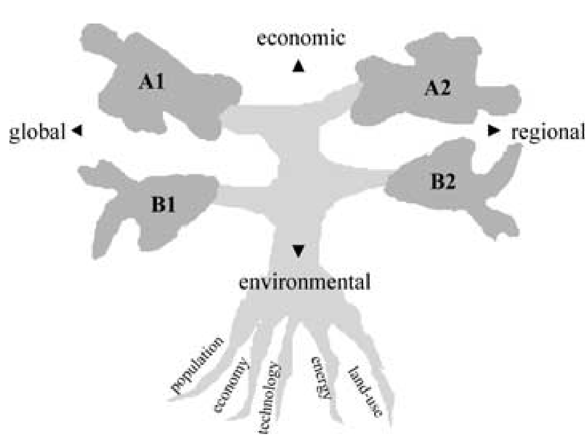

Fig. 1. The IPCC SRES scenarios as branches of a two-dimensional tree. The dimensions indicate the relative orientation of the different scenarios in relation to economic or environmental concerns, and global and regional development patterns.

process therefore led to creation of four scenario "families" or "clusters," each containing a number of specific scenarios.

The first cluster of scenarios [A1] is characterised by fast economic growth, low population growth and the accelerated introduction of new, cleaner and more effective technologies. Under this scenario, social concerns and the quality of the environment are subsidiary to the principal objective: the development of economic prosperity. Underlying themes combine economic and cultural convergence, and the development of economic capacity with a reduction in the difference between rich and poor, whereby regional differences in per capita income decrease in relative (but not necessarily absolute) terms. The second cluster of scenarios [A2] also envisages a future in which economic prosperity is the principal goal, but this prosperity is then expressed in a more heterogeneous world. Underlying themes include the reinforcement of regional identity with an emphasis on family values and local traditions, and strong population growth. Technological changes take place more slowly and in a more fragmented fashion than in the other scenarios. This is a world with greater diversity and more differences across regions.

In the third cluster [B1], striving for economic prosperity is subordinate to the search for solutions to environmental and social problems (including problems of inequity). While the pursuit of global solutions results in a world characterised by increased globalisation and fast-changing economic structures, this is accompanied by the rapid introduction of clean technology and a shift away from materialism. There is a clear transformation towards a more service and information-based economy. And finally, the fourth cluster [B2] sketches a world that advances local and regional solutions to social, economic and ecological problems. This is a heterogeneous world in which technological development is slower and more varied, and in which considerable emphasis is placed on initiatives and innovation from local communities. Due to higher than average levels of education and a considerable degree of organisation within communities, the pressure on natural systems is greatly reduced.

Martens and Rotmans [14] already mentioned some of the shortcomings of the IPCC SRES-scenarios. Their scope is rather narrow, focusing, as mentioned, on population growth, technological and economic development as the major drivers, whereas the broader social, cultural and institutional context is lacking. The scope of these scenarios was broadened by Martens and Rotmans [14], relating them to key developments in water, biodiversity, health and tourism.

Also, major surprises, bifurcations and additional policy interventions are missing, indicating the rather extrapolative and linear thinking underlying these futures. Further, the quantitative aspect is so dominant that it impairs the broad scope introduced by the underlying storylines.

From the multi-scale perspective the IPCC SRES-scenarios mean a step forward compared to previous sets of IPCC-scenarios, in the sense of the distinction between global and regional scenarios. But still, the coupling between the global and regional scale level is rather loose and not dynamic at all. The global and regional scenarios themselves were not developed with a consideration of how they feed back to each other. So these IPCC SRES-scenarios are not really multi-scale, and this rudimentary multiple scale approach needs to be improved over the next couple of years.

A better example of a multi-scale scenario endeavour is the GEO-3 scenario process. In developing the UNEP-GEO-3 scenarios, there was prolonged discussion focusing on the questions of global versus regional and centralised versus decentralised development of and representation in the scenarios. Regional participation and flexibility would be needed to develop the scenarios, but global coherence would also need to be maintained. It was decided to incorporate fully regional views and participation while maintaining a general global framework that builds on the extensive global work that had already been undertaken (e.g., [12, 15, 16]). There would be ''mutual conditioning'' whereby globally consistent themes were to be developed and the regions then given the flexibility to take these issues further. In each region a core team was put together, and existing global scenarios as developed by the Global Scenario Group [16] were used to inform these regional teams. Based on this global scenario context the regional teams produced regional storylines which emerged into regional narratives, which then fed back to and ultimately led to modifications of the global scenarios. Innitially, there remained an unnatural separation between the global and regional narrative scenarios, with little of the detail in the regional narratives represented in the global narratives, and little of the global context and the importance of relationships between the regions reflected in the regional narratives. To address this, the global and regional narratives were integrated to present more holistic stories of the next three decades. The social and environmental implications across the different scenarios at the global and regional scales were assessed. These presented more detailed quantitative analyses that had been undertaken in support of the scenario narratives. Further, regional experts looked at the implications of the different scenarios for specific events or developments within each region.

The blending of the regional and global narratives was difficult and it took some time for a shared understanding to be achieved, and more feedback from the regions would have led to an even higher level of integration of the global and regional scenarios. But the overall result was interesting, and led to a set of four integrated scenarios, with the names: market first, policy first, security first and sustainability first. For an elaborate description of the scenarios the reader is referred to the GEO-3 report [13].

A final scenario example which is interesting from the multi-scale perspective is the VISIONS project. The VISIONS project (1998–2001) was an innovative endeavour in the development of scenarios and integrated visions for Europe. VISIONS' overarching goal was to demonstrate the many linkages between social-cultural, economic and environmental processes, and to show the consequences of these interactions for the future of Europe and European regions from an integrated viewpoint. To achieve these ambitions, a variety of methods were used to develop challenging scenarios for Europe in an innovative and scientifically sound way. It was therefore decided to develop exploratory scenarios that investigate a broad range of long-term futures rather than to develop decision scenarios that primarily generate short-term strategic options. The scenarios would be highly divergent, descriptive rather than normative in nature, and integrate relevant social-cultural, economic, environmental and institutional dimensions. The project was meant to be and experimental arena for testing participatory methods in conjunction with IA-models, supporting the policy-making process for sustainable development.

A unique feature of the endeavour was the use of multiple time and geographical scales. The final scenarios include staggered time intervals that reach 50 years into the future. Global developments provide the context for European scenarios and for three sets of scenarios for three representative European regions: the North-West UK, the Italian city of Venice and the Dutch Green Heart area. For these three European regions and for Europe as a whole different sets of scenarios were developed, using different combinations of participatory and analytical processes. For Europe as a whole, a participatory process of mutual learning was used, based on the so-called ''storyline'' approach. This approach combined knowledge provided by experts through lectures with ''free-format'' brainstorming by stakeholders.

These storylines were fleshed out and enriched, which ultimately lead to three European scenarios: *Big is Beautiful*, *Knowledge is King* and *Convulsive Change*. In Venice, the Green Heart area and North-West UK sets of stakeholder-based scenarios were also developed: four scenarios for NW-UK and Venice, and three for the Green Heart and Europe were developed. A common format of *factors-actors-sectors* was used for designing these scenarios, which describe paths to different European and regional futures. The *factors* are: equity, employment, consumption and environmental degradation. The *sectors* are: water, energy, transport and infrastructure. And the *actors* are: governmental bodies, NGOs, businesses and scientists. The scenarios were developed from qualitative stakeholder input and then underpinned with quantitative information where deemed appropriate. Further, action-reaction mechanisms, bifurcations and surprises were included to counter the overall tendency of many scenarios to merely extrapolate from the past and present and exclude deviations from a particular line of development.

In the final phase of the VISIONS project the regional and European scenarios were integrated into *integrated visions*. These visions are narratives that describe the complex patterns that emerge from the dynamics caused by action-reaction patterns, and that are overlooked in any single-scale scenario study. Integrated visions help to assess complex dynamics and to identify conflict and consensus between different scales and perspectives. The framework for an integration methodology was developed at the start of the project and was further determined during the development of the scenarios. Scenarios were compared in terms of tensions and similarities. This comparative analysis was used to filter out a sensible selection of 144 ($4\times4\times3\times3$) possible scenario combinations. Interesting combinations of dynamics between Europe and the regions and interregional interactions that cannot be seen at a single level were explored in detail. Two *similarity quartets* and one *tension quartet* were selected following the filtering and exploration of the combinations. The respective quartets indicated harmony and conflict between regional and European interests.

Overall, that resulted in three integrated visions: *Living on the Edge*, which depicts a European risk society with many extremities and chaotic situations and managed by some form of permanent crisis management. In *Europe in Transition* the major regional and European developments mutually reinforce each other, leading to a transition to a modern European society with structural changes in the field of work, lifestyles, governance, technology and economy, but with many growing pains. And finally *Shadows of Europe Ltd*, a European Superstate with scale-enlargement in business and government, but also in research, education and NGOs, resulting in a Europe of competition and market functioning, with winning but also losing regions: a divided Europe with many tensions, and a crisis in public governance which generates much confusion and many tensions. For more information on VISIONS the reader is referred to Rotmans et al. [11, 17].

In general, playing around with different spatial and temporal scale levels in scenarios is essential. Usually, the higher the scale level, the more ambitious the policies formulated in scenarios. However, implementing those policies at lower scale levels is another story. Thus, exercises that make the tensions explicit between the different scale levels in terms of policy formulation versus realisation are very useful. Similarly, many policy strategies in scenarios are formulated in the long-term. If it is not clearly indicated what those long-term strategies mean in terms of concrete policy actions, the scenario exercise is only of limited value. And finally, the driving forces and autonomous dynamics need to be expressed and linked at different scale levels. A nice example is globalisation: rather than supposing that globalisation develops similarly along different scale levels, one could suppose countervailing responses at lower scale levels, such as glocalisation.

5. AGENTS AND SCALE

An emerging development in the modelling arena is the phenomenon of agent-based modelling. Also within the Integrated Assessment community agent representation has emerged as an important issue [18]. The basic question that we could ask is: ‘why do we need agent-based models?’ and in particular ‘why do we need agent-based IA-models?’

A number of arguments can be put forward to address this question. Perhaps the most valid argument is that we want to enhance our still poor insight into the dynamic interplay among agents, both in terms of individual agents, and collective agents like institutions and organisations. Until recently, human behaviour, and in particular the behaviour of agents such as stakeholders, has been left out of IA-models and scenarios apart from the representation drawn from neo-classical economics, where agent behaviour follows rational, price-driven decision rules. Jaeger [19] refer to this as the rational actor paradigm. Most of us know, however, that this is not an adequate way of representing human agents, especially in IA-models. This touches upon a second reason for implementing human behaviour in IA-models, we urgently need to offer an alternative to the rational actor paradigm that still prevails in IA-models. Especially the representation of the interaction among human agents, directly and indirectly influencing each other, which is largely neglected in the rational actor paradigm, is of importance.

A further reason is that the inclusion of institutional dynamics through the representation of collective agents in IA-models is of crucial importance. Whereas the economic, ecological and social dimensions are often included in IA-models, the institutional dimension is almost always lacking. Finally, agent representation in IA-models seems a promising way of involving stakeholders more actively in the modelling process. In general, we can distinguish three categories of stakeholders in the IA-modelling process: stakeholders as *advisors*, where the knowledge and experience of stakeholders is used; stakeholders as *users*, where stakeholders use IA-models for various reasons, either strategic and managerial, or for educational or moral reasons; and finally, stakeholders as *actors*, where the stakeholders’ behaviour is a part of the IA-model. From a methodological point of view, the last case is the most interesting but also the most troublesome, which we will further discuss below.

This is not to imply that incorporating agency into IA problems does not pose problems. The first problem is that we have to deal with a wide range of agents, varying from individual agents as consumers, to collective agents as institutions and organisations. Due to the high abstraction level of physical and geographical processes in many IA-models, collective agents naturally coincide more with this level of abstraction than individual agents. But the majority of agent-based models focus on individual agents, representing many of them, sometimes hundreds if not thousands, all identical in their behaviour. Hardly any agent-based model deals with the representation of institutions or organisations, so there is not much we can learn from, apart from some theoretical cognitive research and conceptual modelling work of collective agents [20]. In general, the cognitive basis for the representation of collective agents as institutions and organisations is poor. Conte and Castelfranchi [21] introduced some ideas on social norms as attributes that distinguish institutions and organisations from individual agents. The final problem relates directly to the scaling issue: the variety of agents operates at different scale levels. But agents do not operate primarily on a geographical scale level, but on a functional scale level, that relates to the nature of the functional relationships they have with other agents. This is the ''magic'' third scaling dimension, next to space and time, to which we referred earlier in this article.

One way of representing different functional scale levels for agents is to use a discretization framework. An example of such a discretization form is the multi-scale level concept as formulated for innovation of technologies by Geels and Kemp [22] which distinguishes between the macro-, meso- and micro-level. Applying this to the multi-agent setting, delivers three functional scale levels for different kinds of agents. At the *macro-level* transnational authorities are operating, such us UN-agencies and multinationals. At the *meso-level* institutions and organisations operate, and at the *micro-level* individual agents.

The chosen structure for agents as developed within the FIRMA-project (see box), is that of social, autonomous agents with the following characteristics: goals, beliefs, social norms and modes of interaction. Goals are states of the world desired by a particular agent, which is an assumption for agent activities; beliefs represent the particular world-views (perspectives) of an agent; social norms are obligations on a set of agents to accomplish or abstain from a certain action; and modes of interaction represent the different manners and levels of interaction between agents. We then distinguish between individual agents and collective agents such as institutions, the latter defined as supra-individual systems deliberately designed or spontaneously evolved to regulate the behaviour of individual agents. What collective agents distinguishes from individual agents is the interest that they have, a stake to pursue a certain goal for a group of agents. The rationale behind these attributes of an agent is that they function partly in an autonomous manner,

BOX 1: THE FIRMA PROJECT

The European project FIRMA (Freshwater Integrated Resource Management with Agents) aims to improve water resource planning by combining agent-based modelling and integrated assessment modelling. The very idea is to represent the dynamic behaviour of water managers in their specific institutional and organisational context on the one hand, and the physical, hydrological, social and economic aspects of water resource management on the other hand, in an integrated manner [23]. Six case-studies all over Europe have been selected as study object, and one of the case-studies is the Meuse, in particular the Limburg part of it in the Netherlands.

Below we will briefly discuss this case-study from an integrated angle.

Meuse Case-study

The ongoing planning of Dutch part of the Meuse is a complex, long-term project, called the Maaswerken, involving three main activities: flood control, improvement of the navigation route and nature development. This will be achieved by a combination of deepening and widening of the summer bed, lowering of the floodplains and side gullies, altering embankments, and upgrading the navigation infrastructure.

The proposed model is meant to be a tool for developing a long-term vision of the management of the river Meuse. Because of the complexity of this case study, a successful modelling solution can only be achieved by applying an integrated approach to assess the impacts of the planned measures incorporating the various perspectives of stakeholders by means of agent-based social simulation.

The agent-based model applied in the Meuse case study is based on a complex, cognitive agent approach developed by social psychologists and integrated assessors [24]. Agents represent stakeholders, referred to as actors with their particular world views and actions within the modelled target system. The internal structure of a cognitive agent consists of goals, beliefs, norms and constraints [25]. The agent may be seen as an independent sub-program capable of reflecting on its own goals and beliefs by comparing them to the changing environment at different functional scale levels. The goals and beliefs can adapt to a changing world as well as the changing behaviour of other agents. Adjustments will be triggered by reaching threshold values such as the height of dykes, the area of nature development, the amount of gravel to be extracted, the costs of measures, etc.

The Integrated Assessment model portrays the relevant processes related to the management of the Meuse. It is structured according to the concept of Pressure-Impact-State-Response (PSIR) [26]. The simulation model includes simple hydrological modules to calculate the effects of various river engineering alternatives of the Maaswerken project on the state of the water balance in the province of Limburg. Impact modules relate these results to consequences for river functions such as safety, shipping and nature. Input to the IA-model is derived from a set of perspective-based scenarios that sketch possible changes in climate and socio-economic boundary conditions in a consistent manner.

The Integrated Assessment model and the agent-based model have been coupled in the form of a prototype. The prototype is a highly simplified form of the conceptual model and thus of reality, but it is meant to do some experiments in a straightforward way in order to shed some light on the complex interactions between the agents world and the physical world. In this way we are able to simulate and analyse two types of processes: (i) *agent-environment interaction*: responding to changing river bed geometry, nature development, floods, pollution, side-effects of measures, etc.; and (ii) *agent-agent interaction*: communication about planned measures, negotiation process according to the goals and beliefs of the agents, coalition forming, etc.

Figure 3 gives a representation of an institutional agent as part of the agent-based IA-model. The Figure shows how the different attributes of the institutional agent (goals, beliefs, social norms and constraints) are coupled to different functional scales. Whereas the goals and beliefs are influenced by trends and developments at the macro-level, social norms are more determined by regime developments at the meso-level, and constraints are set by niche developments at the local level. So while an institutional agent on the whole is operating at the meso-level, the other functional scale levels do influence the attributes of the agent.

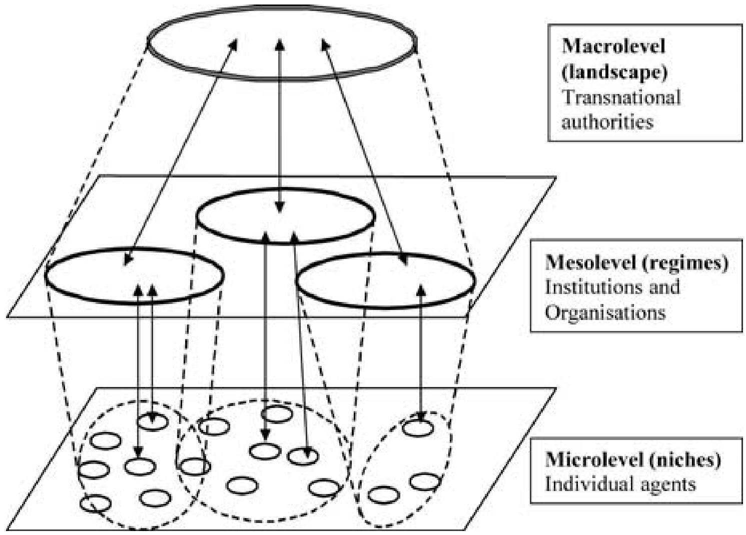

Fig. 2. Different scale levels of agent representation.

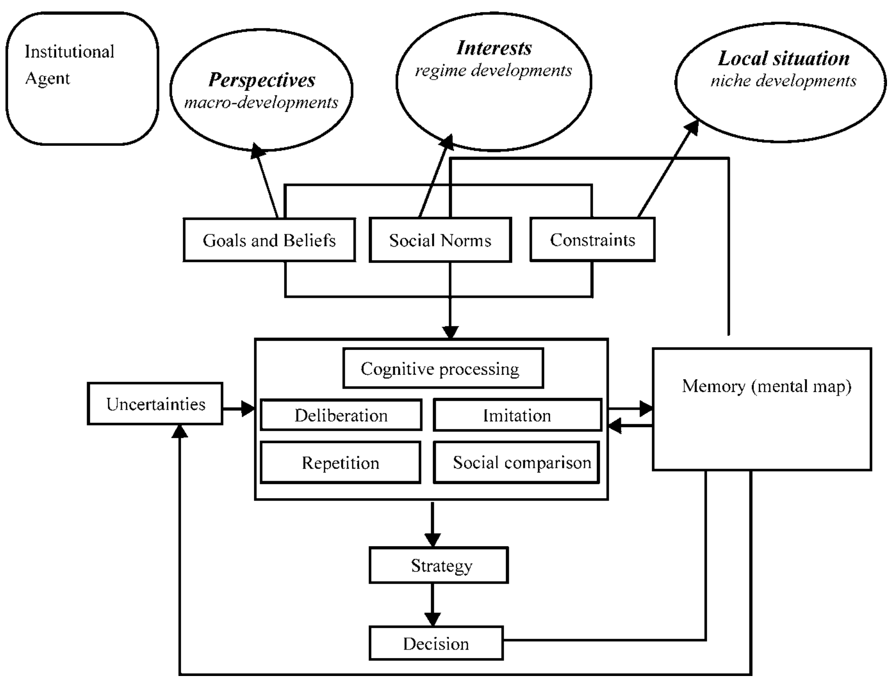

Fig. 3. Multiple-scale representation of an institutional agent.

based on their internal set of criteria, and partly through the interaction with other agents.

Relating these attributes to the different scale levels yields the following picture, as depicted in Figure 2. Goals and beliefs of agents are then represented to the *macro-level* developments, where perspectives change at the macro-level, influencing the goals and beliefs of agents. The social norms of agents are related to regime developments at the *meso-level*, where interests play an important role. The constraints of local circumstances do play a role at the *micro-level*, and could be considered as niche developments.

In conclusion we can say that the incorporation of agents in IA-models is still in its infancy stage. To represent agents at different functional scale levels is a bridge too far at this point in time. Conceptually, we can use a discretized multi-scale level concept and link different functional scale levels to different types of agents. But there is not any operational IA-model that has implemented such a multi-functional scale concept. Some prototyping versions are emerging, however, as for example within the FIRMA-project, which gives some insight for the further development of multiple-scale agent-based IA-models.

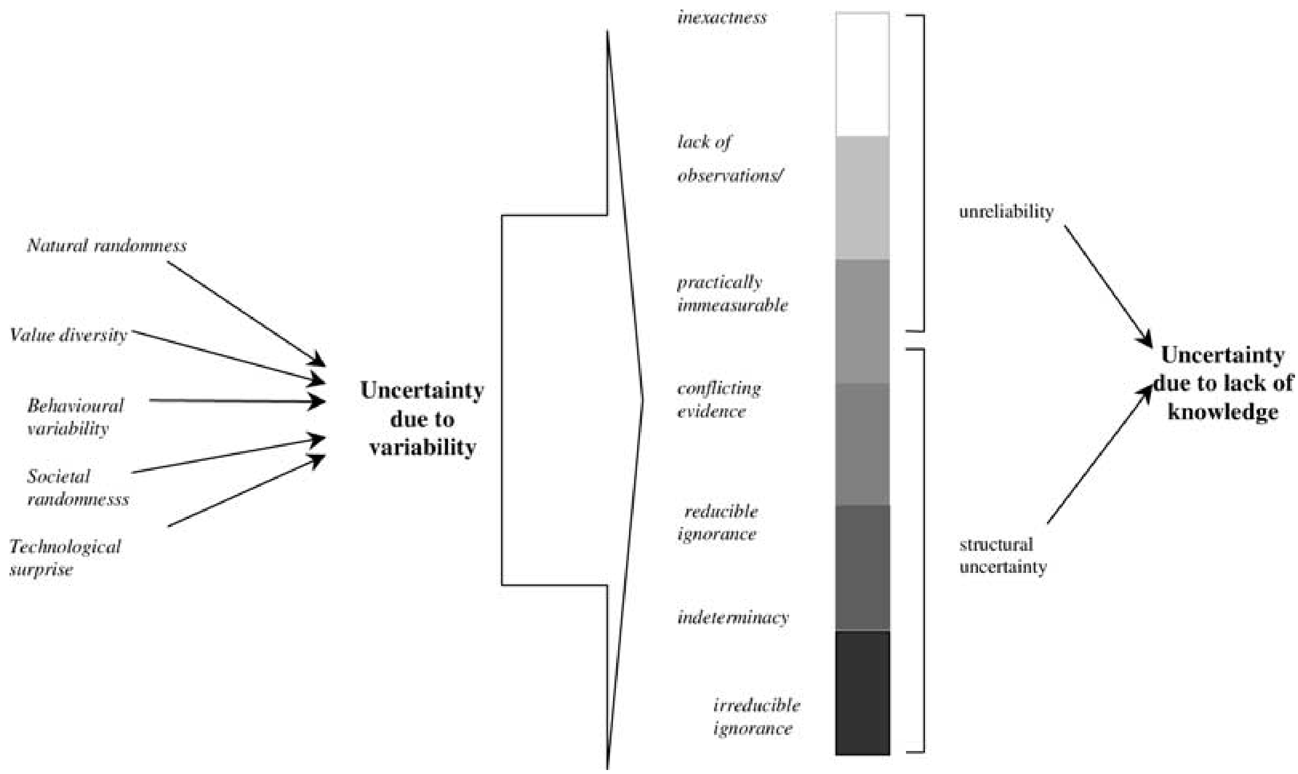

Fig. 4. Typology of sources of uncertainty.

6. UNCERTAINTY AND SCALE

The relationship between uncertainty and scale issue is hardly addressed in the IA-literature [4]. In 1999 in Baden bei Wien an EFIEA-workshop was organised on uncertainty, but the scaling issue was largely ignored at this workshop. Still, however, there is a natural relationship between uncertainty and scale. When we scale up or down processes we automatically introduce new errors and thus uncertainties. By using up- and down-scaling techniques we disaggregate or aggregate in time or/and space. For instance, we can use statistical techniques or metamodels to disaggregate in time model outcomes from monthly estimates to daily estimates, or if we can disaggregate in space from a 5×5 grid cell pattern to a 0.5×0.5 grid cell pattern. By using these statistical techniques and metamodels we introduce new errors and thus also sources of new uncertainties. However, often these uncertainties do not appear in the results presented.

A commonality between uncertainty and scale is that both issues are often treated by IA-modellers as technical problems that can be ‘‘solved’’ by analytical techniques rather than doing a profound analysis. Based on lessons from IA-research over the last decades, however, current insights indicate that these issues need to be addressed in a broader, multi- and inter-disciplinary context, and preferably in a trans-disciplinary context, involving a broad range of stakeholders.

Because uncertainty is a many-headed monster, it is difficult to define uncertainty. Specifying different types and sources of uncertainty would help to clarify the relations with scales. One way of doing this is by using a typology of uncertainties which takes account of different sources of uncertainty. We use here a typology developed by Van Asselt [27] (see Fig. 4), which enables analysts to differentiate between uncertainties and to communicate about uncertainties in a more constructive manner. The taxonomy is meant to be generic, i.e., applicable to all contexts. This implies that it should be possible to trace revealed uncertainties back to one or more sources of the taxonomy.

At the highest aggregation level, the taxonomy makes the distinction between two major sources of uncertainty: that due to variability, and that due to limited knowledge. Uncertainty due to variability reflects the fact that the system/process under consideration can behave in different ways or is valued differently, so variability is an attribute of reality (*ontological*). As indicated in Figure 4, sub-sources considered are nature randomness, value diversity, behavioural variability, societal randomness and technological surprise.

Uncertainty due to limited knowledge refers to the limited state of our current knowledge and to the limited knowledge of the analysts performing a study (*epistemological*). Sub-sources considered for this source are unreliability (inexactness, lack of observations/measurements, practically immeasurable) and structural uncertainty (conflicting evidence, reducible ignorance, indeterminacy and irreducible ignorance).

In further exploring the relationship between uncertainty and scale, we have to specify the nature of the uncertainty in terms of the various sources of uncertainty. The continuum of uncertainty thus ranges from unreliability on the one hand, to more fundamental uncertainty, also referred to a structural uncertainty. Uncertainties in the category of unreliability are usually measurable or can be calculated, in the sense that they stem from well-understood systems or processes. This implies that in principle either margins or patterns can be established, so that usually the uncertainty can be described quantitatively (either in terms of a domain or stochastic equation). On the other end of the continuum are fundamental uncertainties which can at best be roughly estimated. Such fundamental uncertainty generally arises due to conflicting evidence, ignorance and indeterminacy.

From analysing the different sources of uncertainty it becomes obvious that the structural uncertainties are fundamental by nature and scale-independent. Relating these uncertainties to various scales, either temporal or spatial, won't change the nature of these uncertainties. In case of the unreliability as source of uncertainty, the coupling with various scales could make a difference. In particular in uncertainty sources as inexactness and lack of data/measurements, the relation with the scale level is of vital importance. *This means that we first have to identify the nature of the uncertainties and the underlying sources, before we can couple uncertainties to scale levels*.

In studying the relations between uncertainty and scales we distinguish between the coupling of temporal scale and uncertainty vis à vis the coupling of spatial scale and uncertainty. Here we do not take into account the third dimension of scale, the functional scale. Regarding the linkage of temporal scale and uncertainty, a key issue is whether the uncertainty changes if the temporal scale changes. Many systems show variability over shorter time scales (e.g., daily rainfall) that often averages out over longer time periods (e.g., monthly rainfall). We have seen that variability is a key source of uncertainty, which implies that the uncertainty will necessarily increase if we try to model processes at a finer temporal resolution. This means that downscaling in time, i.e., from a coarser to a finer temporal resolution will add a new source of uncertainty (and thus error), higher temporal variability. On the other hand a courser temporal resolution will imply a higher unreliability as source of uncertainty. The greater the time horizon, the greater the unreliability, due to the uncertain knowledge of future (or past) political, social-cultural, economic, environmental and institutional change, and the lack of data and observations.

The same line of reasoning holds for the linkage between spatial scale and uncertainty. Many systems show variability on a smaller spatial scale (e.g., on a local scale) that often averages out on a larger spatial scale (e.g., on a national scale). Knowing variability as a key source of uncertainty, this implies that the uncertainty will necessarily increase if we try to model processes at a smaller spatial resolution. This means that downscaling in space, i.e., from a larger to a smaller spatial scale will add a new source of uncertainty, higher spatial variability. On the other hand a larger spatial scale may imply a higher unreliability because it may be harder to get data and observations on a larger scale. Apart from these single-scale uncertainty relations, a multiple scale spatial analysis induces more uncertainty than a single-scale analysis. A serious problem here is the linkage of the scale levels which is a large source of uncertainty, because our fundamental lack of knowledge of the interlinkages between the scale levels.

The overall picture of uncertainty in relation to scaling is quite ambiguous. We need to dive into the sources of uncertainty before we can further specify these relations. But even then the picture is mixed. In general, multiple scale analysis induces more uncertainty than single-scale analysis. With regard to temporal scales and uncertainty, the variability as source of uncertainty increases as the temporal resolution becomes finer, but the unreliability as source of uncertainty usually decreases. Regarding spatial scales a similar picture unfolds. The smaller the spatial scale level the higher the variability as source of uncertainty, but the lower the unreliability because more reliable data and observations are usually available.

7. IS THERE A SOLUTION?

If no unifying theory exists, how could we address the scaling problem in Integrated Assessment? Without giving the ultimate solution, we present three possible 'escapes,' all of them heuristics. The first one is using up- and down-scaling techniques. Downing et al. (this volume) present a survey of statistical up- and down-scaling techniques which have been developed during the past decades. They present five different upscaling techniques in order to go from the site-level to the regional level, although these terms are not precisely defined. In the field of climate change research these upscaling techniques are used to upscale climate impacts from the local to the regional level, whereas downscaling techniques are used to downscale rough climate patterns from General Circulation Models (GCMs) to more local levels.

In applying these up- and down-scaling techniques (both statistical and non-statistical), however, we must be careful. From complex systems theory we know that up- and down-scaling techniques fail in many cases for various reasons [28]. Major reasons are that different processes dominate at different scale levels, that in complex systems various processes are usually non-linearly linked to each other embedded in spatial heterogeneity, that these processes at different scales do not function independently of one another, and that the pace of these processes may be different at different scale levels. In other words, while heuristic up- and down-scaling methods assume homogeneity and linearity, complex systems behave in a highly heterogeneous and non-linear way. In practice, this means that only a few characteristics of the system under concern are up- or down-scaled, while the other characteristics remain constant. For example, in upscaling human-induced climate impacts for the agricultural sector from the site to the regional level, soil and weather characteristics are usually scaled up, while the water and nutrient availability as well as the effects of diseases and pests and the management type do remain constant.

With regard to downscaling techniques, there is still a gap between the quantitative results using these techniques and the overall qualitative assessments that make use of these results. As the IPCC [12] quotes: "*While a large variety of downscaling techniques have been developed in the past decade, they have not yet provided climate impact research with the required robust estimates of plausible regional and local climate change scenarios, mainly because global climate change models have not yet provided sufficiently converged consistent large-scale information to be processed through downscaling. However, the gap might be filled within a few years*."

A second possibility is to use heuristic concepts which are rooted in complex systems theory. An example forms the concept of a hierarchy, which is defined as a causally linked system for grouping phenomena along an analytical scale [3]. Hierarchy theory supposes that a phenomenon at any scale level (*level n*) is the synergistic result of the faster dynamics among components at the next lower scale level (*level n*−1) and simultaneously constrained or controlled by the slower dynamics of components at the next higher scale level (*level n*+1) [29]. So, the starting point of hierarchy theory is to dissect any complex system as a series of hierarchical entities. This is a useful theory, but it is far from comprehensive, and does not resolve the real scaling problem, nl. which processes at scale level n are contributory to the dynamics ate scale level n+1. What hierarchy theory delivers is a procedure to convert all processes at scale level n to scale level n+1 by means of an extensive parameterisation procedure, but without a selection mechanism for the most determining.

What could be useful, however, is to use concepts from this theory, such as that of '*emergent properties*.' In particular hierarchies, the so-called constitutive nested hierarchies (where most complex systems fall under), processes grouped together at a lower scale level can cluster into a new group of processes with new properties or functions. This means that in constitutive nested hierarchies a group of processes can have different properties showing different behaviour at a higher scale level than the individual processes at a lower scale level. We call this new collective behaviour at a higher scale level an emergent property. For example, consciousness is not a property of individual neurones, but a natural emergent property of the neurones of the nervous system. Neurones have their own structure, but as a whole they have properties that none of the individual neurones have, namely consciousness, which can only exist by co-operation of individual neurones. Hence, only looking at the scale of individual neurones the system as a whole can never be understood properly.

In IA terms an emergent property can be defined as a characteristic of a system under concern that is only recognisable when different domains and different scale levels are analysed or modelled. So studying emergent properties requires an integrated assessment, i.e., a multi-domain and multi-scale approach. Easterling and Kok (this issue) relate the concept of an emergent property to surprises and counter-intuitive results. In detecting emergent properties by studying multiple scales and domains, the nature of the problem may change entirely. This means that emergent properties are of vital importance in IA-modelling, because the dynamics of the system underlying the IA-model is also dependent on emergent properties. In IA-modelling terms this means that emergent properties may appear when experimenting with the IA-model as a whole, but may not be recognised at the submodel (module) level. These emergent properties may arise from the interaction among submodels of the IA-model. Most emergent properties are related to uncertainty due to the natural variability in the system under concern. These emergent properties may occur at every possible scale both in time and space, and can be spotted by detecting so-called 'weak signals' [10] which may become 'strong signals' after a while. For a diversity of examples of emergent properties, from biological to socio-economic the reader is referred to Easterling and Kok (this issue). We present here only a very simple example of an emergent property as presented in the article of Root and Schneider (this issue), where the DICE integrated climate assessment model is extended with a simple two-box ocean model which enables a parametrised representation of the thermohaline circulation, in order to simulate the socio-economic damage as a result of an emergent property, the possible but hypothetical reverse of the thermohaline circulation (or reverse of the Gulfstream). Replacing a fully parametrised ocean representation by a simple two-box ocean model introduces a different scale which allows for the emergent property of the reverse of the thermohaline circulation.

Another possibility is to use cross-scaling concepts or methods, i.e., concepts or methods which go across various scales and are basically not scale-dependent. An example is the Strategic Cyclical Scaling (SCS) method [30]. This method involves continuous cycling between large and small-scale assessments. In modelling or scenario terms such an iterative scaling procedure implies that a specific global model or scenario is disaggregated and adjusted to a specific region, country or river basin. The new insights are then used to improve the global version, after which implementation for another region, country or river basin follows. The SCS method can be used for conceptual

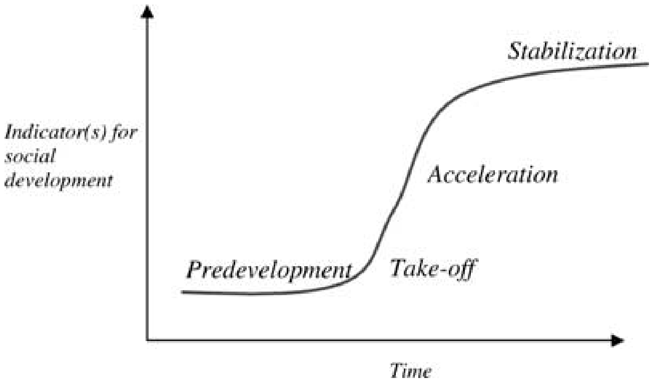

Fig. 5. Four phases of the transition curve.

validation of models and scenarios. In Root and Schneider (this issue) this SCS method is more specifically used within the context of Integrated Assessment and IA-models. An overall problem that remains, however, is that there is no specific strategy how to treat the unlike socio-economic, ecological and institutional processes in the continuous cycling procedure. So far the SCS-method is more directed towards ecological up- and down-scaling, whereas the method needs to be tailored more to the specific multi-domain characteristics of IA-models.

Another example of a cross-scaling method is the transition concept. The heuristic concept of transition is developed to describe and explain long-term transformation processes in which society or a subsystem changes in a fundamental way over a period of one or two generations (i.e., 25 years or more) [31]. The term transition refers to a change from one dynamic equilibrium to another, represented by an S-shaped curve as depicted in Figure 5, which denotes the speed, magnitude and time period of change. Transitions are interesting from a sustainability point of view because they constitute possible routes to sustainability goals.

The transition concept is built up around two concepts: the multi-phase concept, and the multi-level concept. The multi-phase concept concerns four phases: the *predevelopment* phase, the *take-off* phase, the *acceleration* phase and the *stabilization* phase. The multi-phase concept tries to describe the non-linear pattern of the interference of short-term fluctuations and long-term waves, with alternating patterns of rapid change in periods when processes reinforce each other (in the take-off and acceleration phase), and periods of slow change (in the predevelopment and stabilization phase).

The second pillar of the transition concept is the multi-level concept. This concerns three levels, based on Geels and Kemp [22]: the macro-level which describes the changes in the landscape, determined by slow changes in political culture, worldviews and social values; the meso-level at which regimes of institutions and organisations determine dominant rules and practices; and the micro-level at which alternative ideas, technologies and initiatives are developed by individuals or small groups in so-called niches. An essential feature of a transition is the spiralling effect, due to multiple causality and co-evolution of interdependence between economic, social-cultural, technological, environmental and institutional developments. This spiralling effect can only happen if developments, trends and policies at the macro-meso- and micro-level reinforce each other and work into the same direction.

Transitions are not a law of nature, they do not determine what eventually must happen, but what might happen. Transitions are development pathways which have been experienced on a certain scale and may happen on other scales as well. The scale division into macro-meso-and micro-levels is a relative notion, and does not necessarily refer to spatial scale levels, but may also refer to functional scale levels as discussed above. The concept of transitions is supposed to be generic, that means that it potentially can be applied on various scales, both geographically and functionally. Thus a transition which happens at a lower (higher) scale level implies a certain dynamic pathway, which might also take place at a higher (lower) scale level. For example, an economic or demographic transition which occurred at a regional scale level might happen at a continental level or global level as well. This is also the power of the transition concept, that it may serve as a reference framework for a development path at a certain scale level which can be translated to a higher or lower scale level.

The overall conclusion must be that, in the absence of a unifying scaling theory, in doing Integrated Assessment research, we are groping in the dark, but there are some candles that shed some light in the dark. Heuristic methods can be used as a provisional way out: either statistical up- and down-scaling techniques, concepts based on scale-related theories, or cross-scaling methods. Almost all heuristic methods are typical examples of trial-and-error methods, but nevertheless they are useful in the unruly practice. Analysing these multi-scale methods, the conclusion must be that the bulk of the methods are top-down by nature rather than bottom-up. On the other hand it should be noticed that there is a growing interest in bottom-up approaches.

8. CONCLUSIONS AND RECOMMENDATIONS

An overall lesson to be learned is that the scaling problem is much more than a technical problem, and therefore should not be treated as such. Next to the common physical notion of scale, there is a social-cultural and institutional value component. Thus, in addition to the geographical dimensions of scale, time and space, we need a third dimension, the so-called functional dimension. This dimension indicates the functional relations between agents, both individual and collective. How to represent this functional scale is not yet entirely clear, but one way of representing different functional scale levels for agents is to use a discretized multi-scale concept, which distinguishes between the macro-, meso- and micro-level. At the macro-level transnational agencies are operating, at the meso-level institutions and organisations, and at the micro-level individual agents.

Because an overarching theory of how to deal with the three dimensions of scale is lacking, heuristic concepts and methods will continue to be used. Generally, we can divide these heuristics into statistical (and non-statistical) up- and down-scaling techniques, concepts derived from complex systems theory, and cross-scaling concepts. Each has its pros and cons, but further experimentation will hopefully shed light on better practices.

We have discussed these heuristic methods as applied to IA-models and IA-scenarios. IA-models are structured along the lines of vertical and horizontal integration, and not along scaling structures. We all know that nature does not organise itself around grid cell patterns, but most IA-models still use grid cell patterns as an organising principle. In general, IA-modellers do not devote a substantial amount of time to multiple scaling. And when they do, they usually pick from the three heuristic methods available in dealing with multiple scales in IA-modelling: grid-cell based IA-models, cellular automata models and multiple-scale regression models. Unfortunately, these have been developed and applied in isolation from each other, representing different schools that hardly communicate with each other. But blending these heuristics, for instance the cellular automata models with the multiple-scale regression models, which implies replacing correlation patterns by causal patterns in the latter, would already be a significant step forward.

With regard to IA-scenarios the conclusion is that scaling is an underrated issue in IA-scenario development. The vast majority of scenarios that we screened operated on just one scale level. Two exceptions to this rule are the GEO-3 scenarios and the VISIONS scenarios. The IPCC SRES-scenarios operate at both the global and regional scale, but the connection between these scale levels is rather loose and rudimentary. The VISIONS projects resulted in European visions, achieved by the integration of scenarios across the European and regional scale level. The integration of European and regional scenarios was based on a pairwise intercomparison of driving forces, actors/sectors/factors, management styles and future outlooks. In addition to these examples, we definitely need more of these scenario exercises in which multiple temporal and spatial scales are the starting point of the scenario analysis.

The relations between uncertainty and scale is a largely uncultivated area and is at the frontier of IA-knowledge. From our preliminary analysis it follows that the identification of the nature of the uncertainty and the underlying sources of uncertainty is a prerequisite for analysing in more detail the coupling with scales. Whereas in the case of structural uncertainties the linkage with scaling is only of secondary importance, in the case of uncertainty due to unreliability the relation with scaling is more obviously of importance.

In general terms, the scaling issue is of vital importance for Integrated Assessment. An indication hereof is that the nature of an IA-problem may change when considered from a different scale level. Our scaling analysis also shows that emergent properties are of vital importance for IA-models, because it may arise from the interaction of submodels (modules) of the IA-model. Nevertheless the attention for scaling in Integrated Assessment seems inversely proportional to its importance.

The time is therefore ripe to develop a research agenda around the issue of scaling in science, and in particular in Integrated Assessment. In this agenda, fundamental, theoretical scaling subjects, working towards new theories or transformation of existing theories, and practical, technical handwork activities, applying existing methods and concepts deserve a place. The improvement of existing tools and methods should go hand in hand with the development of new theories and methods.

There is also a need for a common language, which is cross-disciplinary. We have found different notions, definitions and interpretations of scaling in different disciplines; economists have a different scaling language than social geographers and IA-modellers have a different interpretation of scaling than the participatory IA-researchers.

Overall, the added value of putting scaling issues high on the IA-research agenda is that it allows for leaving behind the paradigm that scale is merely a technical construct, realising that scale has a meaning to people and our society. In this sense the third dimension of scale, the functional one, is important to underline the relevance of specifying relations between human beings and institutions.

Taking this new scaling paradigm into account, every IA-study should implicitly and explicitly pay attention to this broader interpretation of scale and its implications.

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