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Agent-Based Simulation of Vulnerability Dynamics

A Case Study of the German North Sea Coast

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Agent-Based Simulation of Vulnerability Dynamics

A Case Study of the German North Sea Coast

Doctoral Thesis accepted by
the University of Hamburg, Germany

Springer

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Supervisor's Foreword

Societies are social systems. They consist of a multitude of agents interacting in a non-rational, subjective and relational way—based on perceptions, experiences and relations between agents of the system. Societies are complex systems. They behave complex in the sense of the theory of complexity based on the principles of nonlinearity, dynamics, uncertainty and surprise. The interaction of the agents on the micro level will lead to emergence on the macro level and therefore fosters new system's behaviour.

This thesis constitutes an extraordinary and innovative research approach in transferring the concepts and methods of complex systems to risk research. It ambitiously bridges the barriers between theoretical, empirical and methodical research and integrates these fields into one comprehensive approach of dealing with uncertainty in socio-ecological systems. The developed agent-based simulation aims at the dynamics of social vulnerability in the considered system of the German North Sea Coast. The social simulation provides an analytical method to explore the individual, relational and spatial aspects leading to dynamics of vulnerability in society. Combining complexity science and risk research by the method of agent-based simulation hereby emphasises the importance of understanding interrelations inside the system for the system's development, i.e. for the evolving. Based on a vulnerability assessment regarding vulnerability characteristics, present risk behaviour and self-protection preferences of private households against the impacts of flooding and storm surges, possible system trajectories could be explored by means of simulation experiments.

This work provides a system-analytical approach and contributes to a well-integrated consideration of multi-dimensional and context-sensitive social phenomena such as vulnerability. The study shows how interdisciplinary work can achieve conceptually and strategically relevant implications for risk research and complex systems research. I hope that this approach stimulates further investigations of multi-agent understanding in social systems as dynamic, non-linear and full of surprises and provides new insights into highly relevant hazard research.

Hamburg, June 2012 Prof. Dr. Beate M. W. Ratter

Preface

The presented approach combines risk research and complex system research by using agent-based simulation. The study is exploratory, yet holds great potential as both, risk research and complexity science facilitate an open and interdisciplinary perspective for system analysis. They provide a theoretical research framework to focus on the meaning of interrelations and feedback in systems, for risk and vulnerability, between human and environment or micro and macro. In the same way, agent-based simulation allows to regard vulnerability as a multi-dimensional and context-sensitive social phenomenon that derives from characteristics, behaviour and relationships of individuals in society.

Social simulation is an analytical method and unique tool to explore the individual, relational and spatial aspects leading to dynamics of vulnerability or other social phenomena under uncertainty. By means of simulation the dynamics of the considered system can be studied—to explore the effects of causal relationships and interdependencies in thought experiments and derive theoretical consequences about the future system development. In my model approach, I equivalently considered a theory-based conceptual model and an empirical-based computational model. The theory-based conceptual model development might stress the importance of agent-based modelling in risk research and as a powerful interdisciplinary tool. The computational model and the simulation experiments outline how agent-based models can be combined with empirical data in vulnerability assessments. By using this different methodological approach, schema and vocabulary for system analysis I hope to contribute to a different perspective on the research target of social vulnerability.

Acknowledgments

To reach this point of my academic career, I owe many thanks to several persons that supported me during my Ph.D. research. First of all, I would like to express my sincere gratitude to my supervisor Beate M. W. Ratter for her inspiration and guidance especially in the field of complex systems research. I am deeply grateful for her support and encouragement that I received at Helmholtz-Zentrum Geesthacht (HZG), Germany and beyond. I thoroughly thank also my second supervisor Jürgen Scheffran from the Department of Integrative Geography at University of Hamburg, for his suggestions and advice in the field of agent-based simulation.

Furthermore, I thank my former colleagues at the Department Human Dimensions of Coastal Areas, Institute of Coastal Research at HZG: especially Antje Bruns, Kira Gee and Martin Lange who were always willing to share their experience and thoughts at the beginning of my Ph.D. research. Many thanks also to the LOICZ-IPO at HZG who always made me feel welcome, in particular Barbe Goldberg for her incredibly inspiring mind and warm heart. Special thanks also to Dennis Bray for his patience and helpful advice in our numerous discussions about model building. I honor my recognition to Steffi Ehlert, Nicole Kruse and Katharina Philipp for their assistance during my empirical study in the coastal region of Germany.

Moreover, I would like to express my gratitude to Arnd Holdschlag and Max-Peter Menzel from University of Hamburg for the theoretical input and exchange in our informal complexity discussions. Furthermore, I owe many thanks to Andreas Ernst from Center for Environmental Systems Research (CESR), University of Kassel and his department for sharing their knowledge and the opportunity to thoroughly discuss my simulation model. Great thanks also to the Ph.D. simulation group simsoc@work for the valuable discussions and “mental” support on the face-to-face meeting in Berlin and online. Furthermore, I would like to thank Peter Mandl from University of Klagenfurt, Austria and Daniel Moldt, University of Hamburg, for their advice, time for discussions and special gratitude to Johannes Meyer for his patience to help me with JAVA.

I am very grateful to the people in the coastal regions of Schleswig-Holstein for participating in my empirical study. Without their opinions this work would never been possible—as every opinion meant as much to my agent-based simulation as to other purely social science dissertations. Thank you to all my colleagues and friends for their valuable remarks and proofreading: Sebastian Streitz, Stefan Görlitz, Anna Sobiech, Nicole Kruse, Malte Busch and Anna Schärtel.

Last but not least, I express my sincere thanks from the bottom of my heart to my parents and my beloved sister for their unconditional support and encouragement whatever way I choose to pursue. Seppl I would like to thank for the *lightness* in my life.

Oldenburg, June 2012 Cilli Sobiech

Contents

Abbreviations

ABM	Agent-Based Model
ABS	Agent-Based Simulation
BBK	Bundesamt für Bevölkerungsschutz und Katastrophenhilfe/Federal Office of Civil Protection and Disaster Assistance
BMVBS	Bundesministerium für Verkehr, Bau und Stadtentwicklung/Federal Ministry of Transport, Building and Urban Development
CPSL	Trilateral working group on Coastal Protection and Sea Level rise
DROP	Disaster Resilience Of Place model
GIS	Geographical Information Systems
GOL	German Ordnance Level (Sea Level)
ICDM	Integrated Coastal Defence Management
ICSU	International Council of Science
ICZM	Integrated Coastal Zone Management
IRGC	International Risk Governance Council
LOICZ	Land–Ocean Interactions in the Coastal Zone
LWG	Wassergesetz des Landes Schleswig-Holstein/State Water Act of Schleswig-Holstein
MLUR	Ministerium für Landwirtschaft, Umwelt und Ländliche Räume des Landes Schleswig-Holstein/State Ministry for Agriculture, Environment and Rural Areas of Schleswig-Holstein (formerly MLR)
MSL	Mean Sea Level
MURL	Ministerium für Umwelt, Raumordnung und Landwirtschaft des Landes Nordrhein-Westfalen/State Ministry for Environment, and Agriculture of North Rhine-Westphalia
n.s.	Not specified
ODD	Overview, Design concepts, Details protocol
PAPM	Precaution–Adoption-Process Model
PAR	Pressure-and-Release model
PMT	Protection–Motivation Theory
SARF	Social Amplification of Risk Framework

SARS	Severe Acute Respiratory Syndrome
SFI	Santa Fe Institute
UN/ISDR	United Nations/International Strategy for Disaster Reduction
VBN	Value-Belief-Norm theory
WHG	Wasserhaushaltsgesetz des Bundes/Federal WaterAct

Chapter 1
Introduction

1.1 Background

Risk is a social construct. This statement refers to risk from the perspective of individuals, meaning that risk is shaped by human cognition and influenced by a variety of other social factors of a person (e.g. Acosta-Michlik and Espaldon 2008; Palm 1990). Risk is the result of an individual-intuitive process of risk estimation that may lead to individually different risk concepts and preferences towards risk reduction strategies. Based on this individual perspective, the subjective risk concept, behaviour towards risk can vary and, depending on the person, range from a pro-active and precautionary to a fatalistic attitude. According to this perspective, risk studies address aspects such as the personal experience with risk or the value orientation of individuals to understand the conception of risk and relate it to behaviour.

Another perspective concerning risk is associated with the typically contrasting view between risk experts and lay people, e.g. in the psychometric paradigm of Slovic (1993, 1987). According to this perspective, experts measure risks by the probability of occurrence of a disaster and evaluate the effect of risk reduction strategies in cost-benefit analyses. They follow the objective risk concept which is characterised by probability, intensity and the potential impacts of a disaster. Risk can be defined as the probability of harmful consequences due to conditions of a natural hazard and social vulnerability which together can lead to a disaster. Even though from this perspective, both natural and social conditions have to be taken into account in order to assess the potential impacts of an event (see e.g. Wisner et al. 2004). The hazard is associated with the natural environment such as a potential flood event, storm surges, or droughts whereas vulnerability is associated with the social environment. A hazard can be described by the probability of occurrence of a natural event and constitutes a condition in the natural/physical environment. Vulnerability is the likelihood that a society will be exposed to and adversely affected by the hazard due to the physical, socio-economic, ecological,

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and political-institutional conditions which can vary over space and time (see Cutter 1993).

In vulnerability assessments information about the physical, socio-economic and political-institutional conditions need to be interconnected. By analysing the underlying conditions leading to vulnerability these assessments aim at developing necessary capacities for vulnerability reduction. For this purpose, the multiple factors or dimensions have to be taken into account. But in order to understand the vulnerability of individuals and to find ways to reduce the vulnerability of a diverse society the above subjective risk concept and the subjective aspects shaping risk conceptions of individuals, should be included as well. An important underlying assumption of the subjective concept is that individuals may perceive risks differently, and that although a risk is perceived, people may react with fatalistic behaviour or rely on institutional risk protection instead of actively taking self-protective measures. Or in other words: people act on an internal model of the external environment/reality characterising their human-environment relationship. With regard to the decision context, it should additionally be taken into account that individuals are socially embedded, in what is called the micro–macro relationship between individuals and society. Hence, vulnerability can be described as a multidimensional phenomenon (Kasperson and Palmlund 2005, p. 64). On the one hand, human cognition and beliefs determine the behaviour towards risk, e.g. risk attitude, self-protection motivation and thus the vulnerability of an individual. But on the other hand, the social context, political-institutional conditions and socio-economic attributes, e.g. access to resources, the social network or lack of information influence the vulnerability of an individual.

Thus, for a comprehensive risk management aiming at risk reduction in diverse societies, an integration of these multiple aspects and concepts is required (see e.g. ICSU 2008). Recent integrative approaches emphasise the mutuality of hazard and vulnerability due to the complex interactions between the natural and social system (Hilhorst 2003; Warner et al. 2002). But concerning the individual dimension of risk, it has been emphasised that the way how people live, think and act can considerably reduce the risk a society may face (Tapsell et al. 2010, p. 61). In risk management approaches a tendency towards the allocation of responsibility more to the individual level can be recognised (Steinführer et al. 2009, p. 94). However, with regard to the individual level also the wider context of the decision making framework within which individuals operate, need to be reassessed (Tapsell et al. 2010, p. 61; Bankoff 2001, p. 30). By dealing with interactions and relationships contributing to risk, it cannot be ignored that also dynamic changes can occur, further challenging risk management approaches. The dynamics may be related to temporal and spatial changes of the hazard conditions but also to the social dynamics in diverse societies. Hence, with regard to vulnerability assessments, Birkmann (2006, p. 433) emphasises that one of the major challenges for future research lies in the combination of different methodologies in order to provide a more comprehensive understanding of vulnerability.

1.2 Objective and Research Questions

The objective of the presented approach is to explore the dynamics of vulnerability in a social simulation. The bottom-up approach focuses on the individual level, i.e. on the subjective concept of risk and aims at establishing a relationship between the individual and the dynamics of social vulnerability. Vulnerability here is defined as the characteristics and circumstances of a person or group that make it susceptible to be adversely affected by the impact of a hazard (Cutter 1996). The approach examines the individual vulnerability attributes and "traces" the consequences of individual risk behaviour for the system. The resulting social dynamics derive from heterogeneous individuals, whereas the simulation approach followed here considers different individual, relational and spatial aspects of vulnerability. For understanding vulnerability as a multidimensional social phenomenon, the focus is on various individual attributes *and* on different relationships of individuals. By exploring individual behaviour and interactions between individuals related to vulnerability, this research approach further contributes to the understanding of vulnerability as a context-sensitive and dynamic social phenomenon.

An analytical computer method, which takes into account the micro-behaviour of heterogeneous individuals, is agent-based modelling. Such models aim to explore and understand certain social phenomena from the bottom up; by understanding the determining processes and consequences by means of simulation. The model represents the social world and ongoing dynamic processes which emerge due to the behaviour and interactions of the system elements, called agents. "Agents can be any organisational entity that is able to act according to its own set of rules and objectives" (Billari et al. 2006, p. 3). Agents are heterogeneous in their characteristics, act autonomously, but are not omniscient with regard to the system they belong to (see further Sect. 2.3). In agent-based models (ABMs), the macroscopic regularities are explored which emerge from the micro-based rules. The rules of social behaviour can either be theory-based or empirically-based. Thus, computing is used for the understanding of social processes and as an aid to the development of theories. In the social sciences it aims at the discovery of patterns and rules of social reality for explanation and not for prediction of behaviour (Gilbert and Terna 2000).

Considering the concept of agents (see further Sect. 2.3), research interest lies in the dynamic relationship between individual actions and interactions of agents on the micro level leading to a macroscopic social phenomenon (Gilbert and Terna 2000, p. 61). In the approach presented here, the modelling purpose is to explore the dynamics of vulnerability on the macro level, which is shaped by individual agents' attributes and behaviour on the micro level by means of simulation. Therefore, the research focuses on that kind of changes of the macro-phenomenon of vulnerability which evolve due to the agents' behaviour on the micro level, i.e. whether these micro-based rules can explain macroscopic regularities (Macro-Behaviour). In the developed agent-based model, agents can take decisions towards better self-protection against hazards. During the simulation run, different self-protection measures can be implemented by individual agents/households in order to reduce their vulnerability against hazards (see Sect. 3.2.4). The model includes individual vulnerability attributes and self-protective behaviour of individual households and traces the process of vulnerability reduction on the macro level following the agents' decisions and interactions. Besides the individual aspects leading to dynamics of vulnerability, relational and spatial aspects are regarded too. In order to regard vulnerability as a context-sensitive phenomenon, the micro-macro relationship and the human(agent)-environment relationship are considered. By including agents that are heterogeneous in their individual attributes, relationships and behaviour, the influence on the vulnerability, i.e. the dynamics of vulnerability are explored by means of simulation.The underlying idea is "that societal patterns [of vulnerability] emerge from purposive choices [of self-protection strategies] and not from social facts external to individuals" (Macy and Willer 2002, p. 147).

From the various motivations to use agent-based modelling in the social sciences (see e.g. Axtell 2000), very few approaches so far have explored the application of agent-based modelling for vulnerability assessment–in particular on empirically based "realistic" agents. Studies, for example, focus on vulnerability towards global environmental change, in terms of socio-economic attributes or behavioural strategies to adapt to changing environmental or hazardous conditions (see e.g. Ziervogel et al. 2005; Le et al. 2010; Seidl 2009; Acosta-Michlik and Espaldon 2008; Filatova et al. 2011). These studies often link the natural and the social system in agent-based models in order to assess vulnerability from a human-environment perspective (Acosta-Michlik and Rounsevell 2009, p. 152). While many models are based on empirical evidence, most often the resulting agent-based approach is an abstraction. Instead, in this approach agents are "realistic" in the sense that each respondent in the case study is represented in the model with real vulnerability attributes and self-protection preferences. The agent samples were not scaled up for example to create virtual villages with hundreds of agents. The detailed dynamics of vulnerability are assessed based on empirical data from the selected coastal area of Germany (see Sect. 2.4.2).

The simulation approach requires a conceptual and computational model development process. The social phenomenon needs to be "translated" into a model through a process of abstraction and on the basis of a theoretical understanding. The process of model development involves preliminary interpretation and recognition of the essentials of a certain type of situation (Doran 2006, p. 216). The target of the model presented here are the dynamics of (social) vulnerability in the flood-prone coastal lowland of Germany. In order to describe vulnerability as a multidimensional and context-sensitive social phenomenon, various risk/vulnerability approaches from different disciplines such as psychology, social sciences, geography and sustainability research are taken into account for the selection of the levels of analysis and for the selection of vulnerability indicators (see Sects. 3.2 and 5.1). The research process of conceptual model development can be summarised in the following (first) research question:

- How can risk/vulnerability approaches from different disciplinary perspectives be reconciled with the agent concept in order to assess the dynamics of vulnerability?

Based on the conceptual model framework, the computational model can be developed. But when empirical information "is used as an input for a model, the focus might be to study a particular situation, i.e. the situation from which the data is derived" (Janssen and Ostrom 2006). Here, the advantage of using empirical data for modelling is that the model can be empirically calibrated; it is possible to "fine-tune" the model to a particular (risk) situation. Thus, the model not only yields general insights from theories, but from real-world data with regard to the vulnerability attributes of agents and the self-protective behaviour. In order to gain such input data, the empirical study aimed at the following (second) research question:

- Which agent types concerning vulnerability, present risk behaviour and preferences towards self-protection strategies can be identified in the coastal zone of Schleswig–Holstein/Germany?

The agent-based approach relies on the status quo of vulnerability in the coastal zone but also aims at the dynamics of social vulnerability in the future. By means of simulation, the consequences of agent behaviour changes with regard to self-protection measures can be explored. Based on the empirical data, simulation experiments can be conducted to test the influence of individual, relational and spatial aspects for the dynamics of vulnerability. Thus, the simulation enables to perform thought experiments about better self-protection in the context of possible environmental changes in the coastal zone related to climate change. This part of the research process is expressed in the (third) research question:

- Which trajectories of vulnerability evolve in the system based on the heterogeneous agent profiles concerning vulnerability and self-protection preferences in the coastal zone of Schleswig–Holstein/Germany?

By using an agent-based approach, a better understanding of the determining processes of vulnerability and the consequences in the considered social system might be achieved. But the agent-based approach implies not only a methodical but also a conceptual transfer. It can be asked whether the agent concept can assist in understanding of the model target for risk research—methodically and conceptually. But the conceptual transfer refers not only to risk research but also to complex systems research, as ABMs are based on the concepts of complexity science. Originating from mathematics and physics the concepts of complexity theory have been adopted by the social sciences and also in risk research (e.g. Helbing 2010; Hilhorst 2004; Comfort 1994). "Complexity research is concerned with how systems change and evolve over time due to interaction of their constituent parts" (Manson 2001, p. 406). In comparison to the involved risk/vulnerability approaches, complexity theory here can be seen more as a meta-theory than a theory as it "provides a schema and vocabulary for analysing processes" (Chapura 2009, p. 464). The concepts of complexity thus can help for analysing the dynamics arising in the open complex social systems of the real world and in the simulated sequence. The approach concludes with a theoretical feedback of the methodical and conceptual transfer expressed in the (fourth) research question:

- How can the conceptual and methodical transfer applied in the approach contribute to complex systems research and risk research in the coastal zone?

The explorative vulnerability assessment by means of an agent-based simulation thus makes a contribution to complex systems research and risk research. But in this approach not complexity itself is the object of research, but complexity theory is used in order to lead to a different perspective on the research target. With regard to geography, the simulation approach aims at contributing to the micro-analytical approaches in social geography (see further Weichhart 2008, p. 147) and to integrative approaches in geography by focusing on the human-environment relationships (see Egner 2010, pp. 109–113; Perry 2009). With regard to risk research, the approach tests the methodology of agent-based simulation for understanding the social phenomenon of vulnerability.

1.3 Outline

The research process is described in three parts. After the introduction, the research design and the agent concept are presented (see Chap. 2). Together, this first part introduces the objective and the epistemological framework of the modelling approach with regard to the research questions. Furthermore, the necessary steps of the modelling process are explained; ranging from the framing process to conceptual model development and from the empirical study to the computational model development. In the second part, the theoretical and regional framework of the model is analysed (see Chaps. 3 and 4). The third part is based on the framing process and describes the system analysis including the conceptual and the computational model (see Sects. 5.2 and 5.3). The empirical input data (see Sect. 5.2) is used for simulation experiments (see Sect. 5.4) in order to explore the dynamics of vulnerability due to individual, relational and spatial aspects in the agent system. Before the third part closes with concluding remarks (see Sect. 6.3), the relevance of the agent-based approach is discussed in further detail for complex systems research (see Sect. 6.1) and risk research (see Sect. 6.2).

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Chapter 2
Research Design

"The breakthrough in computational modelling in the social sciences came with the development of multi-agent systems." (Gilbert and Terna 2000, p. 60) Computational modelling has been widely used in the natural sciences until it found its way into the social sciences; in the case of agent-based models in the early 1990s. But other than in the natural sciences the principal value of agent-based models in the social sciences is not prediction but the discovery of mechanisms, patterns and rules of the social reality. It has been realised that computer programmes offer the possibility of creating "artificial" societies, in particular due to the direct representation of individuals and collective actors as computer agents and the observation of possible effects of their interactions (Gilbert 2004). Considering the concept of agents, research interest lies in the dynamic relationship between individual actions and interactions of agents at the micro level leading to the emergence of patterns and structures on the macro level of the agent society. Many different terms are used for agent-based models such as multi-agent system (MAS), multi-agent-based simulation (MABS) or agent-based social simulation (ABSS). In this approach the term agent-based model (ABM) is used consistently.

Each modelling approach involves its own set of theories, concepts, procedures for model construction and testing (Janssen 2002; Peck 2004; Frank and Troitzsch 2005). Due to such differences in the modelling approaches a lot of controversies among modelling studies, scientists and disciplines exist. Therefore, in the first part of this chapter the epistemological framework of research is explained (Sect. 2.1). The model-centred epistemology is described according to Rossiter et al. (2010) and related to the research questions and the aims of simulation in this approach 3 Furthermore, the process of investigation and the research method is explained in more detail. The research design is explained concerning the necessary steps for model development. Section 2.2 outlines the process of *framing* the theoretical and regional context of the model in order to describe the system under study. The theoretical foundation leads over to the agent concept (Sect. 2.3) and the agent-based modelling approach. The process of model building and implementation is described in Sect. 2.4 and further divided into

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subchapters dealing with the conceptual model development, the empirical survey at the German North Sea Coast, the computational model development using Repast Simphony 1.2.0.

2.1 Epistemological Framework of Research

In social research each model starts with a real-world phenomenon the researcher is interested in (see Fig. 2.1). Here, this so-called *target* of the model is vulnerability in the coastal lowland of Germany. The aim is to develop a model "through abstraction from the presumed social processes in the target" (Gilbert and Troitzsch 1999, p. 15). Thus, the model is always simpler than the target. Models can be used to represent theories and/or processes which describe aspects of the real-world empirical data (Rossiter et al. 2010). A simulation is based on models but here the model is run and its behaviour is measured in order to generate simulated data (Gilbert and Troitzsch 1999, p. 16).

2.1.1 Simulation as an Interdisciplinary Tool

Bunge (in Hartmann 1996, p. 81), philosopher of science, stressed that background theories constitute an integral part of a model and developed a conception of models with two compounds: the general theory and a special description of a system or object (Hartmann 1996, p. 81). According to Becker et al. (2005), the construction of a simulation model and also the interpretation of the results depend on the researcher, the research area and the researcher's inherent epistemological perspective. In order to consider the various disciplinary perspectives of vulnerability, not one general theory is used but different approaches reflecting various perspectives are tested for conceptual model development (see Sects. 2.4.1; 5.1).

By taking into account various ways to view and explore vulnerability in an agent-based model, the research approach is expected to meet the requirements of the first research question: How can risk/vulnerability approaches from different disciplinary perspectives be reconciled with the agent concept in order to assess the dynamics of vulnerability? The examination of the risk conceptions and diverse theoretical approaches thus facilitates an open research perspective for the conceptual model development. Consideration of various risk/vulnerability approaches in order to develop a conceptual model might further contribute to Hartmann's statement that "it is apparent that simulations prove to be a powerful interdisciplinary acknowledged tool" (Hartmann 1996, p. 77[1]).

[1] "Given the observation that processes are dealt with by all sorts of scientists, it is apparent that simulations prove to be a powerful interdisciplinary acknowledged tool. Accordingly, simulations are best suited to investigate the various research strategies in different sciences more carefully." (Hartmann 1996, p. 77).

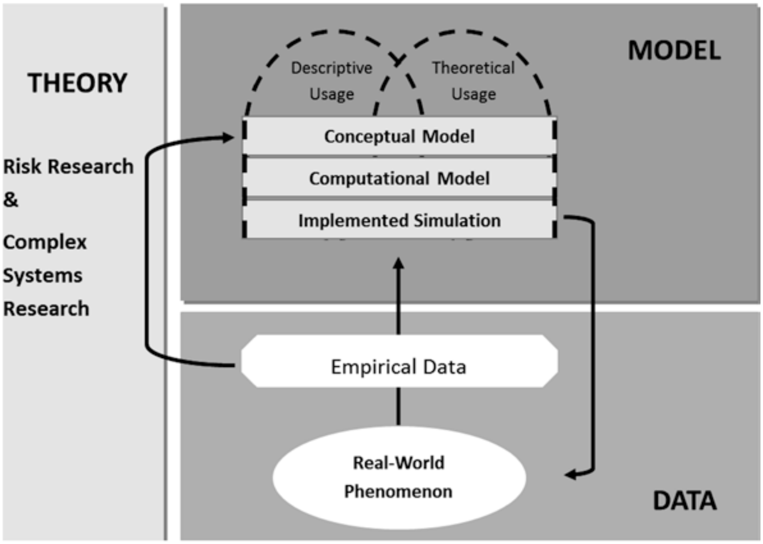

Fig. 2.1 Epistemological framework of research (adopted from Rossiter et al. (2010) on basis of McKelvey′s model-centred epistemology, reproduced by permission of Journal of Artificial Societies and Social Simulation)

2.1.2 *Simulation as a Technique to Investigate the Detailed Dynamics of a System*

The importance of a broad theoretical foundation of the conceptual model was emphasised in the last paragraph. But decisions about the modelling process are closely linked to further implications such as the usage of the model (descriptive and/or theoretical); particularly with regard to further research questions. The research approach involves—besides the conceptual model—the development of a computational model (Fig. 2.1). And in order to investigate the detailed dynamics of a system, the conceptual model is specified to the regional context of the coastal area of Germany (see 5.1). Based on the regional adapted conceptual model, an empirical survey has been prepared and conducted to gain input data for the computational model. The empirical calibration of the computational model is regarded as equally important as the theoretical foundation of the conceptual model.

The adaptation of the conceptual model to the regional framework and fine-tuning of the model to the particular region is necessary due to the lack of statistical data and the scale of the vulnerability assessment. As the unit of analysis households in the exposed coastal region of Schleswig–Holstein were considered and represented by autonomous and heterogeneous agents in the computational model. The empirical survey aimed at vulnerability and preventive behaviour of the households in order to answer the second research question: Which agent types concerning vulnerability, present risk behaviour and preferences towards self-protection strategies can be identified in the coastal zone of Schleswig–Holstein/Germany? In the implemented simulation the detailed dynamics deriving from spatial, individual and relational aspects of vulnerability are assessed.This so-called descriptive usage of the simulation model (according to Rossiter et al. 2010; see Fig. 2.1) allows using empirical values for agent behaviour and exploring the detailed dynamics of vulnerability on macro level.

2.1.3 Simulation as a Thought Experiment

Whereas the empirical data describes the status-quo of vulnerability, the preferences with regard to self-protection concern the future. On the basis of the empirical knowledge about agents′ preferences, the theoretical consequences for the future system development are tested in the model. Through the consideration of relationships and feedback effects in the model system, also cross-level consequences become apparent. Such simulations may help to explore consequences that cannot be investigated by real-world experiments. According to the third research question, the aim of the simulation is to assess: Which trajectories of vulnerability evolve in the system based on the heterogeneous agent profiles concerning vulnerability and self-protection preferences in the coastal zone of Schleswig–Holstein/Germany? Thus, the simulation method enables a prospective process-tracing of the social phenomenon of vulnerability.

Gilbert and Troitzsch (1999, p. 12) point out that computer simulation is "in comparison with some other methods of analysis, […] well able to represent dynamic aspects of change". In a model representing a social phenomenon, experiments can be conducted with the aim to understand the resulting consequences. "One can set up a simulation model and then execute it […] varying the conditions in which it runs and thus exploring the effects of different parameters. Experimental research is almost unknown in most areas of the social sciences, yet it has very clear advantages when one needs to clarify causal relationships and interdependencies." (Gilbert and Troitzsch 1999, p. 13) The method does not aim at prediction but might provide answers about possible system trajectories in the future and underlying mechanisms.

By conducting simulation experiments, the methodical approach can achieve further understanding of the detailed vulnerability dynamics in the considered system. Besides the methodical approach, the implemented simulation (see Fig. 2.1) might in addition provide conceptually relevant implications for risk research and complex systems research. According to the fourth research question, the contribution of the conceptual and methodical transfer to complex systems research and risk research is tested. At this point in the research process the usage of the model changes from a descriptive one to a theoretical one (see Fig. 2.1). Combining risk research and complexity science by the method of agent-based simulation thus might emphasise the importance of understanding interrelations inside the system for the system′s development, i.e. for the evolving. And which further theoretical implications can be achieved by focusing on agents, interrelations and feedback effects in systems and possible system trajectories? The model-centred epistemology at least facilitates integrating theoretical and empirical knowledge in a model that together with the generated data from the simulation runs, can be regarded as a “hybrid” approach—expected to analyse the research target more comprehensive than a one-dimensional research design (Weichhart 2008, p. 246; Creswell 2003).

2.2 System Under Study

To build a model, first the system itself has to be defined including its components, interactions and the system boundary. Here, the *target* of the model is vulnerability in the coastal lowland of Germany and its dynamics. The aim is to develop a model “through abstraction from the presumed social processes in the target” (Gilbert and Troitzsch 1999, p. 15). The description of the model for simulation is restricted to represent the principal behavioural processes of the system; the model cannot represent the whole original system (Bossel 2004, p. 51). The selection of behavioural processes again is determined by the purpose and the formulation of the model.

In the epistemological framework the purpose of the simulation approach with regard to the research questions is outlined (see Sect. 2.1). The theoretical framework and the regional framework of research in the following Chaps. 3 and 4 facilitate to systematically analyse the system under study. The process of *framing* the theoretical and regional context of the model helps to identify system components and component interactions (see further Macal and North 2005, p. 9). Each chapter makes a contribution to this process in a different way.

Complexity research (see Sect. 3.1) introduces the reader to systems thinking, key properties of complex systems and builds the theoretical foundation of agent-based models. Certainly, it postulates that social systems are understood as complex systems; thus for analysis of such systems the key properties of complex systems and “tools” for assessment (see Sect. 3.1.5) need to be taken into account. Complex systems research aims at understanding how systems evolve over time. It calls for a change of science conceptions in order to view the “bigger picture” and to realise that understanding of even more details cannot help for further understanding (Vicsek 2002, p. 131). Complexity theory assumes that the behaviour of the whole system depends on its units—so called agents—but in a nontrivial way. It focuses on patterns and structures emerging from interactions of the system’s elements and accepts that uncertainty, surprise and change are part of the system behaviour. By introducing the conceptions of complexity theory the research aims at encouraging a *different* view on systems—and furthermore introduces the theoretical foundations of agent-based modelling.

Complexity research deals in an interdisciplinary way with the question how certain behaviour emerges from the interactions in systems and asks for its causes in order to gain better insights (Mainzer 2008, pp. 10–11). In the research context presented here, core themes are the analysis of relations between the social sphere and the natural/physical environment, i.e. human-environment relationships as well as the analysis of micro–macro relationships. The social phenomenon taken into account for studying system behaviour and different relationships is vulnerability. The dynamics of vulnerability characterise it as a highly context-specific phenomenon (see Sect. 3.2.2). And thereby render it as an interesting phenomenon for complexity research.

In the second part of the theoretical framework (see Sect. 3.2), the dynamics of vulnerability as well as different risk/vulnerability approaches revealing various perspectives are outlined. The chapter examines how the social phenomenon of vulnerability is conceptualised and which behavioural processes are considered and assessed—in non-agent-based approaches. The various approaches are summarised into three main perspectives: omitting normative risk calculation, approaches range from a psychological to a social sciences and integrative perspective (see Sect. 3.2). The theoretical framework considers these different risk approaches to clarify how they can be reconciled with the agent concept, i.e. by translating non-agent-based approaches into agent-based approaches (see Sect. 5.1). The applicability of the respective approaches and the agent concept is tested based on 12 exemplary concepts of different disciplinary background.

In order to further adapt the model to the real-world phenomenon of vulnerability, the regional research context is introduced (see Sect. 4). The regional framework of research concretises the "objective" and "subjective" risk perspectives (see Sects. 4.2 and 4.3) as well as risk management approaches in the survey region of the North SeaCoast. On the basis of the regional framework, an empirical survey could be developed to gain input data for the computational model (see Sect. 5.2). The regional context introduces the background of the empirical study conducted in the coastal zone of Schleswig–Holstein/Germany to gain model input data. The underlying notion of ABM is that systems are built from the ground-up. In order to develop such bottom-up approach, knowledge of the system elements and the regional context in which they operate have to be taken into account (Macal and North 2005, p. 4). Thus, each chapter concretises the system under study, yet in a different way.

2.3 The Agent Concept

In addition to the definition of the system under study, an agent-based approach requires the identification of agents and a theory of agent behaviour (Macal and North 2005, p. 9). In a looser sense, agent-based models are regarded as models "which explicitly model interacting individuals, typically with variation at the individual level" (Rossiter et al. 2010). The individual entities are implemented in software as objects.[2] Agents are programmed to react to the computational environment in which they are located and they are named and tracked in the process of the computation (Gilbert 2008, p. 5; Edmonds 2006, p. 196). Without intervention of the researcher the agents act in their virtual environment of the model. In social sciences agents can be used to represent human societies as agent-based models consist of a multitude of agents.

There is no universally accepted definition of the term agent; still the most comprehensive is Ferber's definition of an agent (Ferber 1999, p. 9): An agent is a physical or virtual entity that:

a. is capable of acting in an environment,
b. can communicate directly to other agents,
c. is driven by a set of individual objectives or of a satisfaction/survival function which it tries to optimise,
d. possesses resources of its own,
e. is capable of perceiving its environment to some extent,
f. has only a partial representation of this environment,
g. possesses skills and can offer services,
h. may be able to reproduce itself, or
i. whose behaviour tends towards satisfying its objectives, taking account of resources and skills available to it and depending on its perception, its representations and the communications it receives.

Not all of these agent abilities are of the same importance in different applications and domains. A general consensus is reached solely on autonomy that is regarded as the central notion of agency (Wooldridge 2009, p. 21). Wooldridge and Jennings (1995, p. 2) further distinguishes between a weak notion of agency, comprehending autonomy, social ability by interaction and communication, reactivity or pro-activeness, and a strong notion of agency as in the artificial intelligence community that rather emphasises abilities such as knowledge, belief, intention and obligation of agents. And even each of the abilities—autonomy, limited perception, bounded rationality, communication and decision making processes—can vary on a broad spectrum of possible applications according to the modelling purpose.

What results from these agent abilities? First of all, each agent can differ from another agent in all of these abilities named above. This heterogeneity of agents becomes socially relevant because an agent-based model always consists of a number of agents that are interacting with each other in the agent society. Due to

[2] In object-oriented programming objects are defined as computational entities that encapsulate some state (encapsulation), are able to perform actions (methods) on this state and communicate by message passing. Although agents and objects share obvious similarities, Wooldridge (2009, p. 28) examines significant differences concerning the notion of autonomy, the capability of flexible behaviour and the thread of control. Agents are something qualitative new but can be implemented by object-oriented programming techniques (Rölke 2004, p. 23).

their autonomy the diverse, heterogeneous agents are dynamic in their attributes and decide how to act or adapt in order to accomplish their delegated goals (behavioural rules) (Wooldridge 2009, p. 23). But agents may also share some common characteristics. Thus, a model can include different agent types such as cultivators and labourers (Naqvi and Sobiech 2010), life style types or even subtypes such as different life stages (Seidl 2009). In the same way groups of agents can emerge with their own behaviour. Such collectives are "usually characterized by the list of […] agents, and by specific actions that are only performed by the collective, not by their constitutive entities" (Grimm et al. 2010, p. 8). The ability of autonomy, i.e. of each agent to function independently in its environment and in its dealings with other agents (Macal and North 2005, p. 3), at least to a certain extent, can lead to complex agent societies. System level behaviours and patterns emerge from a multitude of local interactions between the agents and between agents and their environment (Perez 2006, p. 27).

Agent-based modelling is a very flexible approach due to the possible variety *of* agent abilities and due to the variety *in* each of the agent abilities itself. Depending on the purpose of application or scientific discipline e.g. the variety of autonomy or heterogeneity of agents can vary. The researcher decides how sophisticated for example behaviour rules are represented: how much information is considered for the agent's decision, how does the internal model of the external world of an agent look like or to what extent the agent retains and uses memory e.g. of past events in its decisions (Macal and North 2005, p. 3).

Each agent acts according to its assigned attributes and behavioural rules. By this set of actions, an agent is able to modify its environment, for example by the usage of resources. An agent is also capable of moving within its environment. Each agent is embedded in its environment; it can perceive its environment to some extent (limited perception) and can have a representation of this environment (see Fig. 2.2). Thus, its behaviour is not solely dependent on its own set of actions but also on perception and representation of the modelled environment and describes the agent-environment relationship. Factors such as resource depletion, physical barriers or the influence of other agents can affect the agent-environment relationship.

But agents are not omniscient due to their capability of perception or representation. Agents neither have global information of the system nor infinite computational power (Epstein 1999, p. 42). Due to this so-called bounded rationality, it is possible to imply different social realities into one model. Other than in the rational actor paradigm, in agent-based models complex and uncertain environments can be described e.g. the unpredictable behaviour of other agents in the social environment restricting the agents′ rationality (Billari et al. 2006, p. 2). Despite their bounded rationality, agents can have memory allowing them to record their perceptions of previous states and actions (Gilbert 2008, p. 21).

The agent-agent relationship also plays a major role in agent societies. Agents can communicate with each other further leading to cooperation or conflicts in the agent society. Agents typically make use of simple rules based on local information (Epstein 1999, p. 42) whereas in order to achieve their goals or to solve problems communication might be necessary (see further in Rölke 2004 and

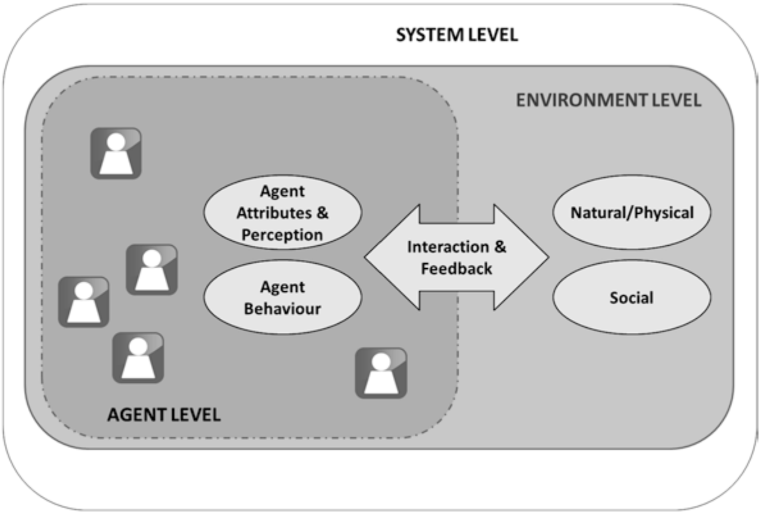

Fig. 2.2 Components of an agent-based model

Wooldridge 2009). Communication and also coordination are controlled by the single agent but become important at the time when a number of agents form an agent society (Rölke 2004, p. 19). According to the modelling purpose such agent relations and agent interactions have to be identified. Learning and adaptive behaviour is also associated with more sophisticated agent-based models. Usually an agent is able to react appropriately to stimuli from its environment; it furthermore might be able to continuously adapt to changes in its environment by learning (Billari et al. 2006, p. 4; Gilbert 2008, p. 21).

Agent level and environment level form together the system under consideration (see Fig. 2.2). The design of the environment depends on the model purpose; whereas it can be used to provide a spatially explicit context or a network of social relations (Gilbert and Troitzsch 1999, p. 167). Also the environment in an agent-based model may have different properties. Wooldridge (2009, p. 25) distinguishes between four environment properties ranging from different degrees of accessibility, determinism, dynamics and discreteness. An agent able of obtaining complete, accurate, up-to-date information about the environment is positioned in a so called "accessible" environment (accessible versus inaccessible). But most environments are rather designed as inaccessible to consider limited perception and bounded rationality of agents. A further difference concerning environment design is made between deterministic and non-deterministic ones. The former describes an environment in which any action of an agent has a single effect without "uncertainty about the state that will result from performing an action" (Wooldridge 2009, p. 25). As an agent may have dynamic properties and is able of changing its behaviour, the environment can be designed as dynamic. An agent may be able to adapt to such changes in its environment (static versus dynamic). Another distinction is made between discrete and continuous environments, i.e. either with a fixed, finite number of actions and percept(s) in it or not. These environmental properties can be used in order to increase the complexity of the agent-based model whereas the most complex kind of environment is inaccessible, non-deterministic, dynamic and continuous (Wooldridge 2009, p. 25).

In general agent-based models aim at exploring and understanding social phenomena, i.e. the determining processes and consequences. By including aspects such as agent autonomy, bounded rationality, perception and communication; the simulations go beyond simple cause-and-effect mechanisms. The integration of different social realities and social relations in networks allows understanding of individual as well as relational factors influencing social (macro) processes, i.e. the micro-macro relationship. Concerning the consequences, ABMs in a way respect that different perceptions of reality can result in different behavioural patterns (Janssen 2002, p. 407). It is the individual agent perception that contributes to a subjective and contextual representation of the environment in a model. Thus, it enables to look at the human-environment relationship, not solely at the environment as a physical space per se. As mentioned before, the environment in ABMs can be a social network and/or a physical space. Edmonds (2006, p. 213) calls for taking the physical and social embeddedness of actors seriously and to model their interactions in both of these "dimensions". He argues that "[…] agent-based simulation seems to be the only tool presently available that can adequately model and explore the consequences of the interaction of social and physical space." (Edmonds 2006, p. 213). Such approaches also have the ability to represent and explore socially and spatially distributed problems (Perez 2006, p. 28). And due to simulation it is possible to explore the target phenomenon over different temporal scales or as an ongoing process.

Model design, in particular agent behaviour is relevant for the model purpose and model usage. Different approaches have been conceptualised by Conte et al. (2001), distinguishing between a representational and foundational perspective. The later uses simulation models to identify important and useful abstractions in the development of social theory, i.e. to specify cognition and agent interaction in the model by the notation of formal logics. In representational approaches Moss (in Conte et al. 2001, p. 186) defines the modelling objective and process as "[a] to start from the identification of the target phenomenon [b] to use agent based social simulation techniques to describe the system of which the phenomenon is a property or outcome and [c] to evaluate the effects on the target phenomenon of different individual behaviours and patterns of interaction among individuals in the system". From this perspective simulation models are viewed as descriptions of observed social systems. This way of modelling can be described as a bottom-up approach, intended to capture what is observed. Moss and Edmonds (2005) outline that such approach "can serve in the social sciences some of the functions of the experimental and observational apparatus". Hereby, agents "should be validated as good descriptions of the behaviour and social interaction of real individuals or collections of individuals" (see further Moss and Edmonds 2005). But not all agent-based model designers have such linear view on the different perspectives (see further Conte et al. 2001, p. 186).

The representational perspective has led to an increasing number of agent-based models where empirical data is either used as input data or as a means to falsify and test a model (Janssen and Ostrom 2006). The former usage of empirical data aims at describing decision processes of simulated agents at the micro level that lead to structures or patterns at the macro level due to the actions and interactions of agents (Janssen and Ostrom 2006). The model outcome is applicable in specific cases and results in a macro pattern or structure. This usage of empirical data—called evidence-driven modelling is also applied in this approach. In such applications prediction is not the aim but exploration of the problem space by means of a model and the further understanding of mechanisms, patterns and rules of the social reality (Gilbert and Terna 2000, p. 59; see further Moss and Edmonds 2005).

These different perspectives and various ways to design ABMs contributed to the fact that no dominant paradigm for social simulation research has emerged; instead a variety of styles of models had been developed "with less efforts towards direct comparison and standardisation" (Rossiter et al. 2010). The lack of standards of practice on how to develop and analyse ABMs, in particular with empirical data, is viewed as a reason that decreases the acceptance of this methodology in the social sciences (Janssen and Ostrom 2006). In order to further contribute to a standardisation in agent-based modelling in this approach three methodological frameworks are used: Rossiter et al. (2010) developed an epistemological framework for simulation in the social sciences, the framework by Smajgl et al. (2011) for parameterisation and the ODD protocol developed by Grimm et al. (2010) is used for model description (see Sects. 2.1, 2.4.3 and 5.3). Still it is often emphasised that the complexity and openness of social systems make it much harder to achieve an adequate description of such systems in models as for example in the natural sciences (Rossiter et al. 2010). The pitfalls connected to the application of the agent-based methodology in this sense are summarised in Wooldridge (2009, p. 190).

2.4 Model Building and Implementation

The process of model building and implementation is described and further divided into subchapters dealing with the conceptual model development, the empirical survey at the German North Sea Coast and the computational model development using Repast Simphony 1.2.0. It underlines the importance of the equivalent consideration of the theoretical and empirical basis for the computational model development.

2.4.1 Conceptual Model Development

Model design implies the determination and conceptualisation of those facts of the model that are indispensable for the explanation of the phenomenon (Schmidt 2000, p. 11). In the case of agent-based models this involves in particular the determination of agents, their attributes and behaviour as well as agent relations—either to its environment or to other agents. Here, the conceptual model design has been split up into two phases: the first to provide the theoretical foundation of the model and the second to prepare for the empirical foundation of the model (see Sect. 5.1). The development of a conceptual agent-based model of vulnerability dynamics in the first phase acts as an abstract framework to provide a general understanding for the application of the agent concept in vulnerability research. It frames non-agent-based risk approaches for the development of an agent-based vulnerability assessment (see Sect. 5.1). In the second phase of model design, the adaptation of this conceptual agent-based model to the regional context is figured out. Whereas the first phase aims at better understanding of the methodical application of an agent approach in risk research, the second design phase narrows down the research to a specific and applicable example of vulnerability in the coastal region (see Sect. 5.1). In order to understand the social phenomenon of vulnerability and its dynamics the model needs to be sufficiently detailed or specific to address the questions it intends to answer (Doran 2006). The development of the two phases is described in more detail.

Various concepts for the assessment of risk and vulnerability are described and systemised in the theoretical research framework (see Sect. 3.2.3.1). The concepts can be grouped into three disciplinary perspectives ranging from psychological, social sciences and coupled approaches. Obviously, the concepts cover and emphasise different theoretical aspects from the risk assessment (including perception and attitude) to the risk management sphere (including risk communication and behaviour). In the conceptual model development these different concepts of risk and vulnerability are considered to reflect relevant aspects from the different disciplinary perspectives (see Sect. 5.1). Meaning that, not one general theory or understanding was used for the conceptual model development but different concepts reflecting various perspectives are analysed with regard to its application in an agent-based model (see Sect. 5.1). The function of the theories is the identification of assumptions on which a model can be built (Gilbert 2004, p. 9). In order to describe vulnerability as a multi-dimensional and context-sensitive social phenomenon, various risk/vulnerability approaches from different disciplinary perspectives are taken into account.

Usually a conceptual model is developed as a basis for any indicator development and assures that assessments "measure the right things, at the right scale, with suitable conceptual underpinning" (Tapsell et al. 2010, p. 61). As this development process has been split up into two phases, one for the theoretical and another for the empirical foundation of the model, a general conceptual model is developed at first and further adapted to the regional context (see Sect. 5.1). The general conceptual model aims at the first research question, i.e. how different disciplinary perspectives in risk/vulnerability approaches can be reconciled with the agent concept. The regional adapted model is adjusted to provide a basis for the empirical assessment of vulnerability in the coastal zone of Schleswig–Holstein. Thus, the regional adapted model allows focusing on the second research question about which agent types concerning vulnerability and risk behaviour can be identified in the coastal zone.

In order to answer the first research question, the applicability of the agent concept on different risk/vulnerability approaches is tested. 12 exemplary risk/vulnerability approaches with different disciplinary or integrative background are discussed in the conceptual model development. It stresses the possible integration of *various* concepts in agent-based models for the assessment of multi-dimensional and context-sensitive phenomena. For this purpose, the different risk/vulnerability approaches are analysed and structured into the essential components of an agent-based model approach: system under study, scope and scale of assessment, agent level and design of environment, etc. (see e.g. Table 5.1 in Sect. 5.1). Thus, the developed agent-based conceptual model results from a theory-based model building process (see Fig. 2.1), i.e. it takes existing risk/vulnerability concepts from different disciplinary perspectives into account. Hereby, the general conceptual model illustrates the applicability of the agent concept in risk research and in which way different disciplinary risk/vulnerability perspectives and the methodical approach complement one another.

The general conceptual model of vulnerability is adapted and applied to the coastal zone of Schleswig–Holstein (see Sect. 5.1.2). The adaptation of the conceptual model to the regional context serves as a further exploratory step. The specification of the scope and scale of assessment to the survey region allows equipping the theoretical model concept with empirical data. It helps to answer the essential questions for the agent-based vulnerability assessment: which information is necessary to decrease the model abstraction and what needs to be measured in the (empirical) vulnerability analysis? As mentioned before, agent-based model design involves in particular the determination of agents, their attributes, behaviours and relationships. Thus, the conceptual model development determines and conceptualises those aspects of vulnerability that are indispensable for the exploration of the dynamic social phenomenon by means of an agent-based approach. An empirical survey was conducted in the coastal zone of Germany to gain model input data based on the conceptual requirements and according to the second research question: which agent types concerning vulnerability, present risk behaviour and preferences towards self-protection strategies can be identified in the coastal zone of Schleswig–Holstein?

2.4.2 Case Study of the German North Sea Coast

Social simulation is an analytical method which is used here as an exploratory approach for (an extended) vulnerability assessment. The aim of vulnerability assessments is to identify and evaluate the multi-dimensional factors influencing vulnerability, e.g. in empirical studies (see further Sect. 3.2.3). The purpose of this approach is the assessment of the vulnerability dynamics in a simulation model based on empirical values. The vulnerability assessment was directed towards the coastal zone of Germany. The empirical data gained in the survey serves as input data for the computational model and allows exploring the detailed dynamics deriving from spatial, individual and relational aspects of vulnerability in the considered agent system.

Besides the theoretical foundation of the conceptual agent-based model, the empirical foundation of the computational model requires the specification of the conceptual model to the regional context of the coastal area of Germany (see Sect. 5.1). The scope and scale of the regional adapted model facilitates the collection of empirical data about vulnerability and preventive behaviour of exposed households in five selected communities at the North Sea Coast of Schleswig–Holstein. The survey aims at bridging the conceptual and the computational model. This bottom-up approach of model building can serve for the assessment of system dynamics and for conducting thought experiments in the social sciences (see further Moss and Edmonds 2005; Hartmann 1996). The application of evidence-driven modelling is discussed in more detail in Janssen and Ostrom (2006); Smajgl et al. (2011); Seidl (2009) or Ziervogel et al. (2005).

The survey region has been selected according to purpose, scope and scale of the research approach. One of the first questions in a vulnerability assessment is: *who* is vulnerable to *what*? The coastal lowland at the North Sea Coast of Schleswig–Holstein is exposed to storm surges and without protective measures or in case of a dike failure flooding could occur due to low elevations (see further Sect. 4). The main exposed areas in Schleswig–Holstein are located at the tidal North Sea Coast where approximately 3.360 km² is protected by dikes lying below GOL +5 m (German Ordnance Level) (Schleswig–HolsteinischerLandtag Schleswig–Holsteinischer Landtag 2009a, p. 6). In the Elbmarsh region of the Wilstermarsch and the Krempermarsch greater areas are lying below GOL +2 m —in particular along the river Stör. About 24 % of the area of Schleswig–Holstein is categorised as flood-prone coastal lowland in the master plan for coastal defence (MLR 2001). Approximately 345.000 people and economic assets of about 45 billion Euros are threatened by storm surges and the further impacts of dike breaching (Hofstede 2004, p. 109).

Five communities were selected for a comparative vulnerability assessment: Wewelsfleth, Borsfleth, Münsterdorf and Kellinghusen in the district of Steinburg and the community Büsum at the Meldorf Bight in the district of Dithmarschen (see further Sect. 4). For the selection not only the location in the potential flooding zone was relevant but furthermore the proximity towards the flood plains of the tide dependent river Stör. Wewelsfleth, Borsfleth, Münsterdorf and Kellinghusen are located along the river Stör, a tributary of the river Elbe, in the Wilstermarsch and Krempermarsch. The river Stör with a total length of 87 km is influenced by the tide from the river mouth up to the conjunction with the river Bramau at Kellinghusen approximately 55 km upstream (Glamann 2010; see further Sect. 4). The tidal range in Kellinghusen is still 1.50 m (BSH 2011). Büsum at the Meldorf Bight is directly located behind the primary North Sea dike (see Fig. 4.1e).

The comparative vulnerability assessment aimed at private households in the exposed areas with different experiences concerning flooding events. The different conditions of (spatial) exposure result in varying experiences—ranging from storm surges and dike breaches to river flooding due to intense precipitation (see Sect. 5.2). Furthermore the time period passed since the last event varies between the different communities. In Borsfleth and Münsterdorf the last event remembered by the respondents happened in 1962, in Büsum in 1976, in Wewelsfleth in 2002 and in Kellinghusen in the year 2010. Moreover, self-protection measures are rather discussed in the context of river flooding (see e.g. BMVBS 2008; MURL 1999; 2007), making a comparison between different conditions of spatial exposure in the coastal zone even more interesting. Such different conditions were purposively taken into account to assess spatial aspects and their influence on the dynamics of vulnerability. As each household included in the empirical study is represented by an agent in the computational model, the heterogeneity of the household profiles played an important role for the creation of heterogeneous computer agents. Regarding this advantage of agent-based simulation, it offered the possibility to assess the relative differences between the households related to vulnerability and preventive behaviour. This type of purposive sampling (see further Babbie 2010, p. 193) serves for general comparative purposes with regard to agent types instead for good description of a larger population. In this way, the empirical study does not aim for representativeness of the vulnerability assessment but for its application in an explorative agent-based approach. Hereby, the explorative approach allows examining how agent-based simulation and empirical based vulnerability assessment can be combined in principle and thus fulfils the purpose of the research approach. In the vulnerability assessment by means of social simulation, 100 households were selected for this (methodical) purpose.

A standardised survey was set up and conducted in the five communities between April and May 2010. The questionnaires were distributed in the communities along the river Stör to households in near proximity to the river flood plain, i.e. as a household drop-off survey (see Appendix A.2). Meaning that in Kellinghusen, Münsterdorf, Borsfleth and Wewelsfleth certain streets were selected due to the proximity to the river flood plain and discussed with the responsible water authority in the Environment Agency office in the district of Steinburg on the basis of the legally binding flood plain maps of the Störriver. The different situations of exposure made a selection of streets necessary that resulted in different sample sizes in each community, e.g. 20 in Wewelsfleth and 7 in Borsfleth. 328 questionnaires were distributed to the households in the Stör communities. After a week, the questionnaires were re-collected from the respondents with a response rate of approximately 20 % depending on the respective community (see Appendix A.2); six questionnaires were sent back by mail. Documentary research and experiences from the survey region gave reasons to describe river flooding rather as a linear hazard, i.e. affecting the streets adjacent to the river. In Büsum a dike breach and the intruding sea water may potentially lead to a more widespread flooding—at least in comparison to the relatively small Stör river catchment. Without the border of a flood plain and due to general categorisation of the coastal lowland as flood-prone (see further e.g. MLUR 2010), in Büsum it was rather difficult to delimit the expansion of the area for the survey on such criterion. The primary dike protecting the community of Büsum could have served as a criterion for selecting streets nearby, yet due to the slow subsidence of the older marsh, areas further inland might be regarded as equally exposed to coastal flooding too (see further Sect. 4.2). Thus, the survey was expanded to a face-to-face street interview survey in the centre of Büsum. In addition to the questionnaire survey, 32 personal interviews were conducted in Büsum. Questions were asked orally to residents and answers were recorded by the researcher. Although the questions were read out to the respondents in Büsum, the exact wording, sequence and structure of the questionnaire was kept as in the household drop-off survey and no further explanations were given in order to achieve comparability. Merely, the question clarifying the type of perceived hazard in relation to the tide dependence of the river Stör was removed, i.e. whether coastal or river flooding is considered as relevant in the river catchment (see Appendix A.1). For the survey in the river catchment the questionnaire aimed at the risk of flooding, in Büsum it aimed at the risk of storm surges. Both survey methods were pre-tested in the respective communities (Diekmann 2010, pp. 485–486), revised after the testing and the comparability of the data collection methods was weighed against the research requirements of the approach.

The questionnaire/interview included mainly closed and a few open questions (see further Babbie 2010, p. 256). On the front page of the household drop-off survey, the intention of the survey was explained shortly as well as information about the anonymity of the survey, instructions for filling in the questionnaire and contact details were given. As the questionnaire also dealt with the implementation of self-protection measures (see further Sect. 3.2.4), it was to be filled in by an adult, i.e. a decision-maker living in the respective household. In the interview situation, this information was also given at the beginning of the interview. For the design of the questionnaire/interview earlier studies dealing with vulnerability and/or self-protection measures in the coastal zone (e.g. Ratter et al. 2009; Knieling et al. 2009; Terpstra 2009 or Kaiser et al. 2004) and the theoretical research framework were taken into account (see further Sects. 3.2 and 4.3). The first part of the questionnaire/interview focused on vulnerability attributes. The following vulnerability attributes were included: evaluation of flooding risk, perception of personal exposure, experience with flooding/storm surges, assets and measures already taken, level of information, social network, attitude towards self-protection measures, expectations concerning future risks. The second part of the questionnaire/interview further focused on self-protection measures. The respondents were asked about their preferences for four different self-protection strategies: going to informative events, insurance coverage and/or implementation of self-protection measures if incentives were given or whether they can imagine migrating from the flood-prone areas (see Appendix A.1).

The research focused on the citizens' preferences regarding the implementation of self-protection measures in the future—in order to explore the prospective development of vulnerability in the social simulation model, i.e. assuming that self-protective behaviour lowers the vulnerability of the households. Thus, the expressed preferences of the respondents are used as behaviour rules for the agents in the computational model. The preferences of the respondents serve as intentions as in the *Theory of Planned Behaviour* by I. Ajzen (1991, p. 181): "Intentions are assumed to capture the motivational factors that influence the behaviour, they are indication of how hard people are willing to try, of how much of an effort they are planning to exert, in order to perform the behaviour." The usage of such empirical data does not aim at the prediction of behaviour in the social simulation but to explore possible trajectories of the system based on expressed preferences. Whereas the empirical data provides information about the status-quo of vulnerability in the survey region, the simulation results constitute thought experiments about the dynamics of vulnerability in the considered agent system. Before the empirical data was used in the computational model, it was inserted into SPSS/PASW Statistics, the statistical programme for conducting further analysis of the data and for the development of agent behaviour rules (see Sect. 5.3).

2.4.3 Computational Model Development

The computational model has been developed using the Repast Simphony 1.2.0 platform. The ABM platform is a Java-based modelling system and open-source software to implement agent-based simulation models (see further Repast 2011). These types of agent programmes are equipped with a variety of example models, tools for visualisation of the models, tools for collecting results for later analysis and can be combined with geographical information systems (GIS), which make them very flexible platforms (Gilbert 2008, p. 46). For support a Repast-Interest mailing list exists to discuss Repast models and related questions as well as a mail archive (see further Repast 2011, Repast Mailing List and the Mail Archive 2011).

The computational model is described in Sect. 5.3. The model description follows the ODD (Overview, Design concepts, Details) protocol developed by Grimm et al. (2006, 2010). The ODD protocol is a detailed common format established for the description of ABMs and individual-based models. It includes the minimum requirements about the model purpose, the model's entities, state variables and scales as well as the model's process overview and scheduling. Furthermore, the design concepts are explained as well as details such as initialisation and input data. The ODD protocol is used for communication of models whereas for smaller models some design concepts may be ignored (see Grimm et al. 2010).

At the core of a computational model needs to be a simple set of driving propositions (Miller and Page 2007, p. 76). These core propositions, here called basic assumptions, are already implied in the conceptual model (see Sect. 5.1), included in the empirical study and are implemented in the computational model in the computer code (see Sect. 5.3). The basic assumption of the simulation model here is that vulnerability to flooding/storm surges can be reduced by better self-protection of private households (see Sect. 3.2.4). Thus, the empirical study aimed at the status-quo of vulnerability in the survey region, present risk behaviour and the households' preferences for self-protection measures. As for dynamic models assumptions about the evolutionary processes are necessary (Hartmann 1996, p. 82), the expressed self-protection preferences are implemented in the computational model as agent decisions and the positive consequences for the future vulnerability of the agent system were explored (see Sect. 5.4). Furthermore, the model assumes that the dynamics of vulnerability are not only determined by spatial and temporal hazard conditions in the communities but by the risk perception and the individual-intuitive process of risk conception of individuals. Thus, the computational model included subjective aspects related to risk, e.g. trust in official risk management and lack of awareness derived from the empirical survey. In consequence, the vulnerability dynamics due to individual, relational and spatial aspects could be assessed in simulation experiments.

The implementation of human decision processes is one of the main strength of ABMs. But Smajgl et al. (2011, p. 837) argue that the agent attributes and behavioural responses representing such processes require knowledge support from empirical sources. In this approach, the specification of the scope and scale of assessment to the regional context allowed equipping the model with empirical data. To empirically calibrate the computational model, the collected data was needed to derive agent vulnerability attributes and self-protective behaviour rules. The decision process of agents with regard to better self-protection has been implemented in the computer code as multi-stage condition-action rules (if/then) for each of the different self-protection strategies (see Sects. 5.1 and 5.3).

For the parameterisation of behavioural traits of human agents the framework developed by Smajgl et al. (2011) is used for orientation. The framework can be considered as an attempt to systematically structure the parameterisation methods for providing empirical support for human agents—and to guide the ABM community towards more robust empirical model development. According to the framework, the parameterisation sequence in this approach can be described as to start with an empirical survey, conducting correlation analyses to derive the further behavioural rules as well as simple cluster analyses in order to group agents based on similar attributes for model analysis. In the presented approach, the parameterisation process revealed independent parameters from the empirical data, i.e. for vulnerability attributes and preferences in the decision processes. Also for the scheduling of processes, such as the dissemination/offering of strategies, empirical data was used in this approach and translated into control parameter (see Sect. 5.3). In correlation analyses the relation between self-protection preferences and agent attributes was tested for the development of the multi-stage condition-action rules. The dependent parameters, e.g. state of vulnerability in the system, as well as the influence of relationships, individual vulnerability attributes and preferences for vulnerability dynamics were explored in various simulation experiments (see Sect. 5.4).

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Chapter 3
Theoretical Research Framework

3.1 Complex Systems Research

Complex systems research derives from developments of the past two decades leading to an array of transformations within various disciplines and a shift towards what is generally known as chaos, complexity, non-linearity and dynamical systems analysis (Urry 2005a, p. 1). From the phases of cybernetics and general systems theories[1] of previous decades an interdisciplinary complexity and system research has developed, and is still an open and evolving research process (Mainzer 2008, p. 13). From literature it is evident that a turn towards complexity thinking took place within various disciplines: complexity *in* physics, mathematics, biology, later also including ecology, neurology, economics and the social sciences (see e.g. Mainzer 2007, 2008; Helbing 2007, 2010; Gell-Mann 1995; O'Sullivan 2004, 2008; Thrift 1999; Byrne 1998, 2005; Casti 1994). Mainzer (2007, p. 1) describes "thinking in complexity" as an interdisciplinary methodology which further spread out to practices outside science. It was recognised, that complex phenomena cannot be explained by single disciplines but require an interdisciplinary understanding (Mitchell 2009). Such complex phenomena are for example weather and climate, global environmental pollution, the functioning of the brain or economic, political and social systems. They challenge our understanding as they are "complex systems", literally translated from its Latin and Greek roots as "entwined compositions" of interacting components forming an integrated whole. And the interactions may happen between elements in natural systems such as in the global climate system, between nations or organisations in socio-economic systems as in the global economy or even as interactions between the natural and the social system. The focus in complexity science therefore is not merely on the constituting elements of a system but on the relationships and interactions between the system's components. Cilliers and Preiser (2010, p. 267) urge to the recognition that "A complex system is not something that exists independently from the parts that

[1] About the detailed history of complex systems research see e.g. Erdi (2008) or Ratter (2000).

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constitute it. In fact, its existence is constituted by means of the interactions that take place between the components."

Usually we look at causes and effects of the interactions between the system's components. But complex systems pose the relevant question: how to investigate cause and effect if the elements are interrelating? In complex systems not the great number of elements is essential for the evolving of collective phenomena but the non-linear interactions (Mainzer 2007, p. 374). Thus in complexity science, instead of thinking in linear causalities the understanding of the behaviour and evolving of systems stems from thinking in non-linear relationships. In mathematics *non-linear* means that "small effects can have significant consequences; conversely, a major effect might yield very little" (Cambel 1993, p. 1). Here, cause and effect are not proportional. The disproportional changes can lead to instability and unpredictability of complex systems' behaviour. Thus a complex system involves intrinsic limits for prediction.

How can understanding about the evolving of systems advance if prediction is impossible? What complexity theory proposes instead are common features and basic principles about the behaviour of complex systems. Complexity seeks to uncover the key properties of complex systems which characterise the behaviour and dynamics of such systems. Complexity scientists search for such key properties as non-linearity and emergence in order to explain different complex phenomena across various disciplines. Although prediction may not be possible, complexity theory can teach what to consider with regard to the dynamic behaviour of complex systems. Goulielmos and Giziakis (2002, p. 20) describe the contribution of complexity theory as to "turn[s] our attention to the dynamic processes that create the various phenomena and encourage[s] a positive attitude towards non-predictability, uncertainty and innovation". Mainzer (2007, p. 16) rather advices to turn away from linear thinking as it "may be dangerous in a non-linear complex reality".

Chapura (2009, p. 464) characterises complexity theory more as "a meta-theory than a theory per se", as it provides a schema and vocabulary for analysis. Indeed one achievement of complexity theory is the development of a common language, used for the communication of basic principles of physical to social systems. This also results in a methodological transfer between different domains and the common focus on dynamics, on the so-called "becoming" of systems (Suteanu 2005, p. 122). Complexity science seems to provide means of transcending divisions between nature *and* society, the natural *and* the social sciences. (Urry 2003, p. 18). The Santa Fe Institute (SFI) for transdisciplinary complex systems research was founded in 1984 to expand these boundaries of scientific understanding. SFI shares the vision that the most interesting observations and most pressing problems in society fall far from the concerns of disciplinary research and its "aim is to discover, comprehend, and communicate the common fundamental principles in complex physical, computational, biological, and social systems that underlie many of the most profound problems facing science and society today" (see SFI 2011; also Waldrop 1992). Complex systems research can narrow the gap between the natural and the social sciences. Still often a distinction is made between a "hard" natural science and the "soft" or metaphorical social science complexity;

whereas Cilliers and Preiser (2010) argue that "Complexity sits at the interface between the two worlds and allows them to interpenetrate in a way which leaves neither untouched." One problem seems to lie in the varying definitions or understanding of complexity. In the following the key terms of systems thinking and key properties of complex systems are introduced; so-to-say the schema and vocabulary which later is used for analysis and the insights gained. And in this context it is seems appropriate also to clarify whether complexity itself is the object of research or if the insights of complexity research lead to a new/different perspective on research objects. The later rather requires a translation process in which the language of complexity research is applied according to the specific research context (Ratter and Treiling 2008, pp. 29–30).

3.1.1 Systems

The term *system* is derived from the Greek word *systema* which means "composition". In a very general sense, the term stands for "a set of some things and a relation among the things" (Klir 1991, p. 5). The "things" building a system are called elements, units or agents (see Sect. 2.3). Among these elements relationships exist. Due to the relationships elements form an integrated whole or unity. A system can be described by the relationships among its elements but also by the properties of its elements. It can further be divided into subsystems which are sets of elements forming different components in the larger system. The state of a system results from the state descriptions of its elements and relationships (Becker and Jahn 2006, p. 295). In complex system approaches focus is rather on understanding the relationships between the elements instead of looking solely for the essential properties in the elements themselves (Cilliers and Preiser 2010, p. 295).

A system can be defined by a researcher according to the function or the purpose it fulfils (Bossel 2004, p. 35). Systems are characterised by the constellation of its elements and the interrelations which together lead to the fulfilment of a certain function. They form the *identity* of a system. The functioning of a system is determined by structural and functional relationships whereas this interconnectivity of the system maintains the system's identity. For examination the researcher also needs to define the boundary of the system. Each system has its own environment and in order to study a system it is necessary to set a system boundary. The system is not completely isolated from its environment and interactions can occur between the system and the environment (Bossel 2004, p. 37). A system can be influenced by its environment (input) and can itself affect its environment (output). Systems thinking thus involves, besides the description of the system's structure and boundary, the examination of relationships and the analysis of interrelating processes between the elements, subsystems and between the system and its environment (Ratter and Treiling 2008, p. 23).

As the state of a system results from the state descriptions of its elements and relationships, the state of system can change if the components and components interactions are transformed. In fact, all systems are *dynamic* in the long term; though here the ascription “dynamic” is used to describe systems which are changing their state during the selected time period of observation and thus show dynamic behaviour (Bossel 2004, p. 36). The dynamics of a system can evolve due to internal feedbacks or external influences, i.e. between the system’s elements or between the system and its environment. State variables provide the necessary means to describe behaviour changes of a system and its environment. Complexity research is about how systems evolve, thus not the separate system states but rather the transformations are of particular interest (Suteanu 2005, p. 122).

For the description of a system further specifications can be added. In terms of dynamic systems, the ascriptions *open* and *closed* are important too. A closed system is defined as having “no relation to any other system that is not a subsystem of it and to which no other system that is not a subsystem of it has any relation.” (Backlund 2000, p. 450). Pidwirny (2006) further distinguishes between *isolated* and closed system. The isolated system has no interactions beyond its boundary layer whereas the closed system transfers energy across its boundary to the environment e.g. a heating system that releases heat energy to its environment. An open system instead transfers energy, information or matter across its boundary. Systems can vary between isolated types of e.g. controlled laboratory experiments and open types e.g. coupled human and natural systems (so-called Chans according to Liu et al. 2007a, p. 639; Gros 2008; Gibbs and Cole 2008) in which human and natural components interact. Biological and social systems are generally open systems. The usage of the terms isolated, closed or open, is not dependent on any intrinsic property of the system itself but on the purpose of the analysis and the research context (Martin and Sunley 2007, p. 577). Properties of isolated systems can be studied neglecting the interactions with an environment as these systems are maintained from internal forces and not influenced by external ones (Erdi 2008, p. 5). In complexity research the scope is on open systems as it aims at examination of relationships and analysis of interrelating processes between elements, and between system and environment. Furthermore, as the definition of the system boundary in open systems is often difficult, the scope of the system under study is determined both by the purpose of the description of the system and the position of the researcher[2] (Cilliers 1998, p. 4).

3.1.2 System Dynamics and Behaviour

Environmental influences as well as internal feedback effects can lead to changes in the system’s behaviour. Behaviour of systems is described in terms of stability and dynamics. Different assumptions about the stability characteristics of systems

[2] Cilliers (1998) refers to the process of defining the system’s border and thus the system’s description as *framing*.

reveal different perceptions of how systems function. Janssen (2002) differentiates between stable and instable systems. According to the "equilibrium myths", systems are in equilibrium (Janssen 2002, p. 6). Although external influences can push the system briefly out of equilibrium, it automatically falls back into the previous equilibrium condition. Thus an implicit assumption of the stability perspective is that the system is capable of damping all sorts of disturbances from its environment. In contrast, instable systems are assumed to be very sensitive to disturbances from its environment. According to this perspective, each disturbance can lead to a collapse of the system. And Janssen (2002, p. 6) introduces a third perspective which characterises systems between stability and instability. Here a system is assumed to be stable within limits; i.e. small perturbations from the environment can be absorbed when the system is managed well.

From a complexity perspective a stable state can suddenly occur in a system—and can also disappear as suddenly as it occurred (Ratter 2000, p. 49). In complex systems, ordered phenomena, patterns or structures emerge from the interactions among the system elements and build temporarily stable states. Important examples are the Bérnard convection cells; although the fluid of a system is in a quite chaotic state and particles are moving rapidly, at a certain temperature, regular stable patterns in form of hexagonal cells can emerge.[3] A well-ordered pattern emerges out of a disordered state, but complex systems are just temporarily in equilibrium as they are dynamic. These types of systems are neither rigidly ordered nor highly disordered (Arrow et al. 2000, p. 38). Thus in complexity research, the perception of how systems function is that systems are dynamic, "they are like a journey, not a destination, and they may pursue a moving target" (Cambel 1993, p. 4).

Complexity research therefore focuses on dynamics, interactions and change processes; not primarily on structure and stability in systems. And as knowledge about these interactions is the key for understanding systems, we must not only ask: "what is the system under study and what are the elements composing it?" but also "how do these elements interact with each other to form the system itself?" Thus, besides deciding about the units and the levels of analysis, it is essential for complexity research to understand *how* to bridge the levels of analysis in order to understand the relationships (Smith 1997). In this approach two types of relationships influencing system dynamics and system behaviour are further outlined due to their conceptual importance for analysis: the micro–macro relationship and the human-environment relationship.

In complexity science interest lies in the relationship between the lower and the higher level of a system, in sociology also known as the *micro–macro link*. Coleman (1964) first formulated the problem of relating the behaviour of individuals, the lower level, to the collective properties and patterns of the social system, the higher level. Epstein (2006, p. 5) has expressed it in the so-called "generativist's question": how could the decentralised local interactions of heterogeneous

[3] The exact description of the formation of Bérnard cells are to be found in Mainzer (2007, p. 55).

autonomous agents generate the given regularity? The collective properties of a system arise due to interactions between the system's elements; they are not inherent characteristics of the elements themselves (Cilliers and Preiser 2010, p. 291). Thus, the physical and social phenomena at macro level emerge from interactions (reinforcing each other). Examples of such regular macro level collective/societal processes are organisational behaviour, political movements, segregation patterns in cities, outbreak of riots and wars, or price equilibrium in decentralised markets.

Fundamental for the micro-macro link is the connectivity of systems. Every change in the relationship between elements or between the system and its environment can result in different system behaviour. The way in which agents are connected and their type of interactions and relationships therefore influences the outcome on macro level. In open systems energy, information and matter can be exchanged. Assuming that e.g. information is exchanged, it would happen on the agents/elements level, i.e. on the endogenous interaction structures inside the system. Here the topology of the social network can affect the information dissemination in a system (Epstein 2006, p. 17). Besides the structure of the network, feedback mechanisms further alter the dynamics of a system; negative feedback leads to stability in the system as changes get quickly absorbed, whereas positive feedback amplifies changes leading to instability (Miller and Page 2007, p. 59). Two aspects related to connectivity are problematic and challenging particularly in social systems. Other than in many physical systems, the interconnections between the elements are not physically visible or observable (Sawyer 2005, p. 26). Another important capacity in social systems is that individuals contain representations of processes inside the system and of the macro patterns.

The micro-macro link thus aims at the question of how the elements interact with each other to form the system itself. Another type of relation in open systems is assumed between the system and its environment. The system is distinguished from its environment by the system boundary; everything which is not assigned to the system thus is environment. In open systems the system boundary is not impermeable but permits interactions between system and environment in form of information, energy and matter. According to the research question and the researcher's conceptualisation of the system under study, the analysis can be directed to these relationships and the emerging patterns. In the study of coupled human and natural systems such interactions between humans and natural components are examined (see e.g. Liu et al. 2007a, b; Janssen 2002; Becker and Jahn 2006). Other than in traditional ecological research which often excluded the human impacts these approaches aim at considering both human and ecological aspects as well as their connections. In human ecology approaches the social and natural processes are related in such way that they lead to a new research perspective and thus facilitate the explicit consideration of socio-ecological processes and emerging patterns (Becker and Jahn 2006). The isolated analysis of social and physical processes seems inadequate due to their strong interconnections and the reference level changed in favour of a coupled socio-ecological systems perspective. The—as relatively autonomous considered—systems *society* and *environment/nature* thus are conceptualised as one socio-ecological system.

The fragmentation of a system destroys what the complexity approach seeks to understand (Cilliers and Preiser 2010, p. 2). Socio-ecological phenomena such as climate change, environmental pollution or land degradation leading to food insecurity and environmental migration or even the extinction of prehistoric societies thus can be studied (e.g. Glaser et al. 2011; Liu et al. 2007b; Epstein 2006; Seidl 2009; Perez and Batten 2003).

As the research approach focuses on the dynamic phenomenon of social vulnerability, which resides at the intersection between the social and environmental system, such further bridging of the levels of analysis seems appropriate. The conceptual understanding of vulnerability from a coupled human-environment perspective is further explained in Sect. 3.2. Micro–macro as well as human-environment relationships are two examples for analysing dynamics and behaviour of systems which are further explained here due their importance for later analysis. Manson and O'Sullivan (2006, p. 681) argue that "Complexity science is broad minded "in the sense that the entities in question might be anything […] and so might the relations be of almost any kind. This said, for any given area of study, certain kinds of relationships are more common, important, or necessary than others". Although such flexibility in research perspective allows to understand different systems constituting of atoms, molecules, organisms, humans or firms and their relationships by means of complexity theory, the complexity approach does not relieve the need to address specific problems and to provide empirical prove of research.

3.1.3 Complex and Complicated

In literature such coupled approaches are often used in combination with the term *complex*; e.g. complex socio-ecological systems, complex adaptive systems, complex coupled human-natural systems. As the technical term plays an important role for understanding the theoretical foundation and selected methodology of the research approach, the meaning and its difference to the notion of *complicated* has to be clarified. The term *complex* in its Latin root *plectere* means: to weave, entwine. In complex systems many simple parts are irreducibly entwined (Mitchell 2009, p. 4). In everyday-language complex is often used to describe a state which appears to be more than complicated (Ratter 2006, p. 110). Cilliers and Preiser (2010) comment that "If a system—despite the fact that it may consist of a huge number of components—can be given a complete description in terms of its individual constituents, such a system is merely complicated". Becker and Jahn (2006, p. 273) argue that the existence of multi-factorial connections in a system, e.g. between a great number of natural and social factors, are described as complex in everyday speech, although they are merely complicated. Thus, a system consisting of a multitude of elements and relations is often termed complex, whereas complexity science in this case refers to compositional complexity. With regard to the multitude of relationships also the term structural complexity is used.

The popular anti-reductionist expression “The whole is greater than the sum of its parts” instead refers to another notion of complexity: behavioural complexity. The interaction among elements of a system and the interaction between the system and its environment are of such a nature that the system as a whole cannot be fully understood by simply analysing its elements (properties) (Cilliers and Preiser 2010). For analysis of behavioural complexity, focus should be on the interactions—as they are relevant for system dynamics and behaviour changes. In a complex system it is not the great number of its elements causing emergence of collective phenomena on the macro level but their non-linear interactions (Mainzer 2007, p. 374). Thus behavioural complexity in a system is determined by the fact that higher level regularities can emerge from the interactions of elements. Higher level regularities are collaboratively created e.g. in ant colonies or bird flocks by simple local interactions; complex systems have their foundation in simpler ones. Thus, in complexity research differing notions of complexity can be distinguished. One aspect of complexity, namely compositional complexity is related to structure, i.e. it refers to the constitution of the system due to its elements and relationships. The notion of behavioural complexity instead refers to the emerging behaviour of the system differing from its component’s behaviour.

3.1.4 Key Properties of Complex Systems

3.1.4.1 Feedback and Emergence

Common sense assumes a single cause-and-effect relationship in systems and that small changes in the cause, result in small changes in the effect (Erdi 2008, p. 6). In such simple systems the behaviour can be predicted. “As opposed to simple systems, where causes and effects […] can be separated, a system is certainly complex if an effect feeds back into its cause” (Erdi 2008, p. 357). Earlier in his book Erdi (2008, p. 8) defines feedback as a “process whereby some proportion of the output signal of a system is passed (feed back) to the input. So, the system itself contains a loop”. And as the output influences the input, Erdi follows there is no clear discrimination between causes and effects. Feedback effects have important implications on systems and result in counter-intuitive behaviour observed in complex systems which will further be outlined.

Feedback loops influence and alter the dynamic behaviour of a system. The effect of feedback on behaviour can either be positive or negative. Negative feedback loops have dampening or stabilising effects and positive feedback loops have amplifying or destabilising effects in systems (Arrow et al. 2000, p. 48). According to this, a positive feedback increases the subsequent output of a system, a negative feedback decreases it. Feedback loops occur e.g. in biological cells, ecological networks and social systems. For social systems Erdi (2008, p. 11) gives examples according to which negative feedback effects “ensure the stability of institutions, while positive feedback effects, i.e. self-amplifying processes may help to diffuse new ideas. The more politicians talk about an issue, e.g. the health-care-system […], the more the public will be concerned with it". For coupled human and natural systems Liu et al. (2007a, p. 640) outlines that positive and negative feedback effects can lead to acceleration or deceleration in rates of change of both human and natural components as well as their interactions. The increase of human activities, such as greenhouse gas emission, since the Industrial Revolution for example, lead in return to growing impacts of these activities on human well-being due to greenhouse effects. Large effects such as stock market crashes, outbreaks of riots and war or traffic jams thus may arise in systems due to feedback. In a traffic jam for example the behaviour of others changes the individual's motives and actions, i.e. the slowing down of other cars forces you to slow down too in order to avoid a crash (Miller and Page 2007, p. 52). In complex systems both positive and negative feedbacks coexist.

As shown in the examples, the interactions in a system containing a feedback loop are not independent but can e.g. reinforce each other. This process can result in behaviour that is very different from the "norm" or from common sense (Miller and Page 2007, p. 50); mutually reinforcing feedback loops can create non-linear behaviour. "A small change in a local variable that triggers a positive (amplifying) feedback loop can ultimately result in a big change at the global level, as interactions among coupled elements at the local level ratchet up to effects that are noticeable at the […] system level (Arrow et al. 2000, p. 50).

These effects noticeable at the system level are for example stock market crashes, riots, traffic jams or fish schools in social systems. Complex systems show so-called emergent properties. From the interactions of individual components some kind of global property can emerge (see Fig. 3.1).

The local interactions between individual entities on the micro level thus lead to an emergent property, structure or pattern that in some sense is disconnected from the individual behaviour. The global behaviour or structure is completely different from its component parts; it is not reducible to or implicit within the lower level entities. Meaning that, the aggregate level is not a simple extrapolation of the individual agent behaviour (Miller and Page 2007, p. 44). The global emergent property again feeds back to influence the behaviour of the individual entities that produced it (Lewin 1999, p. 13; see Fig. 3.1).

Another example of an emergent property given by Urry (2003, p. 25) refers to a jumbo jet: the combination and interaction of interdependent parts produce the emergent property of enabling the plane to fly. Yet, the ability to fly is not present within or reducible to the individual components. The emerging collective properties, patterns or structures on the macro level are not implicit within, or at least not implicit in the same way, within the individual components (Urry 2003, p. 25). Even though, all emergent properties arise from the properties and interactions of their constituent parts (Harris 2007, p. 25). There is no need for external instruction to form global order and structure. And there is no possibility to predict the emergent phenomena, not even from exhaustive information about the properties.

Emergent entities arise from the micro-dynamics of the constituent parts and result in macro-dynamics (see Fig. 3.1). Emergency can appear at many levels: on

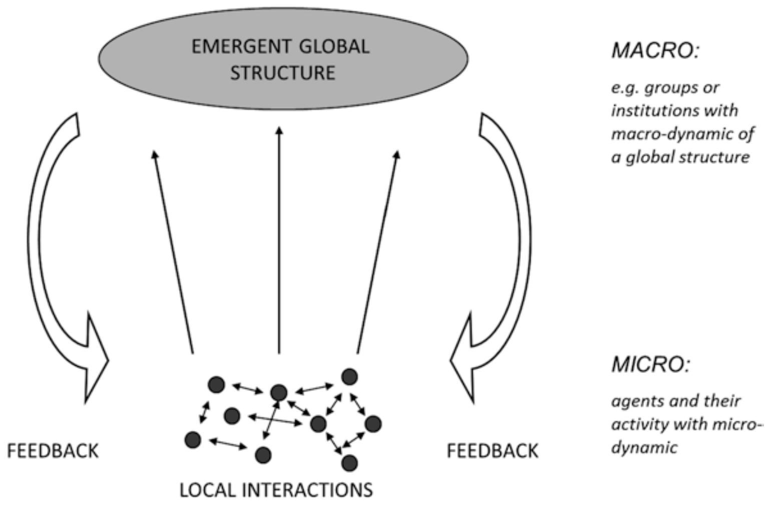

Fig. 3.1 Emergence in complex systems (according to Lewin 1999, p. 13, reproduced by permission of University of Chicago Press)

the macro level groups, organisations, institutions or nations are built and furthermore the aggregate behaviour of companies, consumers and financial markets produce the national or global economic system (Lewin 1999, p. 13). The collective properties can emerge of all sorts of phenomena (Urry 2003, p. 24).Thus, there are also different notion of emergence.

Emergence in complex systems implies to "expect the unexpected" (Lewin 1999, p. 259). Complex systems research examines how components of a system through their interaction spontaneously develop collective properties. The emergent system behaviour does not derive from an adding together of individual components. The key to understand emergence are the interactions inside the system and the key conditions are non-linearity and context-sensitivity (Harris 2007, p. 25). In context-sensitive phenomena interactions are not independent, feedback can enter the system; thus interactions can reinforce one another and result in non-linear complex behaviour (Miller and Page 2007, p. 50). Macroscopic structures emerge from non-linear interactions of the system elements; they occur at so-called critical points in connection with phase transitions (Mainzer 2008: 123; Helbing and Lämmer 2007, p. 4). Macroscopic structures represent patterns or the order of a system. Small fluctuations at the critical points, thus also called critical fluctuations, may become a dominating influence and determine the future fate, i.e. phasesphases[4] of the system (Helbing and Lämmer 2007, p. 4). Complex dynamic systems pass through different phases and every

[4] A phase describes the particular state of a system at a particular time e.g. capitalism in economy or a traffic jam in a social system.

phase transition is related to the emergence of a new emergent structure (Mainzer 2008, p. 123). If a system passes a particular threshold with minor change in the controlling variables, switches may occur and the emergent properties switch or turn over (Urry 2003, p. 25).

3.1.4.2 Phases and Trajectories

Complex systems research examines how from interactions of the system elements macro-properties or patterns emerge. The macroscopic structures emerge at so-called critical points in connection with phase transitions. If a system passes a particular threshold with small changes in the control variables, the system forms a new order (Urry 2003, p. 25). In order to understand emergent behaviour further examination of the responsible properties of complex systems is essential. To unlock the complexity of a system, understanding of interaction and feedback mechanisms is necessary but in order to recognise the *new* order, previous system state(s) are to be known. Meaning that, the evolution of a system becomes important. The history of a system is not only important for understanding of complex systems but it also co-determines the structure of the system. It is difficult, however, to anticipate changes beyond the short term (Manson 2001, p. 410).

What is the meaning of evolution in the complex system context? A complex system may gain structural stability, in form of a recognised order or pattern, but without any guarantee of durability (Mainzer 2007, p. 377). As mentioned before, the ordered patterns or structures build temporarily stable states or so-called phases. Complex systems are dynamic and pursue “a moving target”. Therefore the system evolution is characterised by a series of phase transitions whereas each phase constitutes a different macroscopic pattern or order. The hexagonal Bérnard convection cells for example are such a phase which is maintained only at a certain temperature. The dynamics of the system are to be understood in terms of phase transitions. According to that, the evolution of a system can be shown in phase portraits of the emerging global states or patterns.

The phase space, also known as state space, is all the (theoretically) possible states in which a system might exist (Byrne 1998, p. 24). Thus the phase space represents the habitual tendencies of the changing states of a system. The occurrence of a phase transition towards a new state of the system can be marked by bifurcations points. At bifurcation points the state changes branch out or “bifurcate”, hereby the system leaves its “old” trajectory and follows a “new” one [according to the evolving state]. Bifurcation analysis is used for studying the changes in the long-term behaviour of the system (Erdi 2008, p. 17). By so-called trajectories and bifurcations the changing system states can be further described over time (Mainzer 2007, p. 33). Figure 3.2 illustrates such “bifurcation history” of a system; in particular how the state of a system changes, old order gets instable and the system is able to follow new trajectories and thus can build new order(s).

The question of how system properties or patterns arise from the properties of the interconnected elements should be linked to the question of how the system

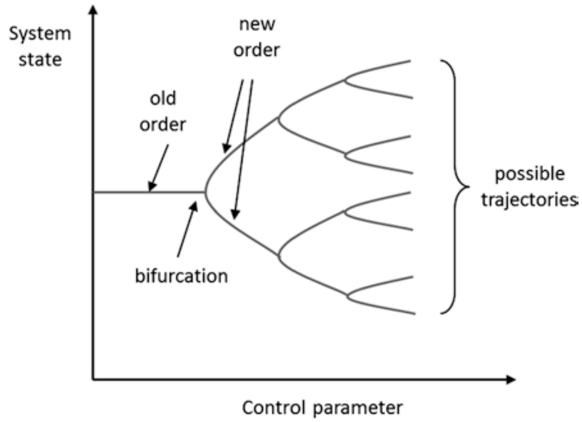

Fig. 3.2 Evolving of complex dynamical systems (according to Mainzer 2008, p. 43)

then further transits from one pattern to another along the phase space. For the transition of one state to another the boundary conditions, also termed control parameters, are important. When a control parameter achieves a certain threshold e.g. a certain temperature, the trajectory of the old state can become instable. At such critical points of the system state, small fluctuations may become a dominating influence and the system is forced into a new and different trajectory. The changes in the control parameters occurring at bifurcation points thus lead into a new order of the system along the possible trajectories. Bifurcations occur if control parameters are changed by the appropriate ratio, i.e. in such way that they affect the order-maintaining parameters (Byrne 1998, p. 53). By further increasing the control parameter, the state of the system becomes instable again and the system might be forced into a new order which again induce further instability. The phase transitions in complex dynamical systems can lead to the emergence of increasing complex order (see Fig. 3.1; Mainzer 2008, p. 43).

Regarding the question of how the system transits from one pattern to another, an important aspect is to understand the possible trajectories and what they are. During its dynamical development the system can be "attracted" to states in the long term. So-called attractorsattractors[5] affect the system's "preferences". The system does not move through all the possible parts of the phase space but instead occupies a restricted part of it (Byrne 1998, p. 168). The system is attracted to certain states e.g. in the simplest form of an attractor it is a point, and the system reaches a stable equilibrium state here. In this case, predictions of future states then become possible on the basis of the current state, deterministic laws and linear description. Instead of a single point, an attractor can also consist of a certain range of values (*fixed-point* and *limit-cycle attractors*). In such cases the attractors are of an oscillating nature (in the range of values), and its exact behaviour state cannot be predicted as it may

[5] For further description of the three attractor types (see Casti 1994, pp. 28–32).

oscillate within the range constituting the attractor (Helbing and Lämmer 2007, p. 2; Urry 2003, p. 26). Feedback mechanisms play an important role for system behaviour within these attractors. Although the system's states inside the phase space are somewhat of "restricted" by the attractor, it still can occupy a certain range of values. Negative feedback mechanisms though cause the system to switch in between the lower and upper limits, i.e. within the range, of the attractor. Moreover, it is also possible that the system state breaks out of the range of values and moves beyond the limits of the restricted (previous) attractor boundary. Such *strange attractors* are very sensitive to changes in the initial conditions. The slightest change in the control parameters determine which of the two radically different trajectories the system settles into (Byrne 1998, p. 28). Although deterministic laws are involved, prediction is impossible as even neighbouring trajectories can separate over time due to sensitivity to initial conditions and chaotic behaviour results.[6]

"Central to the patterning of attractors in time and space are the different kinds of feedback mechanisms.[7]" (Urry 2003, p. 27). Whereas negative feedback mechanisms of limit-cycle attractors determine that the system switches back into the boundaries of the attractor; positive feedback mechanisms amplify the change tendency, the (previous) attractor boundary is broken and the system shifts into a new phase state as in strange attractors. Over time the positive feedback loops reinforce establishing patterns and set up a self-reinforcing system (Urry 2005b, p. 239). This phenomenon, called path-dependence, can lead to an irreversible "lock-in" of a system, i.e. the system is locked into a pattern that is for example far from being "optimal" but still hard to reverse.

3.1.4.3 Non-Linearity and Complexity

As mentioned before, non-linear means that small causes can result in large effects and vice versa. Cilliers (1998, p. 4) describes non-linearity as a precondition of complexity.[8] In fact, small events can become important for the evolving patterns and structures of a system which may then be preserved due to path-dependence. In the most extreme case, the strange attractor, slightest changes in the initial conditions determine which of the different trajectories the system is forced into. Positive feedback mechanisms amplify the change tendency, i.e. the reinforcing feedback loops can create non-linear behaviour. Even neighbouring trajectories

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[6] This effect is also known as the "butterfly effect", i.e. slightest fluctuations in the initial states can result in chaotic behaviour; metaphorically speaking the butterfly's wings can create a tornado on the large global scale.

[7] From Cambel 1993, p. 23: ""feedbacks" describe the continual accretion of effects from previous interactions, which may in turn alter lower-level interactions and higher-level configurations at the next point in time".

[8] Mathematically, non-linearity is a necessary, but no sufficient condition for chaos. (Mainzer 2007, pp. 54−5).

can thus separate over time and lead to differing system states and increasing complexity (see Helbing and Lämmer 2007, p. 3).[9]

Yoshida (2010, pp. 24–25) alludes to non-linearity in ecosystems. Here, non-linearity is a mathematical representation of *autonomia* of a system. Ecosystems go through stable and unstable phases which they manage or eventually cease to exist. In these non-linear systems for example the reproductive rate is changed autonomously in order to survive leading either to stability or to complex and unpredictable oscillations. Thus Yoshida formulates the central problem as to find out how non-linear phenomena self-organise their structures and self-regulate their dynamics.

Mitchell and Streeck (2009, p. 5) point also to "multiple causes at multiple levels of organization operating at multiple time scales" which work together and generate the observed behaviour. They argue that behaviour is not always possible to be explained by a single dominant cause such as in the case of a billiard ball moving due to the impact from the cue ball. In the complex world the involved feedback mechanisms, not primarily the multiplicity of factors, result in non-linear chaotic behaviour either by amplifying or dampening the initial stresses in the system (Mitchell and Streeck 2009, p. 6). In non-linear complex systems the output is not proportional to the input; therefore causal explanations by additivity will fail to understand the (disproportional) perturbations in a system, driving it to a critical point. Instead the recognition of *self-organised criticality*, i.e. where a system is driven towards a critical point, is important in order to understand e.g. cascading effects triggering a disaster or avalanches in the classical example of a pile of sand (see Helbing and Lämmer 2007, p. 5). These effects are not additive, but they evolve by the interactions of the constituting parts of a system. Thus, in order to understand how systems evolve, the system cannot be decomposed into separate elements for analysis. The autonomy of such a system is created by the cooperation of many elements; it is not consolidated in a single parameter (Yoshida 2010, p. 24).

System history matters too; small events influence the evolving of patterns and structures of a system which are then preserved. Non-linear dynamics result in an irreversibility of change and a tendency towards path-dependence in the system's trajectory and behaviour (Martin and Sunley 2007, p. 577). Feedback loops reinforce established patterns and can lead to an irreversible lock-in of the system. As mentioned before, though, the system's evolution results from complex interactions, the present and the past state of the system. For a long-term analysis of the system evolution, phase portraits thus seem essential and further presume the definition of system states and state phases. But Mainzer (2007, p. 377) poses a relevant question related to social and historical sciences: what is the socio-cultural

[9] The strange attractor, a complex mathematical figure is composed of millions of dots all of which represent a single solution to an iterative equation involving feedback (see Eve et al. 1997). It is impossible to predict where the next solution appears, although any dot will fall somewhere within the complex pattern formed by the strange attractor, thus it is also called deterministic chaos (see Eve et al. 1997).

state phase of the WeimarRepublic or of Victorian England? How to analyse such social phenomena in the framework of complex systems without ignoring that the social complex world is an open system and not a trivial sum of actors? For each society and its subsystems many situations can be considered. There are obviously limitations *and* a lot of uncertainty is involved.

There are also multiple degrees of complexity in the real-world. Mitchell and Streeck (2009, p. 8) mention as a further critical aspect in social systems that they are not only shaped by historical events but also self-referential, meaning that they are capable of agency and act intentionally. Although it does not mean that human individuals are omniscient, they do not solely respond to stimuli they are exposed to. The individual intentions of humans on global scale also can result in complex behaviour as Mainzer (2007, pp. 382–384) shows on the basis of a non-linear model of migration. In the example, human migration is intentional and non-linear; the global consequences are deterministic chaos and demonstrate the effects of agglomeration and segregation trends. For dealing with such complex phenomena in the social world Mainzer (2007, p. 382) suggest that: "It is not sufficient to have good individual intentions without considering the non-linear effects of single decisions. Linear thinking and acting may provoke global chaos, although we act locally with the best intentions".

3.1.5 Assessment and Management of Complex Systems

Mitchell and Streeck (2009, p. 5) argue that "The world is complex; so, too, should be our representations and analyses of it" and encourage a shift in our conception of science:

"[…] it requires a recognition that good scientific practice reaches beyond the Newtonian paradigm. It requires, in many cases, a more explicit and detailed analysis of the many roles specific context plays in shaping natural and social phenomena. It means that conditions often relegated to the status of "accidents" or "boundary conditions" on the old paradigm must be elevated to the subject of scientific study in their own right. Historical contingency conspires with episodes of randomness to create the actual forms and behaviors that populate the social world."

For scientific approaches "beyond reductionism" the systems are not broken apart and the component parts are studied separately. To figure out how the system works as a whole, systems thinking and recognition of key properties of complex systems is appropriate. The scientific approach "beyond linearity" demonstrates why linear thinking and the single-cause-and-effect assumptions are unsuitable to assess complex real-world phenomena. Instead the recognition of system dynamics and system state phases offer a different view on the development of context-sensitive phenomena and are applicable over a range of disciplines. For assessment of complex systems one needs to realise that it is also an approach "beyond prediction" but one that recognises sudden changes between order and randomness as part of the system development.

The complex systems approach stemming from the natural sciences has been transferred to and applied in the social sciences by researcher such as D. Harvey and M. Reed, D. Byrne, J. Urry or K. Mainzer. To gain insights into the complex social world, one perspective and methodological approach is the usage of models (see further e.g. Miller and Page 2007 or Cilliers 1998). Here the aim is *not* prediction as in the natural sciences but exploring and understanding the mechanisms, patterns and rules of the social complexity. Although model building requires the reduction of reality—thus also the reduction of complexity—the abstraction process can be handled on the basis of the scientific foundation of complex systems thinking. Complexity theory itself constitutes a tool to handle this abstraction process without fading out the characteristics of complex systems (Becker and Jahn 2006, p. 280).

Considering the usage of models, scenario modelling and analysis is one approach to explore and understand complex systems, in particular human-environment interactions. Models are used to gain projections (*scenarios*) e.g. to compare policy options for different types of futures and give further insights into the robustness of these policies (see further Janssen 2002, p. 408; also Seidl 2009; Ernst 2009). By means of simulation and by the usage of alternative assumptions about differing initial conditions, a detailed analysis of the specific contexts for shaping social phenomena can be provided. Still it has to be made clear that scenario modelling is not an electronic oracle or a prediction machine but deals e.g. as a medium for discussion. Scenario modelling is an approach "beyond prediction" but of projections and what-if futures; and with all its limitations (see further Janssen 2002). In the social sciences it can help to explore influences of different initial conditions, trajectories and sudden changes on long-term system behaviour and dynamics by means of simulation (see also Becker and Jahn 2006, p. 281).

Such models must share the properties of complex systems, i.e. concerning the further requirements of complex systems research they imply anti-reductionism and non-linearity. In order to recognise non-linear dynamics in the system's behaviour the definition of system states and state phases is necessary. One difficulty in the assessment of the complex social world has already been formulated by Mainzer's question (2007, p. 377): what is the socio-cultural state phase of the WeimarRepublic or of Victorian England and how to analyse the social reality without ignoring that the social complex world is an open system and not a trivial sum of actors? Another way of complexity reduction for model building therefore is the appropriate limitation of the system under study (i.e. of the model system). The model thus may be reduced to the typical features of subsystems of the overall system. Considering the human-environment interactions, the appropriate limitation of the system towards its environment may result in the modelling of the corresponding interfaces (Becker and Jahn 2006, p. 281). Whereas Martin and Sunley (2007, p. 578) remark that the "boundary between a complex system and its environment is neither fixed nor easy to identify, making operational closure dependent on context (and observer)". The assessment of complex systems at first involves the description of the system under study which in turn is shaped by the researcher's perspective and interest.

In order to recognise the properties and common features of complex systems in the real-world phenomena, complexity theory has to be related or translated to the social research context. As mentioned before by Chapura (2009, p. 464), complexity theory provides a schema and vocabulary for analysis. Thus relevant properties and common features of complex systems research are to be identified or defined for the system under study. According to the example by Mainzer (2007, p. 376), in the framework of complex systems research, the dynamics of a society are understood in terms of phase transitions of a system. The ongoing interactions in the system or changed boundary conditions can lead to a change from a stable into an unstable phase of the system evolution e.g. the boundary conditions enabling the current democratic revolutions in Egypt, Tunisia, and other countries of the Arab World. Furthermore, the determining factors for system dynamics and behaviour have to be made precise for modelling e.g. as measurable quantities or expressions of the interactions inside the system (Mainzer 2007, p. 377).

Agent-based modelling is an analytical method to explore and understand dynamic social phenomena. According to the agent concept (see Sect. 2.3) societies are not the trivial sum of actors; instead the interactions between the agent and environment level as well as the relationship between micro and macro level are taken into account. Agent-based models are tools to investigate the dynamics of systems as a whole—by including spatial, temporal, relational and individual (i.e. agent) factors of influence. In the artificial societies interactions between agents, between agent and environment as well as the feedback effects of possible agent actions or goals can be simulated. The effects of different boundary conditions and the determining factors for sudden changes in the system behaviour thus can be analysed. By means of simulation a long-term analysis of the system evolution is possible due to the agents' interactions possibly leading to phase shifts on system level. But also the emergence of organisations, cultures, migration trends or political movements are possible application fields for agent-based modelling (see e.g. in Billari et al. 2006; Epstein 2006; Perez and Batten 2003; Sawyer 2005). Agent-based simulation therefore offers a tool for the assessment of complex systems as it explicitly includes the system perspective, feedback effects and interactions, phases and trajectories from which non-linear effects on system behaviour and changes emerge.[10] The bottom-up approach can help to understand how system properties evolve from agent interactions. Model building and implementation, though, requires the aforementioned abstraction and translation process to the specific research context (see Sects. 2.1 and 2.2). As both agent-based modelling and complexity theory capture dynamics and change in systems, they represent a powerful (theoretical and methodological) approach to study dynamic social phenomena (see further Eve et al. 1997).

[10] "Complexity is not something that can be pinned down by analysing the properties of a certain part of the system or by taking the components of the system apart and seeking for traces of complexity within the isolated parts. We are challenged to describe properties that emerge as a result of the interactions amongst the components"(Cilliers and Preiser 2010, p. 44).

The counter-intuitive behaviour of complex systems causes management mistakes and undesired side effects (Helbing and Lämmer 2007, p. 6). In order to prevent such management mistakes knowledge about complex system dynamics, features and behaviour as well as adequate assessment tools for complex systems should be taken into account. Although prediction of complex systems behaviour is not possible, it does not imply to do nothing; instead we "must be prepared to expect the unexpected, and develop routines of action that are ready for it" (Mitchell and Streeck 2009, p. 7).

Helbing and Lämmer (2007, pp. 6–12) summarise why various assumptions of the classical control approach are unsuitable. The key word here is *adaptive management*. As fundamental uncertainties about the dynamics of a system exist, adaptive management means to continually observe the system's development in order to respond with adequate management strategies (Janssen 2002, p. 7). *Adaptive* here refers to the capacity to identify critical fluctuations or changing conditions in the system's development and to react to those correspondingly. Furthermore, the observer even might learn from the system by small human-induced perturbations (Janssen 2002, p. 7). As systems evolve constantly, the aim cannot be to conserve the system states. Instead by recognising the amenable key variables and interactions, the system's trajectory might be modified by management strategies (see further Ratter 2000). And adaptive management does not legitimate each external management intervention. As shown in an example by Eve et al. (1997, p. 280) about the ancient system of water rights surrounding temple life in Bali which supported an, although precariously, but intensive rice-growing economy. The replacement of the indigenous methods of water allocation by foreign experts finally lead to extreme crop losses as the complex adaptive system which has developed over time now was disrupted by external influences. Also Helbing and Lämmer (2007, p. 6) state that complex systems can counteract the accomplished action and that the system behaviour may depend on whether a system is close to a critical state.

The adaptive management framework thus may help to handle uncertainty of social complexity by its flexibility to respond to both new situations and new knowledge of the system (Mitchell and Streeck 2009, p. 8). The aim is not sheer data gathering about the system compartments, but instead the understanding and linking of behavioural patterns and the processes/interactions inside systems. In this sense, Suteanu (2005, p. 136) concludes that "Complexity theory seems to provide a guarantee that the future remains open to new developments and surprises."

3.2 Risk Research

Risk research aims at the understanding of underlying conditions generating disasters and the prevention or reduction of disaster impacts. Scientists from such different disciplines as geography, economy, meteorology, sociology or historical and political science deal with risks. The research arena reflects not merely the varying aspects and impacts of disasters, but also different understanding and research interests. Perspectives how to theorise and assess risks differ enormously between the disciplines and lead in consequence to different research programmes and interpretations of results. According to this, also the definition of the term "risk" varies, even in interdisciplinary research approaches.

In more than half a century of risk research, many risk concepts evolved reflecting the different perspectives as well as the *zeitgeist*. The variety of concepts is often explained against the background of their epistemological foundations (see further Zinn 2008, pp. 3–7). According to Zinn (2008, p. 8), risk epistemology ranges from an understanding of risk as *real and objective* e.g. in technical risk assessments, to being *subjectively biased* e.g. in the psychometric paradigm or *socially constructed* e.g. as in systems theory approaches. In this chapter three perspectives will be introduced: psychological approaches, social science approaches and coupled/integrative approaches for the assessment of risk and vulnerability (see Sect. 3.2.3).

The epistemological framework of this research approach is primarily directed to an agent-based approach, i.e. it is based on a model-centred epistemology (see Sect. 2.1). The application of agent-based modelling in risk research, as underlying research interest here, supposes that risk perspective(s) and methodological approach complement one another. The introduction of relevant approaches of risk and vulnerability from the three different perspectives (see Sect. 3.2.3) thus serves for the development of a theory-based conceptual model—in the agent-based approach (see Sect. 5.1). Before presenting the risk/vulnerability approaches, the key terms are introduced and defined according to the understanding underlying this approach. Hereby the focus is on processes and aspects such as dynamics, interactions, (human) agency and on constituting parts or levels. As the agent concept (see Sect. 2.3) is based on the theoretical foundations of complex systems research (see Sect. 3.1) it also plays an important role for the risk perspective developed here. How to conceptualise disaster, risk and vulnerability according to a complex systems perspective is revealed by researchers such as e.g. Comfort et al. (1997, 2005); Hilhorst (2003, 2004); Downing et al. (2006); Helbing (2010) or the IRGC (2010).

3.2.1 Risk and Disaster

Risk is inherent in social systems and yet something abstract, e.g. a catastrophic potential expressed in the probability of occurrence of a flooding event, something unfamiliar or something we feel exposed to involuntarily.[11] According to the risk research concepts, risks may either be understood as subjective and socially constructed, i.e. as a result of an individual-intuitive risk estimation process or as

[11] Risk is "imaginary, difficult to grasp and can never exist in the present, only in the future. If there is certainty, there is no risk. Risk is something in mind, closely related to personal or collective psychology" (Cardona 2004, p. 47).

objective, i.e. as a probability of losses measured on the basis of quantitative risk parameters[12] (see e.g. Acosta-Michlik and Espaldon 2008; Renn et al. 2007; Kasperson and Kasperson 1996, 2005). But no matter which risk concept we follow, risk becomes real as it manifests to disaster. Risk is the pre-stage of a disaster; impacts and losses are merely *expectations*—whether objectively verifiable or subjectively based.

A disaster instead is defined by referring to the underlying *causes* and resulting *consequences*. A disaster "results from the combination of hazards, conditions of vulnerability and insufficient capacity or measures to reduce the potential negative consequences of risk" (see UN/ISDR 2004). According to another UN/ISDR (2004) definition agreed on by the international community, a disaster is a "serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community/society to cope using its own resources".

The disaster definitions can be reduced to two basic assumptions. First of all, a natural event is not yet a disaster, only due to a certain negative human impact it turns into a disaster. Second, a disaster results from interactions between natural or human-induced hazards and vulnerable conditions of the social system. Solely in combination they lead to the probability of harmful consequences, the risk, or to a disaster. Risk presupposes hazardous and vulnerable conditions, whereas the hazard is usually associated with the natural environment and vulnerability with the human/social environment. A hazard can be described by the probability of occurrence of a natural event (not disaster) and constitutes a condition in the natural environment such as potential flooding events, storm surges or droughts. Vulnerability is the likelihood that a society or individual will be exposed to and adversely affected by the hazard due to the physical, socio-economic, ecological, and political-institutional conditions which can vary over space and time (Cutter 1993; Boruff et al. 2005). The human-environment relationship can be further emphasised by describing vulnerability as "the interaction of the hazards of place […] with the social profile of communities" (Cutter 1996, p. 532).

Although vulnerability can occur only in the presence of a hazard, it does not mean that the primary impulse is localised in the natural environment. Due to the complex relationship between hazard and vulnerability or natural and human environment, the risk process can rather be seen as a co-evolution between both systems and/or states. Despite a meanwhile broad acceptance of disasters as an interaction between the natural and social system, in recent risk approaches the mutually constitutive character of the systems is further emphasised. Disasters are not just seen as a temporally conjuncture of a natural event and human society but as an unfolding process which is "rooted in the co-evolutionary relationship between human societies and natural systems" (Oliver-Smith 1999a, p. 30, see also b). The "traditional" cause-effect-model conceptualising disasters due to a triggering event and a limited number of root causes, has been superseded.

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[12] Also the objective risk estimation underlies subjectivity of the researcher or risk manager.

In this sense, the International Council of Science (ICSU 2008) argues that "Understanding the coupling of human and natural systems is the key to preventing a hazard becoming a disaster". Furthermore Perry (2006, p. 12) concludes that there is wide agreement (outside the classic perspective) that disasters are understood in human interaction. Recent more integrative approaches emphasise the mutuality of hazard and vulnerability due to the complex interactions between the natural and social system (Hilhorst 2003; Warner et al. 2002). Disaster risk is described as a complex phenomenon e.g. by Comfort et al. (2004) whereas the central characteristic of risk in complex systems are interactions among agents that are exposed to a hazard. But also human agency is further emphasised in recent approaches; that risk depends critically on human actions and decisions (see e.g. ICSU 2008, p. 22). Hilhorst (2003) indicates that hazards are increasingly the result of human activity; people are not just vulnerable to hazards. Handmer and Dovers (2008, p. 11) argue that recognizing the importance of human agency "opens the way for the development of institutions, policy and practice aimed at reducing vulnerability […] however, may also encourage attribution of blame, whether deservedly or not, so the shift is by no means entirely positive". Especially in the context of so-called systemic risks the human component is assessed and requires an understanding of the collective social dynamics (see Helbing 2010; IRGC 2010; Renn et al. 2007). Kasperson and Palmlund (2005, p. 64) emphasize that despite the propensity to often convey risk in one-dimensional terms, risk is multi-dimensional. Dealing with such complex phenomena they further define the need for multiple perspectives and differing characterisations of risk.

3.2.2 Dynamics of Vulnerability

Vulnerability here is defined as the characteristics and circumstances of a person or group that make it susceptible to be adversely affected by the impact of a hazard.[13] This definition focuses on vulnerability of individuals or social groups, i.e. the micro or meso-level. Oliver-Smith (2004, p. 11) understands vulnerability rather as something which is "conceptually located at the intersection of nature and culture and [something which] demonstrates, often dramatically, the mutuality of each in the constitution of the other. Disasters seem to be especially apt as contexts and processes that illuminate these complex relationships". He further argues that understanding of vulnerability must include the dialectical human-environment interaction as well as the social construction of risks (Oliver-Smith 2004, p. 17). According to Bankoff (2001, p. 30), disasters emerge as a result of the interactions between humans and their environment, but he further emphasises that "populations at risk are populations actively engaged in making themselves more vulnerable".Besides the micro level, focus can also aim at the micro–macro relationship

[13] Definition is based on Cutter (1993) and Wisner et al. (2004).

e.g. at the relationship between individual behaviour and social constraints. Social vulnerability approaches regard "not just the characteristics of people (individuals) but also their relations within wider society, the nature of the relationships and the physical and societal environment they inhabit" (Tapsell et al. 2010, p. 6).

Assessments of vulnerability thus may include the human-environment interactions as well as the micro-macro relationships. Studies such as the meta-analyses of the CapHaz-Net project[14] propose approaches that explore vulnerability as "highly context-specific in terms of local/regional, socio-economic, demographic, legal, political and cultural contexts" (Tapsell et al. 2010, p. 61). Besides the analysis of the individual, relational and societal aspects of vulnerability, Tapsell et al. (2010, p. 63) point out to further assess social changes due to their potential to increase vulnerability. Kelly and Adger (2000, p. 329) analyse the social construction of vulnerability and "how different socio-economic and political […] *processes* or *trends* influence levels of vulnerability". The emphasis on multi-dimensional aspects seems necessary but also of changes in these aspects over time. "Thus, as susceptibility[15] varies between different individuals, groups or locations, as it increases or decreases over time as a result of physical changes (e.g. to climate or genetic makeup) or behavioural changes (e.g. via learning or changing norms), the consequences of an emerging risk may be amplified or attenuated and its future trajectory may be altered." (IRGC 2010, p. 27). The IRGC (IRGC 2010, p. 26) reasons that for analysis not only the existing variance in vulnerability needs to be considered, but also how vulnerabilities can change over time. The spatial, individual and relational dynamics changing vulnerability over time are further explained in the following paragraphs.

From a multi-dimensional perspective, vulnerability also encompasses spatial or physical aspects that may underlie changes over time. On the one hand, the susceptibility of a human settlement to be affected by a hazard due to its location in the potential area of influence is termed *exposure* (Cardona 2004, p. 49). On the other hand, vulnerability can increase due to a lack of physical resistance, e.g. of infrastructure, or due to the fragility of ecosystems or resources. Spatial/physical aspects of vulnerability can vary over time; vulnerability can increase or decrease e.g. depending on the season of hazard occurrence, on the environmental functions or ecosystem services of the region affected by the hazard. It can vary due to the geographical area affected e.g. densely populated lower reaches or remote upper reaches of a river system. Wisner et al. (2004) further reviewed how global trends can increase the spatial aspects of disaster risk, e.g. urbanisation, resource degradation, global environmental change and sea-level rise, and named these processes *dynamic pressures*. Also Zevenbergen et al. (2010) and Etkin (2009) point out that risk management should consider spatio-temporal relations e.g. how the responses to flood impacts are complicated by environmental and socio-economic

[14] The CapHaz-Net project is a European Coordination Action project within the 7th FP (see further CapHaz-Net 2011).

[15] Here used as a synonym for vulnerability.

changes. Vulnerability analysis of low-lying areas such as coastal regions and cities in Germany, the Netherlands, El Salvador, or Bangladesh thus needs to consider these changes concerning future spatial vulnerability or exposure.

Emphasis on the individual at risk considers that vulnerability is not only a function of exposure to a hazard; it is also shaped by human behaviour and cognition (Acosta-Michlik and Espaldon 2008, p. 554). Risk critically depends on human actions and decisions and accepts the role of humans in creating conditions for disaster (see further Sect. 3.2.4; ICSU 2008). Besides the multiple attributes of vulnerability, risk therefore is associated with decision making i.e. "with something that has to be done, with the execution of an action that ranges from the most trivial to the utmost important" (Cardona 2004, p. 47). As the results of these actions are in the future and uncertain, Cardona emphasises that the "future lines of action" regarding risk need to be evaluated in order to take decisions. Further research gaps are identified in terms of understanding how the perception of vulnerability affects people's reactions and how it shapes people's decisions to respond (Tapsell et al. 2010, p. 63).

Bharwani et al. (2007, p. 19) refers to the importance of *multiple* attributes of vulnerability of the *heterogeneous* groups at risk. Differences in aspects such as individual perception of risk and vulnerability, experience with and information about the hazard, socio-economic conditions of a person, etc. may result in *different* impacts of hazards within communities or societies. Thus, the individual characteristics and response capacities need to be considered also to reveal the vulnerability dynamics *within* a community or society. Not only socio-economic aspects can make people more vulnerable, but also their ability to access and understand information is critical for identifying and prevent risks. Especially the use of social networks "may attenuate risks by helping people to become better informed and thus better able to minimise risks to which they may personally be exposed" (IRGC 2010, p. 31). Group dynamics have an impact on individual risk behaviour within societies too and may further include the analysis of changing societal constraints and dynamic macro-pressures affecting individuals. Dynamics of vulnerability due to heterogeneity of social groups play an important role not only for risk communication (see further Martens et al. 2009; Höppner et al. 2010; Peters and Heinrichs 2005); in a wider context, vulnerability may also change between the different stages of the disaster cycle, and people's vulnerability may change depending upon their position in the cycle (Tapsell et al. 2010, p. 61).

To summarise, an analysis of spatial, individual and relational aspects particularly with regard to their influences on vulnerability dynamics can extend the "static nature of the concept of social vulnerability" (Tapsell et al. 2010, p. 62). On a broader scale, impacts of human and environment behaviour on each other as well as between micro and macro level account for the dynamic notion of vulnerability (see further ICSU 2008; Dougill et al. 2010). Therefore analysis of the multi-dimensional aspects of vulnerability should also encompass how vulnerability changes over time. Garrelts and Lange (2011, p. 207) conclude that complex phenomenon (such as climate change) call for "dynamic conceptualizations which grasp steering as a sequentially progressing and reciprocal process, grasped as a complex pattern of interaction between inter-dependent actors" (see further Scheffran 2011; Füssel 2007; Folke et al. 2002). Considering the vulnerability changes over time, Downing et al. (2006, p. 9) differentiate further between trends of gradual changes[16] varying within predictable limits (e.g. on macro level) and shocks leading to sudden changes (e.g. on micro level) for analysis. Bharwani et al. (2007, p. 18) outline, that "priorities for vulnerability reduction can be identified from the exploration of the *dynamic vulnerability* experienced by a community". In consequence, positive social dynamics decreasing vulnerability need to be reinforced in order to lower society's vulnerability.

3.2.3 Assessment of Risk and Vulnerability

Risk assessment forms the basis for developing risk reduction and disaster response strategies. In the first phase of a comprehensive risk management approach, thus hazard potential and vulnerability dimensions are identified and estimated. According to this knowledge base, risk reduction measures and disaster response strategies can be implemented. The three phases constituting a comprehensive risk management involve different methodological and disciplinary approaches as well as social actors (Cardona 2004, p. 40). As understanding of risk differs between disciplines and actors involved, not solely the risk management phases, but also the differing risk concepts need to be integrated into a comprehensive whole. Risk assessment thus should reflect how risks are perceived in society, how they are represented (models, maps, indicators) and how they are measured (Cardona 2004, p. 40; see further Felgentreff and Glade 2008, p. 93). Zinn (2008, p. 2) comments that it "is as much a discourse on defining a problem, about different values and lifestyles, power relations, and emotions as it is about "real" risks and their rational management.

Risk assessment has strong roots in empirical data gathering; theory construction began later as modelling of risk events was introduced (Krimsky and Golding 1992, p. 5). And as already mentioned a variety of concepts evolved in risk research reflecting the different perspectives and the corresponding *zeitgeist*. Omitting normative risk calculation, risk approaches range from a psychological, social science to a coupled perspective presented in the following subchapters. Theories or concepts usually present a pattern for observation. "However, each analysis is limited by the paradigm which is chosen to be the analytical framework" (Shen 2010, p. 153). From the following psychological, social science and coupled approaches of risk assessment 12 models or concepts are selected. They are described in more detail as they represent and focus on different levels of analysis and vulnerability indicators relevant for later application in an agent-based approach (see Sect. 5.1).

[16] Though, not necessarily linear.

3.2.3.1 Psychological Approaches

The focus of psychological risk approaches is on the individual, i.e. on micro level. The subjective risk judgement of individual sand the plurality of risk acceptance are core aspects of the psychological perspective (Renn et al. 2007, p. 41). From the 1970s onwards, the results of psychological risk approaches have broadened the one-dimensional "objective" risk assessment perspective. According to the psychological approaches, lay people use qualitative and multi-dimensional risk evaluation factors that are composed of more than the quantification of probability of occurrence and expected losses (see e.g. Kasperson and Palmlund 2005; Renn et al. 2007). Contextual or situation-related risk characteristics e.g. the voluntariness of risk exposure, the degree of familiarity regarding the risk or the unambiguity of hazard information are aspects considered in risk perception and evaluation processes of individuals. But other than risk experts, lay people reduce the process of risk assessment and risk evaluation to one step. In order to come to a decision, individuals use simplified approaches for decision making under uncertainty, also termed bounded rationality (Renn et al. 2007, p. 42). The contribution of psychological approaches for risk management thus lies in the broadened understanding of risks not merely as objectively based but also as subjectively biased. Considering the subjective risk evaluation of individuals is insofar important as it provides guide for understanding risk handling and preventive behaviour of individuals. Self-protective behaviour and disaster response capacities of individuals play an important role in a comprehensive risk management leading to more sustainable and resilient societies (see e.g. Grothmann and Reusswig 2006).

Research by Fischhoff et al. (1978) aimed at people's risk acceptance and the factors underlying acceptance such as perception and attitudes. This early psychological approach, also known as the *psychometric paradigm*, was developed as a reaction to Starr's investigations (in Slovic 1987, p. 281; Fischhoff et al. 1978) as a secondary source about societal risk acceptance and his method to weigh the perceived correlation between technological risks and benefits "to reveal patterns of acceptable risk–benefit trade offs" (Slovic 1987, p. 281; Fischhoff et al. 1978). Starr's approach assumed a rather rational considerationof risk judgements, regarded as "laws of acceptable risk".[17] Furthermore, Starr identified voluntariness of risk exposure as the key mediator of risk acceptance. Instead Slovic et al. (1982) concluded that a set of perceived risk characteristics influences risk attitudes assessed in empirical studies.Among the insights of Slovic's application of the

[17] Starr's insights have been summarised in the following two assumptions: "(i) acceptability of risk from an activity is roughly proportional to the third power of the benefits for that activity, and (ii) the public will accept risks from voluntary activities (such as skiing) that are roughly 1000 times as great as it would tolerate from involuntary hazards (such as food preservatives) that provide the same level of benefits" (Slovic 1987, p. 282).

psychometric techniques three general findings are: (i) individuals use heuristics[18] to judge/evaluate the probability of negative consequences, (ii) it is possible to identify similarities and differences between risk perception and attitudes of experts and lay people and (iii) that the understanding of the concept "risk" varies between those groups and different criteria are used when making risk judgements (Bickerstaff 2004, p. 829; see also Slovic 1987; Renn et al. 2007). The psychometric paradigm led to the recognition that "risk" means different things to different people (Slovic et al. 1982, p. 85; Slovic 1993). Although Slovic et al. generalised their method to be meant for predictions about perceived risk, psychological approaches today rather aim at identifying typical patterns that determine the perception and evaluation of risks. Yet, a homogeneous perception and evaluation scheme concerning risks does not exist (Renn et al. 2007, p. 43). Instead further research has identified two types of qualitative perception patterns, risk-related and situation-related patterns influencing risk perception (see further Covello 1983; Renn et al. 2007). Although many of the factors proposed in the psychometric paradigm approach are still considered, e.g. knowledge about risk, control over risk or severity of consequences, further factors from social science approaches are often added (see e.g. Plapp and Werner 2006; Bickerstaff 2004; Sjöberg 2000).

In the study of Slimak and Dietz (2006) for example risk perception is linked to values and general beliefs about the environment as well as to spiritual and religious beliefs of individuals. The research study extends the *Value-Belief-Norm* (VBN) *theory* described by (Stern et al. 1999; Stern 2000), developed in order to find factors influencing environmentally significant individual behaviour. The VBN theory combines a theoretical model of the norm-activation theory, the theory of personal values and the new ecological paradigm as a worldview scheme (see further Stern et al. 1999; Stern 2000). Slimak and Dietz (2006) explored the influence of spiritual values for the awareness of consequences as a measure for risk perception with regard to 24 ecological risk items. As the authors criticise the domination of risk studies focussing on characteristics of the risk source, they include in particular factors describing characteristics of individuals perceiving the risk. Thus, social-psychological variables, e.g. personal values, spiritual beliefs and world views as well as and social-structural variables, e.g. education, income or ethnicity are considered in the research study. The influence of group membership is additionally assessed whereas four different groups are taken into account, namely lay public, experienced public, risk assessors and risk managers (see further Slimak and Dietz 2006). Consistent with the psychometric paradigm, the study differentiates experts and lay public. According to their findings, experts perceive ecological risks (and rank risks) differently than the lay public, hence, their perceptions are also influenced by personal values, beliefs and world views (Slimak and Dietz 2006, p. 1703).

[18] "To simplify risk problems, people use a number of inferential or judgemental rules, known technically as heuristics. […] These judgmental operations enable people to reduce difficult probabilistic and assessment tasks to simpler tasks; however, these judgmental operations also lead to severe and systematic biases and errors" (Covello 1983, p. 287).

The previously introduced research approaches focus on preferences of individuals concerning risk perception, risk acceptance and ranking. In further recent psychological studies also the preferences of individuals concerning policy options are added. In the *model of precautionary action* by Grothmann and Reusswig (2006) the relationship between risk perception and risk preventive behaviour of private households is assessed. The research study conducted in a flood-prone area of Germany compares perceptual factors and socio-economic factors influencing flood adaptation (Grothmann and Reusswig 2006, p. 117). In order to test the hypothesis a socio-psychological model, including e.g. people's subjective perceptions of flood risk and coping abilities as well as a socio-economic model based on objective socio-economic features like households' income are compared to each other. The developed approach is based on *Protection-Motivation Theory* (PMT), one of the major theories within the domain of psychological research on health behaviour. The theory developed by Rogers (in Grothmann and Reusswig 2006, p. 104) as a secondary source has further been tested for application in natural hazards research (Grothmann and Reusswig 2006, p. 104). The PMT takes into account two major perceptual processes of individuals: threat appraisal (risk perception) and coping appraisal (beliefs about the efficacy and practicability of self-protection measures). The results of the German study show that by including psychological variables, the explanatory power of more simple socio-economic models can be improved (Grothmann and Reusswig 2006, p. 117). However, inferring causality of precautionary adaptation was inappropriate in the study; instead it explained influencing factors of perception and beliefs for self-protection. Grothmann and Reusswig (2006, p. 118) conclude that also non-protective responses—like denial, wishful thinking or fatalism—seem to play a major role in de-motivating precautionary behaviour of individuals as well as reliance on public flood protection.

From the results of psychological approaches further lessons can be drawn for improving risk communication. Other psychological approaches therefore focus further on risk communication processes. The model approach developed by Paton (2003, 2008) and McIvor et al. (2009) assesses the factors underlying intentions for disaster preparedness of individuals. The model approach aims at constituting a relationship between individual, community-based and societal factors for preparedness intentions. The components of the model describe a reasoning process whereas preparedness is assessed concerning the individual, community and society dimension (see further Paton 2003; McIvor et al. 2009). Paton (2008) focuses in particular on the role of trust for decision making and the resulting implications for risk communication; i.e. not information *per se* determines action but *how* people interpret it. The results of Paton's and McIvor's et al. studies seem to further explain the non-protective responses already mentioned by Grothmann and Reusswig (2006). They emphasise that information about risks and risk prevention "will be evaluated in terms of peoples' generalised beliefs regarding trust in the social institutions providing information" (Paton 2008, p. 14). Criticism is expressed in particular regarding "risk communication programmes […] [that] do not address themselves to the creation of social contexts conducive to encourage a discourse about natural hazards in ways that will facilitate citizens' active involvement in developing strategies to mitigate their natural hazard risk" (Paton 2008, p. 14). They further express self-protective responses by individuals as depending on the degree to which people perceive that the agencies empower them by providing information that meets their needs (McIvor et al. 2009, p. 40).

Another model considering the processes of adopting risk reducing behaviour is the *Precaution-Adoption-Process Model* (PAPM) by Weinstein and Sandman (1992). As well as in the modelling approach by Paton, social-cognitive variables are taken into account. Whereas the PAPM conceptualises the adoption process as a series of distinct cognitive stages and presumes that each behaviour change can be described by a certain stage. According to Weinstein and Sandman (1992, 2002) stages range from a person being unaware of the threat or of possible protective behaviour to a person that deliberates costs and benefits of changing behaviour towards a stage of acting and further maintenance (see also Sniehotta et al. 2005). The model does not rely on fixed key variables but rather aims at the gap between an individual's intentions *and* actions. Application of the PAPM is rather related to health risks such as AIDS, BSE or Radon. By means of the PAPM such factors can be identified that could induce movements from one stage to another or that people overcome barriers for behaviour change (see further Weinstein and Sandman 2002). By focussing on socio-psychological factors describing risk perception and behaviour of individuals, psychological theories can improve the understanding for a comprehensive risk management. But inclusion of social contexts and relationships, as already conducted in some psychological approaches, might further broaden the micro-perspective (Renn et al. 2007, p. 44).

3.2.3.2 Social Sciences Approaches

Social science approaches in risk research focus on the socio-economic and socio-political conditions of individuals or households, on their social relations as well as on socio-cultural groups. Since the 1980s, social scientist began to emphasise that impacts of disasters are not only dependent on hazard potential but on the capacity of a household, community or society to absorb and recover from the disaster impacts. Risks affect people and populations in different manner mainly due to differences in the society's capacities and vulnerabilities. Capacities vary between e.g. developed and developing countries, cultures, underprivileged social groups or the most vulnerable groups such as the elderly or the poor. Wisner et al. (2004, p. 87) describes the intention behind (social) risk analysis as explaining *why* certain "groups, defined by ethnicity, class, occupation, location of work or domicile may suffer differentially from others". According to Susman et al. (in Vulnerability Net 2008) as a secondary source vulnerability is understood as "the degree to which the different social classes are differentially at risk". Thus, from a social science perspective, vulnerability is established according to the socio-cultural, political and economic conditions in society.

The *Access model*, associated with Wisner et al. (2004), provides an explanatory framework with a focus on the socio-economic processes influencing vulnerability. In the Access model the longer-term social processes are analysed from the point of a natural event onwards. The model acts on the assumption that the amount of *access* people have to the capabilities, assets and livelihood opportunities enables them (or not) to reduce their vulnerability and avoid disaster (Wisner et al. 2004, p. 88). The concept of access refers to material, social and political resources. The model starts with an analysis of the interactions of environment and society at the onset of a disaster and follows possible trajectories of a disaster, e.g. when normal life is interrupted and becomes abnormal. Thus, it explains "at a micro level the establishment and trajectory of vulnerability and its variation between individuals and households" (Wisner et al. 2004, p. 88). According to the Access model, the distribution of or access to capabilities in society is central and herby the differential progression of vulnerability can be explained. The model has been developed in addition to the *Pressure- and-Release model* (PAR; also Wisner et al. 2004). The PAR model focuses on the pre-conditions for a disaster. It leads the researcher from the disaster event back to more distant factors and processes along the "chain of causation" of a disaster (Wisner et al. 2004, p. 87). The Access model instead provides a dynamic framework showing how social systems create conditions in which hazards have a differential impact on various societies and different groups within society.

The Access model supposes that individual decisions are always made in a political-economic environment; it relies on the concept of the socially embedded individual. Another concept dealing with the importance of the social environment is the *Social Amplification of Risk Framework* (SARF) by Kasperson et al. (2005). Whereas in the Access model the socio-economic conditions generating vulnerability are assessed, the SARF analyses the social contexts in which risk are conceptualised, identified, measured and managed. According to the SARF, the social setting of individuals and social stations occupy a primary role in society's risk handling. Amplification refers to the process of intensifying or attenuating signals during transmission of information about risk events from one information source to intermediate transmitters and to the receiver (Kasperson et al. 2005, p. 103). The risk signals are processed by individual as well as social (e.g. institutional) amplification stations. The risk-related information further spawns behavioural responses that in turn result in secondary effects influencing society's risk handling. As these impacts may ripple to another stage of amplification, they can further lead to higher-order impacts e.g. on higher institutional levels, locations or generations (Kasperson et al. 2005, p. 107). The authors of the SARF hold the view "that risk events interact with psychological, social and cultural processes in ways that can heighten or attenuate public perception of risk and related risk behaviour" (Kasperson et al. 2005, p. 101). Instead of insisting on the different disciplinary perspectives, there aim is to provide a framework that aims at understanding the different kinds of public responses concerning risks by including dynamic processes such as learning or social interactions.

In the SARF risk information is transmitted via different social stations. *Cultural theory*, developed by Douglas and Wildavsky (1982), proposes culture as the primary coding principle for risk recognition. The socio-cultural approach claims that different cultures exist with their own characteristic view of the world, of the human-nature relationship and thus also on risk, referred to as cultural biases (Kasperson and Palmlund 2005, p. 57). The application of Cultural theory aimed at understanding risk perception (e.g. Bickerstaff 2004) and risk management approaches of different cultures (e.g. Shen 2010; Leiserowitz 2006) in a wider social, cultural and political analytical frame. Although Cultural Theory has been criticised mainly due to lack of empirical proof (see e.g. Sjöberg 2002), the socio-cultural perspective is viewed as correlate to the research about values and attitudes as it provides a context for differing world views of individuals (Renn et al. 2007, p. 58).

3.2.3.3 Coupled Approaches

The social science and psychological approaches refer to different levels of analysis and vulnerability dynamics. The coupled or integrative approaches selected here, present a more comprehensive perspective on dynamics by cross-level analyses. The framework developed by R. Palm for example focuses in particular on the micro–macro relation as a coherent whole. Thus the framework links the psychological micro level with the social science perspective of the socially embedded individual. Relevant for application in an agent-based approach is not merely the micro–macro relationship but also the human-environment relationship. Other coupled approaches such as the *PAR model* associated with (Wisner et al. 2004) and Cutter's model take human-environment interactions into account. In addition to the vulnerability perspective, they further include aspects of the physical environment or processes between human, physical and natural environment. The analytical framework of coupled approaches focuses in particular on cross-level interactions between different components and thus they approximate the system perspective. For analysis of risk both hazard and vulnerability conditions are recognised according to the well-known formula Risk = Hazard × Vulnerability.

The *Pressure-and-Release* (PAR) *model* by (Wisner et al. 2004) is linked to the already explained Access model. The PAR model builds a broader framework including both vulnerability and hazard aspects, whereas the Access model magnifies the socio-economic conditions of individuals and households at the point of disaster occurrence. Whereas the Access model starts at the point of disaster occurrence and analyses the changes from this point onwards, the PAR model conceptualises the chain of causation leading to the disaster event itself. The PAR *model* thus is covering the processes from the disaster event and its proximate causes back to more distant factors and processes that initially may seem to have little influence on the disaster (Wisner et al. 2004, p. 87). The PAR model analyses the progression of vulnerability including root causes and dynamic pressures that further translate the effects of root causes into unsafe conditions (see Wisner et al. 2004, pp. 51–53). It traces the connections between social factors and processes generating vulnerability and the impact of a hazard. The chain of explanation developed in the PAR model can be related to a series of different types of hazards such as e.g. earthquakes, floods, volcanic eruptions, landslides or droughts by Wisner et al. (2004). But with a special focus on vulnerability, Wisner et al. (2004, p. 56) point out, that no single element of the model should be looked at in isolation from the entire range of factors and processes that constitute this situation.

Another framework focussing on the coupled human-environment system in order to assess vulnerability has been developed by Turner et al. (2003). The *coupled vulnerability framework* by Turner et al. (2003) is based on an understanding of vulnerability from a sustainability science perspective. Other than in risk research where the term vulnerability is rather retained for the social system, vulnerability is additionally related to the biophysical (sub)system (see Wisner et al. 2004, p. 55; Turner et al. 2003, p. 8074). As the framework aims at sustainability, more emphasis is given to the manner in which coupled systems experience hazards and to nested scales and scalar dynamics of hazards. Furthermore, the sustainability science perspective encourages a place-based analysis of vulnerability. Vulnerability is viewed—despite common global scale processes and similar human and environmental influences from outside the place of analysis—as strongly varying by location. Turner et al. (2003, p. 8076) further outline that the term place-based "implies a spatially continuous distinctive "ensemble" of human and biophysical conditions or coupled human-environment systems". More than other frameworks, the coupled vulnerability framework focuses on different scales and scalar dynamics. The components of vulnerability are linked to factors beyond the system under study and across various scales. Thus, the framework comprises in place, beyond place *and* cross-scale dynamics (see further in Turner et al. 2003, p. 8076). But the framework is too comprehensive for real-world data. Another "reduced" vulnerability assessment therefore is framed by Turner et al. (2003) whereas the analysis is affected by the way in which the coupled system is conceptualised and bounded for study; yet it is still embedded within the larger context of the comprehensive framework. Besides the concept of exposure and sensitivity, the reduced vulnerability framework by Turner et al. (2003) includes also a resilience component.

Another recently developed framework by Cutter et al. (2008), the *Disaster Resilience Of Place* (DROP) *model*, refers in particular to community resilience. The authors argue that a conceptual model for disaster resilience is needed as well as potential variables in order to measure resilience on community level (Cutter et al. 2008, p. 598). Another approach by Cutter (1996; Cutter et al. 2003), the *hazards of place model*, failed to further account the larger context and post-disaster phase of response and recovery (Cutter et al. 2008, p. 601). For the development of the DROP model the perspective of a place-based analysis of vulnerability and hazards is maintained. But in addition to other frameworks, the antecedent conditions of vulnerability in the natural and social system as well as in the built environment are taken into account (see further Cutter et al. 2008, pp. 601–603). Furthermore, resilience is considered as having two qualities: inherent, i.e. functioning during the pre-disaster phase and adaptive, i.e. flexibility in responding to the disaster situation. The model thus represents a comprehensive analytical framework including antecedent conditions of vulnerability leading over to the short-term and long-term resilience dimensions with regard to disaster events. The DROP model provides a conceptual framework for resilience of coupled human-environment systems, yet the real-world application of the framework has still to be tested (Cutter et al. 2008, p. 604).

R. Palm's critique of natural hazards research is directed to the ignored linkages between society-environment and individual-environment interactions; "how individual responses can modify the system and how awareness of the constraints of the system affects the selection of micro level behaviors" (Palm 1990, p. 79). In order to better link micro and macro level, Palm advises the understanding of mutual effects[19] instead of focussing on single cause-and-effect mechanisms. The framework does not allow understanding or predicting law-like behaviour but describes rather a cross-level mode of analysis of the human-environment relationship (Palm 1990, p. 79). Palm's approach criticises that the linkages are overlooked by solely focussing on micro *or* macro level of analysis. The conceptualised schema includes relationships among individuals, society and the environment ranging from the micro to the macro scale (see further Palm 1990, p. 81; 93). Another essential element of the research design is the meso scale that is defined as "those factors that link large-scale with small-scale phenomena, while at the same time interacting with these phenomena" (Palm 1990, p. 80). According to Palm (1990, p. 80) not only the existence of the connections but also their strength influences understanding of human behaviour towards risks. By explaining the linkages and understanding the mutual effects, appropriate interventions for better risk prevention can be identified.

The following table (see Table 3.1) gives a synoptical overlook of the indicators used in the vulnerability frameworks from psychological, social science and coupled approaches.

3.2.4 Reducing Vulnerability by Self-Protection Measures

"A risk-free society has never existed and will never exist" (Quarantelli et al. 2006, p. 41). Yet the existing risks can be reduced by risk reduction and disaster response strategies. As already mentioned, assessment of hazard potential and vulnerability dimensions provides the knowledge base for a comprehensive risk management and its implementation. The rationale behind vulnerability analysis and indicator development has been further outlined by Birkmann (2006, pp. 55–57). Accordingly, vulnerability assessment aims at e.g. developing actions, monitoring progress and analysing trends as well as anticipating undesirable states of vulnerability (Birkmann 2006). Yet, the vulnerability assessment is also determined by the levels of analysis;

[19] Palm (1990, p. 79) compares the understanding of mutual effects to a fishnet "in which both the holes and the material defining them create meaning: here, one must understand both the structure of the macro forces in society (the political economy and its cultural context) and the nature of individuals, as well as the transmission of interactions between them, in order to comprehend the place of given behavior in an environment".

Table 3.1 Indicators of psychological, social sciences and coupled risk approaches with regard to different levels of analysis (micro, macro & human, environment)

	Indicators influencing risk perception, evaluation & response		
Psychological approaches	Micro ←	(Macro)	Label of Analysis
	Personal control over risk components, voluntariness of risk exposure, impression of benefit-risk distribution, trust in institutional control & management of risks, reliance on public risk protection, previous experience, hazard knowledge, reliability of information sources, unambiguousness of information, salience, relevance, perceived vulnerability, values (e.g. concerning nature, religion, spirituality), etc.		Human ↓
	Perceived protective response efficacy/outcome expectancies, perceived self-efficacy, protective response costs, belief in preparing, influence of others, awareness of issue, personally engaged in issue, acting, etc.		
	Perceived catastrophic potential of risk source, perceived probability of fatal consequences e.g. for future generations, reversibility of risk consequences, familiarisation to risk source, perceived naturalness vs. artificiality of risk source, etc.		(Perceived) Environment
	Indicators influencing vulnerabilities & capacities to respond		
Social sciences approaches	Micro ←	Macro	Label of Analysis
	Age, gender, education, ethnicity, income, unsafe conditions/livelihood, social protection, access to capabilities and assets, world views (social, political, cultural attitudes), personal experience, receipt of information about risk, etc.		Human ↓
		Social relations, structure of domination, social protection, world views mediated by social relations, information flow in society, secondary impacts of behavioural responses in society, etc.	
	Nature of hazard (time/space), event characteristics		Environment

(Continued)

Table 3.1 (Continued)

	Indicators for assessing mutual effects on various levels		
Coupled approaches	Micro ⟵	Macro	Label of Analysis
	Exposure, limited access to resources & structures, income, knowledge, lack of appropriate skills, past experience, goals & expectations, role, etc.		Human ↓
		Sensitivity of human conditions, political system, lack of disaster preparedness, resilience, macro-economic pressures, social change, social relations, cultural values in society, etc.	
	Event characteristics, sensitivity of environmental conditions, changes in ecosystems, dangerous location, unprotected buildings & infrastructure, etc.		Environment

ranging from a top-down macro perspective to a bottom-up meso or micro perspective (Tapsell et al. 2010, p. 26). With regard to the individual dimension of risk (see Sect. 1.1), further consideration of individual capacities might be necessary. The individual risk and its calculation besides the societal risk is gaining importance and more attention in recent risk concepts (see e.g. Bründl et al. 2009). Lagadec (2006, p. 502) expresses the need for strengthening the civil society because we "can not longer rely on our vision of a state that provides solutions to passive groups of people within a "Command and Control" philosophy". Due to various experiences in terms of the limits of states in managing disaster events such as 9/11, the heat wave in Southern Europe 2003, the SARS epidemic 2002/2003 spreading over Asia, America and Europe, the tsunami 2004 affecting Asia, hurricane Katrina 2005, etc (see e.g. Adger et al. 2009) the strengthening of individual response capacities has gained more importance. Furthermore, it might result from a stronger recognition of the societal context in which risks occur. Rodriguez et al. (2006, p. 486) comment that if "we continue to emphasize the study and development of technology, while ignoring the social forces that shape individual and community behavior and response to hazards generally […], then we may have "improved" technology without understanding the complexities of human dynamics".

Self-protection capacities are viewed as one determinant reducing risk. The German Federal Office of Civil Protection and Disaster Assistance (BBK[20])

[20] Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (BBK).

defines *self-protection* as comprising "all measures taken by the population which are suited to prevent, alleviate or remedy hazards which are impending or have occurred in their own residential and working environments in a case of defence, in particular to life and health, vital facilities and goods" (BBK 2005). Alternatively the terms *individual precautionary adaptation* or *individual adaptive capacity* are used. Grothmann and Reusswig (2006, p. 102) for example distinguish *administrative* adaptation measures taken by public agencies from *private* adaptation measures taken by residents or firms at risk. They further differentiate between the potential damage and the actual damage, whereas the later depends on the ability of the people to avoid some of the potential damages through adjustments in the systems affected by the hazard. Goersch (2010, p. 18) characterises self-protection as knowledge *and* abilities of individuals that are strongly interrelated. The background and relationship of risk and prevention need to be understood in order to be able to acquire additional capacities in self-protective behaviour (Goersch 2010, p. 18). Besides the acquisition also the implementation of such abilities has to be trained and optimised. Thus, self-protection measures can be understood as both preventive measures before disaster strikes and as "self-help" measures, i.e. people's abilities to help themselves in the immediate situation of a disaster until further help is arriving (see further Goersch 2010, pp. 17–20; BBK 2007).

Self-protection measures have been further categorised as behavioural, structural and financial measures (see e.g. BMVBS 2008; MLUR 2008; MLUR 2007; MURL 1999). The measures can help to limit the adverse impacts of a hazard whereas all implicate risk awareness and knowledge of the affected households (Dehnhardt et al. 2008). In the case of flood hazards the area affected can be known due to earlier events, but can be very problematic in the case of earthquakes or hazard events with a low probability of occurrence (Wisner et al. 2004, p. 205). Behavioural measures of the exposed households imply e.g. to develop actions to avoid and reduce the risk as well as to prepare for effective response in case of an early warning. Such measures include for example drinking water and food supplies for 3 days, possession of flashlights, battery powered radio and first aid kit, knowledge of emergency numbers and evacuation plans. Structural measures refer to any physical construction to reduce or avoid possible impacts of the hazard by protecting buildings and private property (UN/ISDR 2004). They can be applied in the long-term as stationary measures, e.g. adapted design and implementation of building codes, and in the short term as non-stationary measures before the disaster event. Financial measures related to private households refer to insurance coverage, i.e. instruments of financial risk transfer.

A commission in Germany indicated a lack of self-protection and a lack of motivation for self-protective behaviour in their report about hazards and risks affecting the population (BBK 2006, p. 9). These lacks might be related to a low level of knowledge and of abilities with regard to self-protection in the German population. According to other research studies, people also tend to overestimate or underestimate different risks or even perceive a lack of control over risks (see e.g. Terpstra 2009). Though, Goersch (2010, p. 53) characterises these lacks rather as an underlying problem of awareness and perception of the topic. Further studies focussing on the underlying factors for self-protection or preparedness of households, in particular risk perception are e.g. Wachinger and Renn 2010; Steinführer et al. 2009; Terpstra 2009; Plapp and Werner 2006; Grothmann and Reusswig 2006; Kaiser et al. 2004. Despite these approaches, the meta-analysis conducted within the CapHaz-Net project (2011) still identifies a research gap in understanding of how the perception of vulnerability affects people's reactions and decisions to respond (Tapsell et al. 2010, p. 63). Yet, another European study by Steinführer et al. (2009, p. 33) concludes that "there is no linear or direct route from risk awareness to mitigation behaviour" or a "direct, immediate, and univocal link between perceptions, opinions, and attitudes on the one hand and actual actions and behaviours on the other".

In terms of assessing the dynamics of vulnerability, it seems important in particular to investigate and understand the self-protection behaviour of individuals. It seems important to consider that vulnerability is not only a function of exposure to a hazard; but that it is also shaped by human behaviour and cognition. In order to understand vulnerability as a dynamic process means to understand how it is rooted in the behaviour and action of individuals.The framework developed by Downing et al. (2006) therefore differentiates between vulnerability attributes and adaptive capacity. They further describe the dynamism of vulnerability as iterative: "The actions of actors are constrained by their [vulnerability] attributes, the inherent characteristics of individuals and groups that define their social vulnerability; equally actions lead to new attributes and mitigate or exacerbate their vulnerability" (Downing et al. 2006, p. 12). By focussing on dynamics of vulnerability depending on the individual attributes, the individual adaptive capacities or both, thus facilitates vulnerability assessments that allow analysis of trends, anticipating undesirable states or progress of vulnerability as well as further identification of necessary actions (Birkmann 2006). But due to the complexities of human dynamics, still many factors of vulnerability are beyond the control of individuals. Yet, from a complex system view, dealing with self-protective behaviour means to test the system-level adaptive capacity as an emergent attribute of lower order vulnerability (Downing et al. 2006, p. 26).

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Chapter 4
Regional Research Framework

4.1 The German North Sea Coast of Schleswig–Holstein

The State of Schleswig–Holstein in the north of Germany is embedded between the North Sea and the Baltic Sea. The western coastline is characterised by the North Sea with a length of 553 km and the eastern coastline by the Baltic Sea with a length of 637 km. About 24 % of the area of Schleswig–Holstein is categorized as flood-prone coastal lowland, namely about 3,700 km² of the total area of 15,800 km² (MLUR 2010, p. 2). Towards the north, Schleswig–Holstein shares a border with Denmark, towards the south with the State of Lower Saxony/Niedersachsen and the Free and Hanseatic City of Hamburg (see Map 4.1). The river Elbe separates Schleswig–Holstein from Lower Saxony while most of the river flowing through Schleswig–Holstein is dominated by the influence of the tide. The Elbe estuary, also called Tidal Elbe to differentiate it from the Middle and Upper Elbe, ranges from the weir in Geesthacht about 140 km to the North Sea (HPA/WSD-Nord 2006). Schleswig–Holstein can furthermore be characterised by many smaller river sand about 300 lakes as well as the Kiel Canal connecting the North Sea and the Baltic Sea. The most significant river Eider at the North Sea drains the hinterland whereas the river Stör is a tributary of the Tidal Elbe (Map 4.1).

Along the North Sea Coast, the district of Dithmarschen stretches from the estuary of the Eider River in the north to the estuary of the Elbe River in the south (see Map 4.1). The peninsula of Büsum projects into the Meldorf Bight, separating the Dithmarscher Nordermarsch from the Südermarsch (Vollmer et al. 2001, p. 135). Further towards the south-east, the district of Steinburg stretches from the estuary of the river Elbe towards the Elbe tributary Krückau. The river Stör subdivides the marshland of Steinburg into the Wilstermarsch and the Krempermarsch.

“No place in Schleswig–Holstein is further off the coast than about 60 km” (Innenministerium des Landes Schleswig–Holstein 2003, p. 4). And yet, the coasts of the North Sea and the Baltic Sea in Schleswig–Holstein differ with regard to geomorphological, geographical, ecological and cultural aspects. According to a

C. Sobiech, *Agent-Based Simulation of Vulnerability Dynamics*, Springer Theses,
DOI: 10.1007/978-3-642-32365-2_4,

Map 4.1 German North Sea Coast and the survey locations in Schleswig-Holstein (C. Carstens)

geomorphological perspective, coast is "a zone of varying width, including the shore[1] and extending to the landward limit of penetration of marine influence" (Bird 2000, p. 2). The Baltic Sea as a brackish inland sea shows typical forms of a glacial ingression coast in Schleswig–Holstein such as bays and water inlets of the Baltic Sea (e.g. Eckernförder Bucht, Kieler Förde, Flensburger Förde); the North Sea as a marginal sea of the Atlantic Ocean is characterised by wide marine wetland areas, mudflats islands and salt marshes (Kelletat 1999, p. 110). During the maximum extent of glaciation 18,000 years ago—the Weichselian Glaciation in northern Europe—the sea level was about 120–130 m below the present level (Köhn 1991, p. 82). The Baltic coastal region was morphologically shaped during and after the Weichselian Glaciation, whereas the North Sea Coast remained free of ice and was an area of widespread deposition of glacial outwash deposits during Pleistocene times (Sterr 2008, p. 380). With the melting of the ice sheets the sea level increased to a level of −60 to −70 m MSL (mean sea level) at the beginning of the Holocene about 10,000 years ago. The transgression of the North Sea led to the formation of the English Channel and of marine wetlands, the Wadden Sea between 8,000 and 7,000 years ago.

The German North Sea Coast is part of the trilateral Wadden Sea Region ranging from the western Netherlands and Germany to western Denmark (Kabat et al.

[1] Bird (2000, pp. 1–2) defines shore as the "zone between the water's edge at low tide and the upper limit of effective wave action".

2009, p. 22). In Schleswig–Holstein it covers an area of 2.600 km² (Schleswig–Holsteinischer Landtag 2009a). The Wadden Sea Region can be described by six distinct geographical landscape types with a high level of regional variation: dunes and moraine islands, littoral landscapes, coastal and tidal-river marshes, polder lands and drained lakes, fenlands and cut-over raised bogs as well as upland moors (see further Vollmer et al. 2001, pp. 15–22). The dominating landscape types of Schleswig–Holstein are the sea marshes in the district of Nordfriesland and Dithmarschen as well as the Elbmarsh region in the Elbe estuary. Further inland, the landscape changes from the low geest to the high geest and to the uplands of Schleswig–Holstein with gentle hills, lakes and water inlets of the Baltic Sea.

The Dutch-German Wadden Sea region was inscribed on the World Heritage List in June 2009. The Wadden Sea is a highly productive and dynamic ecosystem, in which the natural structures of habitats and species are still present (CWSS 2005, p. 12). The functions and features of the region according to the CWSS (2005, p. 12) are "high dynamics of abiotic and biotic components of the system and as a consequence its flexibility to changing environmental conditions, its function as a sink for sediment and organic matter and the decomposition capacity, the high biological production and reproduction rates as well as the high degree of specialization of plants and animals".

According to the LOICZ[2] project, the coastal zone represents the interface between land, sea and atmosphere and provides more than half of the global ecosystem goods (e.g. fish, oil, minerals) and services (e.g. natural protection from storms and tidal waves, recreation) (LOICZ 2011). Also in the economic structure of Schleswig–Holstein typical sectors such as tourism, fishery and maritime economy reflect its location between two seas. More recently, further competence in life sciences, micro- and nanotechnology as well as in renewable energies is being developed in Schleswig–Holstein (see further Landesregierung Schleswig–Holstein 2010).

Without massive investments in coastal defence, such development at the North Sea Coast would not have been possible. Although the islands at the North Sea Coast protect the mainland from storm surges, i.e. as a natural barrier (see further Küster 2007; Kramer 1989) nowadays, the marsh areas were affected by alternating transgression and regression of the sea constantly reshaping the coastline up to early modern times. The building of dikes had far-reaching consequences for the sea marshes as it protected the marshes from the direct influence of the sea and thus permitted extensive settlement also due to the regulation of the internal draining of water (Vollmer et al. 2001, p. 139; see further Allemeyer 2006; Küster 2007). Today, the district of Dithmarschen has a population of 135,279/1,428 km² and Steinburg a population of 133,370/1,056 km² (Landesregierung Schleswig–Holstein 2010, p. 4).

[2] Land–Ocean Interactions in the Coastal Zone (LOICZ) is a core project of the International Geosphere-Biosphere Programme and the International Human Dimensions Programme on Global Environmental Change investigating the global changes in the coastal zone from natural and social science perspective (see further LOICZ 2011).

4.2 Risk of Storm Surges and Flooding in the Coastal Lowland

About 24 % of the area of Schleswig–Holstein is categorised as flood-prone coastal lowland. Approximately 345,000 people and economic assets of about 45 billion Euros are threatened by storm surges and the further impacts of dike breaching (Hofstede 2004, p. 109). At the North Sea Coast of Schleswig–Holstein about 425 km of the coastline is protected by primary sea dikes against flooding and coastal erosion (CPSL 2010, p. 21). The yearly gross value added in the coastal lowlands amounts to 8.5 billion Euros in comparison to the yearly expenditures of Schleswig–Holstein for flood defence and protection of 0.045 billion, i.e. 45 million Euros (Hofstede 2004, p. 109). Furthermore, about 85,100 working places at the North Sea Coast and 32,000 bed capacities of the tourism sector are exposed (see further Hofstede 2004, p. 112). Thus, coastal defence measuresin Schleswig–Holstein focus on those areas that are exposed due to low elevations, i.e. up to where flooding could occur without protective measures or in case of a dike failure. At the Baltic Sea coast approximately 320 km² are below GOL (German Ordnance Level) +3 m and need to be protected by coastal defence measures. The main exposed areas in Schleswig–Holstein are located at the tidal North Sea Coast where approximately 3,360 km² is protected lying below GOL +5 m (Schleswig–Holsteinischer Landtag 2009a, p. 6).

Coastal lowland is protected by primary state dikes and secondary dikes. In the district of Dithmarschen and Steinburg the dikes hold a length of approximately 35 km and 82 km; protecting an area of about 1,060 km² and 620 km². In the Elbmarsh region of the Wilstermarsch and the Krempermarsch greater areas are lying below GOL +2 m—in particular along the river Stör. Also the lowest elevation in Schleswig–Holstein with GOL −3.54 m is located in the Wilstermarsh near Neuendorf (Schleswig–Holsteinischer Landtag 2009a, p. 7). In the Elbmarsh region, the development of dikes can be traced back to a period before 1500 (see further Allemeyer 2006). Also the area around Büsum in Dithmarschen has been protected by dikes before 1500—mainly for land reclamation—as cooperatives began to enclose the sea marshes within dikes from the 11th/12th centuries onwards (Vollmer et al. 2001, p. 139). In the course of the sea level rise in the 11th century, the population in the marshlands settled on artificially earth fills, so-called Warften, in order to be secure against flooding due to storm surges or fluvial flooding (Allemeyer 2006, p. 43). Yet, formerly protected marshlands were drowned again such asin the Meldorf Bight. During such catastrophic tidal flooding the seaward marsh areas were re-flooded e.g. in the 14th century or 1634 where 168 people drowned in Büsum and 102 houses were destroyed (Vollmer et al. 2001, p. 139).

Storm surges, more precisely storm tides, are tides that are intensified by a storm. Storm surges occur in the German Bight due to combined effects of winds blowing over the North Sea mainly from N to N–W, high wind speed over a minimum duration of 3 h and furthermore depend on the path of the cyclones (Gönnert et al. 2001, p. 479). In general the wind presses sea water against the coast with its special topography and thus blocks the outflow of the water from the German Bight, whereas the critical wind direction for each location along the coast can differ. Together these influencing factors cause high water levels at the coast and in the tidal rivers. The highest storm surge level in the German Bight was reached during the storm surge of 1976 with a level of 370 cm over mean high tide level and 1,010 cm above MSL (Gönnert et al. 2001, p. 471).

The major storm surges between the 11th and the 18th century caused devastating impacts on the coastline, on the land reclamation and the coastal population (see further Kramer 1989). In the chronicles two destructive storm surges stand out: the first “Grote Mandrenke” of the 16 January 1362 with up to 100,000 fatalities and the second “Grote Mandrenke” of the 11 October 1634 (Kramer 1989, p. 35). In the 19th century, the storm surge at the 03/04 February of 1825 as well as at the 13 March of 1906 reached very high water levels at the German coast of Schleswig–Holstein and Lower Saxony.

The storm surge of the 16/17 February 1962 changed the standard in coastal dike protection of Germany (see e.g. Kramer 1989; Stadelmann 2008). This storm surge affected the German Bight especially along the rivers Ems, Weser and Elbe within the cities of Emden, Bremen and Hamburg (Gönnert et al. 2001, p. 471). At the coast of Schleswig–Holstein 70 km of dikes were destroyed so devastatingly that the dikes could not just be reconstructed. About a length of 80 km the dikes showed severe damages and about 120 km at least significant damages; i.e. about half of the dikes in Schleswig–Holstein were affected by the storm surge (Stadelmann 2008, p. 10). At the whole North Sea Coast, the dikes broke at 60 locations and 315 people died during the flooding. In Büsum, the dike got very severely damaged; while a dike breach could finally be averted. At the river Stör dike breaches occurred and flooded in particular areas of Itzehoe and Münsterdorf (see Fig. 4.1c), in other parts the dikes were severely damaged and had to be rebuild (see further Stadelmann 2008, p. 98). In the area around Münsterdorf dike breaches occurred, leading to flooding of agricultural land, streets and buildings as well as to the evacuation of the affected population (Schwichtenberg 2009). Further downstream in the area of Wewelsfleth and Borsfleth (see Fig. 4.1b and a) the damages at dikes were merely moderate, but in some parts also severe damages occurred (see further Stadelmann 2008, p. 98). As a consequence of the severe damages, until 1975 a flood barrier has built at the Stör estuary (Fig. 4.1f).

Yet, the flooding only affected about 3 % of the area flooded during the event of 1825; in particular due to the dike improvements over the century and further dike reinforcements after 1953 (Stadelmann 2008, p. 10). The storm surge of 1953 mainly hit the coasts of England and the Netherlands. The experience of such destructive storm surge led in the Netherlands also to a changed standard in dike protection and improvement in storm surge warnings. Due to this, the storm surge of 1983, potentially as destructive as the storm surge of 1953, caused considerable lower damages to property and fatalities (Gönnert et al. 2001, p. 471). In the same way, the experience of the storm surge of 1962 and the changed standards in dike protection, protected the German coast from higher damages during the storm surge of 03/04 January of 1976—despite higher water levels. The storm surge of 1976 hit the coast of Lower Saxony and Schleswig–Holstein and caused damages

A dike separates the community Borsfleth from the flood plain of the river Stör.

In Wewelsfleth (Außendeich) traditional houses are built on so-called Warften, artificial earth fills.

A memorial plaque located in Münsterdorf to remember the storm surge of February 1962.

In Kellinghusen houses are directly located at the river Stör.

Dike protection in Büsum at the North SeaCoast. (N. Kruse)

Mouth of the river Stör, flowing into the river Elbe near Wewelsfleth.

Fig. 4.1 Photographs of survey locations in Schleswig-Holstein—the communities Borsfleth, Wewelsfleth, Münsterdorf and Kellinghusen at the river Stör and the community Büsum at the North Sea Coast. **a** A dike separates the community Borsfleth from the flood plain of the river Stör. **b** In Wewelsfleth (Außendeich) traditional houses are built on so-called Warften, artificial earth fills. **c** A memorial plaque located in Münsterdorf to remember the storm surge of February 1962. **d** In Kellinghusen houses are directly located at the river Stör. **e** Dike protection in Büsum at the North Sea Coast (N. Kruse). **f** Mouth of the river Stör, flowing into the river Elbe near Wewelsfleth in particular in those areas that have not yet been enforced after the storm surge of 1962. The recently erected flood barriers along the coast of Schleswig–Holstein at the river Eider, Stör, Krückau and Pinnau protected the areas further inland from the incoming storm tide. The average wind speed in Büsum achieved a maximum of 101 km/h and peak gusts of 145 km/h (Stadelmann 2008, p. 100). Only 18 days later another storm surge followed on the 21 January of 1976 but with lower peak water levels at the coast of Schleswig–Holstein.

Further severe storm surges occurred between 1967 and 1995, e.g. a series of storm surges between November and December of 1973, 26–28 February of 1990 and in January of the years 1993–1995 (see further Stadelmann 2008). In general, during the second half of the 20th century a clustering of storm surges has been noted, yet the intensity of storms did not change significantly even though there was a trend towards stronger storms between 1975–1990 (see e.g. von Storch et al. 2008, p. 738; Stadelmann 2008, p. 102). What changed indeed is the increase of storm surge heights recorded in Hamburg since 1962; reflecting in considerable part the results of the improvement of coastal safety measures (von Storch et al. 2008, p. 737). According to von Storch et al. (2008, p. 739) it furthermore seems that the rise in mean sea level during the past decades plays only a minor role in the changing storm surge risk in Hamburg.

For the North Sea Coast of Schleswig–Holstein, Sterr (2008, p. 390) concludes that an accelerated sea level rise will create a considerably increased danger of flooding; but sea level rise is a factor among others such as the likely changes in storminess, ongoing coastal erosion and the slow subsidence of the older marsh areas. Almost all tide dependent tributaries of the Elbe and Eider have been protected by storm surge barriers since the 1950s and currently allow the natural drainage of inland waters at low tide cycles. Due to sea level rise, the efforts and costs for the drainage and avoidance of salt water intrusion into groundwater and agricultural areas might increase making continuous pumping necessary (Sterr 2008, p. 391; see also Kramer 1989, p. 275; Frank 2007). The additional costs for artificial drainage and groundwater management by 2100 are assumed to increase in Schleswig–Holstein by +60 % (see further Sterr 2008, p. 387).

Besides the improvement of coastal safety measures in the Elbe estuary also the modifications of the river channel and the loss of shallow waters due to siltation and land reclamation changed the storm surge heights in Hamburg (see further von Storch et al. 2008). Due to the topography of the Elbe estuary (see further Gönnert et al. 2001, pp. 128–32) the tidal waves of a storm surge are often 0.5 m higher in Hamburg, i.e. about 100 km further inland, than in Cuxhaven at a further exposed location at the North Sea. The problem of siltation in the North Sea coastal area has also been of concern for the working group "coastal lowlands 2050″ in Schleswig–Holstein. The so-called tidal pumping effect, i.e. the transportation and sedimentation of material further upstream, reduces the retention area in tide dependent rivers and adequate drainage of the coastal lowland of Schleswig–Holstein (Schleswig–Holsteinischer Landtag 2009b, p. 5). In combination with further adverse factors such as higher precipitation in the winter months and a higher sea level due to climate change, the working group assumes an increase of water levels in the coastal lowland (see further Schleswig–Holsteinischer Landtag 2009b). In further publications (see e.g. Spekker 2009; Kramer 1989, p. 189) the risk of an overlap between storm tides and high inflow of surface water e.g. due to torrential rain contributing to critical peak water levels has been described. During the Elbe flood in January 2003 for example the increased tidal water level impeded the run-off of the flood wave further out of the Elbe estuary (Schleswig–Holsteinischer Landtag 2003, p. 4). In smaller river catchments such as the Elbe tributary river Stör rather local torrential rain events and the snow melt in spring cause flooding e.g. as in the case of Kellinghusen in 2003, 2004 or 2010 (see Fig. 4.1d). Frank (2007, pp. 6–7) follows that in order to understand and analyse such risk overlaps, an assessment of the capability of the whole river-sea system is necessary in particular with regards to its coherence and the combined factors.

4.3 Risk from the Perspective of the Coastal Population

Whether these risks play a decisive role in the perception of the population has been assessed in various empirical studies. Common underlying assumption is that society′s understanding and ranking of risks determines the handling of risks and the efforts undertaken to prevent disaster impacts (e.g. Knieling et al. 2009; Hofmann and Kaiser 2007; Kaiser et al. 2004; Markau 2003; Terpstra 2009; Ratter and Sobiech 2011). Therefore aspects such as risk perception, risk evaluation and personal relevance of risk exposure have been investigated in research studies in the German coastal region as well as on European level (see e.g. Knieling et al. 2009; Koerth 2009; SAFECOAST 2007; Kaiser et al. 2004). A recent qualitative empirical study conducted in Schleswig–Holstein and Lower Saxony with >860 participants revealed that STORM SURGES and CLIMATE CHANGE are the most relevant hazards from the people′s perspective (Ratter et al. 2009, p. 59). About 1/3 of the answers (33 %; n = 1307) refers to STORM SURGES and CLIMATE CHANGE forming the main hazard category in the study with great distance from other categories (see Fig. 4.2).

The hazards named in the study can be associated with the coastal or the rural/peripheral character of the region (see further Ratter et al. 2009, p. 60). Due to the exposure of the coastal lowland and the importance of coastal defence in this area STORM SURGES and CLIMATE CHANGE definitively represent important hazards in the perception of the population. But which hazards are perceived in areas where storm surges and river flooding may coincide due to the tide and the interdependence between the fluvial and the marine system? Whereas in the low lying coastal zone storm surges are relevant, in river catchments an overlap of tide and inflow of surface water can contribute to critical peak water levels (see further Spekker 2009; Frank 2007). Thus, for the study in the district of Steinburg and Dithmarschen the hazard type RIVER FLOODING was added, while the main hazard categories with 7 % from Ratter et al. (2009, p. 58) were kept. The results of the study provide evidence for the importance of river flooding. People are mainly concerned about

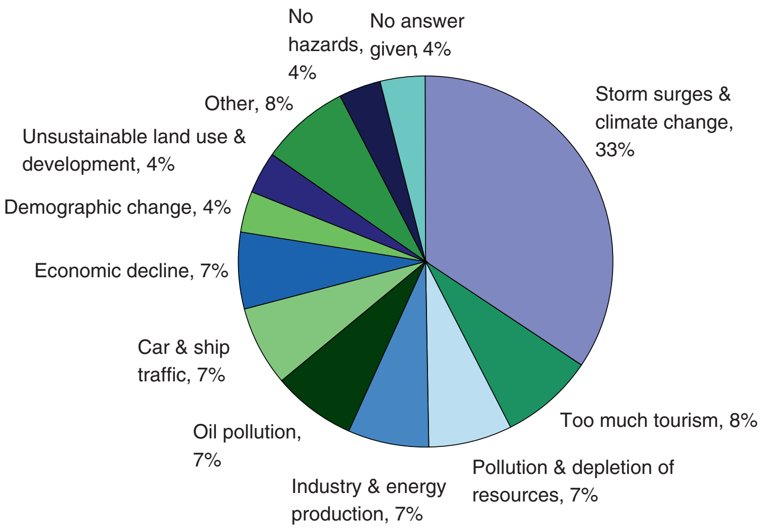

Fig. 4.2 Risk perception in the coastal zone of Germany: Which hazards do you consider as relevant for your region? (n = 1307; multiple answers allowed; according to Ratter et al. 2009, p. 58, reproduced by permission of Helmholtz-Zentrum Geesthacht)

RIVER FLOODING (33 %; N = 100) but also ECONOMIC DECLINE (32 %; N = 100) as well as about STORM SURGES and CLIMATE CHANGE (10 %; N = 100) (see Fig. 4.3). The five communities show further variety in understanding of risk presented in more detail in Sect. 5.2; but in general it indicates that the intuitively perceived hazard is related to the location of the communities in the catchment area of the river Stör and to a lesser extent related to the coast as in Büsum.

Besides the perception of hazards also the evaluation of risks might increase or decrease people′s efforts to prevent major disaster impacts. The INTERREG IIIB project COMRISK[3] (common strategies to reduce the risk of storm floods in coastal lowlands) assessed and evaluated the coastal defence strategies of five European countries in order to promote the exchange of experience and knowledge. A comparative study, conducted within the COMRISK project framework, also focused on the role of risk perception and estimation with regard to public participation in flood defence processes in coastal regions of North Sea States. Table 4.1 shows the result of the risk estimation of coastal flooding events in different countries.

The risk of flooding is considered as high or very high by 1/3 of the respondents in the coastal zones (33 %; n = 411)—but only 7 % had taken personal measures to be prepared for the next storm flood (Kaiser et al. 2004, p. 79). The COMRISK SP3 project team reasoned that apparently people know about the risks

[3] In the INTERREG IIIB North Sea Programme (2000–2006) Theme 2 focused in nine different projects on risk management along rivers and coasts e.g. in COMRISK, COMCOAST, SAFECOAST, ESCAPE or STORMRISK.

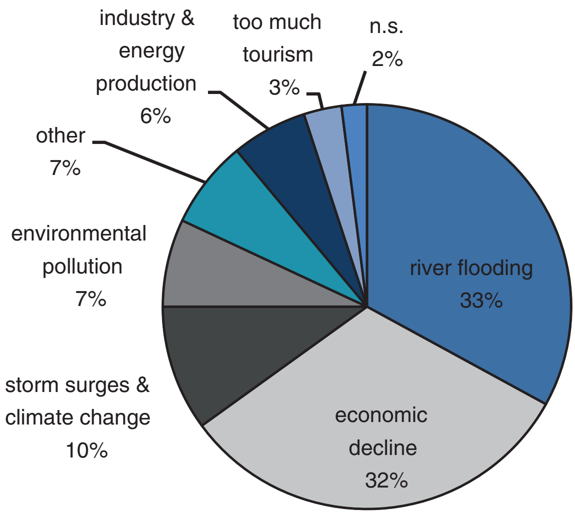

Fig. 4.3 Risk perception in the districts Steinburg and Dithmarschen: Which hazard do you consider as most important for your community? (N = 100; n.s. = not specified; categories according to Ratter et al. 2009, p. 58)

Table 4.1 Estimation of the occurrence of coastal flooding in five European countries (n = 411; Kaiser et al. 2004, p. 64)

	How high do you estimate the probability of coastal flooding? (in %; n = 411)	
Country	Very high–high	low–very low
Belgium	42	54
Denmark	24	73
Germany	30	65
Netherlands	24	74
UK	30	65
Total	33	65

but they are not aware of the consequences; do not know what to do or how to prepare. COMRISK SP3 furthermore provided recommendations on public information and participation measures. In their conclusions, the authors rather emphasise the significant deficit with respect to information policies than risk perception and estimation. Thus, the importance of an improved policy for a better informed and actively participating public in coastal defence planning processes is highlighted: “Sufficient and comprehensive information are seen as the basis and a prerequisite for a wider involvement of the public, which is the next step on the way to an efficient coastal management scheme” (Kaiser et al. 2004, p. 159). As revealed in the expert interviews, a main criterion to increase people′s willingness to participate in such planning processes is their knowledge about the personal concern, i.e. how they might be affected by a flooding event (Kaiser et al. 2004, p. 146). With regard

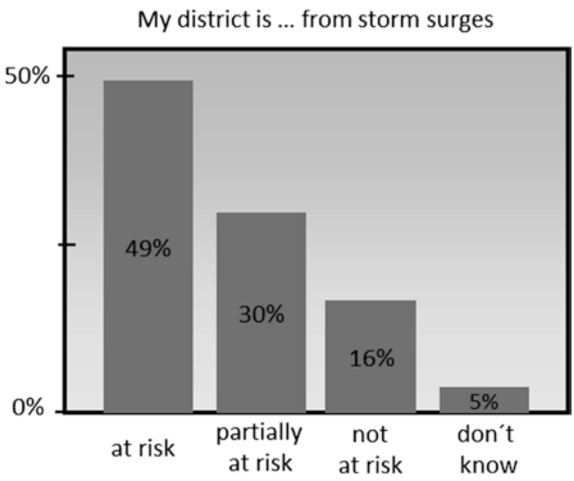

Fig. 4.4 Estimation of storm surge risk in the urban district Wilhelmsburg/Hamburg (N = 305; reproduced by permission of Knieling et al. 2009, p. 64)

to the experience of a disaster and the time passed since the last event the findings of the study revealed that these aspects matter for the perception of risk but no apparent correlation exists between experience and behaviour concerning precaution against the risk of storm floods (Kaiser et al. 2004, p. 81).

Another study conducted in Hamburg on the river island of Wilhelmsburg, situated between the Northern and Southern branches of the Elbe, also focused on risk perception and evaluation as well as on the personal relevance of the storm surge risk (see further Knieling et al. 2009). According to the findings of the study about 79 % (N = 305) of the respondents considered their urban district AT RISK or at least as PARTIALLY AT RISK (see Fig. 4.4). In Wilhelmsburg risk perception of people with experience of storm surges is not necessarily higher than of people without such experience (see further Knieling et al. 2009, p. 66). But the historical background of the storm surge 1962—207 of the 315 fatalities occurred in Wilhelmsburg (see further Sonderheft Wilhelmsburger Zeitung 1963)—seems to affect in parts the collective perception of storm surges in Wilhelmsburg. More than half of the respondents (53 %) furthermore estimate personal consequences due to a storm surge as likely or possible.

Given the fact that many people regard personal consequences of storm surges as likely/possible, to which extent do people consider themselves as responsible to implement self-protection measures? About 64 % of the respondents in the Wilhelmsburg survey felt responsible for getting information about storm surge risks and regarded it as a duty of the local population (Knieling et al. 2009, p. 72). Yet, the willingness to implement self-protection measures is low; 59 % reject the implementation of such measures. Currently only 22 % of the respondents implemented own measures to better protect their property (Knieling et al. 2009, p. 77). But as the majority of the local population does not consider such measures as unnecessary, the authors see a general acceptance of self-protection measures.

In the frame of the FLOODsite project it was furthermore investigated how people estimate the usefulness of and responsibility for different protection and mitigation measures concerning river flooding. The FLOODsite project/Task 11 presented the findings of a questionnaire survey carried out in the Mulde catchment in Germany about social vulnerability and the 2002 flood; it was part of the FLOODsite project about integrated flood risk analysis and management methodologies co-funded by the European Community. People′s attitudes towards different public and private measures, i.e. of public or personal responsibility were assessed in the study. The self-protection measures BETTER INFORMATION ON PRIVATE MEASURES was ranked as very useful by 71 % (n = 324) and PRIVATE MITIGATION MEASURES by 48 % (n = 231) of the respondents. In comparison, highest scores achieved the categories ADDITIONAL RETENTION AREAS (78 %; n = 348), EXTENSION OF WARNING PERIOD (77 %; n = 354) and IMPROVEMENT/REPAIR OF DIKES (77 %; n = 342). With regard to the results the authors came to the conclusions that "measures based on individual actions (like private mitigation measures and public disaster drills) are rated as least useful" (Steinführer and Kuhlicke 2007, p. 97). In comparison with most other measures, they conclude that PRIVATE MITIGATION MEASURES are not understood as very useful. People seem to have doubts about the actual relevance of private measures. Furthermore, the study revealed that the degree of information about precautionary measures and the perception of the usefulness of different private and public measures does not account for any variance in the application of precautionary measures (Steinführer and Kuhlicke 2007, pp. 98–100). Further assessment of the motivations for rejecting self-protection measures pointed to many problems e.g. that people were either not financially in the required position, that they did not know what to do or did not see any possibility to mitigate the impact of a flood (see further Steinführer and Kuhlicke 2007, p. 103). Regarding the last problem, the controllability of risks, has usually a minor importance for the individual evaluation of *natural* hazards in comparison to technological hazards. Natural hazards are normally regarded as uncontrollable (Kaiser et al. 2004, p. 55). Yet, in the case of river flooding a medium level of controllability is usually attached due to the influence of the human-environment interactions in river catchment areas (see further Karger 1996). Summing up it seems that there are rather manifold motivations why some people might not feel capable to implement self-protection measures while others feel that it is something going beyond their individual responsibility.

4.4 Risk Management in the Coastal Zone of Schleswig–Holstein

The Federal Water Act (Wasserhaushaltsgesetz 2010, WHG) provides the foundations for the management of surface waters, coastal water and groundwater at national level. Since 2006 the water legislation is part of the concurrent legislation meaning that the states and the federal level have a common responsibility in

Germany. Due to the concurrent legislation, states in Germany can implement further diverging laws in so far as the federal level makes no use of its legislative power in the same field (Deutscher Bundestag 2011). The new Federal Water Act entered into force in March 2010 and aimed at achieving a more systematic and standardised federal water legislation in Germany; also for the implementation of several EU provisions. In this context e.g. the Flood Risk Management Directive (2007/60/EC) for better standards in the assessment of flood risks and risk management have been implemented. Furthermore the Federal Water Act provides the following obligations for persons affected by flooding: according to § 5 (2)[4] each person affected by floods is obligated within the limits of the person′s possibilities to take preventive measures in order to reduce the impacts of flooding and mitigate further flood damages.

In Schleswig–Holstein coastal defence is regulated by the State Water Act (Wassergesetz des Landes Schleswig-Holstein 2008 LWG). Coastal lowland in Schleswig–Holstein is protected by 425 km of primary state dikes; secondary dikes extending to 570 km give additional safety for the population behind (CPSL 2010, p. 21). The primary dikes are built and maintained by the coastal division of the state and the secondary dikes are in the responsibility of the regional water boards (Kaiser et al. 2004, p. 33). The state responsibility for coastal defence holds the State Ministry for Agriculture, Environment and Rural Areas (MLUR). The objectives of coastal defence, the technical and financial concept as well as the public strategy are established in the master plan for a period of 15 years (Generalplan Küstenschutz Schleswig–Holstein; MLR 2001; see further Hofstede 2004). Although the master plan is not a legally binding document, it is viewed as a (strong) self-commitment of the State Government (Hofstede 2004, p. 110). The master plan’s consensus is that in Schleswig–Holstein coastal defence outweighs all other interests, e.g. nature conservation. Accordingly, the goals of coastal defence must also be considered in other sectors such as tourism and spatial planning (MLR 2001, p. 1; Hofstede 2004, pp. 110–111). The financial resources for the coastal defence are provided by the State Government as well as by the Federal Government co-financing up to 70 % of the capital measures (Kaiser et al. 2004, p. 33). Presumably from 2012 onwards the population living in the flood-prone coastal lowland of Schleswig–Holstein has to pay 10 % of the expenses for the annual coastal defence measures (see further MLUR 2010).

Besides the master plan for coastal defence, a master plan for river flood protection and flood retention of Schleswig–Holstein (Generalplan Binnenhochwasserschutz und Hochwasserrückhalt Schleswig–Holstein; MLUR 2007) regulates the reduction and management of flood risks. The master plan

[4] WHG § 5(2) “Jede Person, die durch Hochwasser betroffen sein kann, ist im Rahmen des ihr Möglichen und Zumutbaren verpflichtet, geeignete Vorsorgemaßnahmen zum Schutz vor nachteiligen Hochwasserfolgen und zur Schadensminderung zu treffen, insbesondere die Nutzung von Grundstücken den möglichen nachteiligen Folgen für Mensch, Umwelt oder Sachwerte durch Hochwasser anzupassen.”

considers the Flood Risk Management Directive (2007/60/EC) and the Water Framework Directive (2000/60/EC). Moreover, it provides information about the legally binding flood plains e.g. at the river Stör based on a bicentenary flood event (HQ_{200}) and further requirements for better risk management strategies, e.g. the re-evaluation of flood plains (see Landesverordnung 1977). The river basin management plans for the Water Framework Directive have been established in Schleswig–Holstein also taking into account the requirements of the Flood Risk Management Directive while implementation is to start in 2012.

The main types of technical measures in coastal defence are dikes, sand nourishment, protection from coastal erosion and salt marsh management (see further Hofstede 2004; MLR 2001; Hofstede and Hamann 2000). Demands arising from the debate on climate change call for the supplementation of lineal coastal protection, i.e. by dike lines with elements of spatial planning (see further Garrelts and Lange 2011, p. 205). The master plan for coastal defence of 2001 makes specifications about Integrated Coastal Defence Management (ICDM), based on the principles of Integrated Coastal Zone Management (ICZM; see further Hofstede 2004). It enhances the traditional methods by considering coastal defence as a spatial planning process, by further involving the public into the planning processes as well as taking into regard climate change and the involved uncertainties (Hofstede 2004, p. 115). Yet, in a report of the Common Wadden Sea Secretariat, the members of the trilateral working group on coastal protection and sea level rise (CPSL 2010, p. 45) conclude that the "current spatial planning instruments, however, need to be further developed in order to cope fully with anticipated impacts of climate change". The master plan for river flood protection recommends besides the technical-structural measures also behavioural and financial measures as well as spatial planning and flood retention (see further MLUR 2007). Other than in the coastal defence master plan, here also the individual obligations to implement self-protection measures are specified (MLUR 2007, p. 25). In case of a river flooding, the owner is responsible for the protection of its private property as defined in the WHG of 2010.

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Chapter 5
System Analysis

The agent-based model aims at exploring the dynamics of vulnerability due to individual, relational and spatial aspects. In order to explore vulnerability as a multidimensional and context-sensitive social phenomenon based on the agent concept, the approach required an own conceptual and computational model development. Besides the model design, also the empirical data base of the case study is presented. Thus, the system analysis allows answering the first, second and third research question (see Sect. 1.2). According to the first research question, the conceptual model development analyses how to reconcile risk/vulnerability approaches from different disciplinary perspectives with the agent concept (see Sect. 5.1). Model input data is derived from an empirical study in the selected coastal zone of Germany. The study aimed at the vulnerability and self-protection preferences of private households against flooding. According to the second research question, it revealed agent types concerning vulnerability, present risk behaviour and preferences towards self-protection strategies (see Sect. 5.2). The computational model development outlines how agent-based models can be combined with empirical vulnerability assessments (see Sect. 5.3). Vulnerability attributes and preferences are implemented in the computational simulation model. Hence, the model reflects the status-quo of vulnerability in the coastal zone and analyses the short-term effects of self-protection preferences for the future system. According to the third research question, various simulation experiments can be conducted in order to explore the trajectories of vulnerability in the flood-prone coastal zone (see Sect. 5.4). The verification and validation of the model is discussed in Sect. 5.5.

5.1 Agent-Based Conceptual Model Development

Model development begins with defining the purpose of the modelling approach. Here, the general conceptual model is an abstract framework for *agent-based* vulnerability assessments. The conceptual model results from an analysis of various vulnerability assessments in the theoretical research framework (see

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Sect. 3.2.3). 12 exemplary risk/vulnerability approaches are further analysed according to a certain structure including the purpose of the approach, the system under study, the scope and scale of assessment, details about the agent level, etc. (see Tables 5.1, 5.2 and 5.3). This structuring aimed at the first research question: how can risk/vulnerability approaches from different disciplinary perspectives be reconciled with the agent concept in order to assess the dynamics of vulnerability? The 12 exemplary risk/vulnerability approaches are examined according to the proposed structure in order to show their applicability in an agent-based vulnerability approach. To bring these approaches together into one abstract framework, the general conceptual model should be reduced to the main components and relationships of an agent-based system *and* the conditions of a vulnerable system. Before the risk/vulnerability approaches from different disciplinary perspectives and their contribution to agent-based vulnerability assessments is analysed, few general remarks are put forward about the conceptual model development and its purpose.

The conceptual model is developed for the analysis of vulnerability in the pre-disaster phase, i.e. the system under study is a risk situation. Although the agents might be influenced by a disaster experience, agents in the model are exposed to the hazard not the disaster situation. With regard to hazards and vulnerability, the model should still be open for including different attributes and processes related to vulnerability, hazard and risk. Another assumption that is important for the purpose of the model refers to the human(agent)-environment relationship: On the one hand risk depends critically on human actions and decisions; but on the other hand human behaviour needs to be assessed in the context of the decision making framework within individuals operate (ICSU 2008, p. 22; Bankoff 2001, p. 30). These assumptions are inherent in the agent concept: Agents can act autonomously and purposive, have some means to affect and communicate with the environment and can also influence other agents, but at the same time they are subject to influences from their local environment too (Gilbert and Troitzsch 1999, p. 167).

The system under study here is agent-based. In other risk/vulnerability approaches introduced in Sect. 3.2 the system under study can be concretised by the scope of assessment. The user may emphasise certain theoretical aspects according to the purpose of the approach and thus determines what will be simulated in detail. How these own interpretations and priorities with regard to vulnerability e.g. from different disciplinary perspectives can be included in the model is further summarised in e.g. Table 5.1. Some risk/vulnerability approaches might not cover all components of the agent concept, making a combination of different approaches necessary. Some approaches consider—besides the risk situation—also the disaster process and might need an extension of the model to the post-disaster phase. The assumptions and theories chosen for the conceptual model development determine the outcome of the model process; e.g. the theory used for micro level agent behaviour will determine the macro-effects measured on the system level. Also the selection of indicators and levels of analysis for vulnerability assessments—as summarised in Table 3.1 on p. 63–64)—influence the model design and outcome.

An agent is a social entity whether representing a stakeholder, a social group, an organisation or institution or a national state. The scale of assessment in a model depends on the purpose of the approach and on the definition of agents. As the methodological concept allows equipping agents with different attributes, preferences and goals, the user may choose which agent scale and indicators to select. It further allows mixing of different agent classes or scales in one model whereas the classes/scales may be defined by the agents' roles, goals or e.g. by the contrasting perceptions of experts and lay people.

The unit of study also affects the design of the environment. Whether we deal with individuals, institutions or nations might lead to the selection of certain spatial and/or social worlds in which agents interact, e.g. mountainous areas, markets or social networks. Combining vulnerability assessments with land-use models or geographical information systems can result in very detailed spatial models such as in Acosta-Michlik and Rounsevell (2009). As the various risk/vulnerability approaches (see Tables 5.1, 5.2 and 5.3) consider different hazards, the design of the environment may also depend on the type of hazard and the spatial extent of the hazard. Besides the scale of investigation, the context may as well result in very different environments e.g. in case of vulnerability assessments related to heat waves/droughts in urban or rural areas. Agent-based models with a detailed spatial representation of the environment appear to be more realistic. But spatially and temporally discrete models may also lead to a misunderstanding of such models as "prediction machines" or "electronic oracles" (Janssen 2002, p. 408).

Besides the purpose of the approach, these general aspects such as the scope and scale of assessment are important for the model development. Details about the design of agent and environment level contribute in particular to the development of an agent-based model. Therefore, the 12 exemplary risk/vulnerability approaches are analysed according to this structure: purpose of approach, system under study, scope and scale of assessment, and further details about the agent and environment level (see e.g. Table 5.2).

The analysis of the 12 exemplary risk/vulnerability approaches revealed various ways of assessing vulnerability and risk. In terms of the purpose, these approaches regard differences in risk perception, patterns of vulnerability and/or the divergence in risk behaviour (see e.g. Table 5.2). Whereas psychological and social sciences approaches rather direct to interactions in the social environment influencing risk handling and management; coupled approaches focus on the coupled human-environment system by including also the physical/built environment. The approaches emphasise various theoretical aspects from different disciplinary perspectives and thus determine what might be simulated in detail. The analysis revealed that psychological approaches emphasise either risk perception and/or risk behaviour across individuals and relate it to specified hazard sources. The purpose of such approach can be the explanation of differences in risk perception e.g. between risk experts and lay people as in the psychometric paradigm by Slovic et al. (1982) and Slovic (1987) (see Table 5.1). The process of risk construction can also lead to the acceptance of risk or changes in the behaviour towards risk. Perceptual aspects are therefore combined with behavioural aspects in further psychological approaches such as in the model of precautionary action developed by Grothmann and Reusswig (2006). The model

Table 5.1 Psychological approaches of risk/vulnerability assessments (see Sect. 3.2.3.1) reconciled with the agent concept (see Fig. 5.1)

Psychological approaches					Agent level		Environment level		
Approach & Author	Purpose	System under study	Scope of assessment	Scale(s) of assessment	Agent attributes & Perception	Agent preferences & Behaviour	Social influence & Feedback	Hazard type	Policy options
Psychometric Paradigm associated with B. Fischhoff, P. Slovic and S. Lichtenstein; extended by O. Renn	Analyse differences in risk perception: situation-related and risk-related patterns influencing perception and mean risk perceptions in society	Risk situation/ health threats: rather technological hazards	Risk perception: Influencing factors & characteristics for risk perception and evaluation of different risk sources identified and compared	Individuals (experts & lay people)	Personal attitudes and interests, understanding of risk, unambiguousness of hazard information, experience with technology and nature, trust in official control/ management of risks, catastrophic potential of risk, etc.	expressed preferences of individuals concerning risks and benefits: "acceptable" risk-benefit trade-offs	Risk-related factors may increase perception due to fatal consequences for society: undesirable consequences for future generations, effects for vulnerable persons/children	Technological risks rather than natural risks	Not further specified
Value-Belief-Norm (VBN) Theory described by Stern et al.; extended by M. W. Slimak and T. Dietz	Analyse differences in risk perception and divergence in risk behaviour: variation in risk perception across individuals and pro-environmental behaviour	Risk situation/ environmental concern	Risk perception: focuses on characteristics of individuals and group membership influencing risk perception and ranking	Lay public, experienced public, risk assessors, risk managers	Personal values, set of beliefs or world views, awareness of consequences, ascription of responsibility, personal norms for pro-environmental action, also social demographic and socio structural	Risk ranking and risk scales	Group membership	Ecological risks (24 risk items ranging from hazardous waste sites to global warming and oil extraction)	Not further specified
Model of Precautionary Action by T. Grothmann and Reusswig based on Protection-Motivation Theory (PMT) by R. W. Rogers	Analyse divergence in risk behaviour: in the context of health threats from natural and technological hazards; test the relevance of socio-economic and socio-psychological factors for explanation in comparison	Risk situation/ health threats from natural to technological hazards	Risk perception & behaviour: explain the variance of intention and action according to flood protection (in flood-prone areas of Germany)	Household's long-term precautionary action to avoid flood property damage	Threat appraisal (including perceived probability, perceived severity, and fear), coping appraisal (including perceived protective response efficacy, perceived self-efficacy, and protective response costs), also socio-economic variables (ownership, household income), etc.	Non-protective responses (fatalism, denial, wishful thinking), protection motivation (intention), and/or protective responses (actual behaviour = damage prevention)	Feedback loops in the PMT model of flood preparedness (degree of threat appraisal is reduced after either protective responses or - non-protective responses)	Floods (also other risk situation/ health threats from natural to technological hazards)	Measures of self-protective behaviour: getting information, avoidance (e.g. no expensive furnishing in basement), devices (purchase of flood protection), structural measures

(Continued)

Table 5.1 (Continued)

Psychological approaches					Agent level		Environment level		
Model of Risk Communication and Community Preparation by D. Paton and D. McIvor	Analyse differences in risk perception and divergence in risk behaviour: intentions to prepare for hazards are influenced by individual, community and societal factors; especially the role of trust for decision making	Risk situation: comparison between communities with different hazards and with low and high familiarity/information (scenarios)	Risk perception & behaviour: with a specific focus on building trust and risk communication	Individuals (in different Communities)	including individual factors: critical awareness, positive and negative outcome expectancy, action coping, information availability, trust	Intentions to prepare for hazard	including community and societal factors influencing the individual's decision process: e.g. collective efficacy (problem articulation) and levels of community participation, empowerment	Natural hazards (infrequently-occurring)	individual self-protection measures not further specified
Precaution Adoption Process Model (PAPM) associated with N. D. Weinstein and P. M. Sandman	Analyse differences in risk perception and divergence in risk behaviour: process of adopting risk-reducing behaviour by perceived costs and benefits of changing one's behaviour and action	Human health risk situation: from individuals (mental states) to general stages	Risk perception & behaviour: relevant for behaviour which requires deliberate action instead of gradual habit changing	Individuals, also including experts and media	Personal experience, perceived susceptibility and severity, perceived self-efficacy, perceived barriers, resources (conceptualise the precaution adoption process as a series of distinct cognitive stages of agent)	Intentions and actions (gap between)	Social norms and barriers, communication and assistance for action taking, media messages, public–private partnerships	Rather related to health risks (AIDS, Radon, BSE, etc.)	Intervention strategies for every cognitive stage to overcome barriers for behaviour change (that people better respond to information & strategies)

Table 5.2 Social sciences approaches of risk/vulnerability assessments (see Sect. 3.2.3.2) reconciled with the agent concept (see Fig. 5.1)

Social sciences approaches					Agent level		Environment level		
Approach & Author	Purpose	System under study	Scope of assessment	Scale(s) of assessment	Agent attributes & Perception	Agent preferences & Behaviour	Social influence & Feedback	Hazard type	Policy options
Access model, associated with B. Wisner, Blaikie, Cannon and Davis	Analyse patterns of vulnerability: to show rather socio-economic processes influencing vulnerability	Risk situation: longer-term social processes to trace the transition of "normal life" to disaster (as a socio-economic change)	Risk behaviour, risk/disaster management: role and agency of people before/after disaster impact; reflecting the pattern of access in society	Micro level: establishment and trajectory of vulnerability and its variation between households	Deals with the amount of "access" people/households have to resources and assets, income opportunities, access qualifications, livelihood opportunities and decisions; also shaped by social relations and structures of domination	Securing livelihoods and maintaining expectations in life (model allows implicitly that people develop strategies to try to achieve these ends)	Social relations, structures of domination, social protection, overarching political economy	Natural hazards/ disasters	Social protection measures, reaction, coping, adaptation, interventions etc.
Social Amplification of Risk Framework (SARF) by Kasperson et al.	Analyse differences in risk perception and divergence in risk behaviour: to illuminate full complexity of risk amplification and attenuation at different social and individual stations; analysis is sensitive to the social setting in which risk processes occur and recognizes that social interactions and feedback may change risk handling	Risk situation: social setting of individual and social stations which occupy a primary role in society's handling of risks	Risk perception, behaviour and management: social contexts in which risks are conceptualised, identified, measured and managed	Individual and different social stations (e.g. news media, opinion leader) as well as their interactions	Individual Stations: A) Attention filter B) Decoding C) Intuitive heuristics D) Evaluation and interpretation E) Cognition in social context	Social stations vary greatly in their goals for and commitments to risk management; Institutional, group and individual behaviour varies in relation to: A) attitute and attitude changes B) political and social actions C) behavioural and organisational responses D) social protest and disorder	Social interactions may either amplify or attenuate the signals to society about the risk; different information resources and information channels are taken into account	Not further specified	"Nodes" of risk amplification and attenuation transmit signals to society; organisational changes, regulatory actions, in/decrease in physical risk

(Continued)

Table 5.2 (Continued)

Social sciences approaches					Agent level		Environment level		
Cultural Theory associated with Douglas and Wildavsky	Analyse differences in risk perception and divergence in risk behaviour: to show role of social values and world views for risk perception and behaviour; each worldview represents a different 'rationality' or a set of presuppositions about the ideal nature of society	Risk situations: those risks that threaten people's preferred way of life according to worldview	Risk perception & behaviour: research studies operationalised cultural theory as an independent set of variables to test the theorized relationship between worldview values, risk perceptions and policy preferences	How different individuals and groups interpret the world in different, yet patterned ways according to four basic (ideal type) world views: hierarchical, fatalistic, individualistic and egalitarian	World views: general social, cultural and political attitudes towards the world and "orienting dispositions" that guide individual responses in complex situations and result in different risk perceptions	World views lead each group type to prefer different policy responses	World views are mediated by social relations: an individual is either more group-oriented or individual-oriented	Not further specified	Not further specified

Table 5.3 Coupled approaches of risk/vulnerability assessments (see Sect. 3.2.3.3) reconciled with the agent concept (see Fig. 5.1)

Coupled approaches					Agent level		Environment level		
Approach & Author	Purpose	System under study	Scope of assessment	Scale(s) of assessment	Agent attributes & Perception	Agent preferences & Behaviour	Social influence & Feedback	Hazard type	Policy options
Pressure-and-Release (PAR) model associated with Wisner, Blaikie, Cannon and Davis	Analyse patterns of vulnerability: social processes and underlying causes leading to vulnerability: root causes, dynamic pressures and unsafe conditions in the social and physical environment	Risk situation: trace the connections that link impact of a hazard with a series of social factors and processes generating vulnerability	Risk assessment: historically and locally-based research is necessary to uncover the vulnerability process	Households are embedded in political & economic system and influenced by macro-forces on societal level as well as by local level economy and social relations	Root causes: limited access to power, structures, resources etc.; unsafe conditions: low income level, unprotected building and infrastructure at dangerous locations, etc.	Further specified in Access model	Root causes: political & economic system; dynamic pressures: lack of standards in public life, rapid urbanisation, deforestation, etc.; unsafe conditions: lack of local institutions or appropriate skills	Natural hazards	Not further specified
"Reduced" Vulnerability Framework based on the Coupled Vulnerability Framework by Turner II et al.	Analyse patterns of vulnerability: framework (not explanatory) for the coupled system's vulnerability to hazards: "reduced-form" analysis of the larger systemic character	Risk situation: factors and linkages that potentially affect the vulnerability of the coupled human-environment system in a place; identification of critical interactions and potential dynamics	Risk assessment, risk/disaster management: analysis is affected by the way in which the coupled system is conceptualized for study	Including cross-scale and beyond place dynamics; analysis is affected by the way in which the coupled system is conceptualized for study	Sensitivity of human conditions e.g. social capital that influences the existing coping mechanisms of individuals; coupled with the environmental conditions of sensitivity	E.g. individual actions/coping mechanisms	E.g. human influences outside the place: macro-political economy, institutions, global trends and transitions;	Not further specified	Building resilience: coping as well as adjustment & adaptation (e.g. new programs, autonomous options)

(Continued)

Table 5.3 (Continued)

Coupled approaches					Agent level		Environment level		
Disaster Resilience of Place Model (DROP) by Cutter et al.	Analyse patterns of vulnerability/resilience: to understand and to measure community-level resilience to natural hazards from a processual perspective of hazard/disaster and vulnerability/resilience	Risk situation: place-specific multiscalar processes that occur within and between social, natural and built environment system: short and longer-term impacts of hazards/disasters	Resilience assessment & risk/disaster management & recovery process: to compare between places or to analyse resilience trends over time	Community level & broader scales (inherent, endogenous and exogenous vulnerability/resilience factors)	Social & demographic characteristics e.g. education, insurance; economic resilience: employment, value of property, municipal finance/revenues; social resilience: social networks and social embeddedness; community competence resilience: local understanding of risk, counselling services, etc.	Not further specified	Social network as well as built environment network resilience: lifelines and critical infrastructure, transportation network, etc.	Natural hazards/disasters	Institutional resilience: e.g. participation in hazard reduction programmes, hazard mitigation plans, emergency services, zoning and building standards, emergency response plans
R. Palm's Cross-Level Framework	Analyse differences in risk perception and divergence in risk behaviour: focus on micro–macro relation to integrate individual and societal (agency and structure) responses to hazards; to understand both the structure of macro-forces in society and how the micro level behaviour/responses can modify the system; to link various levels of decision making into a coherent whole	Risk situation: human-environment interactions across the full range of scales of analysis including micro- & macro level as well as physical environment	Risk perception & assessment: micro & macro are endpoints of a continuum and may be defined based on the size and complexity of the study group; may shift with particular problem investigated (cross-level mode of analysis)	Individuum, household, gatekeeper, society and the linkages in between	E.g. for individuum: knowledge about & awareness of hazard, personal experience, how the individual personalises the general notion of risk; e.g. for society: authority over land-use decisions	Multiple, competing objectives between agents; different goals according to the agent's role and power	Constant political, economic and social constraints influence any locational decision (location theory); societal/cultural norms controlled/realised by gatekeeper	Environmental hazards	Not further specified

approach developed by Paton (2003, 2008) and the PAPM approach by Weinstein and Sandman (1992, 2002) further focus on pro-active behaviour and how the barriers for a behaviour change can be overcome.

Social sciences approaches rather emphasise the social setting influencing risk perception, vulnerability and behaviour towards risks; whereas they look at the individual level *and* the societal level. They consider that individuals are embedded within a social context; meaning that constraints and opportunities exist which feed back to the individual. These approaches identify and explain patterns of vulnerability deriving from the individuals' situation and from the societal and economic context. In the Access model associated with Wisner et al. (2004) the process of vulnerability is explained on the basis of patterns of access in society, i.e. socio-economic processes shape vulnerability and the role and agency of people before or during a disaster. The SARF approach by Kasperson et al. (2005) further emphasises the role of social stations such as the news media and opinion leader in amplifying or attenuating risk perception in society.

The coupled approaches of risk/vulnerability assessment additionally include aspects of the physical environment and explicitly focus on interactions between the human and physical environment sphere (see Table 5.3). They facilitate a place-based and processual understanding of vulnerability. The PAR model associated with Wisner et al. (2004) for example emphasises factors and processes which can be quite remote from the disaster event itself—temporally and spatially. Also the coupled vulnerability framework by Turner II et al. (2003) indicates the potential place-based and beyond-place dynamics in order to understand critical interactions. Cutter's Disaster Resilience of Place Model (DROP; Cutter et al. 2008) further extends the pre-disaster perspective to disaster recovery and resilience trends over time.

5.1.1 Agent-Based Conceptual Model of Vulnerability Dynamics

In summary, these risk/vulnerability approaches provide a necessary theoretical foundation for the agent-based vulnerability assessment, the possible target of the model as well as the possible structure of the model. On the basis of this theoretical foundation from risk research (see Sect. 3.2.3) a general conceptual model could be developed which combines the relevant aspects and processes from the risk approaches *and* the agent concept. The general agent-based conceptual model of vulnerability dynamics is depicted in Fig. 5.1.

The general conceptual model consists of two main components—AGENT LEVEL and ENVIRONMENT LEVEL—which together form the SYSTEM under consideration. Agent and environment level are coupled and due to their interactions the system behaviour emerges. Relationships, processes and possible feedback effects represent the system's connectivity. Due to the agent-environment relationship in the conceptual model, exposure of the agents to the HAZARD is assumed. Whereas the hazard constitutes a condition in the environment level, social vulnerability is bounded to

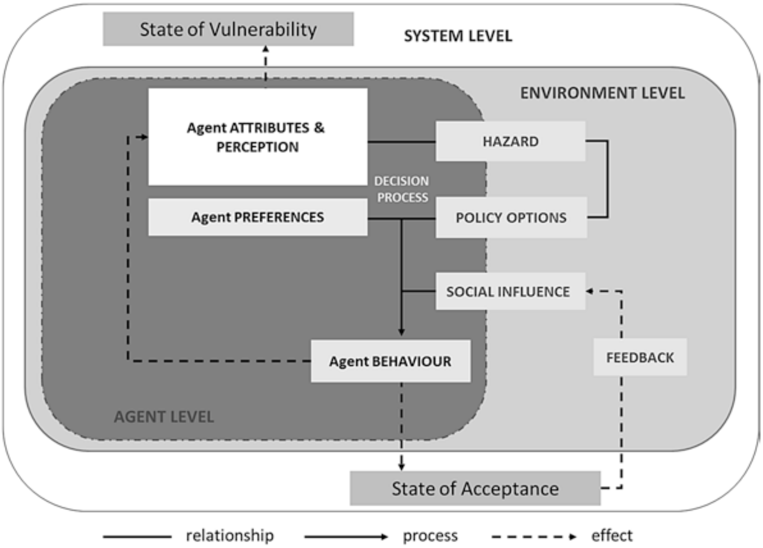


Fig. 5.1 General conceptual agent-based model of vulnerability dynamics

the agents' conditions. The agent ATTRIBUTES & PERCEPTION as well as their PREFERENCES and BEHAVIOUR in the system therefore shape vulnerability in the model. Meaning that, vulnerability does not occur solely due to exposure; instead each agent may further decrease or increase its vulnerability level due to social attributes and/or behaviour. Furthermore, each agent can be influenced by the social setting due to agent–agent relationships representing the SOCIAL INFLUENCE inside the system.

In the conceptual model an AGENT is described by social ATTRIBUTES & PERCEPTION which might lead to a vulnerable state of the agent in combination with the HAZARD impact. Perception of the hazard exposure is regarded as a precondition to establish risk behaviour. Agents may develop PREFERENCES how to react to the hazard. Although agents can react with fatalism or denial, the model assumes that POLICY OPTIONS are offered to the agents. These policy options might provoke pro-active agent behaviour such as the implementation of self-protection measures. They are developed in the agent's environment according to the existing hazard type e.g. to prevent flood damage local authorities can promote the usage of pumps or small structural barriers in private properties. In the model the implementation of PREFERENCES into BEHAVIOUR is considered as a DECISION PROCESS. As social vulnerability in the model is bounded to the agent's conditions, also the positive agent decisions with regard to the policy options can lead to a decrease in the system's vulnerability. Whereas the offered policy options depend on the hazard conditions, the agent decision process is also determined by certain influences. Besides the agent's preferences, the agent decision process can be interfered by a SOCIAL INFLUENCE from the agent environment. Although an agent may have a preference, the social sphere can influence its decision process and lead to a change in behaviour or to rejection of the offered policy options. Positive agent decisions effect not only the agent's vulnerability attributes, they furthermore FEEDBACK into the system and intensify the social influence during the agent's decision processes. On the system level it can be observed how the STATE OF VULNERABILITY and the STATE OF ACCEPTANCE co-evolve. Acceptance refers to the decision process of agent's with regard to the offered policy options.

To decrease the abstraction of the model Amblard et al. (2001, p. 846) supposes to increase the realism of the model along one or more axes: the environmental model design, the agent model design, the relation model design and/or the organisation model design. Under consideration of the exemplary risk/vulnerability approaches (see Tables 5.1, 5.2 and 5.3) further theoretical input for each model component will be discussed. By decreasing the abstraction of the general conceptual model, it furthermore shows the possible applicability of the model.

Beginning with the design of the AGENT & ENVIRONMENT LEVEL, the scope and scale of the assessment is important. As neither the scope nor the scale of assessment is fixed in the general conceptual model, it can be designed according to the purpose of the respective approach. In psychological approaches the environment level (see Table 5.1) is reduced to a social construct, i.e. to a perceived environment. Thus, agent behaviour might rather be determined by the perceived probability of hazard, by its perceived severity and other risk-related aspects such as the impression of reversibility of risk consequences. Also social sciences approaches take risk perception into account but refer to a broader social context. Risk perception here is not only the result of personal attributes; it is mediated by social relations and interactions (see Sect. 3.2). Also patterns of vulnerability are not mainly derived from the individual but from the social and economic context (see e.g. Wisner et al. 2004). The social setting, group behaviour and/or the network relations might thus be considered for environmental model design from a social sciences perspective. Increasing the environmental model design could imply for example to add (physical) environmental criteria and their dynamics e.g. the hazard characteristics. Detailed hazard conditions such as frequency are not explicitly considered in the approaches—though some approaches are developed for a specific hazard or have been investigated on a selection of certain hazardous events. The approach by Grothmann and Reusswig (2006) for example examines risk behaviour against floods whereas Stern et al. investigates risk perception with reference to 24 environmental hazards ranging from hazardous waste sides to global warming and oil extraction. In many approaches rather the general hazard type is considered such as technical and environmental/natural hazards or is not further specified at all.

In the conceptual model an AGENT is described by social ATTRIBUTES and PERCEPTION. In order to decrease the abstraction of the agent model design, detailed internal agent properties could be added. In psychological approaches differences in risk perception are measured by relating it to people's experience with and awareness of hazard, their world views or the perceived susceptibility, etc. (see e.g. Table 5.1). Agents could be equipped with rich cognitive profiles on the micro level in order to see how differing perception patterns emerge on the macro level. From a social sciences perspective, agents might rather be described by socio-economic or demographic attributes such as income level, resources, level of education or gender to measure differences in vulnerability. Attributes describing the agent's role or position in society can also be used for describing the process of vulnerability under certain structures of domination in society (see e.g. Access model by Wisner et al. 2004).

Agents act upon their assigned goals and behaviour rules. Different types of AGENT PREFERENCES and BEHAVIOUR can be transferred from the theoretical frameworks in order to decrease the abstraction of the conceptual agent model. Psychological approaches for example reason how individual characteristics and hazard-related aspects lead to risk ranking, certain preferences for risk handling or intentions for self-protection. They also aim at the gap between intention and action or include social norms and barriers as well as different cognitive stages of agents. The PAPM approach by Weinstein and Sandman (1992) defines individual's behaviour as ranging from unawareness, to decision and acting stages. Other approaches include also non-protective responses such as denial of hazard or fatalism e.g. the model of precautionary action developed by Grothmann and Reusswig (2006). Distinct agent roles or memberships such as risk managers or lay people might further increase the agent model design from a psychological perspective. In social sciences approaches agents may aim at securing livelihoods as in the Access model; in the approaches by Kasperson et al. (2005) and Palm (1990) multiple, competing goals could derive in the model due to the agent's social role or power (see Table 5.2).

In order to increase the realism of the model interactions can be more detailed, i.e. the agent-agent interactions as well as the agent-environment interactions. Relation model design may concern for example the exchanges or communication between entities. The considered coupled approaches integrate the social and the physical environment; whereas they omit a rich cognitive description of individuals and rather focus on broader scales such as communities or nations (see Table 5.3). By focussing on the relation model design, these approaches might enrich our understanding of the human-environment relationships. The model approach by Paton (2003, 2008) and McIvor et al. (2009) could furthermore increase the agent-agent relation model design as it constitutes a relationship between individual, community-based and societal factors in the model (see also Palm 1990).

The organisation model design refers to an increase of the features taken into account for the organisation in the social environment e.g. new group behaviour which emerges due to the agent's social relations. Social sciences approaches emphasise the social setting influencing risk perception, vulnerability and behaviour towards risks. They may support in particular social relation and organisation model design. Cultural theory for example considers that world views shaping risk perception and policy preferences are mediated by social relations (Douglas and Wildavsky 1982). Also the Access model may be interesting for developing a detailed agent network which reflects the pattern of access in society and the structures of domination (see Table 5.2). Detailed organisation model design may additionally be covered in the SARF approach by Kasperson et al. (2005). The different social stations considered in the approach could be used to explain how transmitted signals in the network of stations can attenuate or amplify risk and which role these social stations play for the emergence of new individual behaviour. Also psychological approaches dealing with behaviour change can be used for increasing the detailed organisation model design. Here all agents of the same cognitive stage might experience the same barriers for behaviour change which might afford communication and assistance for action taking.

The risk/vulnerability approaches thus can support an agent-based conceptual model development in many ways. Based on the abstract framework of the general conceptual model (see Fig. 5.1), it was possible to decrease the abstraction of the model by including certain theoretical aspects and different disciplinary perspectives. The approaches might not cover all components of the agent-based model e.g. policy options and might make a combination of different approaches necessary. Some approaches consider besides the risk situation also the disaster process and might need an extension of the model to the post-disaster phase. Yet, the conceptual model development showed how risk/vulnerability approaches from different disciplinary perspectives can be reconciled with the agent concept in order to assess the dynamics of vulnerability. In this approach, the developed conceptual model is not used for theory development only. For an empirical-based vulnerability assessment the general conceptual model needs to be adapted to the regional context. Hereby, the model could be provided with empirical data from the case study area of the German North Sea Coast.

5.1.2 Adaptation of the Conceptual Model to the Regional Context

The general conceptual agent-based model is adapted to the regional context (Fig. 5.2). As neither the scope nor the scale of analysis is fixed in the general conceptual model, it can be adapted to the purpose of the respective approach. Here, the purpose of the regional adapted model is the understanding of vulnerability dynamics in the selected coastal region of Germany. The assessment aims at the individual, relational and spatial aspects influencing vulnerability dynamics over time. The specification of the scope and scale of assessment to the regional context allowed equipping the model concept with empirical data.

The basic assumptions and the structure of the conceptual model are maintained (see Fig. 5.2). The system consists of coupled agent-environment levels with hazardous and vulnerable conditions. The system under study represents a risk situation. As already mentioned before, the model presupposes that agents are (spatially) exposed to the hazard, yet it is still open for including different attributes and processes related to vulnerability.

The scope of assessment allows describing patterns of vulnerability and preventive behaviour at the German North Sea Coast. On system or macro level the model focuses on vulnerability dynamics in particular due to preventive behaviour of agents. It observes—as the general conceptual model—how the STATE OF VULNERABILITY and the STATE OF ACCEPTANCE co-evolve on the macro level (see Fig. 5.2). Acceptance refers to the decision process of agent's with regard to the offered policy options; vulnerability is bounded to the agent's conditions. The model assumes that due to the acceptance of self-protection measures, vulnerability can be reduced.

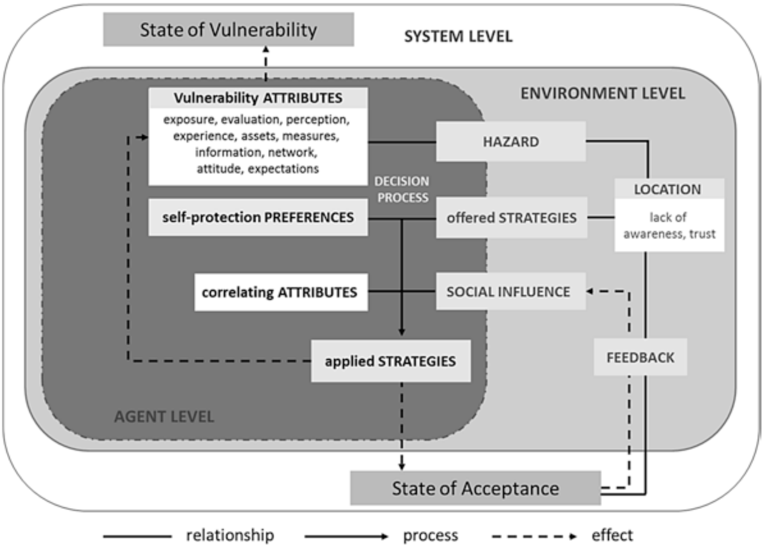


Fig. 5.2 Conceptual agent-based model of vulnerability dynamics adapted to the regional context

Vulnerability in the model derives from the micro level of agents which are characterised by selected vulnerability ATTRIBUTES (see Fig. 5.2). Analysis of theoretical risk/vulnerability approaches (see Sect. 3.2.3) and conducted vulnerability studies in the coastal area (see Sect. 4.3) revealed ten vulnerability attributes which were considered due to their relevance in this approach. Concerning the scale of assessment, an agent represents a household in the case study region. Each agent is equipped with vulnerability ATTRIBUTES and PREFERENCES that determine its behaviour during the DECISION PROCESS in the model (see Fig. 5.2). As the model focuses on private households, the offered policy options are specified to four different self-protection strategies which can be applied by the households in order to reduce vulnerability (see Fig. 5.2). Accordingly, agents can react to the offered self-protection STRATEGIES and decide to apply it. The four self-protection strategies are: informative events to learn about prevention measures, better protection by insurance, incentives given by the government to invest in self-protection measures and as the most radical strategy migration out of the flood-prone coastal zone. As each agent can be distinguished by its vulnerability attributes and self-protection preferences, the model consists of heterogeneous and autonomous agents. The individual agent profile determines the vulnerability level of the agent and contributes to the state of vulnerability on the macro level.

Vulnerability can vary between individual entities and spatially between e.g. communities as described in the Sect. 3.2.2. To include the spatial dimension of vulnerability the model is adapted to the regional context, meaning that each agent is located in the respective communities selected for the case study. Besides the individual attributes for agents thus also locational variables are added to the regional adapted model. These variables do not focus on hazard conditions but on the subjective risk concept of agents; here expressed as the human(agent)-environment relationship. The model assumes that not only the perception and evaluation of the HAZARD is related to the LOCATION but as a result also the perception of offered self-protection STRATEGIES. Whether agents perceive the offered self-protection strategies thus is related to the LOCATION variables LACK OF AWARENESS with regard to the hazard and TRUST in official dike protection. The model assumes that a high lack of awareness level and a high level of trust in official dike protection diminishes the agent's self-protection actions and decisions. The decision process of agents thus can be further influenced by the agent's human-environment relationship.

As in the general conceptual model, the decision process can be interfered by SOCIAL INFLUENCE from the agent environment. The communities of the case study area might provide agents with a social network from which these influences can derive. Due to bounded rationality, agents in the model are not able to perceive the whole system; the perception of hazard and offered strategies depends on their human-environment relationship. The social network of agents thus is also restricted to the respective agent community, representing the micro–macro relationship of agents. Besides the micro-macro relationship, also individual correlating ATTRIBUTES might affect the decision process of the agent and the application of the respective strategy. Positive agent decisions effect not only the agent's vulnerability attributes, they furthermore FEEDBACK into the system and intensify the social influence during the agent's decision processes. Hence, each agent's decision determines the STATE OF VULNERABILITY and the STATE OF ACCEPTANCE on the macro level (see Fig. 5.2). Also a temporal relationship is assumed between the agents` decisions and the location. Whereas the state of acceptance is updated during the model process, the lack of awareness with regard to the hazard further increases, represented as a negative feedback effect.

The agent-based model includes individual, relational and spatial aspects of vulnerability. The heterogeneous agents are able to autonomously take their decisions; by means of simulation the model enables to derive the dynamics of vulnerability on the macro level emerging from the agents' decisions and interactions.

5.2 Model Input: Empirical Data Base of Vulnerability Assessment

The adaptation of the conceptual model to the regional context decreases the abstraction of the model and allows equipping the model with empirical data. The quantitative empirical survey provides the necessary input data for the agent attributes as well as for agent behaviour. The usage of empirical data increases the realism of the model and facilitates assessing vulnerability from the bottom-up. The empirical study was conducted in the flood-prone area of the German North Sea Coast. It aimed at vulnerability, present risk behaviour and self-protection preferences of private households against flooding. The communities Kellinghusen, Münsterdorf, Borsfleth and Wewelsfleth at the tide dependent river Stör and the community

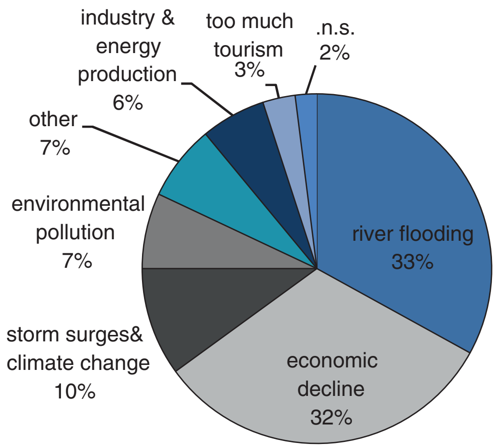


Fig. 5.3 Risk perception in the districts Steinburg and Wilstermarsch: Which hazard do you consider as most important for your community? (N = 100; n.s. = not specified; categories according to Ratter et al. 2009, p. 58)

Büsum at the Meldorf Bight (see Map 4.1) were selected for a comparative vulnerability assessment. Individual, relational and spatial aspects of vulnerability were assessed. In order to bridge the conceptual and the computational model a bottom-up approach was chosen and revealed agent types concerning vulnerability, present risk behaviour and preferences towards self-protection strategies. The considered system is restricted to 100 households as it aimed to show in principle how the system analysis can be empirically based. An overview of the characteristics of the survey locations is given in Appendix A.2 and the questionnaire in Appendix A.1.

5.2.1 Perception and Evaluation of Hazards and Risk

The question *who* is vulnerable to *what* is paraphrased to who *feels* vulnerable to what? In order to discover the risk understanding in the case study region, the perception and evaluation of hazards, risk and exposure of the respondents is captured. Which hazard type people consider as most important in their communities? Hazard categories, ranging from STORM SURGES & CLIMATE CHANGE, RIVER FLOODING, ENVIRONMENTAL POLLUTION, INDUSTRY & ENERGY PRODUCTION, TOO MUCH TOURISM and ECONOMIC DECLINE (see Fig. 5.3) were previously defined (according to Ratter et al. 2009). Own suggestions could also be added (OTHER). The study revealed that people are mainly concerned about RIVER FLOODING (33 %; N = 100) and ECONOMIC DECLINE (32 %; N = 100) as well as about STORM SURGES & CLIMATE CHANGE (10 %; N = 100). Also the hazards ENVIRONMENTAL POLLUTION and INDUSTRY & ENERGY PRODUCTION account for 6–7 % of the responses. Furthermore a spectrum of OTHER hazards (7 %; N = 100) is given such as unsustainable land use, the financial or political system, etc.

Due to the different location of the communities distinctions in hazard perception can indeed be made between the survey sites. The five communities either show a high concentration in a specific hazard or rather a wide dispersed hazard ranking. In Kellinghusen for example 67 % of the respondents view RIVER FLOODING as the main hazard for their community. ECONOMIC DECLINE accounts for 28 %; other categories are neglected (5 % OTHER and N.S.). Also in Münsterdorf, respondents regard RIVER FLOODING as the main hazard for their community (80 %). In Büsum the ECONOMIC DECLINE with 47 % is considered as the most important hazard, yet also ENVIRONMENTAL POLLUTION (16 %), STORM SURGES & CLIMATE CHANGE (13 %), TOO MUCH TOURISM (9 %) as well as the category OTHER (16 %) get a recent number of mentions.

Due to a nuclear power plant in Brokdorf, the hazard type INDUSTRY & ENERGY PRODUCTION accounts for 20 % in Wewelsfleth and for 29 % in Borsfleth. Moreover, the categories STORM SURGES & CLIMATE CHANGE and RIVER FLOODING receive considerable attention in Wewelsfleth (each 15 %) and in Borsfleth (each 29 %). Still, in Wewelsfleth ECONOMIC DECLINE is regarded as the main hazard with 30 %. In comparison, these answers indicate that not only the location of the communities decide about the intuitively perceived hazards. Although in Kellinghusen, approximately 55 km upstream, storm surges are not regarded as hazardous, in Wewelsfleth at the river mouth of the Stör more respondents regard STORM SURGES & CLIMATE CHANGE as a hazard than in Büsum which is located right at the North Sea.

To make the distinctions more precisely, an additional question aimed at the risk of flooding in the river catchment. Is the risk of flooding rather related to STORM SURGES AT THE COAST, to RIVER FLOODING FROM THE HINTERLAND or BOTH? With regard to this question, the relevance of storm surges decreases with increasing distance from the coast. Whereas in Wewelsfleth 50 % regard STORM SURGES & CLIMATE CHANGE as the most relevant source of flooding, in Kellinghusen RIVER FLOODING counts for 56 % of the mentions (3 %: STORM SURGES & CLIMATE CHANGE). Münsterdorf, located approximately 38 km upstream, shows nearly an equal distribution about all three categories. The category distributions highlight differences in the conceptualisation of the flooding risk in the case study region. The results of the questionnaire show that for example in Kellinghusen (33 %) and Wewelsfleth (25 %) the hazard is related to BOTH, meaning that people are also aware of the tide dependence of the river system.

Besides the type also the evaluation of risk was enquired in the empirical survey: is the risk of flooding in the communities rather evaluated as VERY HIGH–HIGH, MEDIUM–LOW or as VERY LOW–NOT AT ALL (see Fig. 5.4). In Büsum the question referred to the risk of a storm surge. About half of the respondents (53 %; N = 100) regard the risk of flooding/a storm surge as MEDIUM–LOW; additionally 34 % (N = 100) regard it as VERY HIGH–HIGH. In Kellinghusen, risk evaluation lies considerably higher than average with 64 % of respondents evaluating the flood risk as VERY HIGH–HIGH. In Wewelsfleth and Borsfleth risk evaluation is comparable to average (50 % & 57 %: MEDIUM–LOW) but with a tendency towards a lower evaluation of risk (VERY LOW–NOT AT ALL: 30 % & 29 %). Most respondents in Büsum (69 %) and Münsterdorf (80 %) consider the risk as MEDIUM–LOW. According to the second research question–which agent types concerning

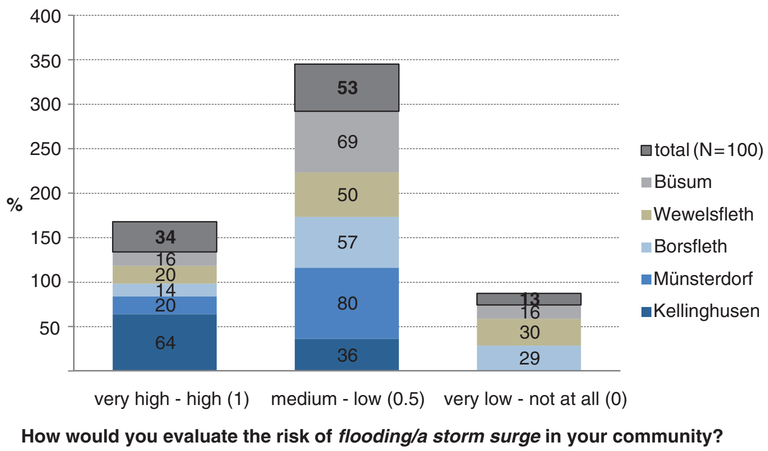


Fig. 5.4 Agent types (1/0.5/0) with regard to risk evaluation (N = 100)

vulnerability, present risk behaviour and preferences towards self-protection strategies can be identified in the coastal zone of Schleswig–Holstein – the categories are used to build agent types (1/0.5/0) with regard to the risk evaluation categories VERY HIGH–HIGH/MEDIUM–LOW/VERY LOW–NOT AT ALL (see Fig. 5.4).

To what extent do people perceive the risk as a personal risk? As the coastal lowland in Schleswig–Holstein is categorised as flood-prone (see further Schleswig–Holsteinischer Landtag 2009a, pp. 6, Chap. 4), perception of exposure can be rated as important. Thus, residents were asked whether they live in a flood-prone area, i.e. an area that could be flooded in case of a dike breach or due to the failure of flood barriers (see Fig. 5.5). On average 78 % (YES; N = 100) are aware of the exposure; 19 % have a different view (NO; N = 100) whereas 3 % are not sure about the exposure (DON'T KNOW; N = 100). With regard to differences between the communities, in Kellinghusen and Borsfleth (each 86 %) more than average recognises the risk situation. All respondents in Münsterdorf regard themselves as living in a flood-prone area (100 %). In Büsum solely 66 % answer in the affirmative, whereas 25 % deny exposure to risk and 9 % are unsure about exposure (YES/NO/DON'T KNOW). This uncertainty about exposure is not expressed in any other community. The corresponding agent types (1/0.5/0) with regard to perception of exposure (YES/DON'T KNOW/NO) are depicted in Fig. 5.5.

5.2.2 Experience with and Information about Events

Knowledge of risk might also be related to experience and can result in different impacts of hazards within communities or societies (see Sect. 3.2). About 54 % of respondents (N = 100) already experienced impacts of a flooding event or a storm

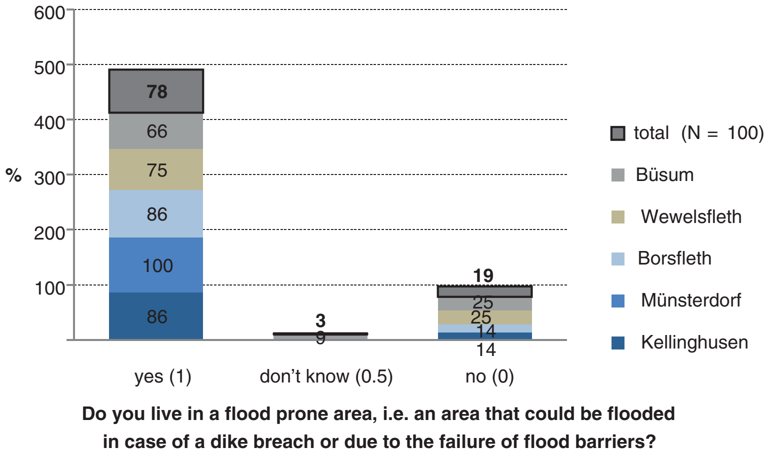


Fig. 5.5 Agent types (1/0.5/0) with regard to perception of exposure (N = 100)

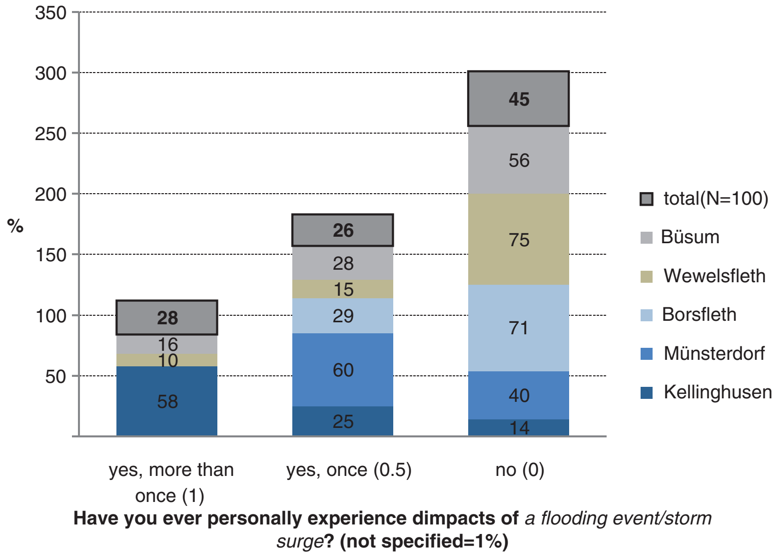


Fig. 5.6 Agent types (1/0.5/0) with regard to flood/storm surge experience (N = 100; not specified = 1 %)

surge (see Fig. 5.6). 26 % of all participants in the study experienced impacts of an event at least once (YES, ONCE), 28 % even more than once (YES, MORE THAN ONCE). About 45 % have no experience with impacts of floods or storm surges (NO and 1 % = NOT SPECIFIED). By further consideration of the communities, greater differences occur also concerning experience. In Kellinghusen, only 14 % of the

Table 5.4 Year of the last event remembered in each community (N = 100)

Location	When did you experience the last event [year]? (N = 100)
Kellinghusen	2010
Wewelsfleth	2002
Büsum	1976
Borsfleth	1962
Münsterdorf	1962

respondents have not gathered experience with flooding yet. The majority of 58 % have experienced the impacts of floods more than once and 25 % at least once (see Fig. 5.6). Personal experience with flood impacts is also high in Münsterdorf where 60 % of the participants refer to one flood event (YES, ONCE). In Büsum, a considerable level of 16 % of participants has experienced impacts of more than one storm surge (YES, MORE THAN ONCE) and 25 % at least of one (YES, ONCE). But more than half of the respondents in Büsum have not gained experience with storm surge impacts yet (NO: 56 %). Meaning that in Kellinghusen approximately twice as many respondents have experience with impacts in comparison to Büsum (83 % vs. 44 %; see Fig. 5.6). In Borsfleth and Wewelsfleth the level of experience among participants only reaches 29 % and 25 %, whereas 10 % refer to more than one experience in Wewelsfleth (YES, MORE THAN ONCE); the majority of 71 % and 75 % does not have experience with flood impacts. The agent types (1/0.5/0) are developed according to the households experience (YES, MORE THAN ONCE/YES, ONCE/NO).

People were also asked about *when* they last experienced an event and to give a short description *what* they experienced. In Table 5.4 the year of the last event remembered by respondents is recorded and reflects some of the already mentioned events in Chap. 4. According to the responses, people in Borsfleth and Münsterdorf still keep the storm surge of 1962 in memory; an event that happened nearly 50 years ago. In Büsum this time span amounts to 35 years, here respondents referred to the storm surge(s) of 1976 (see Chap. 4). In Wewelsfleth less than 10 years passed since the last event in 2002, whereas in Kellinghusen only a couple of months passed since the last event. Many respondents were unsure about the exact year.

Furthermore, respondents were asked to describe *what* happened during the event. Due to the different types of events the experiences vary in the communities. Most details were given in Kellinghusen about a flood that occurred only few months before in January 2010. About 28 % of the respondents in Kellinghusen refer to this flood. They report that basement and/or ground floor of their houses were flooded due to ground water intrusion and/or surface water of the river Stör. Residents in Kellinghusen also name preparation measures such as the usage of sandbags and pumps to cut the losses in their houses. Some even stabilised the river bank adjacent to their garden to improve protection against river flooding. In general, respondents in Kellinghusen mention that river flooding occurs seasonally

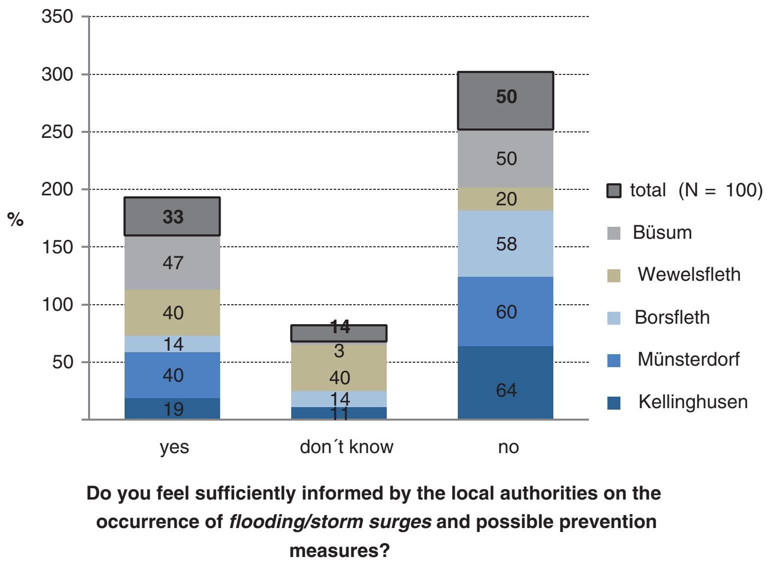


Fig. 5.7 Level of information (variable information [1]; N = 100; not specified = 3 %)

in spring and autumn. They remember in particular the floods of 1995, 1998, 2002, 2005, etc. People also report that in case of a flood, streets in Kellinghusen are often impassable and that sometimes properties are unapproachable. Wewelsfleth experienced the last event in 2002. Here, the respondents report about torrential rain fall and backwater in the river Stör and in retention basins. To protect the area from further flooding, the fire brigade had to assist. The last event remembered in Büsum is the storm surge(s) of 1976. Residents had to wait anxiously for a possible evacuation; others participated in dike protection measures. In Münsterdorf and Borsfleth the participants refer to the storm surge of 1962 (see Chap. 4). Whereas in Borsfleth no further details are given about the course of the event, in Münsterdorf people report about flooded basements and ground floors of houses adjacent to the river and about the danger of building collapses.

A further question aimed at the information and knowledge level of residents: do you feel sufficiently informed by the local authorities on the occurrence of flooding/storm surges and possible prevention measures? (see Fig. 5.7) In the case study region, half of the respondents do not feel sufficiently informed about flooding/storm surge events and prevention measures (NO: 50 %; N = 100). Additionally, a percentage of 14 % (N = 100) seems to be unsure how to judge the level of information (DON'T KNOW). About a third of the participants feels sufficiently informed (YES: 33 %; N = 100). Respondents in Münsterdorf (YES: 40 %), Wewelsfleth (YES: 40 %) and Büsum (YES: 47 %) feel better informed than average. In Borsfleth and Kellinghusen the level of information is considerably below average (YES: 14 % and 19 % only). Both rather count with an above average level with regard to the lack of information (NO: 58 % and 64 %). In Büsum nearly

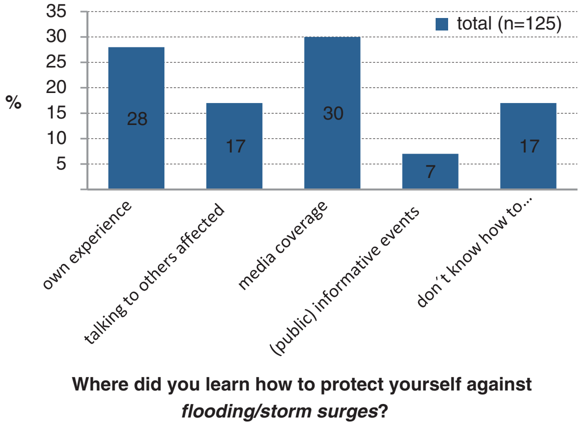


Fig. 5.8 Source(s) of information (variable: information [2]; n = 125; not specified = 1 %)

half of the respondents mention that they are not sufficiently informed (NO: 50 %). In Wewelsfleth the amount of indecisive residents is with 40 % considerably high (DON'T KNOW) but below average concerning the lack of information (NO: 20 % instead of 50 % on average). The respective agent types (1/0) depend on both conditions, i.e. information [1] and information [2].

Residents in Borsfleth and Kellinghusen give as reasons for their low information level that either no information was given to them or that information did not focus (enough) on their community. Additionally, they criticise that local authorities react late or solely upon making enquiries and that residents are reliant upon information from other sources such as radio, internet or television. People in Kellinghusen felt that it was/is necessary to organise a citizens' initiative dealing with flooding and the possible prevention measures. In case of flooding the local authorities for example distribute sandbags in Kellinghusen. In Wewelsfleth, where the percentage of people with low information level is quite small but the percentage of unsure people very high, other reasons were given. Participants here mentioned that they count on the experience of the older generation or that they know how to help themselves. One resident admitted that he did not bother to get information. Some residents in Büsum named brochures that were distributed but also criticised that information was too general, i.e. on state level.

5.2.3 Capacities of Residents

Some participants already mentioned that they searched for information independently instead of relying on the authorities. A further question aimed at the information sources of the population: where did you learn how to protect yourself against flooding/storm surges? (see Fig. 5.8). The answers reveal that 17 % do not know exactly how to protect themselves from flooding/storm surges (DON'T KNOW HOW TO…; n = 125). 30 % account for MEDIA COVERAGE, thus making it the most

Table 5.5 Number of agents with social network (N = 100; in %)

Location	Percentage of respondents in the communities talking to others affected
Kellinghusen	25
Wewelsfleth	20
Büsum	25
Borsfleth	14
Münsterdorf	0

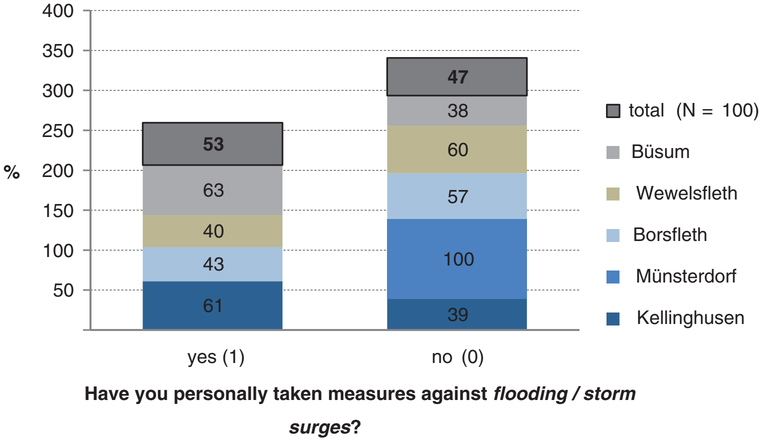


Fig. 5.9 Agent types (1/0) with regard to measures (N = 100)

important source of information in the case study region. 28 % of all mentions refer to OWN EXPERIENCE as their source of information. Few people seem to share their experiences and information as only 17 % mention that they talk to other people affected (TALKING TO OTHERS AFFECTED).

Although the social network seems to be used as a source of information, it is not of major significance. Also PUBLIC INFORMATIVE EVENTS (7 %) rather seem to play a minor role for getting information, also because only a few communities for example Kellinghusen offered this type of information exchange.

For the different communities it could be assumed that up to 25 % of respondents use the social network as a source of information (see Table 5.5). In Münsterdorf no information is exchanged by personal communication channels (according to Fig. 5.8).

Knowledge of risk and possible prevention measures might increase the implementation of preventive strategies or lead to changed behaviour concerning risks. The following question (see Fig. 5.9) captured the state of already applied measures in the communities. Accordingly, about 53 % of respondents already implemented measures against flooding/storm surges (YES; N = 100; NO: 47 %). Figure 5.9 shows the resulting two agent types (1/0).

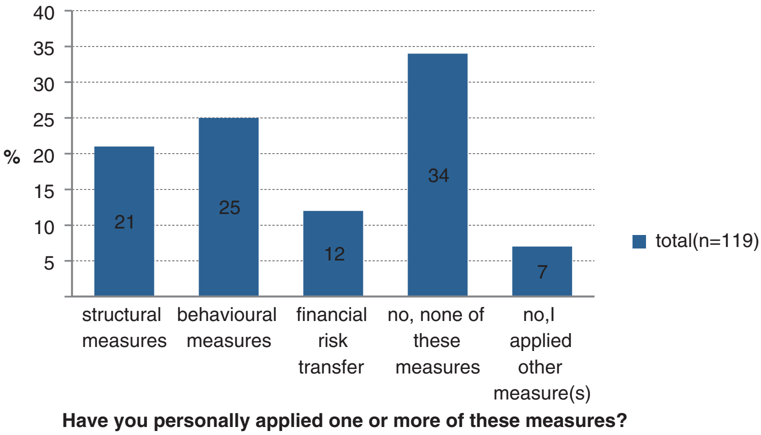


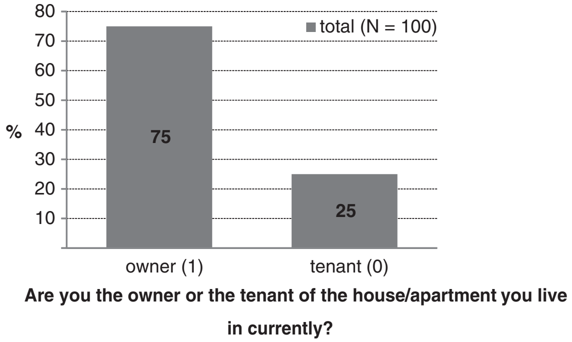
Fig. 5.10 Types of self-protection measures applied by respondents (n = 119; not specified = 1 %)

The responses from communities deliver considerable reason to differentiate between the local self-protective behaviour. Whereas in the communities Büsum with 63 % and Kellinghusen with 61 % more respondents have taken preventive measures, the other communities are considerably below average. 47 % of all respondents did not take measures, but in Wewelsfleth and Borsfleth about 60 % and 57 % are not prepared. In Münsterdorf no household at all (NO: 100 %) has taken measures against flooding. These results again allowed deriving two different agent types, i.e. households with (YES) or without (NO) already implemented measures against flooding/storm surges (see Fig. 5.9).

In order to get a more detailed impression of self-protection measures, people were asked to classify the implemented measures according to the following types: STRUCTURAL MEASURES, BEHAVIOURAL MEASURES and/or FINANCIAL RISK TRANSFER (see Fig. 5.10). 58 % of the responses (n = 119) refer to the three self-protection options, whereas 41 % of 100 households still cannot refer to any of the mentioned measures (NO, NONE OF THESE MEASURES; N = 100). 16 households named at least two types of measures implemented against flooding/storm surges (n = 119).

According to Fig. 5.10, about 25 % of responses consider BEHAVIOURAL MEASURES (n = 119). These residents have taken preparations for a flooding/storm surge event and know what has to be done in case of an event. About 21 % of all mentions refer to STRUCTURAL MEASURES (n = 119) that included e.g. to build property on higher grounds or without a cellar, to seal doors and windows in case of flooding, to avoid oil heating systems or to protect it against flooding. Only half as many, namely 12 % only, took measures of FINANCIAL RISK TRANSFER, i.e. they are insured against losses (n = 119). About 7 % of the mentions were not classified according to the proposed measure types (NO, I TOOK OTHER MEASURES; n = 119). Here, residents annotated that they live in the first floor of the building, that they installed pumps or joined the auxiliary fire brigade.

Fig. 5.11 Agent types (1/0) with regard to assets (N = 100)



In particular the implementation of structural measures might depend on the tenure pattern. Therefore, people were asked whether they are the owner or the tenant of the house/apartment they currently live in (see Fig. 5.11). It was assumed that people with own property might rather be able to realise measures or might also be more motivated to invest in self-protection measures. A total of 75 % are OWNER in the case study region and 25 % of the respondents rented the house or apartment they currently live in (TENANT). In Büsum the percentage of households with own property is below average and about 34 % are tenants.

With regard to the tenure pattern, it could be shown that a higher tendency of owners has taken measures. According to the data, tenants implemented measures less often than average (44 % instead of 53 % on average) whereas owners slightly more often than average implemented measures (56 % instead of 53 % on average).

5.2.4 Attitude towards Measures and Future Expectations of Residents

An important motive for private households to implement measures might be the perceived effectiveness. Whether people think that they are able to reduce individual/household vulnerability by self-protection measures was aimed at in the question: Do you think that you can personally diminish the impacts of flooding/storm surges effectively by self-protection measures? The fact that 70 % (N = 100) of all participants regard these measures as not effective indicates an adverse attitude towards self-protection measures in the case study region (see Fig. 5.12). Only 16 % support the effectiveness of self-protection measures and 13 % do not know how to evaluate the effectiveness of such measures. With regard to the communities, some variations become apparent in comparison to average. In Borsfleth and Kellinghusen more residents assign the effectiveness of self-protection measures (28 % and 19 % instead of 16 % on average). Especially in Büsum and in Münsterdorf participants support the view that self-protection measures are not efficient (81 % and 100 % instead of 70 % on average). In Borsfleth the uncertainty about effectiveness of self-protection measures is much higher than

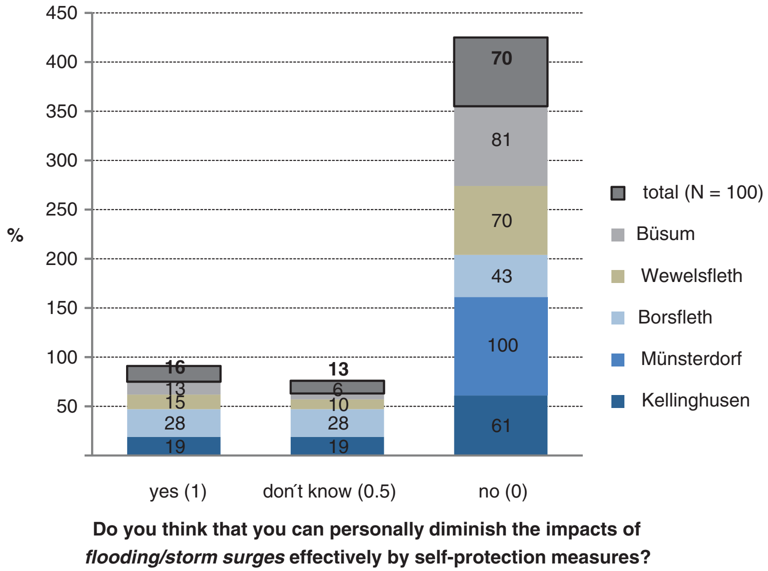


Fig. 5.12 Agent types (1/0.5/0) with regard to attitude towards self-protection measures (N = 100; not specified = 1 %)

average (28 % instead of 13 % on average) which might be related to the low level of information with regard to self-protection measures (see Fig. 5.7). Three agent types (1/0.5/0) were defined according to the answers (YES/DON'T KNOW/NO).

Residents were asked to give further details about the type of self-protection measures they consider as effective. Only 15 out of 100 participants answered and most often mentioned temporary structural measures such as the usage of sandbags, flood barriers and pumps as well as moving furniture or installing electrical items above flood level. Few residents furthermore named the importance of information and knowledge of emergency and evacuation plans in case of flooding.

People were also asked about their future expectations concerning floods and storm surges. To what extent do residents in the flood-prone coastal lowland think that losses might increase in the future (see Fig. 5.13)? Nearly half of the participants rather evaluate the risk of losses as the same in future (NO: 47 %; N = 100) whereas 29 % opine that flood losses or losses in case of a storm surge in the future will happen more often 23 % are unsure about future impacts (N.S.: 1 %).

In Borsfleth residents more often deny possibly increasing losses (NO: 14 %) and in Münsterdorf increasing losses are completely denied (NO: 0 % instead of 29 % on average). In Kellinghusen the relation between optimists and pessimists concerning future impacts is equally distributed with 39 %. In Wewelsfleth and Büsum the opinions equal the measured average (see Fig. 5.13). Uncertainty is much higher in Münsterdorf with 40 % than on average (DON'T KNOW: 23 %).

In addition to the question about effectiveness of self-protection measures, participants were asked: Assuming that the risk of flooding/storm surges increases

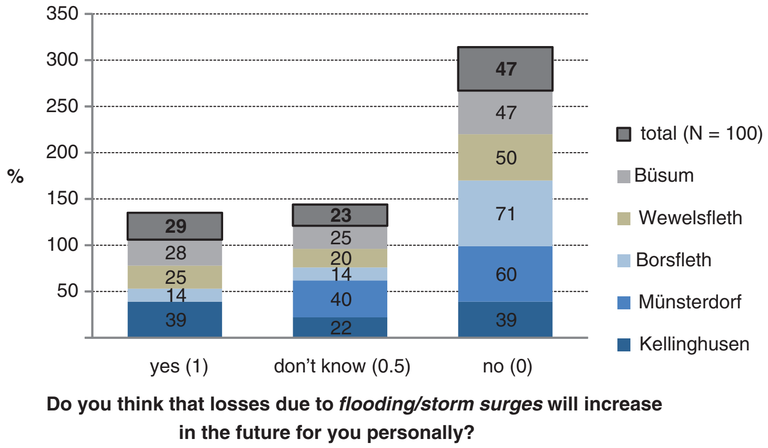


Fig. 5.13 Agent types (1/0.5/0) with regard to expectations of future losses (N = 100; not specified = 1 %)

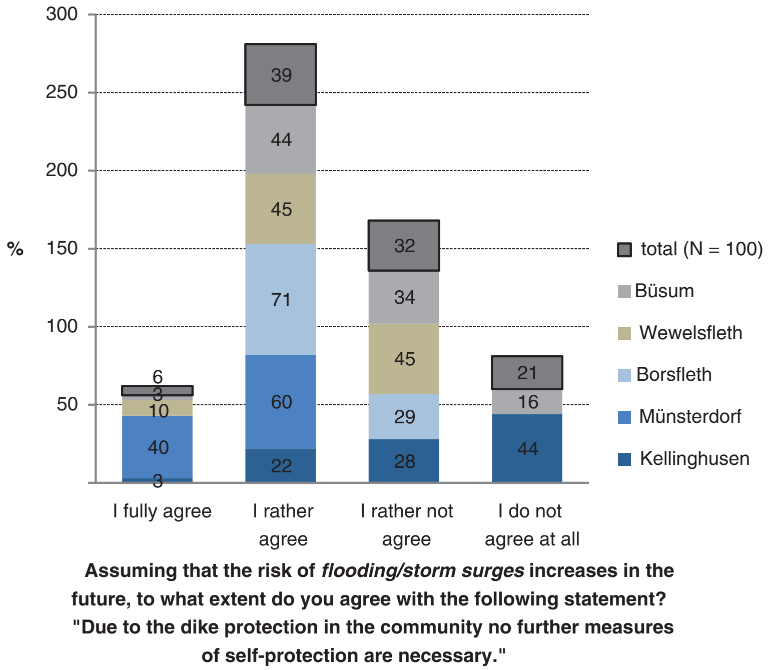


Fig. 5.14 Trust in official dike protection (N = 100; not specified = 2 %)

in the future, to what extent do you agree with the following statement? "Due to dike protection in the community no further measures of self-protection are necessary." Most participants are averse to agree to the statement with 53 % and 45 % (N = 100) agree to this statement (see Fig. 5.14).

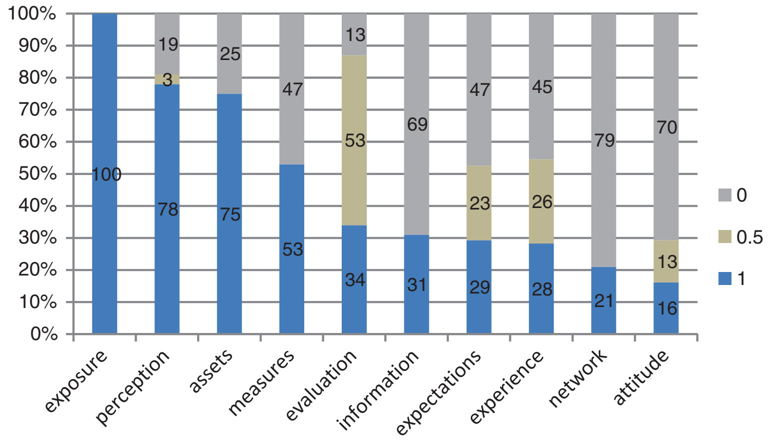


Fig. 5.15 Agent types (1/0.5/0) or (1/0) with regard to all vulnerability attributes in the case study region (attribute information is derived from information [1] & information [2]; exposure is predetermined for all)

Considering the answers given in each community, further differences can be recognised. Remarkably small in comparison to average is the agreement in Kellinghusen with 25 % (I FULLY AGREE & I RATHER AGREE). About 44 % DO NOT AGREE AT ALL and 28 % RATHER NOT AGREE to the statement. The fact that already 61 % of respondents in Kellinghusen have implemented any type of self-protection measure might be related to this small trust in the official dike protection. In contrast, the agreement to the statement in Borsfleth is rather high with 71 % which rather agree and in particular in Münsterdorf all participants agreed (I FULLY AGREE & I RATHER AGREE: 100 %). In Büsum both agreement and disagreement is comparable to the average (47 % and 50 %). Here, 63 % already rely not only on official dike protection but took additional self-protection measures. In Wewelsfleth a tendency towards agreement can be observed (I FULLY AGREE & I RATHER AGREE: 55 %).

The comparative vulnerability analysis revealed considerable differences with regard to vulnerability attributes and present risk behaviour in the five communities. Furthermore, the comparative analysis allowed deriving agent types with regard to vulnerability attributes and present risk behaviour. Thus, the agent types (1/0.5/0) refer to individual households and their characteristic vulnerability values. The vulnerability attributes are sorted according to relevance in Fig. 5.15. In order to answer the second research question, the relevant agent types concerning vulnerability and present risk behaviour can be identified in the coastal zone of Schleswig–Holstein.

As the low-lying case study region was selected due to exposure (see Chap. 4), the attribute exposure is predetermined for 100 % of agents. Yet, the empirical study revealed that not all households are aware of exposure; merely 78 % of agents have perception of exposure (see Fig. 5.15). 21 % of the households have no perception, rendering this agent type more vulnerable to flooding events. The main agent type with regard to the attribute assets with 75 % is owner of a house/apartment. With regard to the tenure pattern, it could be shown that a higher tendency of owners has already taken measures. Still, the more vulnerable agent type without measures represents 47 % of the sample.

Although only very few agents underestimate the risk (13 %; see Fig. 5.4), 69 % of households recognise a lack of information with regard to events and prevention measures. The informed agent type represents only 31 % of the sample. Concerning the vulnerability attribute expectations, the empirical study indicated that the main agent type with 47 % does not expect increasing losses regarding future risk. A considerable group of agents (with 23 %) could be identified that expressed their uncertainty about future risk (see Fig. 5.15). However, the survey revealed that most households can rely on experience with flooding/storm surges as this agent type represents 54 % of the sample. But few agents (21 %) use their social network in order to exchange experiences and information about self-protection. Need for action becomes apparent in order to reduce the considerable agent group regarding self-protection measures as not effectively (70 %).

5.2.5 Preferences for Self-Protection Strategies

The last part of the questionnaire aimed at the residents' preferences concerning better self-protection in the future. Thus, it allowed extending the vulnerability assessment by a forward-looking perspective (see further Birkmann 2006, p. 69). People in the communities were asked about their preferences for four different self-protection strategies.

Assuming that the risk of flooding/storm surges increases in the future, people were asked whether they would migrate to less exposed areas or they would still live here (MIGRATE or STILL LIVE HERE)? Only a small amount of participants consider migration as an option (13 %; N = 100) whereas the majority of the people reject this type of strategy (STILL LIVE HERE: 82 %; OTHER: 5 %; N = 100). But participants in the communities show differences in their negative attitude (see Fig. 5.16). In Münsterdorf and Borsfleth none of the respondents can imagine migrating (STILL LIVE HERE: 100 % in both communities). In Büsum, the percentage of people considering migration as an option to decrease risk, is higher than average with 19 %. In Kellinghusen and Wewelsfleth migration is considered as an option by 14 % and 10 % of the residents. Whereas most people from Büsum can imagine migrating (19 %), the preference for staying in the community is lowest in Kellinghusen with 75 %. In all other communities more than 80 % and up to 100 % would prefer to live in their communities despite an assumed increase of risk (see Fig. 5.16). Whereas in Büsum other options are not mentioned (OTHER: 0 %), in Kellinghusen and Wewelsfleth a small amount of participants take also other options into account such as investing in further measures to protect their property or to call for better dike protection in the river catchment (OTHER: 11 %

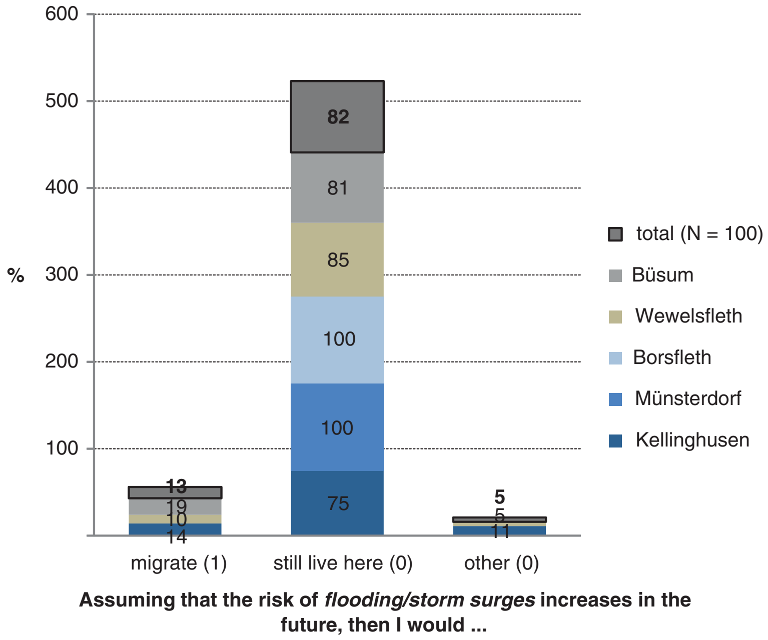


Fig. 5.16 Agent preferences (1/0) with regard to the strategy migration (N = 100)

and 5 % in comparison to 5 % on average). Agent types were also derived from the self-protection preferences (see Fig. 5.16).

People in the communities were also asked about their interest in further information about self-protection measures: Are you interested in events that inform you about self-protection measures? The acceptance of this strategy is considerably higher with 51 % (yes; N = 100; see Fig. 5.17). Despite higher acceptance of this strategy, 12 % are unsure (don't know; N = 100) and 37 % (no; N = 100) reject informative events. Additionally, the respondents indicated how much time they would spend on it. About 78 % (n = 51) of respondents preferring the information strategy regard informative events as adequate each year–every six month, and solely 18 % more often (every three months–each month; n.s.: 4 %). The agent types (1/0.5/0) result from the preferred time rate of the information strategy (every three months–each month/each year–every six month/no).

With regard to the communities, the acceptance level of informative events varies (see Fig. 5.17). Maximum acceptance levels reached the strategy in Wewelsfleth and Münsterdorf with 60 %. Whereas in Kellinghusen the level of acceptance is comparable to average with 50 %, in Büsum and Borsfleth acceptance is slightly decreased to 47 % and 43 %, yet almost half of the respondents regard informative events as a preferred option. Rejection concerning such informative events is particularly high in Borsfleth with 57 %, i.e. 20 % higher than on average (37 %; N = 100), and particularly low in Wewelsfleth with 25 %.

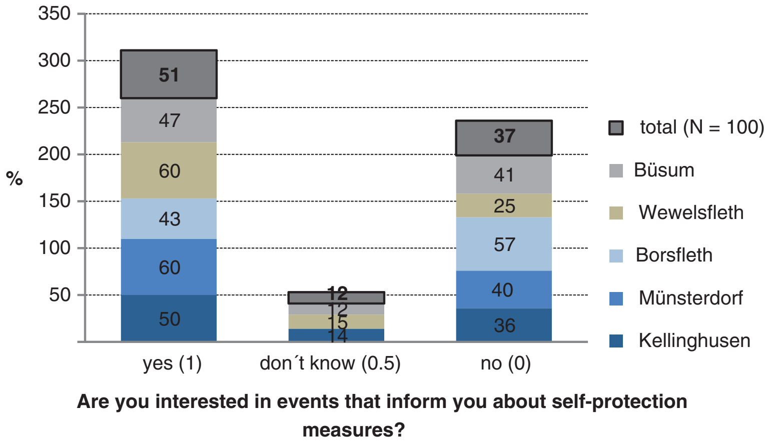


Fig. 5.17 Agent preferences (1/0.5/0) with regard to the strategy information (N = 100)

In Kellinghusen, Münsterdorf and Büsum the percentage of respondents that refuse the strategy varies between 36 % and 41 % and thus is around average. In the communities Büsum, Kellinghusen and Wewelsfleth still about 12 %, 14 % and 15 % of respondents are indecisive about this strategy.

Furthermore, a better self-protection by insurance was suggested (see Fig. 5.18). On average the acceptance of insurance coverage is not as high as the information strategy. Most people refuse this strategy with 49 % (NO; N = 100), 33 % (YES; N = 100) would prefer an insurance coverage and 16 % are indecisive (DON'T KNOW; N = 100; N.S.: 2 %;) about this type of self-protection strategy. 12 % of the households are already insured as shown in Fig. 5.10 (FINANCIAL RISK TRANSFER).

Also the acceptance of insurance coverage varies across the communities. Maximum levels of acceptance are achieved in Borsfleth with 57 % and in Büsum with 44 % in relation to 33 % on average. In Kellinghusen and Wewelsfleth the acceptance level of financial risk transfer is about 25 %. Respondents from Münsterdorf have little interest with 20 % only. According to this, in Kellinghusen and Münsterdorf rejection is much higher with regard to insurance coverage, i.e. at 56 % and 60 % (NO). In Wewelsfleth, Büsum and Borsfleth it is approximately at average level (see Fig. 5.18). Many respondents in Wewelsfleth are uncertain about choosing to be insured (DON'T KNOW: 30 %), whereas in the other communities uncertainty is approximately on average.

In addition to these three strategies, the study revealed whether people would implement measures if incentives/subsidies were given by the government (see Fig. 5.19). On average the acceptance of incentives to improve self-protection is by 37 % (YES; N = 100). Similar values are achieved in the other categories; about 30 % of the respondents are unsure (DON'T KNOW; N = 100) and 31 % reject such strategy (NO; N.S.: 2 %; N = 100).

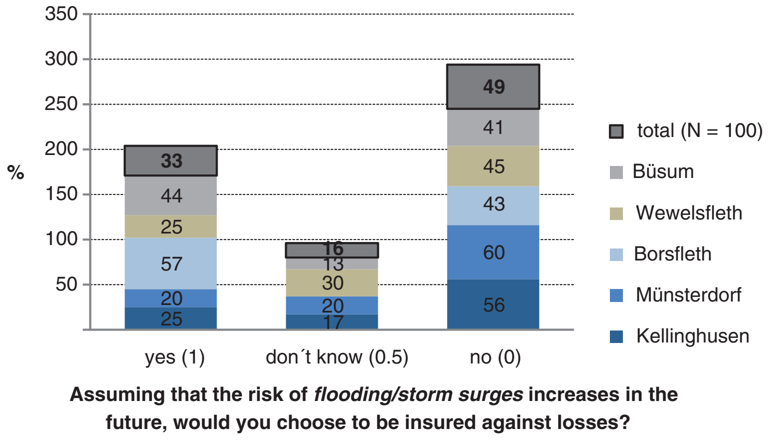


Fig. 5.18 Agent preferences (1/0.5/0) with regard to the strategy insurance (N = 100; not specified = 2 %)

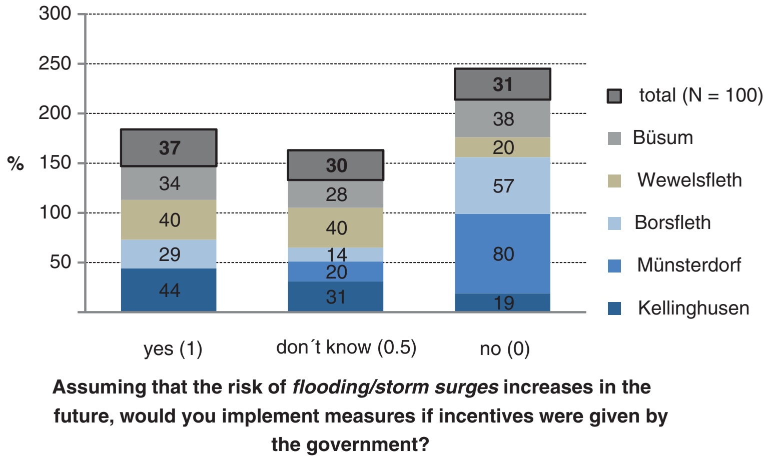


Fig. 5.19 Agent preferences (1/0.5/0) with regard to the strategy incentives (N = 100; not specified = 2 %)

With regard to the acceptance of the incentives strategy in the communities, a different impression can be obtained (see Fig. 5.19). From no acceptance at all in Münsterdorf, the acceptance increases in Borsfleth with 29 % to average level in Büsum with 34 %. In Wewelsfleth and Kellinghusen the level of acceptance with regard to incentives is above average with 40 % and 44 %. Uncertainty is particularly high in Wewelsfleth with 40 % and on average in Kellinghusen with 31 % and in Büsum with 28 %. Especially in Münsterdorf and in Borsfleth most respondents refuse the incentives strategy (80 % and 57 %). In Kellinghusen and Wewelsfleth the percentage of residents expressing rejection is below average with 19 % and 20 %. In Büsum no clear tendency could be observed.

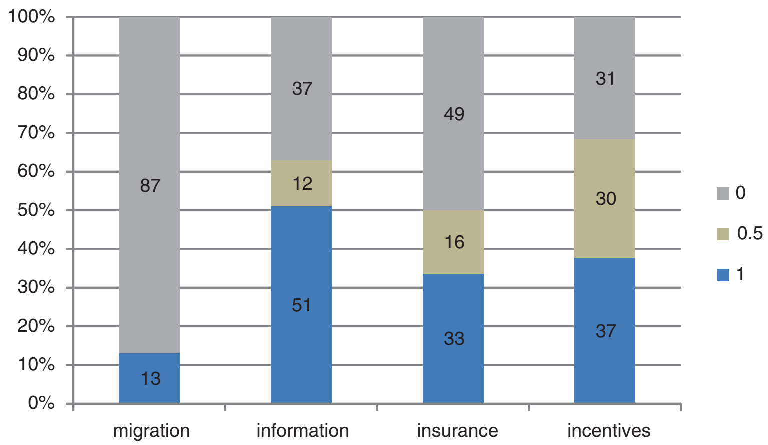


Fig. 5.20 Percentage of the different agent types (1/0.5/0) with regard to all strategies in the case study region (insurance: 2 not specified & incentives: 2 % not specified)

In summary, it can be stated that also with regard to the self-protection preferences certain agent types dominate in the sample (see Fig. 5.20). 87 % of the household refuse the migration strategy (type 0), thus a very small agent type with a preference remains (13 %). The acceptance of the information strategy is considerably higher as 51 % of the households can be assigned to this agent type (1). The insurance strategy is preferred by an agent type (1) that represents merely 33 % of the sample; the agent type (0) that refuses this strategy is more common with 49 %. Equally distributed are the agent types (1/0.5/0) with regard to the incentives strategy (see Fig. 5.20). Uncertainty about preferences for the strategies are expressed by 12 % of the agents for the information strategy (type 0.5), by 16 % for the insurance strategy and by 30 % for the incentives strategy.

5.3 Model Design: Simulation Model of Vulnerability Dynamics

Computational models can be designed "in which abstractions maintain a close association with the real-world agents of interest" (Miller and Page 2007, p. 65). Here, the computational model is based on assumptions implied in the conceptual model (see Sect. 5.1) and empirical data from the case study (see Sect. 5.2). The computational model merges conceptual and empirical specifications of the considered system of the German North Sea Coast. The specifications are implemented in the computer code and allow uncovering the implications of the system development with regard to vulnerability. The model description follows the ODD (Overview, Design concepts, Details) protocol developed by Grimm et al. (2010; Grimm et al. 2006). The ODD protocol is a detailed common format established for the description of ABMs and individual-based models. It includes the model's purpose, the model's entities, state variables and scales as well as the model's process overview and scheduling. Furthermore, the design concepts and further details are explained.

5.3.1 Overview

5.3.1.1 Purpose

The overall aim of the simulation is to explore the dynamics of vulnerability[1] due to individual, relational and spatial aspects. Based on empirical values of the case study, the model assesses possible system trajectories with regard to vulnerability of the agent system.

The computational model reflects the status-quo of vulnerability in the considered coastal zone and implements the agent's preferences for self-protection strategies against flooding/storm surges (see Sect. 5.2). By means of simulation the short-term effects of self-protection preferences and of further agent vulnerability attributes can be analysed. Thus, it reveals how the behaviour of agents on the micro level drives the system's vulnerability on the macro level. Various simulation experiments can be conducted in order to explore the detailed system's dynamics and possible vulnerability trajectories in the case study region. Based on an empirical vulnerability assessment at the German North Sea Coast, the simulation extends the assessment through a forward-looking perspective.

5.3.1.2 Entities, State Variables and Scales

"An entity is a distinct or separate object or actor that behaves as a unit and may interact with other entities or be affected by external environmental factors." (Grimm et al. 2010, p. 2763). In the ODD protocol four types of entities are distinguished: agents, collectives, spatial units and environment.

Agents

The system under study consists of 100 human agents representing the micro level entities of the model. Each human agent in the computational model stands for one household included in the empirical survey (N = 100). Vulnerability characteristics and further information collected in the survey specify the human agent

[1] Vulnerability here is defined as the characteristics and circumstances of a person or group that make it susceptible to be adversely affected by the impact of a hazard (see Sect. 3.2.2).

profiles in the computational model. Thus, each agent can be distinguished from other agents by its profile, i.e. by the set of attributes and behavioural strategies that distinguishes an entity from other entities of the same type (e.g. human agent) or traces how the entity changes over time (Grimm et al. 2010, p. 2763). Two main sets are included in the model for the description of human agents that contain:

- Vulnerability attributes and
- Self-protection preferences as behavioural strategies of the human agents.

The set of state variables regarding vulnerability includes different attributes such as exposure, evaluation of risk, experience with events, attitude towards self-protection measures, expectations concerning future risk, social network, etc. (see Table 5.6). The state variables describing human agents reflect different dimensions of vulnerability or levels of analysis. The selection of the vulnerability attributes and behavioural strategies resulted from the framing process (see Sect. 2.2). It helped to clarify the theoretical and regional context for the model (see Chaps. 3 and 4) and to identify the system components for the theory-based conceptual model development (see Sect. 5.1). Values for the state variables were derived from the empirical survey at the German North Sea Coast (see Sect. 5.2). According to the characteristic values of these vulnerability attributes, the potential vulnerability `(potVul)` of each human agent can be assessed. The vulnerability attribute `exposure` is predetermined due to the selected survey region, i.e. due to the low-lying and flood-prone case study region exposure is predetermined. According to the answers collected in the social survey, the state variables are provided with numerical values expressing the strength of the vulnerability attributes. The values are in accordance with the agent types (1/0.5/0) or (1/0) that resulted from the empirical survey (see Sect. 5.2). Table 5.6 gives an overview of the state variables set with regard to vulnerability.

The vulnerability attributes determine the individual vulnerability profile of each agent. Due to the predetermined vulnerability attribute `exposure`, each agent has an initial vulnerability (`initialVul`) value of 10. According to the characteristic values (`0/0.5/1 or 0/1`) of the nine further vulnerability attributes, the potential vulnerability (`potVul`) of each human agent can be assessed. For each attribute a model rule has been defined based on the theoretical background (see Tables 5.6 and Sect. 3.2). In order to regard vulnerability as a multidimensional and context-sensitive social phenomenon, different levels of analysis are taken into account, e.g. human-environment relationship, micro and macro level (see Table 3.1). At the beginning of the simulation the potential vulnerability (`potVul`) demonstrates the status quo of vulnerability in the survey region.

The second set includes the self-protection preferences of the human agents. The preferences represent the behavioural strategies of human agents and correspond to the preferences for self-protection strategies in the case study region (see Sect. 5.2). The agent's preferences for self-protection are implemented in the computational model and can lower the vulnerability levels of agents (see Table 5.7):

In the model a relationship between vulnerability and self-protection preferences is established. The primary aim of the vulnerability attributes is to determine

Table 5.6 State variables with regard to vulnerability of the human agent entity

Entity	State variable	Description	Data type: Value(s)	Model rule	Level of analysis
Human agent	`exposure`	Vulnerability Attribute	`boolean: true`	Each human agent is exposed (predetermined)	micro
	`initialVul`	Initial vulnerability level due to exposure to hazard	`int: 10`	Each human agent has an initial vulnerability level of initialVul = 10 due to exposure (predetermined)	micro agent and macro system level
	`evaluation`	Vulnerability Attribute	`float: 1/0.5/0 according to categories` VERY HIGH-HIGH/MEDIUM–LOW/VERY LOW-NOT AT ALL	The lower the evaluation of the flooding risk, the higher the agent's vulnerability	human-environment
	`perception`		`float: 1/0.5/0 according to categories` YES/DON'T KNOW/NO	Perception of exposure decreases the agent's vulnerability	human-environment
	`expectations`		`float: 1/0.5/0 according to categories` YES/DON'T KNOW/NO	Agent's vulnerability decreases if agent is aware of possible risk changes in the future	human-environment
	`network`		`int: 1/0 according to categories` YES/NO	Access to social network lowers vulnerability of agent	micro–macro
	`measures`		`int: 1/0 according to categories` YES/NO	Already implemented self-protection measures lower vulnerability of agent	micro
	`information`		`int: 1/0 according to categories` YES/NO INFORMATION[1]&[2]	Lack of information increases the agent's vulnerability	micro
	`attitude`		`float: 1/0.5/0 according to categories` YES/DON'T KNOW/NO	Averse attitude towards self-protection increases the agent's vulnerability	micro
	`assets`		`int: 1/0 according to categories` OWNER/TENANT	Home owner's motivation to implement self-protection measures is higher, thus lowering vulnerability	micro
	`experience`		`float: 1/0.5/0 according to categories` YES, MORE THAN ONCE/YES, ONCE/NO	Experience(s) with flooding/storm surges lowers the agent's vulnerability	micro
	`potVul`	Potential vulnerability level is calculated according to vulnerability attributes of agent	`int: 1 - <20`	Derived from the characteristic values of vulnerability attributes (agent vulnerability profile)	micro agent and macro system level

Table 5.7 Self-protection preferences as behavioural strategies of the human agent entity

Entity	Behavioural strategy	Description	Data Type: Value(s)	Model rule	Level of analysis
Human agent	p_information	Preferred self-protection measure: informative events (behavioural measure)	float: 1/0.5/0 according to categories YES/DON'T KNOW/NO	If strategy is offered, agent can decide to attend informative events, lowering its vulnerability level	micro
	p_timeRate	Preferred time rate for informative events	float: 1/0.5/0 according to categories EVERY THREE MONTHS-EACH MONTH/EACH YEAR-EVERY SIX MONTH/NO	Agents decide how often they attend informative events; it can accelerate the process of vulnerability reduction	micro
	p_insurance	Preferred self-protection measure: insurance coverage (financial risk transfer)	float: 1/0.5/0 according to categories YES/DON'T KNOW/NO	If strategy is offered, agent can decide to get an insurance, lowering its vulnerability level	micro
	p_incentives	Preferred self-protection measure: government incentives for preventive actions (structural measure)	float: 1/0.5/0 according to categories YES/DON'T KNOW/NO	If strategy is offered, agent can decide to accept incentives for preventive measures, lowering its vulnerability level	micro
	p_migration	Preferred self-protection measure: migrating to safer regions	float: 1.0/0.0 according to categories MIGRATE/STILL LIVE HERE/OTHER	If strategy is offered, agent can decide to migrate, agents are deleted from context	micro

the potential vulnerability (`potVul`) of each agent at the beginning of the simulation run. Agents are able to lower their vulnerability level by deciding for better self-protection strategies in the computational model. The self-protection strategies were selected based on the theoretical research framework and constitute measures that can be implemented by private households to reduce vulnerability (see Sect. 3.2.4). The household's preferences for the four different self-protection strategies against flooding/

storm surges were collected in the empirical study (see Sect. 5.2). According to the agents` preferences the self-protection measures, i.e. informative events, insurance, incentives and migration are implemented and allow tracing the changes in vulnerability due to behaviour changes of the agents during simulation runs. Besides the preferences of the agents on micro level, other individual, relational and spatial aspects can further influence the decision making process of agents.

Collectives

Groups of agents can have their own behaviour, so it can make sense to distinguish them as a collective entity (Grimm et al. 2010, p. 2764). Human agents here are organised in five different collectives representing the five survey communities in the coastal zone. By the location variable (`location`) each agent thus can be assigned to one of the community collectives. The collectives are of different sizes e.g. in Kellinghusen 36 agents build the collective or in Wewelsfleth 20 agents depending on the number of valid questionnaires (see Table 5.8).

The agents in the collectives are characterised by certain location-specific attributes: lack of awareness towards risk and trust in dike protection by official risk management (see Table 5.8). The empirical survey revealed considerable differences between the communities concerning the time passed since the last flooding/storm surge event (see Table 5.4) and trust in official dike protection (see Fig. 5.14). The state variables `lackOfAwareness` and `trust` express these different human-environment relationships of the agent collectives. The variables refer to the agent's bounded rationality, i.e. agents are not omniscient with regard to the system but they are influenced by these location-specific attributes. Thus, in this model the agent's behaviour is driven—besides their preferences—also by the human-environment relationship and varies between the human agent collectives.

Due to bounded rationality, also the social network of human agents is limited to the location and thus to the collective. Agents with the location attribute Büsum merely interact with human agents designated with the same location attribute. Furthermore, only those agents with the vulnerability attribute `network` participate in the social network. Meaning that, agents in the community collective Büsum with a `network` attribute are capable to interact with those 31 other agents in Büsum that are equipped with a network attribute as well. Each agent in the model can be identified by its `agentID` and by its `location` attribute (see Table 5.8).

The values for the control parameters `lackOfAwareness` and `trust` are derived from empirical values. The `trust` values correspond to the percentage of agents trusting the dike protection in their community (see Fig. 5.14); i.e. in Münsterdorf 100 % (1.0), in Borsfleth 70 % (0.7), in Wewelsfleth 55 % (0.6), in Büsum 47 % (0.5) and in Kellinghusen only 25 % (0.3). The values concerning `lackOfAwareness` are further shown in Table 5.9 and are based on the time period between the last flooding/storm surge event remembered by respondents (see Table 5.4) and the reference year of the model, e.g. a time period of 49 years in Borsfleth or Münsterdorf.

Table 5.8 State variables of the human agent collectives with regard to location

Entity	State variable	Description	Data type: Value(s)	Model rule	Level of analysis
Human agent	`agentID`	Individual identification of agent	`int`: according to number of questionnaire	-	micro
Human agent collectives	`location`	By location attribute each agent is assigned to a collective entity	`string`: according to name of community Kellinghusen: 36 agents Büsum: 32 agents Wewelsfleth: 20 agents Borsfleth: 7 agents Münsterdorf: 5 agents	By location the agent's social network is defined and other location-specific attributes	meso
	`lackOf Awareness`	Location-specific attribute for perceptual threshold	`float`: according to community Kellinghusen: 0.1 Wewelsfleth: 1.0 Büsum: 4.0 Borsfleth: 5.5 Münsterdorf: 5.5	Lack of awareness towards risk delays the dissemination of self-protection measures	human-environment
	`trust`	Location-specific attribute for perceptual threshold	`float`: according to community Kellinghusen: 0.3 Büsum: 0.5 Wewelsfleth: 0.6 Borsfleth: 0.7 Münsterdorf: 1.0	A high level of trust in official risk management/ dike protection delays the dissemination of self-protection measures	human-environment

Spatial Units and Environment

As the conceptualisation of vulnerability presupposes exposure to the hazard, this model assumption is fundamental. In order to show exposure in the model the environment is a continuous space covered with elevation agents that are equipped with the same state variable exposure as the agent class. As the coastal lowland is exposed or flood-prone due to low elevations below +6.5 m GOL and +6.0 GOL (see MLUR 2010), elevation agents marking exposure have been chosen for model design. The agent collectives are spatially arranged as groups on the continuous space in the model.

Hazard and environment are not modelled explicitly, as e.g. in event-driven simulations, but the determining factors of agent behaviour are assumed to be related

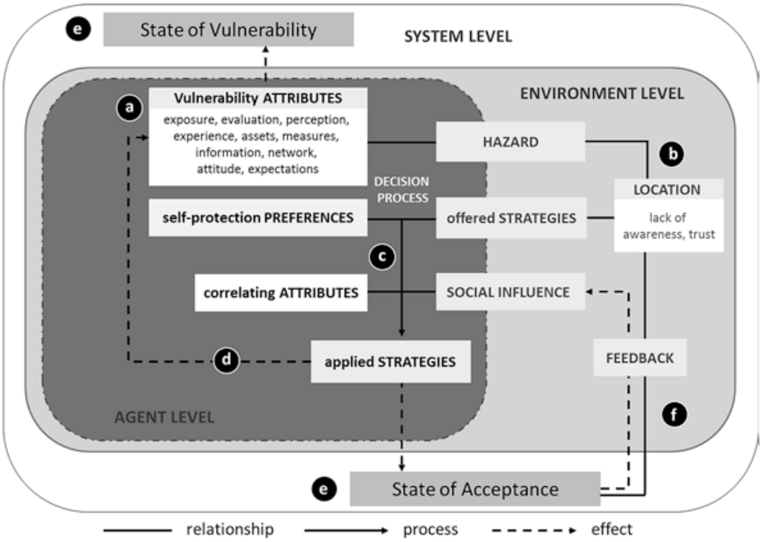


Fig. 5.21 Model processes a to f

to the perception of environment/hazard and to other social factors (see Fig. 5.21). As the model constitutes a pre-disaster or risk situation, the behaviour changes of agents only result from their decision process, they cannot result from a disaster. Yet, the human-environment relationship of agents expressed by such variables as `lackOfAwareness` can influence agent decisions. The model thus intends to include the subjective aspects of risk handling and emphasises bounded rationality.

The Model's Spatial and Temporal Scales

Most ABMs represent time by using time steps (Grimm et al. 2010, p. 2764). Also in this approach time is represented by time steps, whereas five time steps in the model represent 1 year in real-world. The temporal scale of the model is based on empirical evidence, i.e. from the behavioural strategy `p_timeRate`. In order to develop a forward-looking perspective for vulnerability assessment, the reference year of the model is 2011. Input data was gathered from empirical work in 2010.

The scheduling of dissemination of self-protection strategies also depends on the time steps. Once the strategies are offered, they are executed in a sequential order within one (model) year. Furthermore, the time-dependent variable `lackOfAwareness` increases over the simulation run, i.e. the awareness of agents decreases with further time distance from the last flooding/storm surge event (see Table 5.9). The system parameters are synchronously updated during the model run.

The model is not spatially explicit, agent collectives are spatially arranged as groups on the continuous space in the model.

5.3.1.3 Process Overview and Scheduling

In this section the model processes and scheduling is described in more detail. During the simulation, the model processes are executed; marked in the conceptual model framework as model processes a–f (see Fig. 5.21).

All state variables values are read from the input data table. The model defines the following processes:

(0) Creation of 100 agents according to the input data table—containing all agentIDs, state variables and state variable values derived from empirical survey.

(a) Calculation of the potential (baseline) vulnerability of each agent

Each state variable with regard to vulnerability (see Table 5.6) is considered and the potential vulnerability is calculated based on the initial vulnerability of 10 (`initialVul`). The method is implemented in the following (pseudo-)code for each individual agent; the exact code and complete calculation is included in Appendix A.3:

```
  public int getPotVul() {
          int ret = initialvul;
          if (evaluation > = 0.5)
              ret–;
          else
              ret ++;
          if (perception == 1.0)
              ret–;
          else
              ret ++;
          if (assets == 1)
              ret–;
          else
              ret ++;
[…]
          return ret;
}
```

Based on this example focussing on `evaluation`, `perception` and `assets`, the (pseudo-)code shows, that depending on each attribute value the vulnerability of the agent is either decreased or increased (see Appendix A.3). According to the characteristic values of the nine vulnerability attributes (see Table 5.6), thus each agent gets a potential vulnerability (`potVul`) level that ranges between 1 and <20. Depending on the model rules defined for each vulnerability attribute, the agent's vulnerability level is either increased or decreased; always starting with an `initialVul` of 10. The vulnerability profiles are calculated at t = 0 and represent the agent's potential vulnerability at the beginning of the simulation run as shown in Fig. 5.22 .

Vulnerability attributes are not weighted, they all contribute to the same extent to the vulnerability profile of the agent. The vulnerability profiles are used for comparison between the agents.

(b) Scheduling of the dissemination of self-protection strategies

The model assumes that offered policy options might provoke pro-active agent behaviour, here the implementation of self-protection measures by private

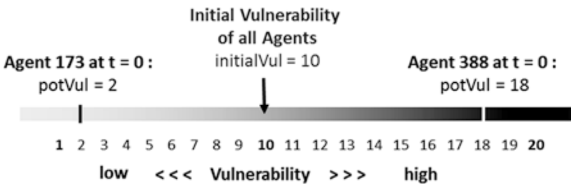


Fig. 5.22 Two examples of agents with their potential vulnerability values at t = 0

households (see Sect. 5.1). Before the behavioural strategies/self-protection preferences of the human agents are read from the input data table, the schedule for the dissemination of the self-protection strategies is generated. The model assumes that an initial impulse for agent behaviour changes, i.e. towards better self-protection, is needed. But the behaviour change of agents is not event-driven e.g. by the occurrence of a flooding event in the environment. The behaviour change of agents is driven by a perceptual threshold that has to be overcome. This perceptual threshold depends on the location-specific variables describing the human-environment relationship (see Table 5.8) of the human agent collectives.

Thus, the scheduling is location-specific and depends on the human-environment relationship of the agent collectives. Two control variables representing the human-environment relationship influence the offering of self-protection strategies. The values of the state variables `lackOfAwareness` and `trust` determine the perceptual threshold that has to be overcome for scheduling of the offered strategies. As these values differ for each community (see Table 5.8), the resulting schedule can also differ. In general, high values for `lackOfAwareness` and `trust` result in a time delay of the scheduling and thus in the dissemination of self-protection strategies. Only by exceeding the threshold, the strategy is offered in the respective location.

The perceptual threshold is calculated by the following (pseudo-)code:

```
numberOfStrategyByLocation = 1 – (lackOfAwareness + trust)
        if (numberOfStrategyByLocation > = 0.5f)
            return 1;
        else
            return 0;
```

Once the threshold is achieved, the strategies are offered to all agents located in the respective community or collective. Scheduling of the self-protection strategies is done by the `executeCounter` (see further Appendix A.3) in the following order along four consecutive time steps: information, insurance, incentives, migration (see Table 5.7). If the threshold is not yet exceeded in the first step of the simulation run, each time step +1 is added. Although the threshold can be exceeded after e.g. five time steps, the dissemination/offering of strategies is delayed in comparison to collectives with lower `lackOfAwareness` and `trust` values.

The values for the control variables `lackOfAwareness` and `trust` are derived from the empirical survey. But in order to respect the dynamics of vulnerability, awareness of the hazard further decreases during the simulation. As the lack of awareness is calculated based on the time passed since the last event remembered

Table 5.9 Increasing lack of awareness during the simulated time period starting (2011)

		Lack of awareness			
Location	Time period [years] between last event and 2011	Value 2011 [*reference year*]	Value 2012 [*2011* + 0,1]	Value 2013 [*2012* + 0,1]	Value 2014 [*2013* + 0,1]
Kellinghusen	1	0.1	0.2	0.3	0.4
Wewelsfleth	9	1	1.1	1.2	1.3
Büsum	35	4	4.1	4.2	4.3
Borsfleth	49	5.5	5.6	5.7	5.8
Münsterdorf	49	5.5	5.6	5.7	5.8

by the residents (see Table 5.4), also in the simulation the awareness decreases as the time period between the last flooding event and the simulated year further increases. Each year in the model, equivalent to five time steps thus the lack of awareness (`lackOfAwareness`) increases by 0.1 (see Table 5.9). The agents' awareness decreases with time distance from the last event in memory of agents and the values for `lackOfAwareness` change during the simulation (Table 5.9).

(c/d) Decision processes of Human Agents concerning Self-Protection Measures and effects for vulnerability profiles

Once the strategies are offered in the respective agent collectives, the decision making process of the agents is simulated in the model. Overall, the preferences for self-protection measures together with different micro, micro–macro and human-environment factors determine the outcome of the decision process. The related factors are depicted in Fig. 5.21, model process c.

The relevant factors are requested during this model process and can result in behaviour changes towards better self-protection. These factors are: preferences of the individual agents concerning each offered self-protection strategy (e.g. preference for the insurance strategy: `p_insurance = 1`), correlating attributes of the agent vulnerability profile and possible social influence by other agents (`SocialInfluence`). The model thus not solely implements agents expressed preferences but includes the context affecting the decision process.

The agent's preferences are derived from the empirical data base. During the simulation run it is tested whether the agent vulnerability profile correlates with the respective strategy. Hereby, the evidence from empirical data and statistical analysis of correlations between household preferences and vulnerability attributes are linked in the model. Between the correlating attributes and the self-protection preferences small negative/positive correlations could be observed by statistical analyses (see Table 5.10). The decision process is described based on the example of the insurance strategy. For further details and strategies see further Appendix A.3.

Preference for the insurance strategy can lead to a behaviour change towards better financial risk transfer of the agents. Once the strategy is offered, an enquiry is made about the agent's preference for the insurance strategy (`p_insurance`).

Table 5.10 Correlating attributes with level of significance (p), model rules and the effects of positive agents decisions on the vulnerability profile

Entity	Acceptance of behavioural strategy	Correlating attribute	Model rules	Effects on vulnerability profile
Human Agent	`strategy_information`	`p_timeRate information` (small negative correlation; $p \leq 0.05$)	`p_timeRate` determines how often an agent would attend informative events - it can accelerate the process of vulnerability reduction; agents with the attribute `information` = 1 reject this strategy	Values of variables are changed to: `information = 1` `network = 1` `attitude = 1.0` `perception = 1.0` `measures = 1`
	`strategy_insurance`	`experience` (small negative correlation; $p \leq 0.05$)	Agents with the attribute `experience` ≥ `0.5` reject this strategy	Values of variables are changed to: `attitude = 1.0` `measures = 1`
	`strategy_incentives`			
	`strategy_incentives`	`p_insurance` (small positive correlation; $p \leq 0.05$)	Agents with preferences also for strategy `p_insurance = 1` accept this strategy too	Values of variables are changed to: `attitude = 1.0f` `measures = 1`
	`strategy_migration`	`expectations` (small negative correlation; $p \leq 0.05$)	Agents with the attribute `expectations` ≥ `0.5` reject this strategy	Agent is deleted from context

But an explicit preference for the insurance strategy can also delay the decision process, if the agent shows the correlating attribute for insurance (`experience`). The attribute `experience` correlates negatively with the preference for insurance coverage, i.e. according to the statistical data agents that already experienced flooding (agent type 0.5 and 1) rather tend to reject the strategy insurance. Again, a threshold is defined for this model process. For the strategy insurance the (pseudo-)code tests the correlating attribute `experience`:

```
//*****Strategy Insurance********
private void strategy_insurance(boolean log)
//Preference for insurance is correlating with attribute experience: test the agent preference and the correlating attribute-
float appliedStrategyInsurance = p_insurance - experience;
//if the preference is above threshold, the strategy is applied
if (p_insurance! = 0.0f && appliedStrategyInsurance > 0.5f)
```

Once the threshold is exceeded, the strategy is applied by the agent. In consequence the agent's vulnerability level decreases as the insurance strategy influences the vulnerability attributes attitude and measures. Other strategies can act differently upon the agent vulnerability profile, e.g. on the level of information or the network of the agent (see Appendix A.3).

```
//and the acceptance of the strategy lowers the agent's vulnerability level
attitude = 1.0f;
measures = 1;
```

If the threshold is not exceeded yet, the agent can be persuaded by other agents that successfully applied the respective strategy by `SocialInfluence`. Social influence is requested in the agent's network and it is checked whether another agent already applied the respective strategy. This process presumes that both agents have access to the social network in the same community/agent collective by the attribute `network == 1`.

The (pseudo-)code is the following:

```
//if the preference is below threshold, the social influence is checked
private float getSocialInfluenceForInsurance() {
        if (network == 1) {
            Iterator it = ContextUtils.getContext(this).
iterator();
            while (it.hasNext()) {
            Human temp = (Human) it.next();
            if (temp == this)
            continue;
            //is it MY Network??
            if (temp.getNetwork() == 1
                && location.equals(temp.getLocation())) {
            if ((temp.p_insurance - temp.experience) > 0.5f)
            return 2.0f;
            }
            }
        }
        return 0.0f;
}
```

For the other self-protection strategies, the following correlating attributes, model rules and effects on the vulnerability profile are defined (see Table 5.10). The decrease in vulnerability due to the acceptance of strategies can vary between the strategies. The effects of strategies are weighted. By acceptance of the information strategy the agent can decrease its vulnerability level by up to 5 levels, by acceptance of the incentives strategy by up two levels and by migration the vulnerable agent is deleted from the system context (see Table 5.10).

(e) System Outcome

A system's state can change, if components and component interactions are transformed (see Sect. 3.1.1). The dependent variables on system level are state of vulnerability and state of acceptance (see Fig. 5.21). The agent's vulnerability level is changed due to the positive effects of the implemented strategies resulting from the agents' decisions. Besides the agent's vulnerability, also the state of acceptance for self-protection strategies in the system increases due to the positive agent decision. Each time step the new agent's vulnerability level and the state of acceptance can be calculated and updated. The state of acceptance results from the number of offered strategies and the number of applied strategies in the system, expressed in the following way: *State of Acceptance = applied Strategies In System/number of Offered Strategies In System*.

The agent's decreasing vulnerability affects the aggregated system vulnerability, i.e. the state of vulnerability in the system. During the simulation run, the decrease in vulnerability on system level, resulting from the agent decisions, can be traced. Thus, the overall system's vulnerability is connected to the acceptance of self-protection strategies on the micro level.

(f) Feedback effects

Positive and negative feedback effects are included in the model and already described in the model processes b and c/d. The positive feedback effect occurs while the successful application of self-protection measures can further persuade other agents. Thus, the positive feedback is related to the acceptance of strategies, the social network and social influence in the model. The negative feedback effect increases the perceptual threshold, i.e. it delays the scheduling of the strategies (see Table 5.9). As the state of acceptance is updated during the model process, the lack of awareness with regard to the hazard further increases.

5.3.2 Design Concepts

5.3.2.1 Basic Principles

This section is provided in the ODD protocol to allow modellers to describe the theories, hypotheses and modelling approaches underpinning the design. These aspects are explained in further detail in the conceptual model development (see Sect. 5.1). Here, only a short summary of the main assumptions with regard to the state variables is given.

The social phenomenon of vulnerability is conceptualised in the simulation model based on empirical evidence. The dynamics of vulnerability which derive from individual, relational and spatial aspects of vulnerability are assessed. Thus, the state variables describe different levels of analysis ranging from micro to macro level and micro–macro or human-environment levels (see e.g. Table 5.6). These levels are considered in order to investigate the connectivity and the dynamics of the system under study.

The analysis by means of simulation follows the subjective risk concept, i.e. it assumes that an individual-intuitive process of risk estimation may lead to individually different risk concepts and preferences towards risk reduction strategies (see Sects. 1.2, 3.2 and 4.3). Therefore, the empirical survey addressed aspects such as evaluation of risk, perception of personal exposure, level of information concerning self-protection or expectations concerning future risk (see Sect. 5.2). Furthermore, perceptual thresholds are defined that drive the agent behaviour as they are related to the different human-environment relationships in the survey communities. The model regards the (unintended) macro results that evolve from these subjective agents` actions and interactions.

The state variables concerning vulnerability have been selected based on theoretical and regional context (see Chaps. 3 and 4). The underlying notion to include awareness for the hazard in the model is the importance of the so-called "window of opportunity". This window describes the time period shortly after a disaster event when perception and motivation to implement better self-protection are higher due to the experience of a disastrous event. This opportunity decrease with further time distance from the event (see e.g. Steinführer and Kuhlicke 2007, p. 58). The factor trust, representing the human-environment relationship, is incorporated in the model process to express the agent's "feeling of security". The model considers this factor as further influencing the lack of motivation for self-protection behaviour (see e.g. BBK 2006). Why should I change my behaviour without seeing the necessity to do so? The results of the empirical data show considerable differences between the communities with regard to these human-environment relationships (see Sect. 5.2). The model assumes that a high feeling of security in the official risk management and dike protection slows down the model process of behaviour change towards better self-protection.

The decision to apply self-protection measures is described as a model process of behaviour change towards better self-protection. It implies the model assumption that risk decisions depend on the social context, therefore individual, relational and spatial aspects are influencing the agent's decisions. Vulnerability of individuals thus is considered as a context-sensitive phenomenon. The development of the decision making process was not only based on the expressed preferences from empirical data but furthermore supported by statistical analysis.

Based on the theoretical background (see Sect. 3.2), the implied model assumptions can be summarised:

- Vulnerability results from a multitude of factors on micro level, micro–macro and human-environment relationship level
- Self-protection measures can lower vulnerability of agents
- An initial impulse for agent behaviour changes, i.e. towards more self-protection measures, is needed
- Such initial impulse is depending on the human-environment relationship of the agents, i.e. on subjective factors related to risk handling
- The decision for better self-protection measures can be influenced by factors of the micro level, micro-macro and human-environment relationship level

On the basis of the model assumptions, the *emerging* model output can be assessed in the developed ABM.

5.3.2.2 Emergence

The model explores how the preventive behaviour of individuals drives the system into a less vulnerable state. Under the influence of the agents' self-protection preferences and vulnerability attributes, further factors as well as feedback effects a "culture of prevention" can emerge in the simulated system. In simulation experiments it can be discovered how the diverse agent types and combination of factors either facilitate or diminish the reduction of vulnerability (see Sect. 5.4). The simulation experiments and the resulting trajectories demonstrate the dynamics of vulnerability under the different influences. Yet, the whole model is restricted to a short-term consideration of the system. The "culture" thus should be rather understood as a short-term "trend" or "wave" of prevention in the agent system. It results from the empirically based status-quo of vulnerability in the case study region and the expressed preferences of private households.

5.3.2.3 Objectives

Objectives of agents are derived from the empirical data base and during the simulation the preferences of the households in the coastal zone of Germany are implemented. The objective of agents can either be the acceptance of self-protection measures or the rejection. Yet, agents are not able to increase their potential vulnerability level they had at the beginning. The level either decreases or stagnates. Meaning that, risk reduction measures—as dealt with in the empirical survey—lead to a decrease in vulnerability. The agents in the model behave according to the empirical survey, i.e. the expressed preferences for self-protection strategies are implemented during the simulation run in order to observe the consequences for the system's vulnerability. The main objectives of the simulation model are:

- Representation of the dynamics of vulnerability
- Analysis of individual, relational and spatial aspects influencing vulnerability reduction over time

5.3.2.4 Interaction

At the initial model state, merely 21 of 100 agents have a network attribute. Furthermore, the social network of human agents is limited to the location, i.e. agents with the location attribute Büsum merely interact with human agents designated with the same location attribute. The interaction between agents is indirect, i.e. indecisive agents search in their network whether other agents in that same network already applied the respective strategy and are “persuaded”. During the simulation run the interaction increases as more agents get connected to the network.

5.3.2.5 Collectives

The human agents are organised in five different collectives representing the five survey communities in the coastal zone. By the location variable (`location`) each agent thus can be organised into one of the community collectives. The collectives are of different group sizes, e.g. in Kellinghusen 36 agents are building the collective or in Wewelsfleth 20 agents (see Table 5.8). The agents in the collectives are characterised by location-specific attributes.

5.3.2.6 Observation

The model is deterministic as it implements the expressed preferences for self-protection strategies collected in the empirical study. The agent’s decisions are further backed up by statistical analyses. While agents inter/act in the model, the vulnerability baseline, i.e. the reduction of vulnerability, over the simulated time period is observed. By changing the initial conditions the simulation model allows a comparative vulnerability assessment. In the simulation experiments the influence of individual, relational and spatial aspects of vulnerability can be explored over the simulated time period (see Sect. 5.4). Different agent types with regard to the preferences, vulnerability attributes and with regard to the human-environment and micro–macro relationship are regarded and the resulting vulnerability trajectories are compared in order to observe the detailed dynamics of vulnerability.

5.3.3 Details

100 agents are created from the input data table for model initialisation. According to empirical data base agents are equipped with potential vulnerability values (see Fig. 5.22) and further attributes describing the agent profile, e.g. agentID, lackOfAwareness values. While the model is running the empirical values for lackOfAwareness can change. With the first model step, the scheduling of strategies starts. The initial desktop view is depicted in Fig. 5.23.

Different model runs can be conducted in order to assess the dynamics of vulnerability. The influence of individual, relational and spatial aspects on vulnerability reduction is tested by various simulation experiments in the following Sect. 5.4. At first, the vulnerability baseline is produced by running the model with the complete data base of 100 agents.

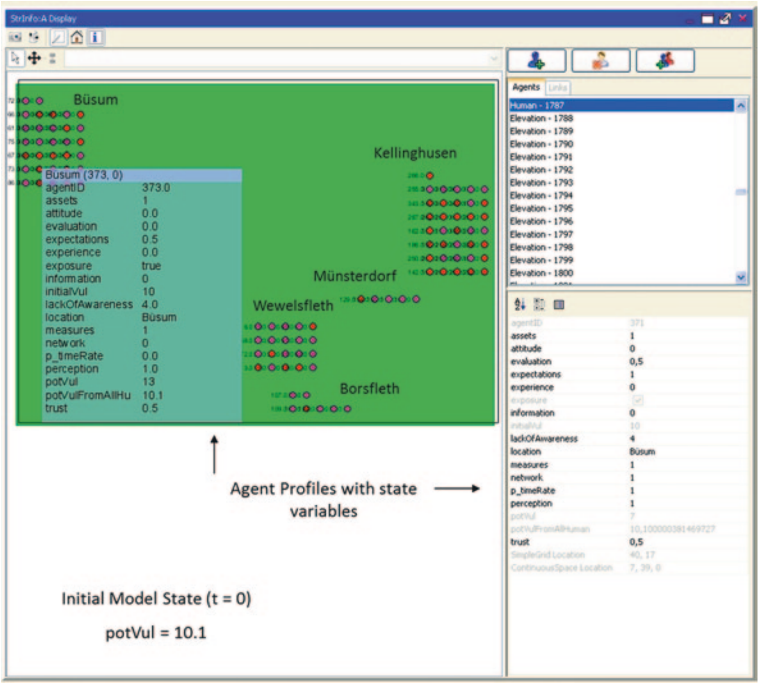


Fig. 5.23 Desktop view of initial model state (t = 0) with 100 agents

5.4 Model Output: Vulnerability Dynamics in the Coastal Zone

5.4.1 Vulnerability Baseline

The reduction of vulnerability due to behaviour changes in the agent system is traced during the simulation. The vulnerability attributes determine the potential vulnerability level (`potVul`) of each agent and characterise the heterogeneity inside the system. At the beginning of the simulation, the potential vulnerability of all 100 agents is calculated. While all agents start from an initial vulnerability value of 10 due to exposure (see Sect. 5.3), the potential vulnerability level can either be lower or higher due to the agent's individual vulnerability profile. The following potential vulnerability values of all 100 agents are calculated at t_0 (see Fig. 5.24).

Each individual agent and its vulnerability level are represented on the vulnerability scale between 1 and <20. According to the results, most agents are slightly above the initial vulnerability value: 26 % are described by a higher vulnerability value of 11 and 27 % with a value of 13. Only 4 % of the agents have a level of 15 or higher, with the highest score of 17. 43 % of the agents can be characterised by

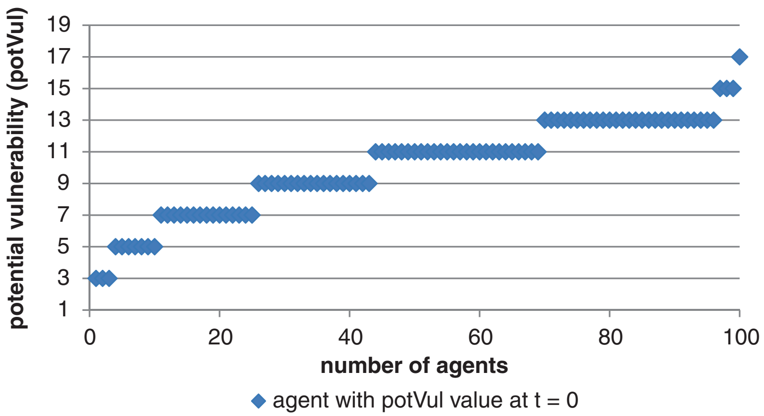
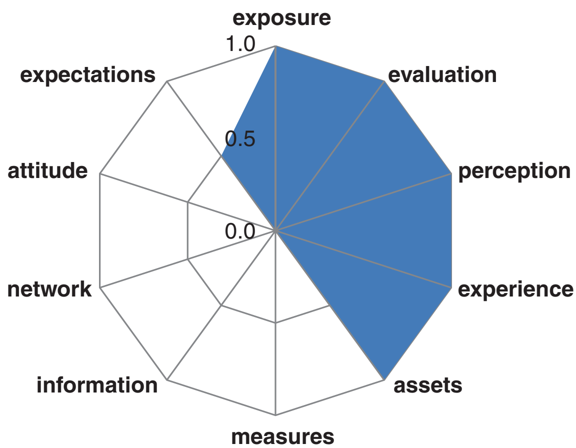


Fig. 5.24 Potential vulnerability values of all agents at t = 0 (N = 100)

Fig. 5.25 Vulnerability profile of agent 255 with a potential vulnerability level of 11 at t = 0



a lower vulnerability level according to their vulnerability attributes. About 18 % have a potential vulnerability value of 9 and 15 % a level of 7. Whereas only 3 agents show a potential vulnerability value of 3, a total of 10 % are at least at a level of potVul = 5 or below. The mean value of vulnerability related to the whole agent system (N = 100) is 10.1 at the beginning of the simulation. Thus, the mean potential vulnerability does not differ significantly from the initial vulnerability value due to exposure. In comparison to the system level, each agent can be described in more detail by an individual vulnerability profile representing the micro level. In Fig. 5.25 an example of a vulnerability profile is given for agent 255 starting as every agent with a vulnerability of 10 due to exposure[2]:

Once the simulation run is started, the scheduling of the self-protection strategies is processed and the agents act according to their behavioural strategies.

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[2] Model rules and calculation see Sect. 5.3 and Appendix A.3.

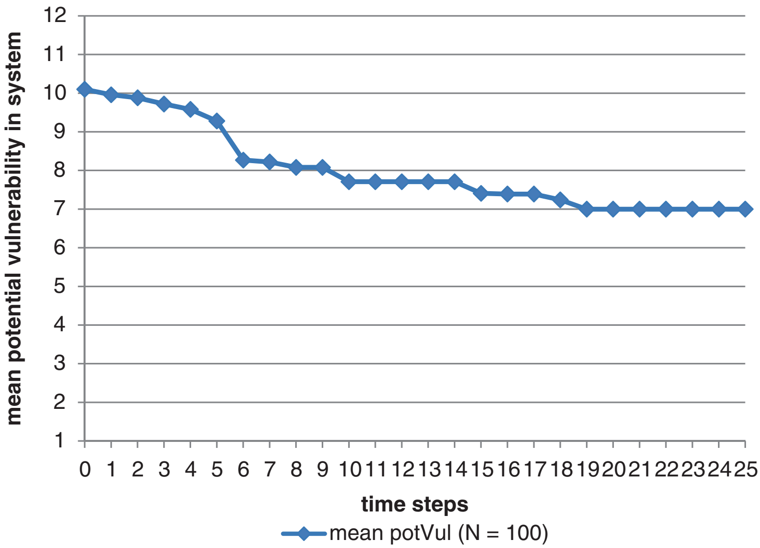

Fig. 5.26 Decreasing mean vulnerability (potVul) on the macro level during simulation run (N = 100)

The resulting simulation trajectory given in Fig. 5.26 represents the decreasing vulnerability baseline of the agent system.

By executing the model, the simulation run produces a simulation trajectory. Figure 5.26 shows the decrease in the mean vulnerability level of the agent system over the simulated time period. On macro level the vulnerability level is decreasing due to the agents' behaviour on micro level concerning better self-protection. At the beginning of the simulation the mean potential vulnerability level is 10.1; after 25 time steps the mean level decreased to 7. Over time the mean vulnerability decreases, though, not constantly by the same level. At certain time steps, as shown in Fig. 5.26, the vulnerability level drops more significantly; at other time steps it stagnates. Concerning the trajectory, each time step the vulnerability level declines by 0.12 on average. Major decreases of vulnerability can be identified in the trajectory for example between time step 5 and 6, between time step 9 and 10, 14 and 15 as well as between 18 and 19. While the vulnerability decreases steadily at the beginning of the simulation, from time step 10 till 14 and from step 20 onwards, the vulnerability level stagnates.

The agent's vulnerability level changes due to the effects of the implemented strategies resulting from the agents' decisions (see Sect. 5.3). As the vulnerability level is related to the agents decision, for explanation of the decrease in baseline vulnerability, a further look on the number of offered and accepted strategies in the system is necessary (see Fig. 5.27). Agents can decide to accept a strategy but merely if the strategy is offered at the agent's respective location—this process depends on the perceptual threshold as described in Sect. 5.3. Before an offered strategy is accepted, the agents go through the

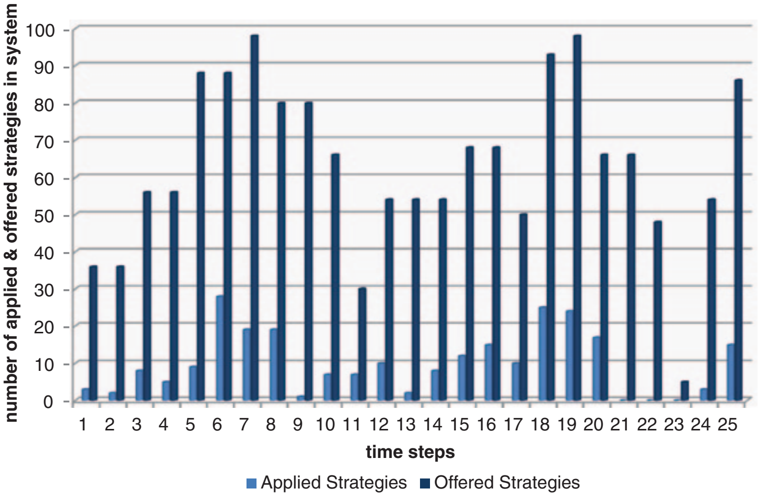

Fig. 5.27 Total number of offered and applied strategies in agent system over simulated time period (N = 100)

decision making process (see Fig. 5.21). As it is shown in Fig. 5.28, the number of offered and accepted strategies varies over the simulated time period. It can be observed, that from the first time step onwards, strategies are offered and accepted by the agents. Meaning that, the perceptual threshold and the decision making has been achieved already in the model system. However, the highest value of offered strategies is 98 at time step 7 and 19. For the system's vulnerability, the state of acceptance with regard to self-protection strategies is more important. It results from the relationship between applied and offered strategies in the agent system (see Sect. 5.3):

State of Acceptance = applied Strategies In System/number of Offered Strategies In System.

Regarding the applied strategies in the system, the highest value is 28 at time step 6 and in other time steps no strategy is applied at all. Figure 5.28 marks high states of acceptance of around 20 % and higher e.g. between time step 6 and 8 (32 %; 19 %; 24 %) as well as between time steps 11 and 12 (23 %; 19 %) and between 15 and 20 (18–27 %). Very low states of acceptance below 4 % can be observed in the middle of the simulation run at time step 9 and 13 as well as at the end of the simulation between time steps 21–23. On average the state of acceptance during the simulated period of 25 time steps is 13 %.

By further analysis of the state of acceptance in the system, the effect on vulnerability reduction can be explored. Whereas the state of acceptance in the first time steps of the simulation are between 6 % and 14 %, in time step 6 and 8 the acceptance state is at about 20–30 % for the first time. According to the trajectory of the vulnerability baseline (Fig. 5.26), a considerable decline of vulnerability can be identified between time step 5 and 6 that can result from the high state of acceptance with 32 %. At other time steps with relatively high states of

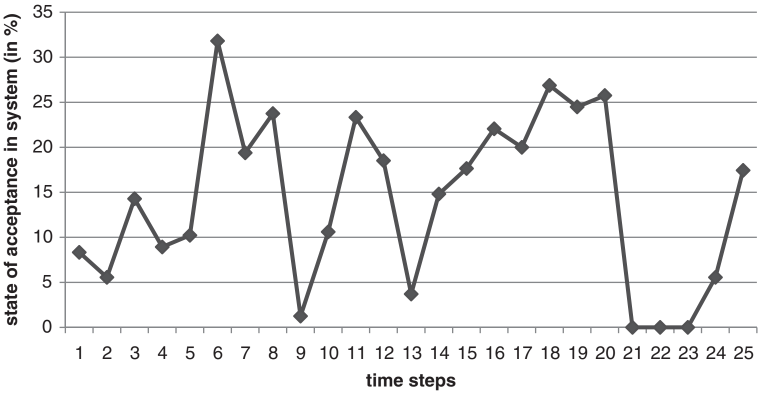

Fig. 5.28 State of acceptance for self-protection measures on macro level over simulated time period (in %; N = 100)

acceptance values of around 20 % smaller declines in vulnerability of 0.3 are reflected, i.e. between time steps 14 and 15 (18 %) as well as between time step 18 and 19 (24 %). But other decreases in vulnerability by about 0.3 cannot be related to the state of acceptance. Neither the small state of acceptance of 10 % at time step 5 nor of 11 % at time step 10 seems to correspond with the reduction of vulnerability by a level of 0.3–0.4 in one time step as in the example before. By considering other peaks in the state of acceptance, e.g. between time steps 11 and 12 (19 %) or between 19 and 20 (26 %) seems to have no effect as the vulnerability reduction stagnates (Fig. 5.26). Furthermore, between time steps 11 and 14 the system's vulnerability stagnates although the state of acceptance varies between 4 and 23 %. Thus, the state of acceptance cannot completely explain the varying vulnerability reduction in the system. With regard to the dynamics of vulnerability, other factors describing the micro level of agents, their behaviour as well as their micro-macro relationship is further explored in the simulation experiments.

While these considerations are based on the macro level, the vulnerability profile of each agent changes during the simulated time period too. The individual vulnerability profile of agent 255 thus changed according to its micro level behaviour (see Fig. 5.29).

The resulting distribution of vulnerability values after 25 time steps is the following (see Fig. 5.30).

In terms of the factors of influence, the micro agent level can be considered for the reduction of vulnerability. The development of each individual agent and its vulnerability level after 25 time steps is represented in Fig. 5.30. Compared to the potential vulnerability value in the agent system at $t = 0$, vulnerability has decreased to a mean value of `potVul = 7 (n = 98)`. Only two agents migrated, both from the community of Wewelsfleth. According to the results, most agents are below the initial vulnerability value: 73% are described by a vulnerability value of ≤ 9 (n = 72) and 27 % with a value of ≥ 11 (n = 26). Only 10 % of

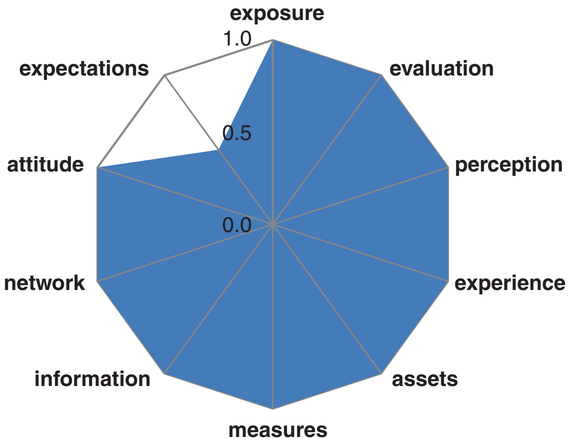

Fig. 5.29 Agent vulnerability profile of agent 255 with a different potential vulnerability level of 3 after 25 time steps

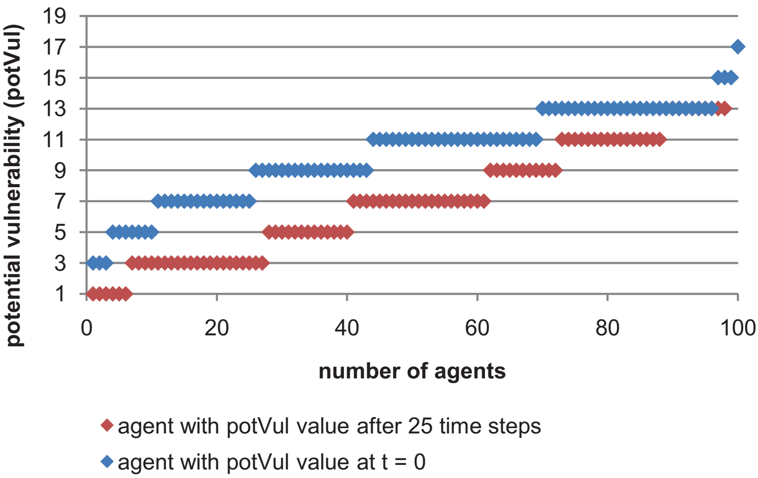

Fig. 5.30 Potential vulnerability (potVul) values of all agents at t = 25 (N = 98; *red*) in comparison to potential vulnerability values of agents at t = 0 (N = 100; *blue*)

the agents have a level of 13 and no agent at all has a vulnerability level higher than 13; before the self-protection strategies about 31 % have been characterised by a vulnerability level of 13 and higher. Due to their behavioural strategies, now 41 % of the agents show a low vulnerability level of ≤5. Thus, after 25 time steps only about 11 % hold a potential vulnerability value of 9 in comparison to 18 % before the simulation run and about 21 % in comparison to 15 % have a level of 7. Whereas at the beginning of the simulation only 3 agents reached a potential vulnerability value of 3, after 25 time steps a total of 21 % are at least at a level of potVul = 3 and another 6 % at a value of 1. In order to understand the reduction of vulnerability it seems appropriate to have a further look on the micro-behaviour and the influence of the self-protection preferences of agents.

5.4.2 *Influence of the Agent Preferences for Self-Protection Strategies*

The vulnerability baseline records the system development based on the model assumptions in Sect. 5.3. It shows the decrease of the mean potential vulnerability (potVul) in the agent system over the simulated time (see Fig. 5.26). The simulation trajectory, i.e. the sequences of states, can vary according to the experimental frame that might be changed for each simulation run. In order to observe the system under study, different simulation experiments are conducted in the following subchapters. They focus on the individual, relational and spatial aspects influencing vulnerability (see Sect. 3.2.2). For simulation experiments, the set of circumstances defining the experimental frame are essential, determining amongst others the observational variables of the experiment. Besides the state of vulnerability (mean potVul), the state of acceptance on macro level have been observed so far. The experimental frame in the following focuses on the self-protection preferences of the agents and the relative differences in vulnerability reduction. The influence of these preferences is explored by separating the respective agent types in the model input data and tracing the resulting trajectories. The trajectories are compared to each other and to the vulnerability baseline (mean `potVul`).

With regard to the information strategy (`p_information`), three agent types have been identified in the coastal zone of Germany (see Sect. 5.2): agents have a preference (`p_information = 1`), are indecisive whether to attend informative events (=0.5) or reject this type of strategy (=0). The simulation trajectories according to the agent preferences for the information strategy are depicted in Fig. 5.31 and compared to the mean potential vulnerability decrease. About 51 % of the agents declare their preference for the information strategy (n = 51). By comparison to the averse or indecisive agent types, differences result in the trajectories of vulnerability reduction (Fig. 5.31). While all 100 agents start at a very similar level of vulnerability around 10 at t = 0, the resulting vulnerability reduction differs by level of 4.5 between the agent type with preferences and without preferences. Independently from the initial vulnerability profile of the agents, the varying preferences for the information strategy resulted in relatively different vulnerability reduction. Furthermore, temporal differences can be observed in the sequence of the vulnerability states. Whereas, agents with a preference directly reduce their vulnerability level and after various constant steps end on a stable vulnerability level of 4.9, agents with other preferences stagnate on relatively high vulnerability values. The agent type without a preference for the information strategy merely decreases its vulnerability value by 0.6; that are after all about 37 % of the whole agent system. Those agents with neither a clear preference nor rejection

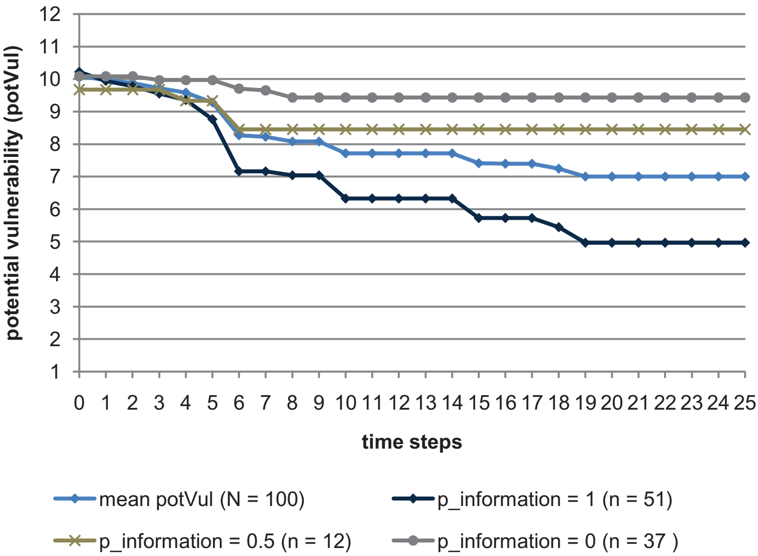

Fig. 5.31 Vulnerability trajectories of agents with different preferences for the information strategy (N = 100)

at the beginning of the simulation, at least decreased their vulnerability level by 1.2 (see Fig. 5.31). In the case of indecisive responses (0.5), agents diminish vulnerability between time steps 3—6 before the vulnerability level stagnates afterwards. They rather prefer other strategies and thus still reduce vulnerability.

Separating the agent type with a preference for the information strategy by the attribute `p_timeRate`, offers a more detailed analysis of the respective vulnerability trajectories. The preferred time rate for the informative events has an important influence (see Fig. 5.32). The effect of the preferred time rates becomes evident in the progression of states. Whereas the agent groups start with a difference in vulnerability levels of 1.8, it increases during the simulation run to a difference of 3.4 at time step 2 and nearly 6 at time step 5 until the trajectories converge again. At the end of the simulation run both agent types reduced their vulnerability level by a value of 4.9 and 5.4 and the difference in vulnerability levels only amounts to 1.3. But a preferred time rate for informative events each 6–12 months `(p_timeRate = 0.5)`, results in a slower reduction of vulnerability compared to a preferred time rate of each 3–6 months `(p_timeRate = 1)`. The more active the agent type, the earlier a lower vulnerability level is achieved. While the agents with a preferred time rate of 3–6 months for informative events reached a stable less vulnerable state after one year, in the other agent group it takes nearly up to four years to reach this state (see Fig. 5.32).

In the same way, an experiment can be conducted with the observational variable `p_insurance`. Again, agents either have a preference for the insurance strategy `(p_insurance = 1)` or not (=0) or they are uncertain about insurances

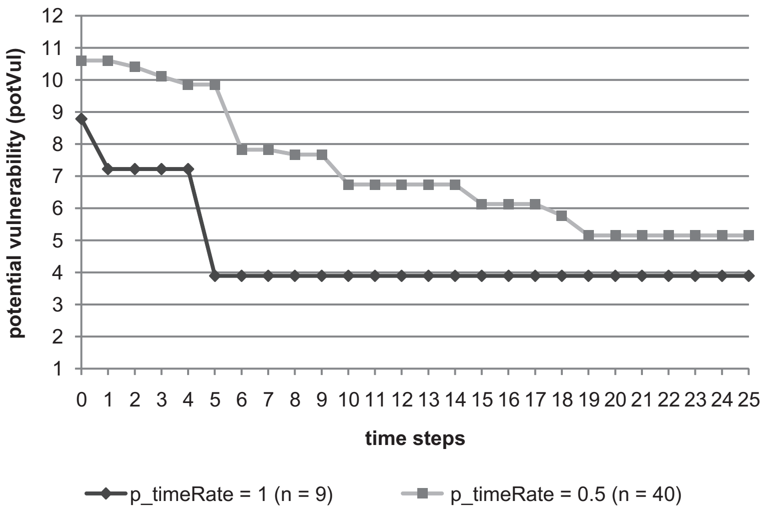

Fig. 5.32 Vulnerability trajectories of agents preferring the informative events at different time rates (n = 51; not specified: n = 2)

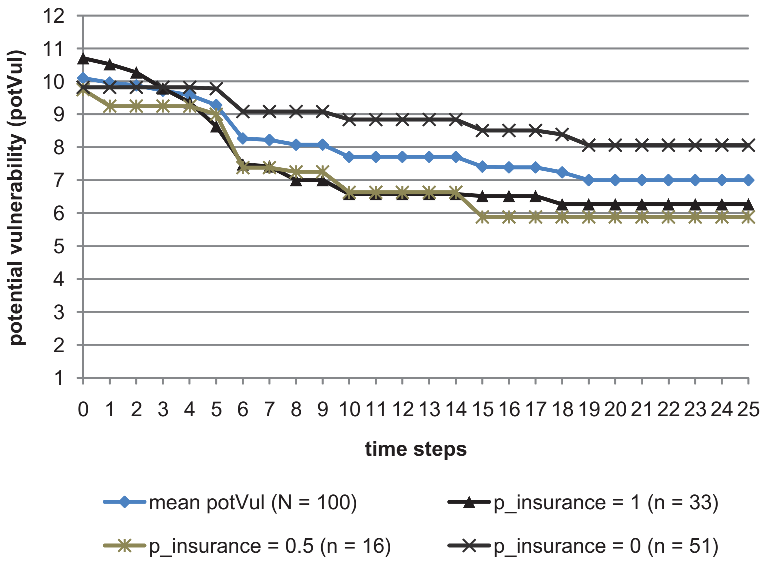

Fig. 5.33 Vulnerability trajectories of agents with different preferences for the insurance strategy (N = 100)

(`p_insurance = 0.5`). In comparison to the information strategy, only 33 % of the agents have a preference and about 51 % refrain from this type of self-protection measure (see Fig. 5.33). The vulnerability trajectories resulting from the simulation experiment reveal a lower effect of the insurance strategy on vulnerability

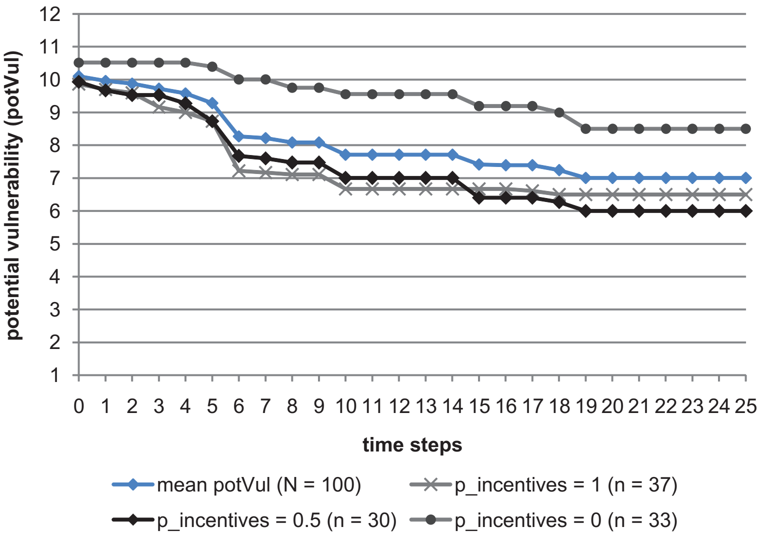

Fig. 5.34 Vulnerability trajectories of agents with different preferences for the incentives strategy (N = 100)

reduction. Agents with a preference for this strategy reduce their vulnerability level by a value of 4.4 until a stable vulnerability state of 6.3 is reached. This agent type decreases its vulnerability value in particular during the first six time steps.

Interestingly, the vulnerability reduction of indecisive agents is quite high (reduction by 3.8; see Fig. 5.33) whereas the reduction takes part in the middle of the simulation run. They rather implemented other measures, start later in the strategy schedule or were convinced later in the simulation run by the first agent group (type = 1) that applied the insurance strategy and thus are "available" for the convincing process of other agents from the second indecisive type (0.5). However, also the third agent group without a preference for this strategy (0) realises a vulnerability reduction by a level of 1.7. Although it represents the most vulnerable group type at the end of the simulation, it reached a lower vulnerability level of 8.1—and yet higher than the vulnerability baseline level of mean potential vulnerability (see Fig. 5.33). This considerable group of 51 averse agents reduces vulnerability rather other types of measures.

The results of the simulation experiment focusing on the incentives strategy (`p_incentives`) show some similarities with regard to the insurance strategy. In Fig. 5.34 it can be observed that the vulnerability of the indecisive agents again decreases over the simulated time period.

The 30 indecisive agents achieve even a better vulnerability reduction (by 3.9) in comparison to the agent group with a preference from the beginning onwards (n = 37; reduction by 3.4). Although the most vulnerable group of agents is the averse one, it still aims to reduce vulnerability by 2.0 by other strategies. The relatively similar trajectories of the insurance and the incentives strategy might

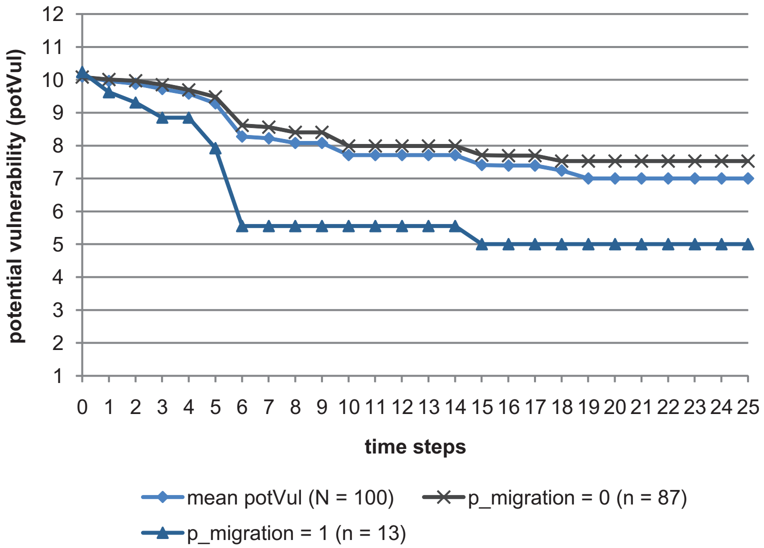

Fig. 5.35 Vulnerability trajectories of agents with different preferences for the migration strategy (N = 100)

be related to the correlation between the two strategies, i.e. agents with a preference for this strategy accept it only directly if they also have a preference for the insurance strategy. As also the effects of these strategies on the agent profile are identical (see Table 5.10), the similar trajectories can be explained.

The last strategy offered to the agents during the schedule is migration (see Fig. 5.35). Agents can decide between the option to migrate (`p_migration = 1`) or to still live in the exposed area (`p_migration = 0`; including the category OTHER; see Sect. 5.2). 13 % of all agents have a preference for the migration strategy. But after the decision process (see Fig. 5.21), merely two agents migrate definitively and are deleted from the model context. In the simulation, the migrating happens in the agent collective Wewelsfleth during the 6th time step. The other eleven agents from this group finally still live in the exposed area and reduced its vulnerability by the implementation of other strategies. The 87 % of agents without a preference for the migration strategy still are able to steadily decrease their vulnerability to a level of 7.5. And thus, nearly to the mean potential vulnerability level (N = 100).

To sum it up, the vulnerability trajectories of agents preferring all strategies or no strategy at all are compared to each other (see Fig. 5.36). Only three agents prefer all four self-protection strategies, 11 % of all agents have no preferences at all (N = 100). Although the strategies are not necessarily applied by all agents—due to the influences during the decision making process—the preferences of agents at the beginning of the simulation indicate a significant reduction in vulnerability towards the end of the simulation. The agent group preferring all four strategies starts at a moderate vulnerability level of 8.3, it decreases its vulnerability level

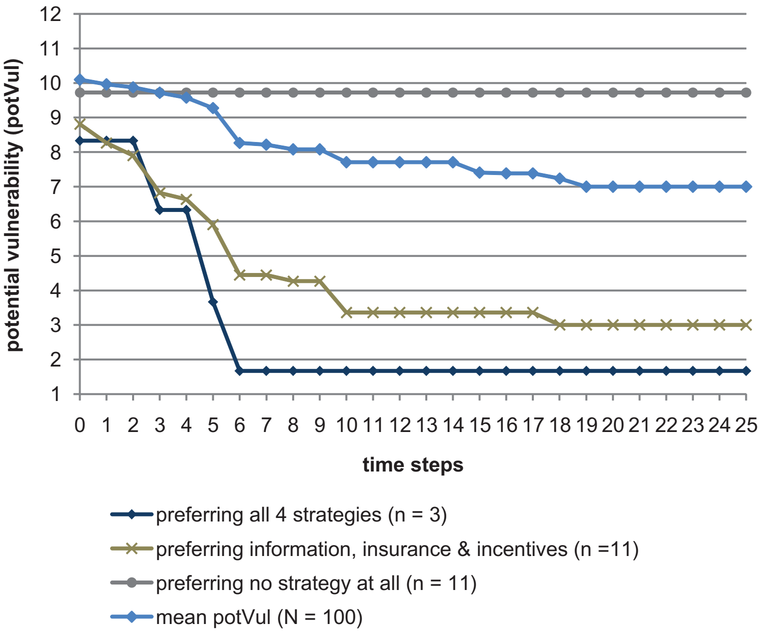

Fig. 5.36 Vulnerability trajectories of agents with preferences for three or four strategies in comparison to agents with no preferences at all and the mean potential vulnerability

by 6.6 after only 6 time steps. Hence, the resulting vulnerability level of 1.7 represents the lowest level achieved in the simulated trajectories. It results from a combination of a moderate agent vulnerability level at the beginning, preferences for the strategies that are offered in an early strategy scheduling and the acceptance of strategies. Although the migration strategy is preferred by the three agents, at the end they are not migrating due to the influence of the correlating attribute. After the decision process the migration strategy is rejected by these three agents.

Also in the case of the agent type preferring three strategies, namely information, insurance and incentives (n = 11), the preferred strategies are not necessarily applied due to the agents' decision processes. The vulnerability level of 8.8 at the beginning is at least reduced by 5.8. After 18 time steps the agents stagnate on a very low vulnerability level of 3 (see Fig. 5.36). The agent type having no preference at all (n = 3) stays constantly on a vulnerability level of 9.7 as it shows no activity to reduce vulnerability by better self-protection.

In Fig. 5.37 the vulnerability trajectories of agent types with at least two preferred strategies are depicted. According to the empirical data, 65 agents prefer at least two strategies. Five agent types manage to reduce their vulnerability level below 5 by their preferences for: information and migration (n = 9), insurance and migration (n = 5), incentives and migration (n = 5), information and incentives (n = 19) as well as for insurance and incentives (n = 18). Although agents preferring the information and insurance strategies (n = 10) also reduce

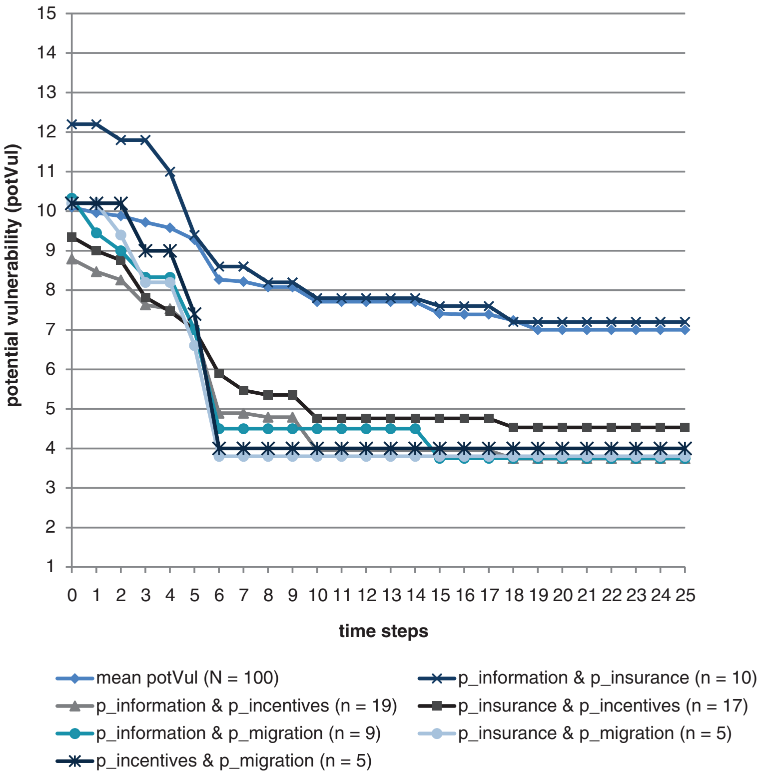

Fig. 5.37 Vulnerability trajectories of agents with preferences for two strategies

their vulnerability by a level of 5, vulnerability stagnates on a value of 7.2 due to the high vulnerability at the beginning (see Fig. 5.37). They represent in this simulation experiment the agent type with the highest vulnerability value after 25 time steps.

In particular agent types preferring the migration strategy in combination with another strategy, reduce their vulnerability by a level of 6 over the simulated time period. These might represent the most "risk-averse" agents in the simulation, as the migration strategy constitutes an extreme measure. By the combination of the insurance and incentives strategy (n = 17), the effect on vulnerability reduction is smaller. It can be related to the overlapping effects of these strategies on the vulnerability attributes, as both affect the attributes `attitude` and `measures` of the agent profile.

The vulnerability reduction resulting from different self-protection preferences can be observed also with regard to the (initially) most vulnerable and least vulnerable agent types. During the simulation run, the strategies lead to different levels of vulnerability reduction of these groups (see Fig. 5.38). Due to preferences for the information strategy `(p_information = 1)` and the migration

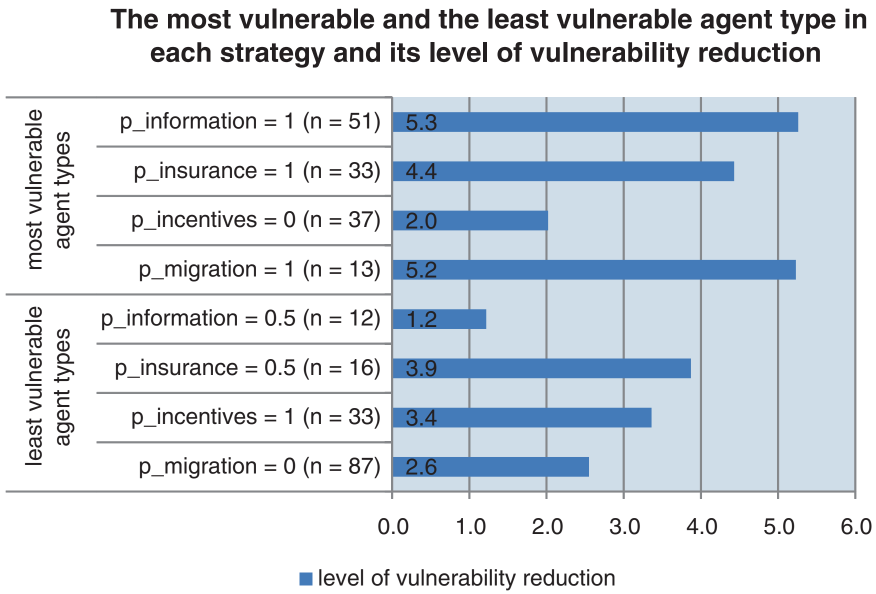

Fig. 5.38 Level of vulnerability reduction of the most vulnerable and the least vulnerable agent types with regard to the strategy preferences

strategy `(p_migration = 1)`, the most vulnerable agent types achieve a decrease in vulnerability by 5.3 and 5.2 As the number of agents preferring the information strategy is considerably high (51 %), this type of agent can be regarded as important for the system's vulnerability reduction. The positive effects of the information strategy are achieved mainly due to the influence of the strategy on the agent's vulnerability profile, e.g. on perception, information and network (see Table 5.10). The least vulnerable group of indecisive agents with regard to the information strategy `(p_information = 0.5)` decrease by only 1.2.

With regard to the strategy `p_insurance`, the most vulnerable agent type has a preference and the least vulnerable is uncertain at the beginning of the simulation. Yet, both agent types reach a considerable reduction of vulnerability by 4.4 and 3.9 (see Fig. 5.38). The uncertain agents decided for other strategies or still could be persuaded during the model run that contributed nearly as much as in the first agent type `(p_insurance = 1)` to a decrease in vulnerability. Yet, the greater group of agents with a preference ($n = 33$) might play a more important role for the overall system development. The most vulnerable agent type with regard to the incentives strategy refuses the strategy and the vulnerability level only drops by 2.0. In this case, the least vulnerable agent type at the beginning benefits from its preference for the strategy `(p_incentives = 1)` and manages to reduce vulnerability by a level of 3.4. Although most agents preferring the migration strategy finally are not implementing it, the last simulation experiment showed that agents with this preference seemed to be rather risk averse and reduce vulnerability by also preferring other strategies.

5.4.3 Influence of the Human-Environment Relationship

Additionally to the individual preferences for self-protection strategies, relational aspects might lead to vulnerability dynamics in the agent system (see Sect. 3.2.2). To observe the system under study, simulation experiments are conducted focusing on the influence of the human-environment relationship on the vulnerability trajectories. The human-environment relationship is an important factor in risk concepts (see Sect. 3.2) and might help in exploration of the vulnerability development in the model system. Again, the influence of the human-environment relationship is explored by separating the respective agent types in the model input data and tracing and comparing the resulting trajectories. Four observational variables are taken into account for analysing the influence of the human-environment relationship: lack of awareness and trust in connection with the location as well as evaluation, perception and expectations. Lack of awareness and trust are related to the meso level of agent collectives and the influence can be measured when distinguished by location as shown in Figs. 5.39 and 5.40.

In comparison to the baseline vulnerability in the agent system, the trajectories of the communities reveal considerable differences in the process of vulnerability reduction. Thus, by distinguishing the agent system into the agent collectives, i.e. by the communities, the influence of the different human-environment relationships can be observed. The meso level offers a more detailed analysis of the heterogeneous agent system. With regard to vulnerability, it further specifies the relational and spatial aspects influencing the social phenomenon. The differences concerning the human-environment relationship in the communities (see Sect. 5.2) can now be explored over the simulated time period. From the time period passed since the last flood/storm surge event (see Table 5.4) and the trust in official dike protection (see Fig. 5.14), the state variables `lackOfAwareness` and `trust` were derived. As these variables determine the scheduling of strategies in the communities, different vulnerability trajectories arise.

During the 25 time steps, the mean potential vulnerability of the agent system ($N = 100$) decreases gradually from alevel of 10.1 to 7. The significant steps in the baseline trajectory (see Fig. 5.39) are not identical with the significant steps in the agent collectives. Due to the different perceptual thresholds derived from the lack of awareness and trust values, the scheduling of the dissemination of strategies is delayed in some collectives (see Sect. 5.3). This delay can be observed comparing the trajectories e.g. of the collectives Kellinghusen and Büsum (see Fig. 5.39). In the former, from the first time step onwards the vulnerability diminishes. It indicates that agents take positive decisions towards the application of the offered self-protection strategies.

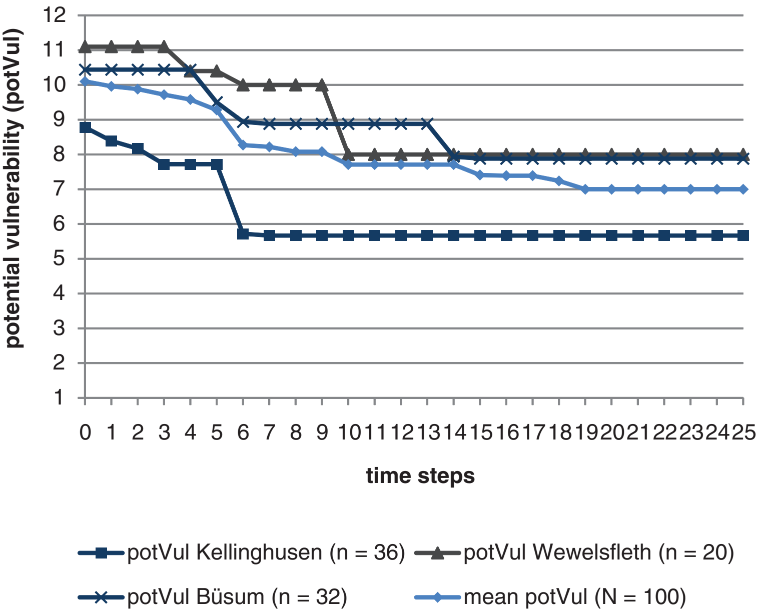

Fig. 5.39 Vulnerability trajectories in the sample of Kellinghusen, Wewelsfleth and Büsum in comparison to the mean potential vulnerability of agent system

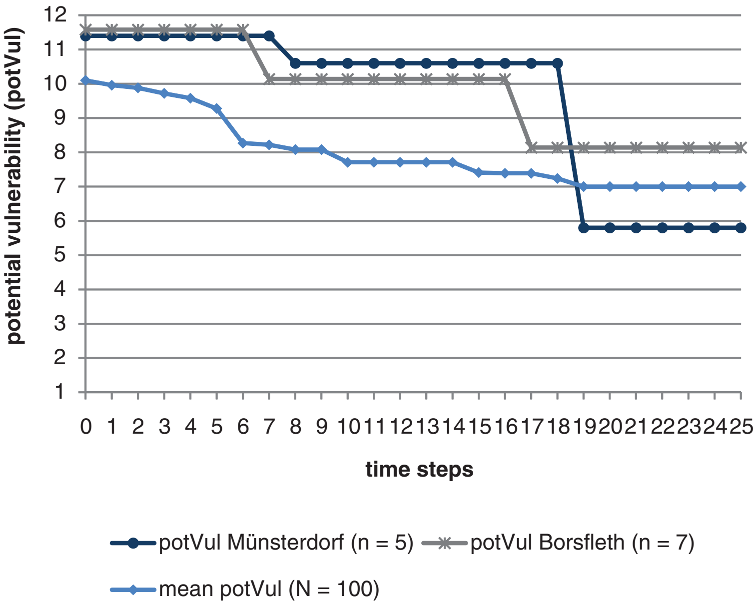

Fig. 5.40 Vulnerability trajectories in the sample of Münsterdorf and Borsfleth in comparison to the mean potential vulnerability of agent system

Major steps in reduction of vulnerability are achieved in particular between time steps 0–3 and between 5 and 6 over the simulation run. Vulnerability does not further decrease after time step 7 and stagnates on a level of 5.7. In the later, the vulnerability decreases not until the 5th time step. The perceptual threshold for the strategies is not achieved due to the high lack of awareness and trust values in Büsum (see Table 5.8). In consequence, the decision processes towards better self-protection are further delayed in comparison to the collective Kellinghusen. Until all agent decisions with an effect are completed it takes until the 15th time step, i.e. 8 time steps longer equivalent to nearly 2 years. The level in the collective Büsum stagnates at 7.9.

In Fig. 5.40 it can be observed that in the collectives Borsfleth and Münsterdorf the dissemination of self-protection strategies is even further delayed. The first reduction in vulnerability due to positive agent decisions occurs at the 6 time step in Borsfleth and at the 7th time step in Münsterdorf. Although both collectives share the same lack of awareness, as the last event happened in 1962 in both communities (see Table 5.8) the higher trust value is even more unfavourable for vulnerability reduction; the increasing lack of awareness in the second year (see Table 5.5) in Münsterdorf further prolongates a possible vulnerability reduction. Whereas the vulnerability level stagnates for a certain time during the simulation, the trajectory indicates further positive agent decisions at the 16 and 18th time step. In the agent collective Münsterdorf vulnerability decreases considerably in the 19th time step (see Fig. 5.40).

Besides the progression of vulnerability reduction, also the states of vulnerability differ in the communities. At the beginning of the simulation run, the agent collectives start with a potential vulnerability level lying above the mean potential vulnerability value of 10.1—except Kellinghusen with a value of 8.8. The sample from Borsfleth shows the highest vulnerability level of 11.6. In comparison, the decrease of vulnerability due to the agents decisions amounts to a difference of 3.1 in 7 time steps in the collectives Kellinghusen and of 2.6 in 14 time steps in Büsum (see Fig. 5.39). In the collective Münsterdorf vulnerability mainly decreases towards the end of the simulation by 5. It is further delayed by the increasing lack of awareness over the simulated time period. Agents in Büsum, Wewelsfleth and Borsfleth stagnate on a level of approximately 8; agents in Kellinghusen and Münsterdorf achieve a vulnerability level below 6.

The agent collectives differ according to the potential vulnerability at the beginning and the positive decisions of the agents for self-protection measures, but the trajectories are considerably influenced by the different human-environment relationship (lack of awareness, trust). In another simulation experiment, the perceptual threshold in the agent collective Büsum is decreased to the values calculated for Kellinghusen. The result can be seen in Fig. 5.41. Especially in the first 5 time steps, the activity of agents in Büsum is increased due to the modified perceptual threshold. Though, the vulnerability level at the end of the simulation has not changed. Agents in Büsum however would be less vulnerable in the first year in comparison to the former trajectory due to the increased activity of agents at the beginning.

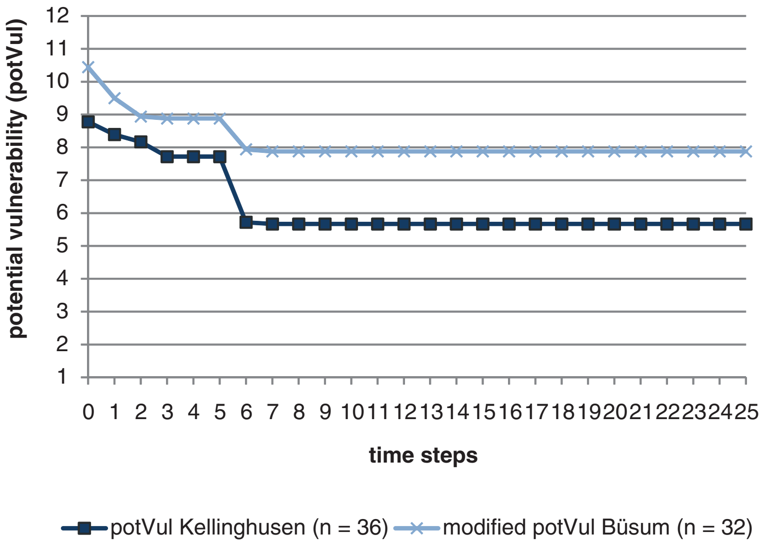

Fig. 5.41 Modified vulnerability trajectory of agents in the sample of Büsum due to a decreased lack of awareness and trust as in the sample of Kellinghusen

The vulnerability attributes evaluation, perception and expectations furthermore describe the human-environment relationship of the agents. The state variables are related to the micro level of agents, thus the influence on the vulnerability trajectory is measured by considering the different values for the state variables, e.g. `expectations` = 1, = 0.5 or = 0.

Considering the state variable `evaluation`, in three agent collectives up to 30 % of the agents consider the risk of flooding/storm surges as very low to not at all (see Sect. 5.2). This group is represented in the simulation experiment with an evaluation value of 0 (evaluation = 0; n = 13). In the agent collectives Kellinghusen and Münsterdorf all agents regard risk at least as medium to low in their community (`evaluation` = 0.5) or as very high to high (`evaluation` = 1). On average, most agents evaluate risk as medium to low (n = 53), but about 1/3 of the agents (n = 34) evaluate risk as very high to high. According to the agents' risk evaluation, the vulnerability trajectories differ as depicted in Fig. 5.42.

During the simulation, the human-environment relationship leads to different trajectories starting at different initial vulnerability values. Agents with no or very low risk evaluation begin with a vulnerability level of 12.7 and the decrease in vulnerability starts not until the 4th time step of the simulation run; approximately 1 year passes. At the end of the simulation run vulnerability stagnates at a level of 10.1 and approximately at the initial vulnerability value in the agent system (see Sect. 5.4.1). The two other agent types, although starting between a level of 9 and 10, decrease their vulnerability level by 2.9 (`evaluation` = 0.5) and 3.4 (`evaluation` = 1) from the first simulation step onwards. They stabilise at a vulnerability level of 7.1 and 5.8. Though, all agents reach a stable level after 18–19

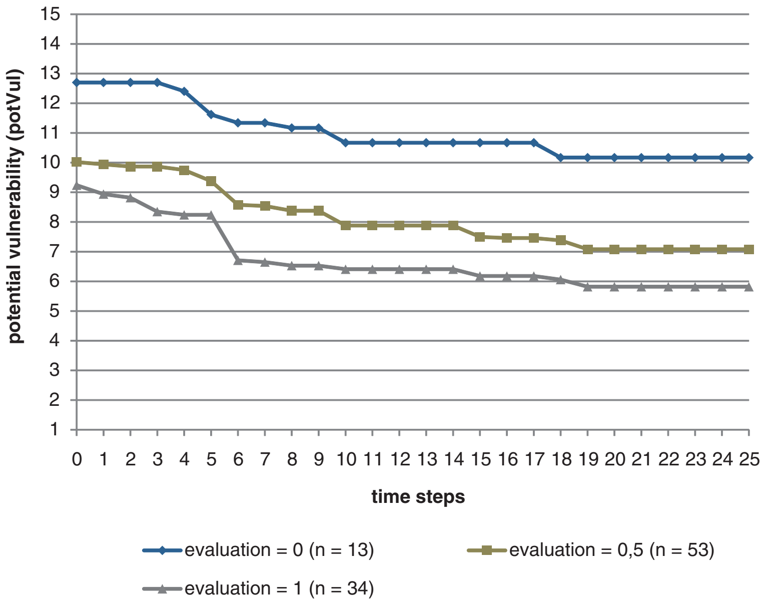

Fig. 5.42 Vulnerability trajectories of agents with different risk evaluation (N = 100)

time steps. The influence of the vulnerability attribute risk evaluation thus is rather relevant for the agent's individual vulnerability profile at the beginning of the simulation. How risk is evaluated thus rather affects the agent profile at the beginning, than the trajectory of the agent types over the simulated time period. Whereas in other simulation runs the trajectories converge or cross each other, here the initial differences cannot be balanced over the simulated time period. Instead, the initial differences between the vulnerability levels of the three agent types are even slightly increased.

The trajectories look quite different when considering the vulnerability attribute perception. Different trajectories result from the varying perception values as depicted in Fig. 5.43. Agents with risk perception (`perception` = 1; n = 78) are able to decrease their vulnerability level during the simulation run by 3.3, i.e. starting at a comparatively low level of 9.4 and reducing it to 6.1. The other agent types also manage to decrease their vulnerability level, though not in the same time period. Whereas agents with risk perception reduce vulnerability from the first time step onwards, the agent type without perception (`perception` = 0; n = 19) takes about 4 time steps to come to positive decisions with regard to self-protection. In the case of agents that are unsure about their exposure (`perception` = 0.5; n = 3), this process even takes until the 14th time step. Though, both more vulnerable agent types are able to reduce vulnerability level by 2.6 and 2.1 at approximately the average vulnerability level of 10. The most vulnerable agent type in this experiment still achieves a considerable reduction in vulnerability (see Fig. 5.43).

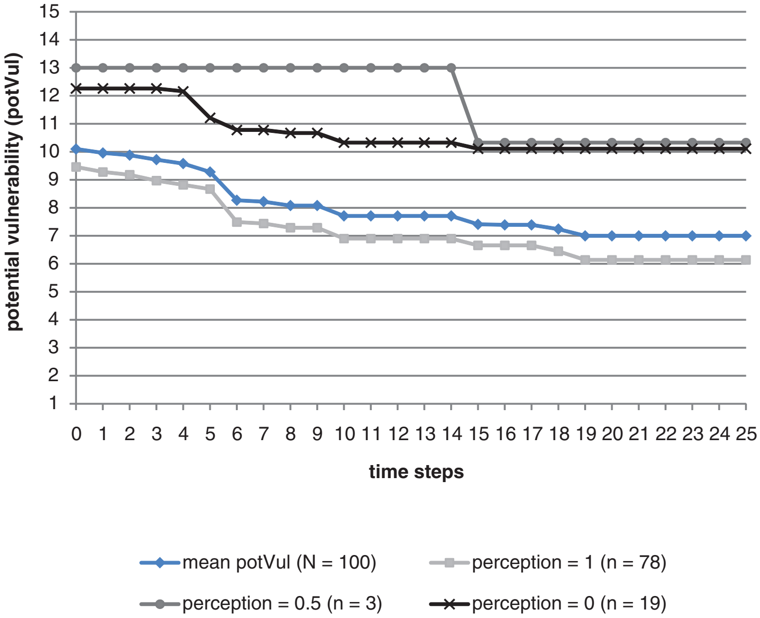

Fig. 5.43 Vulnerability trajectories of agent system with different perception values in comparison to vulnerability baseline (N = 100)

By separating agent types with or without evaluation *and* perception, much more dynamics can be observed in the trajectories (see Fig. 5.44). A more detailed view of the processes inside the system can be given.

The type of agent evaluating risk as medium to low and with a risk perception constitutes the largest group (n = 41) in this simulation experiment. Agents with evaluation and perception values of 1, i.e. they consider risk as very high to high and have a perception of exposure build the second biggest group (n = 28). According to the trajectories, these two agent types achieve the lowest vulnerability values at the beginning and at the end of the simulation. Anyhow, also the agent type denying the risk (`evaluation` = 0) and no perception of personal exposure (`perception` = 0) achieves to considerably reduce its vulnerability level by 4 due to its positive decisions towards better self-protection. Whereas the most vulnerable agent at the beginning thus manages to reduce vulnerability, other agents seem to stagnate from the beginning of the simulation on their vulnerability values; in other cases it takes further time steps to begin reducing their vulnerability level (see Fig. 5.44).

The influence of the vulnerability attribute `expectations` is furthermore tested to regard the influence of the human-environment relationship. Most agents expect that the impacts in consequence of flooding/storm surges will not increase in the future (see also Sect. 5.2). Agents with expectations concerning increasing impacts (=1) manage to reduce their vulnerability in particular in the first six time steps and more effective in comparison to agents without such expectations

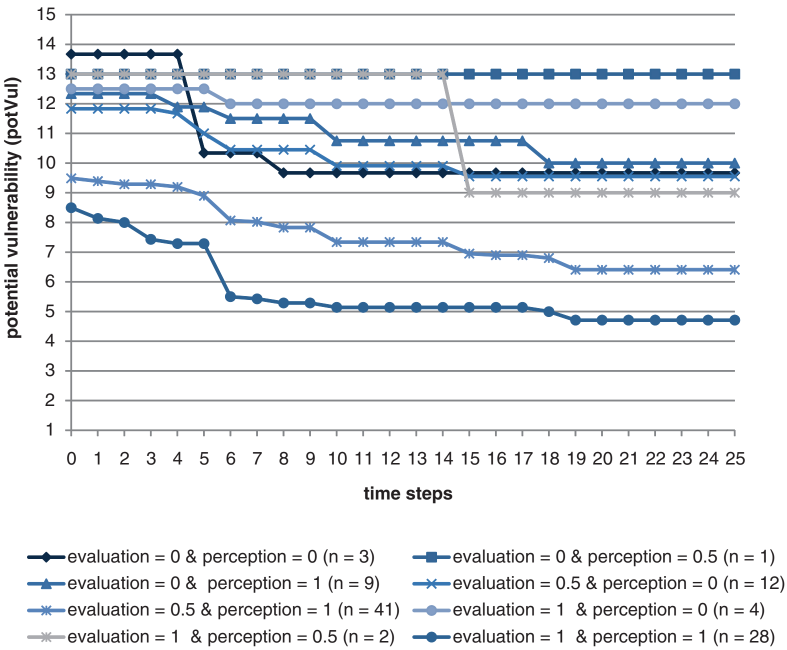

Fig. 5.44 Vulnerability trajectories depending on the attribute values for evaluation and perception (N = 100)

(see Fig. 5.45). This agent type decreases by a level of 3.5 especially in the first time steps, the agent type without expectations by 2.2 in a gradually decreasing trajectory. Notably is, that those agents unsure about the future expectations manage to reduce their vulnerability level by 4.3 and thus approach further to the least vulnerable agent type with a value of <5.

The vulnerability reduction resulting from different human-environment relationships is summarised with regard to the (initially) most vulnerable and least vulnerable agent types. During the simulation run, the different attributes considering the human-environment relationship lead to different levels of vulnerability reduction of these groups (see Fig. 5.46). The most and the least vulnerable agent type by location as well as by the vulnerability attributes evaluation, perception and expectations are compared to each other. On average the vulnerability in the system (mean `potVul`) decreases by 3.1. The most vulnerable agent type with regard to the location constitute agents in the sample from Borsfleth (n = 7); the least vulnerable agent type represent agents in the sample from Kellinghusen (n = 36). Agents from both locations are able to diminish vulnerability by a level of 3.4 and 3.1 (see Fig. 5.46). The different initial conditions in terms of the last disaster event remembered by the residents and trust in official dike protection affect the trajectories temporally. By focusing on the whole agent system, these differences cannot be uncovered. And although the agent collective Borsfleth is much smaller than the collective Kellinghusen, the different progression of

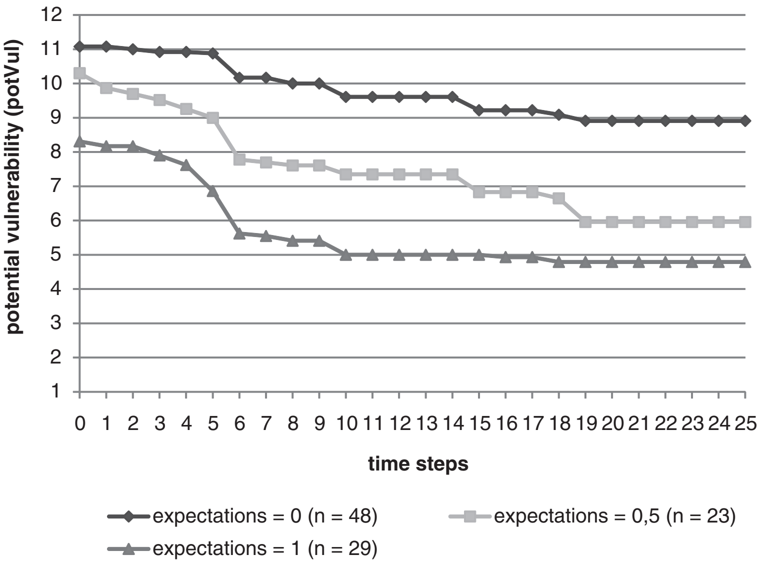

Fig. 5.45 Vulnerability trajectories depending on the attribute values for expectations (N = 100)

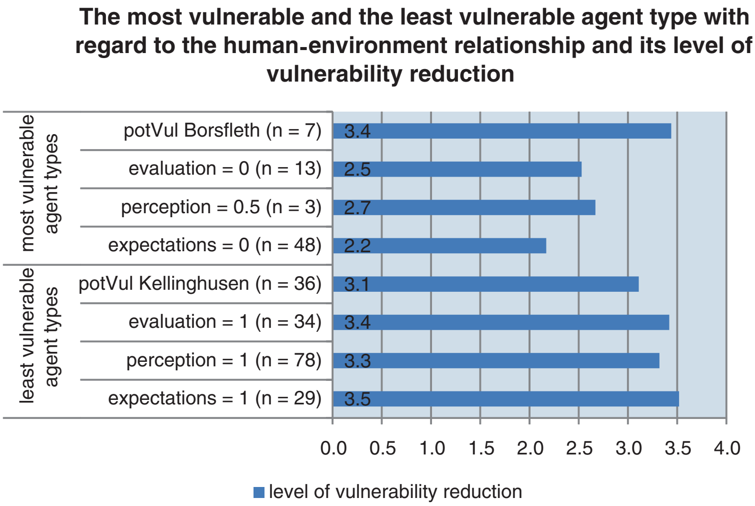

Fig. 5.46 Level of vulnerability reduction of the most vulnerable and the least vulnerable agent types with regard to the human-environment relationship

vulnerability reduction might be important under spatio-temporal aspects. Due to different initial conditions, it takes 2 years longer in the agent collective Borsfleth to achieve the final vulnerability level.

The results in terms of the vulnerability attributes perception and evaluation, reveal that the least vulnerable agent types are rather able to reduce vulnerability. Less vulnerable agents attenuate vulnerability by 3.3 and 3.4, more vulnerable agents without perception and risk evaluation by 2.7 and 2.5 (see Fig. 5.46). Whereas the percentage of agents without perception is very small (n = 3), agents evaluating the risk as very low constitute a considerable group in the agent system (n = 13). The most considerable difference in vulnerability reduction can be assessed between agents with and without expectations. Yet, in all three experimental sets the most vulnerable agent types at the beginning are still the most vulnerable at the end of the simulation run. Thus, these types of agents still represent an important group for (better) risk communication and management approaches. By certain combinations of attributes some agent types still can achieve better decreases in vulnerability (see Fig. 5.44).

5.4.4 Influence of the Micro–Macro Relationship

The observational variable `network` describes the micro–macro relationship of agents. In the empirical survey respondents stated whether they use their social network for information exchange about self-protection measures (see Sect. 5.2). The influence of the variable values and combinations with other vulnerability attributes, e.g. network and level of information is tested with regard to the reduction of vulnerability. The simulation trajectories can outline the possible influences on the dynamics of vulnerability.

In the first simulation experiment, the variables social `network` and level of `information` of the agents is tested (see Fig. 5.47). To what extent are socially embedded and well informed agents different concerning vulnerability reduction and agent behaviour? Figure 5.47 demonstrates that agent types with information and network (`network` = 1 & `information` = 1; n = 7), starting at varying initial vulnerability levels, act differently in comparison to agent types without a network. They are able to reduce vulnerability by 2.0 in comparison to 0.7 in case of the informed agents without a network (n = 25). The model assumes that under the influence of the social network, indecisive agents could still be persuaded during the simulation run and could benefit from the network by reducing their vulnerability.

But this effect of the network is outweighed in the case of agents with a low level of information at the beginning. Agents without sufficient information and network (`network` = 0 & `information` = 0; n = 54) achieve the highest reduction in vulnerability by a level of 4.2. This agent type, starting at a vulnerability level of 11.1, manages to constantly reduce its vulnerability to a level of 6.9 due to its preferences rather than due to the social network. The negative correlation between the information strategy and the level of information (see Table 5.10), has the effect that informed agents are rather not attracted to the information strategy. The uninformed agents thus benefit when accepting the strategy as they get

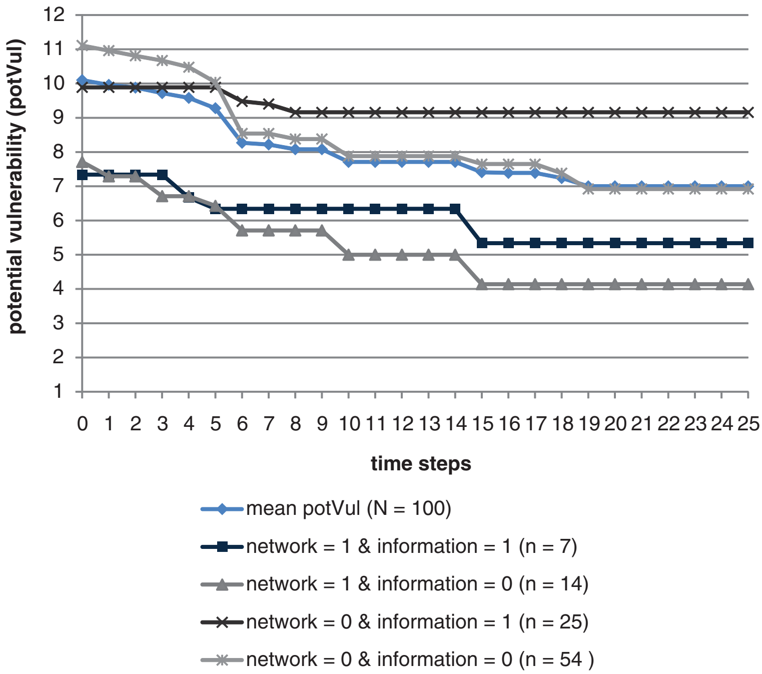

Fig. 5.47 Vulnerability trajectories of agents with different information and network values in comparison to vulnerability baseline (N = 100)

connected to the social network and are able to reduce vulnerability due to the positive effects of the information strategy. After 19 time steps the agents reach the mean potential vulnerability level. Nevertheless, the agent type without information but a network (`network` = 1 & `information` = 0; n = 14) can benefit from the positive social influence in the network and the positive effects of the information strategy (if preferred). They can be characterised by the lowest vulnerability level in the simulation experiment with a value of 4.1 due to a reduction in vulnerability by 3.5 (see Fig. 5.47).

Another simulation experiment with the variable `network` is conducted in combination with the social attribute age. In Fig. 5.48 the vulnerability trajectories of agents with the age >65 and <65 years are compared to each other and in relation to the network values.

In comparison to the mean potential vulnerability of the agent system, the agent type with network access and age <65 years achieves the lowest vulnerability level of 4.7 already after 14 time steps (`network` = 1 & `age` < 65; n = 18). Though, also the agents ≥65 years old and access to the social network manage to reduce their vulnerability level from 10.5 to 6.5, i.e. slightly below average. Agents without access to the social network start with a higher potential vulnerability at the beginning of the simulation (see Fig. 5.48). Yet, agents of this type can also

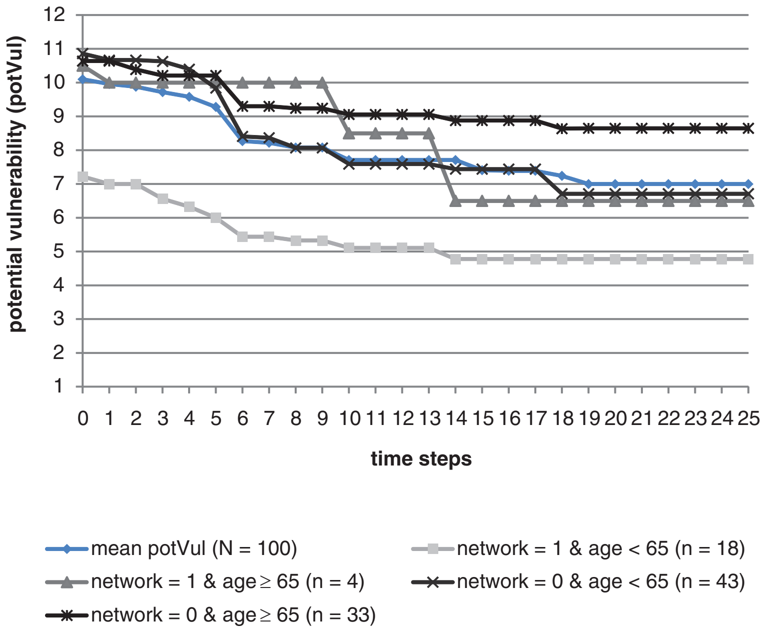

Fig. 5.48 Vulnerability trajectories of agents with/out network and age </≥65 years (N = 98; n.s. = 2 %)

considerably reduce the vulnerability level. In case of the agents below <65 years old, the vulnerability level drops also by 4.1 (`network` = 0 & `age` < 65; n = 43). Although reduction of vulnerability lasts until the 18th time step, it stagnates on a low vulnerability value of 6.7. Agents with a network—independent from age—reached their stable vulnerability state nearly a year before (see Fig. 5.48). Agents without network access and ≥65 years old (n = 33) can be described by a high vulnerability level of 10.6 at the beginning, diminish vulnerability merely by 1.9 and end up on the highest vulnerability level in this simulation experiment.

The influence of the micro–macro relationship is further assessed by changing the size of the social network in the following simulation experiment. It tests in how far the size of the social network can influence the system's development. According to the empirical data base, 21 of the 100 agents initially participate in the community networks. The simulation can be run with varying sizes of the (initial) social network: with 0 agents participating, with 21 agents as in the empirical data base, with 73[3] or 100 agents participating in the network (N = 100). The vulnerability trajectories of agent systems with different network sizes at the beginning of the simulation are shown in Fig. 5.49. Although the agent systems with

[3] The 21 agents that already participate in the social network according to the empirical data base and 52 additional agents were randomly selected and integrated into the network.

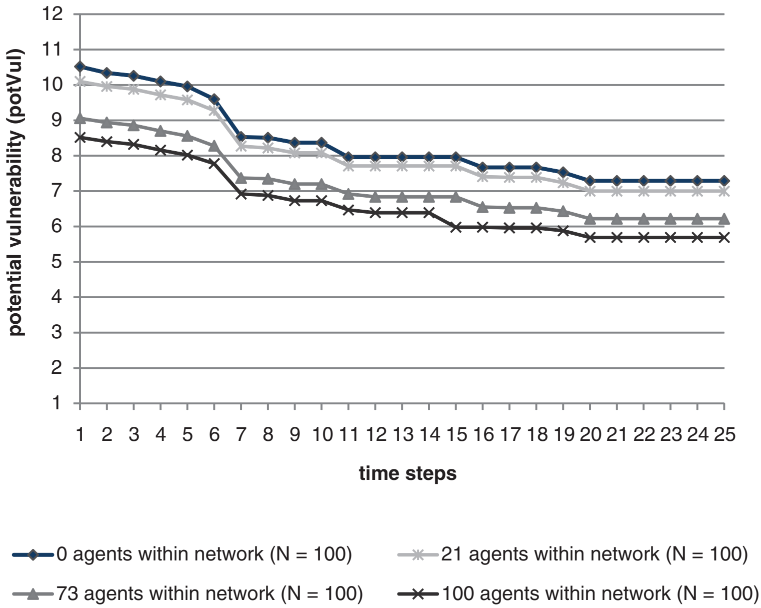

Fig. 5.49 Vulnerability trajectories of agent system with different network sizes (each N = 100)

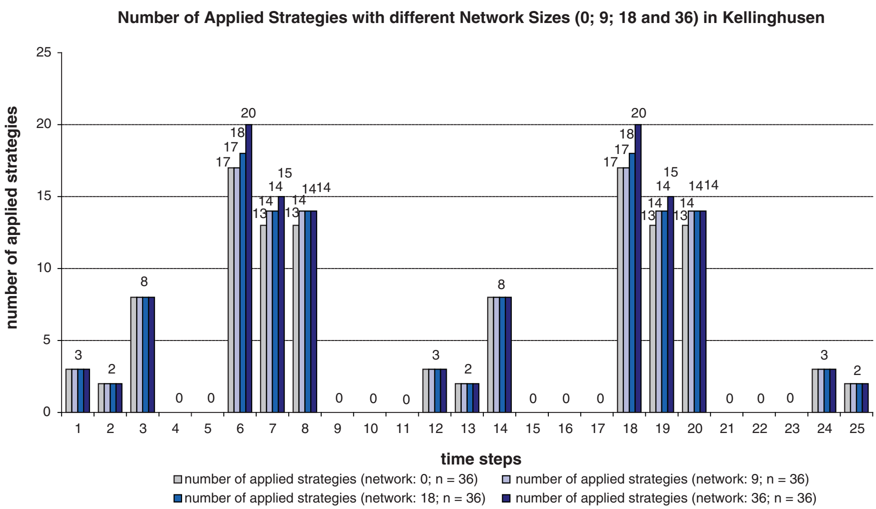

Fig. 5.50 Number of applied strategies in system of agent collective Kellinghusen with different network sizes (each N = 36)

smaller network sizes start at a higher vulnerability level, the trajectories of vulnerability are proceeding quite parallel. Thus, vulnerability reduction seems to be relatively independent from the initial network size. In order to better understand the processes in the differently sized networks, a simulation experiment with different network sizes is conducted in the agent collective Kellinghusen (see Fig. 5.50).

The social network is restricted to the agent collectives, i.e. agents interact on the meso level of the agent collectives, not on macro level. In the collective Kellinghusen 9 out of 36 agents have a social network attribute (`network` = 1) based on empirical data. This initial network is changed to a size of 0 agents participating in the network, 9 agents as in the empirical data base, 18 agents or all 36 participating. Again, the vulnerability trajectories proceed quite parallel and reduction seems to be relatively independent from the initial network size. The agent collectives with a smaller network size also start at a higher vulnerability level at the beginning, but the trajectories run parallel until the 25th time step.

Variations in the initial network size seem to have no considerable effect on the system development. In order to understand the trajectories, the number of accepted strategies for each time steps is mapped over the simulated time period and under different network size assumptions. In Fig. 5.50 the differences with regard to the number of accepted strategies in the system are recorded. According to the model output, the number of accepted strategies each time step is slightly increased e.g. at time steps 6, 7 and 8 due to the bigger network size. Over the simulated time period, the number of accepted strategies increases when the strategies are offered for the second and fourth time. While at these time steps usually those agents accept the strategies that were indecisive (e.g. `p_insurance` = 0.5) in the last offering, i.e. during the first and third offering, now a few additional agents are persuaded. As this mechanism requires a social network attribute, the more agents are connected to the social network, the more indecisive can be persuaded. But comparing the effect of a network with 0 or with 36 agents shows a difference of 2 more convinced agents that applied the insurance strategy in time step 7.

For explanation of the small differences concerning network size it has to be taken into account, that during the simulation run the network size changes dynamically. Due to the positive agent decisions to attend informative events (`p_information`), agents connect to the social network. In the case of the agent collective Kellinghusen, the network size increases from 9 to 10 after the first time step and to 24 after the 5th time step due to the acceptance of the information strategy. As only those agents can persuade others that already applied the strategy, not the initial size of the network but the preference for the information strategy and other strategies is important for the system development as it increases the social network *and* the acceptance in the system.

In summary, the vulnerability reduction due to different micro–macro relationships is regarded for the most and the least vulnerable agent groups. Differences in vulnerability reduction can also be observed concerning the micro-macro relationship (see Fig. 5.51). The most vulnerable agent types can decrease vulnerability by a considerable level in the conducted simulation experiments. The greatest difference between the most and the least vulnerable agent types can be identified for agents with/out network and with/out a sufficient information level. The most vulnerable without network and without sufficient information at

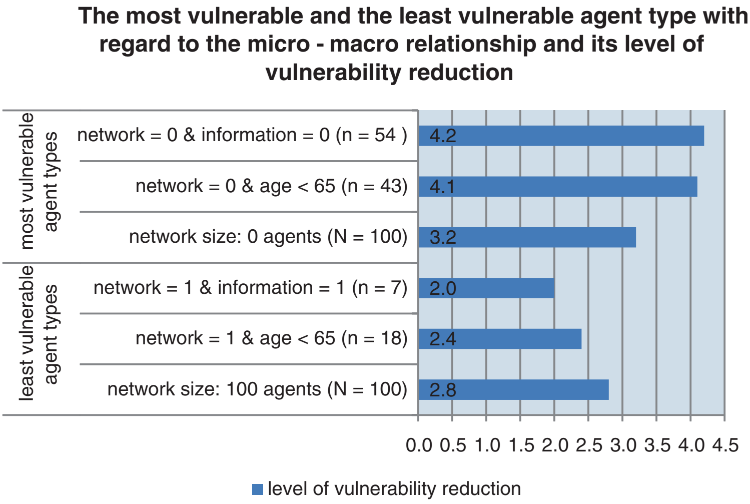

Fig. 5.51 Level of vulnerability reduction of the most vulnerable and the least vulnerable agent types with regard to the micro–macro relationship

the beginning of the simulation run, achieve a reduction in vulnerability that is twice as high as the level reached by the least vulnerable group. In this simulation experiment it could be shown that the most vulnerable agent type at the beginning is not necessarily the most vulnerable at the end due to its preferences for self-protection. Also in case of the agents with/out network and an age of <65 years, the most vulnerable agent type benefits during the simulation run and reduces vulnerability by a level of 4.1. Although the most vulnerable agent types build a majority in the agent system at the beginning, the levels of vulnerability reduction can now positively affect the system development. The underlying mechanisms of these results were already explained in the description of the simulation experiments. By considering the most and the least vulnerable groups concerning network size, the difference in vulnerability reduction is smaller with only 0.4. The small difference in the level of vulnerability reduction in the system with 0 agents and 100 agents initially participating in the network can be explained in so far, the reduction in vulnerability by getting access to a network is not counted, i.e. the information strategy has less positive effects for this agent group of 100 agents with network.

5.4.5 Further Simulation Experiments

In order to analyse the influence of the individual vulnerability attributes on the system's trajectories, further micro level variables are selected for simulation experiments. The vulnerability attribute `experience` is tested according to its

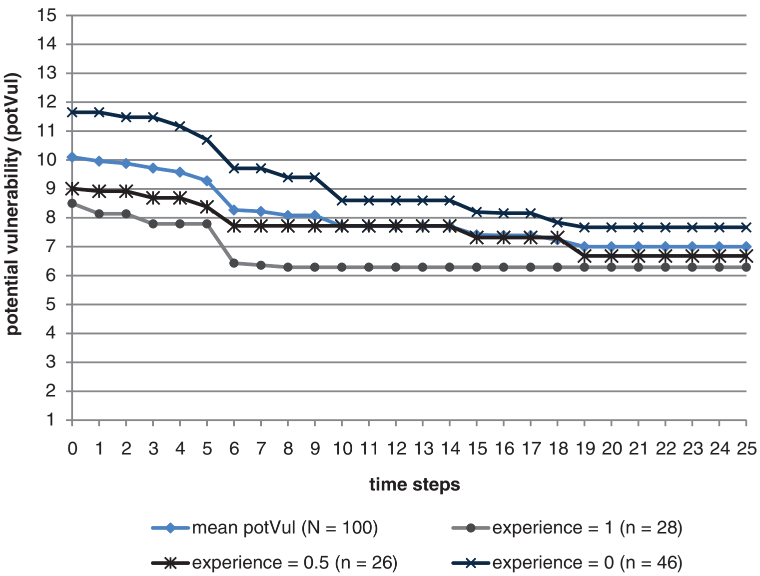

Fig. 5.52 Vulnerability trajectories of agent system with different experience values in comparison to vulnerability baseline (N = 100)

influence on the trajectory. In comparison to the other simulation experiments, the resulting trajectories here converge towards the end of the simulation run (see Fig. 5.52). Although the different agent types start at a different vulnerability level at the beginning of the simulation, at the end of the simulation this difference has been reduced from 3.1 to 1.3. This approximation of the trajectories has been achieved mainly due to the reduction of vulnerability of the agents without experience (`experience` = 0; n = 46). This agent type manages to decrease its vulnerability level from 11.6 to 7.6, i.e. by a level of 4. Agents that experienced floods/storm surges more than once, approach only a vulnerability reduction of 2.2 (`experience` = 1; n = 28). The agent type with less experience (`experience` = 0.5) reaches a similar reduction by a level of 2.3. According to the model rule, agents without experience accept the insurance strategy in comparison to the other agent types due to the negative correlation, explaining the higher reduction of vulnerability in the first group. All trajectories converge between a vulnerability level of <8 - >6.

By further simulation experiments with the vulnerability attribute information other dynamics of vulnerability can be explored. The simulated trajectories of agents with (`information` = 1; n = 31) and without (`information` = 0; n = 69) sufficient information about flooding and possible prevention measures are compared to each other and to the mean potential vulnerability trajectory (see Fig. 5.53). An interesting effect can be observed regarding the vulnerability trajectory. Those agents without sufficient information, thus starting on a higher potential vulnerability level (10.4) end up on a lower vulnerability level (6.7) than the

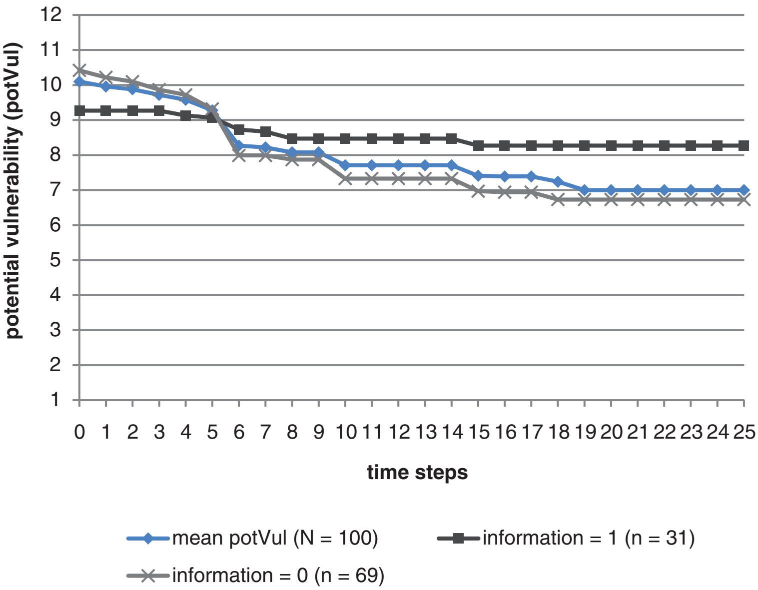

Fig. 5.53 Vulnerability trajectories of agents with different information values in comparison to vulnerability baseline (N = 100)

other agent groups regarded in the simulation experiment. Agents with sufficient information start at a vulnerability value of 9.2, stagnate at a level of 8.2 and fail to achieve the mean level of potential vulnerability (7.0). Meaning that, agents with sufficient information about flooding and prevention measures at the beginning of the simulation react more reluctant during the simulation run.

As the attribute `information` = 1 leads to a rejection of the information strategy `p_information` (see Sect. 5.3), the agents' vulnerability level is merely reduced by 1.0 during the simulation run (see Fig. 5.53). Due to the correlation, only those agents accept the strategy that have a preference for the strategy `p_information` and an `information` value of 0.[4] In this case, sufficiently informed agents are not attracted to this strategy and vulnerability reduction.

The vulnerability attribute `attitude` is also tested according to its effect on the vulnerability trajectory. Do agents considering self-protection measures as effective (`attitude` = 1) differ in their vulnerability trajectory from agents regarding measures as ineffective (`attitude` = 0) or are they rather uncertain (`attitude` = 0.5)? Only 17 agents consider self-protection measures as effectively reducing their risk at the beginning of the simulation run (see Fig. 5.54). According to the trajectory, they start on a moderate vulnerability level of 8.1 and

[4] Also those agents that are not sure about being sufficiently informed are classified with the value information = 0.

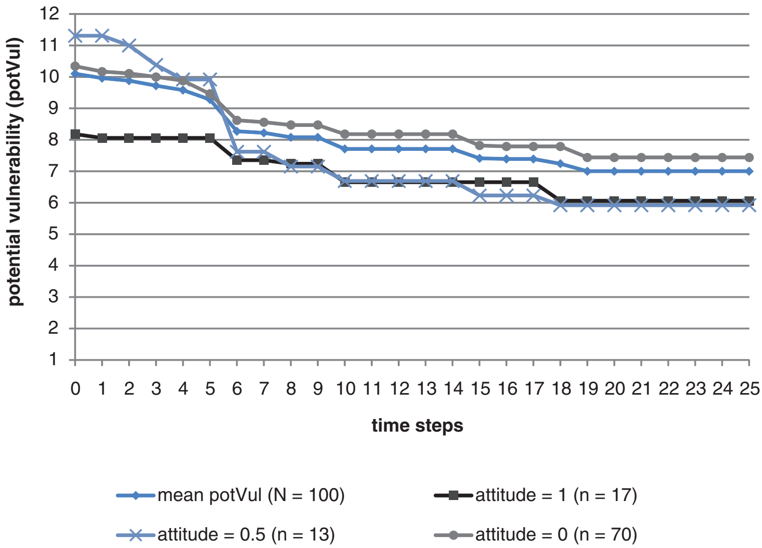

Fig. 5.54 Vulnerability trajectories of agent system with different attitude values in comparison to vulnerability baseline (N = 100)

manage to reduce it by 2.1 on a stable vulnerability level of 6.0. Those agents considering self-protection measures as ineffective (n = 70) start on a vulnerability level of 10.3 and reduce it to 7.4. This difference of 2.9 in vulnerability level still keeps them on a comparable level to the baseline trajectory. The decisions for better self-protection changes the agent's attitude and vulnerability.

The type of agents unsure about the effectiveness of self-protection measures achieves the highest reduction in vulnerability and diminishes by a level of 5.3. The 13 agents reduce vulnerability from the highest level at the beginning (11.3) to quite the same level as the agents with a positive attitude towards self-protection measures after 25 time steps (5.9). Thus, in this experiment the uncertainty with regard to this vulnerability attribute proves to be favourable for the vulnerability trajectory. The reduction of vulnerability is mainly achieved in the first 2 years (10 time steps) of the simulation experiment and thus can be regarded as a positive temporal aspect of this characteristic value.

Furthermore, the influence of the already implemented `measures` by the agents is tested (see Fig. 5.55). Although without intersecting trajectories as in the last experiments, the vulnerability trajectories also converge towards the end of the simulation run. The difference in the vulnerability level between agents with measures (`measures` = 1; n = 53) and those without measures (`measures` = 0; n = 47) at the beginning of the simulation run amounts to 3.0. The more vulnerable agent type without measures is described by a level of 11.7 at the beginning, the other agent type by a moderate level of 8.6. After 25 time steps the initial difference in vulnerability diminishes to 1.1 between the two agent types. Meaning that during the simulation the less vulnerable agent type reduces to a level of 6.4,

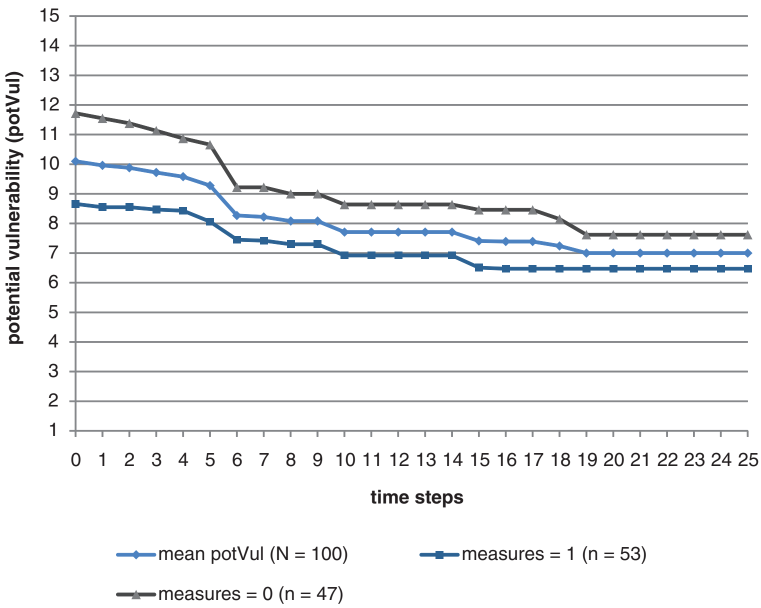

Fig. 5.55 Vulnerability trajectories of agent system with/out measures in comparison to vulnerability baseline (N = 100)

whereas the other agent type without measures at the beginning manages to reduce to a stable vulnerability level of 7.6.

Thus, the final difference in vulnerability between the trajectories only accounts for 1.1. A major decrease in vulnerability is achieved between the 5 and 6th time step in case of the agent type without measures at the beginning. The other agent type reduces vulnerability more constantly until it reaches its stable state. However, these agents achieve a stable low vulnerability nearly a year earlier, i.e. 4 time steps than agents without measures at the beginning.

A simulation experiment (see Fig. 5.56) regarding the vulnerability attributes `measures` and `assets` reveals that about 42 house owners have already taken self-protection measures (`assets` = 1 & `measures` = 1) in comparison to 33 house owners without self-protection measures so far (`assets` = 1 & `measures` = 0). The former agent type can be described by a moderate vulnerability level of 8.0 that is reduced by 2.3 over the simulated time period, ending on a level of 5.6. All other agent types in this simulation experiment stay above the mean level; yet they achieve a relatively high reduction of vulnerability due to the agent decisions. Especially the agent types without measures obtain a decrease in vulnerability during the simulation run: home owners with no measures so far by a value of 3.7 (`assets` = 1 & `measures` = 0) and the small group of agents (n = 14) characterised as tenants without measures (`assets` = 0 & `measures` = 0) even by 4.8. Both agent types drop from a vulnerability level of 11.3 and from 12.5 to a level of 7.5 and 7.7.

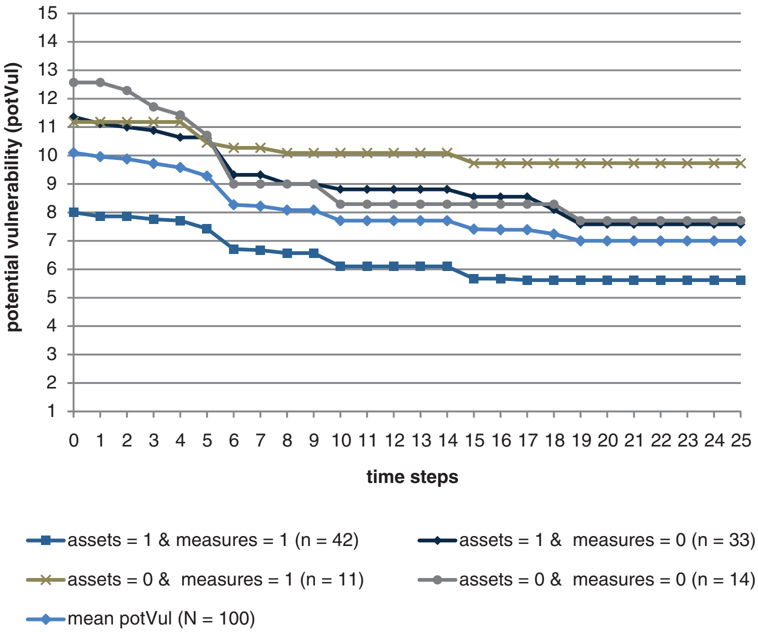

Fig. 5.56 Vulnerability trajectories of agent types with/out assets and with/out measures in comparison to vulnerability baseline (N = 100)

Thus, in particular in case of tenants without measures so far the change of mind has very positive effects on the agent's vulnerability trajectory. Tenant agents with measures (`assets` = 0 & `measures` = 1) also stand out regarding their trajectory. Starting with a vulnerability level of 11.1 they achieve to reduce vulnerability merely by a level of 1.4. They stagnate on a level of 9.7 already after 15 time steps. This small group of agents (n = 11) gets inactive after a short time period and the applied measures, probably due to their satisfaction with applied measures.

Further socio-structural variables of the agents can be included in the simulation experiments. In Fig. 5.57 the influence of age and household size is compared to the baseline vulnerability in the agent system. Elderly in single-person households might be regarded as a very vulnerable group. According to the simulation trajectory this type of agent (n = 10) accounts for 10 % of the whole agent system. Independent of age, both agent types reduce their vulnerability level by about 2.4–2.6. Though, single-person households below 65 years old (n = 11) start at a significant lower vulnerability level at the beginning and stagnate on a low vulnerability level of 5.7. The final vulnerability level of the elderly agents reaches a stable state at approximately 9. After 7 time steps only, agents stagnate and do not further reduce their level as the younger agent group or as in the baseline trajectory. Further influence is needed in order to re-activate the preventive behaviour of this vulnerable group; offering of strategies has no effect anymore.

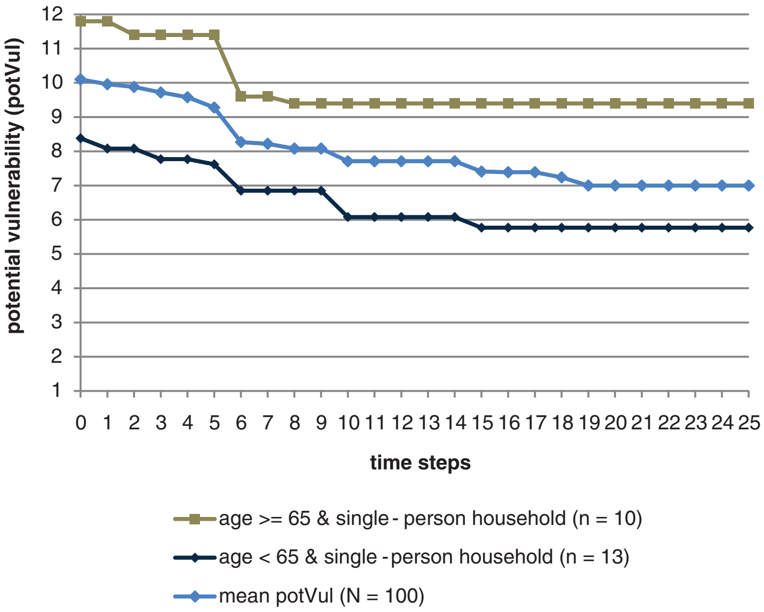

Fig. 5.57 Vulnerability trajectories of agents </≥65 years old in single-person households in comparison to vulnerability baseline

The level of vulnerability reduction regarding the described vulnerability attributes in this experimental set is summarised in Fig. 5.58 and categorised into the most and the least vulnerable agent types. For nearly all attributes considered in the experimental set, i.e. experience, information, attitude, measures, assets & measures, the (initially) most vulnerable types of agents succeeded most in reducing vulnerability except for the attribute age & single-person household. The other most vulnerable types achieve a decrease in vulnerability that is approximately twice as high as the decrease of the least vulnerable agent types. Agents with a low level of information (n = 69) at the beginning of the simulation for example benefit from the self-protection strategies and reduce vulnerability by a level of 3.7, in comparison to agents with information (n = 31) that only approach a decrease of 1.0 (see Fig. 5.58). These differences result in particular from the positive effects of and correlations with the information strategy (see further Fig. 5.53). Due to the considerable size of this agent group without information, the reduction can be regarded as a very positive influence for the system development.

No differences can be observed concerning the attribute age & single-person household. In this case, both agent types diminish vulnerability by a level of 2.4 and 2.6. Also after the decision processes, the more vulnerable single-households of elderly people are still more vulnerable. As single-person Shouseholds account for 23 % of all households included in the study (n = 23), the low level of vulnerability reduction in the simulation experiment can underline the importance of this group in risk communication, in particular with regard to the elderly.

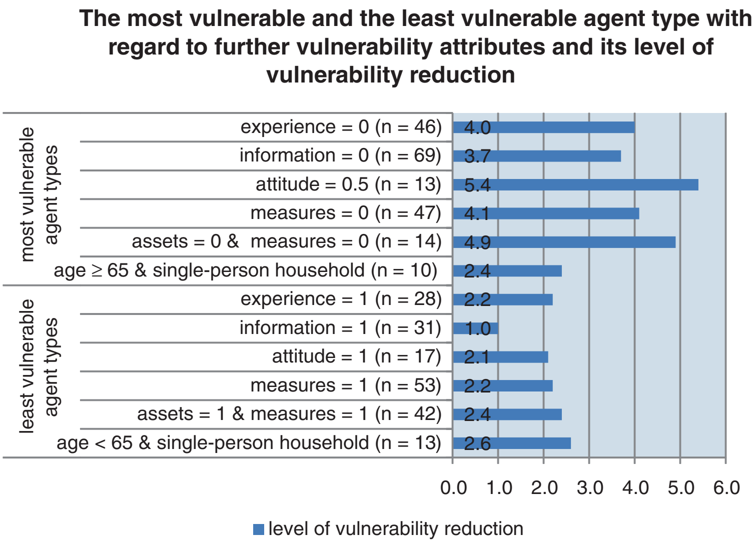

Fig. 5.58 Level of vulnerability reduction of the most vulnerable and the least vulnerable agent types with regard to further vulnerability attributes

The empirical study revealed that most respondents (n = 70) did not consider self-protection measures as effective (see Sect. 5.2). Yet, in the simulation experiments this agent type decreased vulnerability by a level of 2.9 (`attitude` = 0). In comparison, agents with a positive attitude towards self-protection measures at the beginning of the simulation reduced vulnerability by 2.1 (`attitude` = 1; n = 17). In this experiment the agent type that was still indecisive at the beginning of the simulation (`attitude` = 0.5; n = 13) benefited most from the self-protection strategies. This small group of most vulnerable agents reaches the highest level of vulnerability reduction—by 5.4—in the conducted simulation experiments. Thus, the vulnerability attribute `attitude` turned out to be relevant in the empirical study (see Fig. 5.15) as well as in the simulation experiments. Furthermore, it can be recognised that the most vulnerable agent types without experience (n = 46) and without already implemented measures (n = 47) are able to reduce their vulnerability level by 4.0 and 4.1. As both groups are of considerable size, the decrease can be regarded positive for the overall system development.

The third research question focused on possible vulnerability trajectories that might evolve in the system based on heterogeneous agent profiles and self-protection preferences. The results of the simulation experiments highlight, that by exploring vulnerability under different levels of analysis the various dynamics of the social phenomenon can be observed. The trajectories demonstrate that the micro level, the human-environment relationship and the micro-macro-relationship can be regarded as relevant for the system development. Differences concerning agent vulnerability attributes, self-protection preferences and relationships can result in very different vulnerability trajectories over the simulated time period in the model system. However, these differences become only evident when considering individual, relational and spatial aspects influencing vulnerability dynamics (see Sect. 3.2.2). During the baseline simulation run (see Sect. 5.4.1), all dimensions of vulnerability affect the system development. The simulation experiments allow focusing on the respective dimension of vulnerability and facilitate further understanding of the influences inside the system. Thus, the experiments should be understood as a possible tool to simulate and explore the detailed dynamics that can characterise multi-dimensional and context-sensitive social phenomena.

5.5 Model Verification and Validation

Model development and model validation are regarded as subjective processes (Bossel 2004, p. 62; Janssen 2002, p. 399). Küppers and Lenhard (2005) reflect the different meanings of validity in the natural and social sciences and conclude that the very meaning of validity is dependent on the purpose of the simulation. Also Sargent (2005, p. 130) states that a “model should be developed for a specific purpose (or application) and its validity determined with respect to that purpose”. Acosta-Michlik and Rounsevell (2009, pp. 165–67) argue that models that seek to explore future scenarios, as in this approach with regard to vulnerability dynamics, are impossible to validate completely.

Summarised in the epistemological framework of the research (see Sect. 2.1), the purposes of the developed agent-based model approach are: to reconcile risk/vulnerability approaches from different disciplinary perspectives with the agent concept for conceptual model development, to investigate the detailed dynamics of the considered system based on empirical data and to derive methodical and conceptual implications of the approach for risk and complexity research. Thus, the validity of the model here will be outlined with regard to these purposes of the developed approach. Sargent (2005) identifies four verification/validation techniques or steps in the model development process: conceptual model validation, computerised model verification, operational validation and data validity. Model verification in fact is a debugging step; it is checked if the model is correctly implemented and is working as intended whereas validation means ensuring that the behaviour of the model does correspond to the behaviour of the target (Gilbert and Troitzsch 1999, p. 22; Troitzsch 2004).

In the first step, the conceptual model has to be validated, meaning to test whether theories and assumptions underlying the conceptual model are correct and the model representation of the system under study or phenomenon is “reasonable” for the intended purpose of the model (Sargent 2005, p. 132). Here, the conceptual model has been developed according to an extensive analysis of the system under study by considering the theoretical and the regional research framework (see Chaps. 3 and 4). Furthermore, the applicability of the developed conceptual model has been tested based on 12 exemplary risk/vulnerability frameworks (see Sect. 5.1). According to the conceptual model purpose, the risk/vulnerability approaches from different disciplinary perspectives (see Sect. 3.2.3) were reconciled with the agent concept (see Sect. 5.1). The regional research framework (Chap. 4) was analysed in order to develop a reasonable regional adapted model of vulnerability (see also Sect. 5.1). It focused on the model purpose to investigate the detailed dynamics of the system under study based on empirical data. The specification of the scope and scale of assessment to the regional context allowed equipping the model with empirical data in a further exploratory step (see Sects. 2.4.1, 5.2 and 5.3).

Computerised model verification is described in Sargent (2005, p. 132) as testing whether the computer programming and implementation of the conceptual model is correct. As no random values or elements are implied in the model, model verification here could be realised based on the empirical data. The calculation of vulnerability profiles during model initialisation, the correct scheduling of strategies and decision processes, etc. was checked against the empirical data and on basis of the defined model rules.

The operational validity, i.e. whether the model's output behaviour has sufficient accuracy for the model's intended purpose, is tested in the different simulation experiments (see Sect. 5.4). The model purpose to investigate the detailed dynamics of the considered system could be realised by various simulation experiments. Hereby, the dynamics of vulnerability are investigated by focussing on different influences such as the self-protection preferences, the human-environment relationships etc. The simulation experiments allowed exploring different vulnerability trajectories according to the third research question. The analysis of the system behaviour is based on theoretical assumptions about the importance of spatial, individual and relational aspects influencing vulnerability over time (see Sect. 3.2.2).

To further test the data validity, one has to ensure that the data necessary for model building and conducting the model experiments are adequate and correct (Sargent 2005, p. 132). As already mentioned before, the specification of the scope and scale of assessment to the region, allowed equipping the model with necessary empirical data about agent vulnerability. Furthermore, the empirical calibration of the computational model, in particular the self-protection preferences of the households could be used to represent decision processes of agents affecting the vulnerability dynamics. Also the time frame of the model is derived from empirical values of the survey data. On basis of the own empirical data set, further statistical analyses were carried out to provide adequate model rules. Considering the behavioural rules of the agents, the statistical significance of correlating vulnerability attributes was tested and applied in the model. Thus, the empirical data could be used in order to develop independent parameters, control parameters for model processes and dependent parameters for assessment of model behaviour (see Sect. 5.3).

As said at the beginning, it is impossible to completely validate models that seek to explore future scenarios (Acosta-Michlik and Rounsevell 2009, pp. 165–67). During the simulation run, the preferences of the agents are implemented into positive or negative decisions towards the self-protection strategies. Although the condition-action rules are derived from empirical data and backed up by statistical analyses, the simulation constitutes a process-tracing of the social phenomenon of vulnerability that is prospective; and hence it cannot be validated on real-world data.

The simulation runs allow an exploratory analysis of system trajectories and system interdependencies with regard to vulnerability dynamics; yet they produce synthetic data based on (observational) preferences of households in the case study region.

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Chapter 6
Reflexion

Under consideration of individual, relational and spatial aspects of vulnerability, the social simulation explored the dynamics of vulnerability in the coastal zone of Germany. The exploratory assessment of vulnerability by means of an ABM might in the first way be considered as a methodological approach. But the agent concept (see Sect. 2.3) offers also a conceptually different approach for vulnerability assessment as it implies "thinking in complexity" (Mainzer 2007). Complexity theory builds the theoretical foundation of agent-based modelling (see Sect. 2.2) and introduces the reader to systems thinking and key properties of complex systems. By using the schema and vocabulary of complex systems research for analysis, the research target of vulnerability can be assessed with regard to dynamics, relationships, feedback and interaction effects. Thus, the theoretical foundation and implications of the developed agent-based simulation (ABS) of vulnerability dynamics might facilitate a different perspective on the research target also conceptually (see Sect. 6.1). The implications for risk research by an agent-based vulnerability assessment are explained in more detail in Sect. 6.2. It focuses on the agent-based simulation as an approach to investigate the detailed vulnerability dynamics of the system under study and as an integrating tool to consider various risk/vulnerability approaches for model development. The next two chapters focus on the fourth research question; they comment how the conceptual and methodological transfer contributes to complex systems research and risk research in the coastal zone. The reflexion ends with concluding remarks (Sect. 6.3).

6.1 Relevance (of the ABS) for Complex Systems Research

According to complexity theory, the research interest lies in the understanding of how the elements interact with each other to form the system itself. The considered system is characterised by vulnerability that derives from the agent (micro) level. In the developed agent-based simulation the vulnerability decreases over time due to the acceptance of self-protection strategies on that same level (see Fig. 5.24).

C. Sobiech, *Agent-Based Simulation of Vulnerability Dynamics*, Springer Theses, DOI: 10.1007/978-3-642-32365-2_6,

However, observation on the macro level by the variable state of acceptance cannot completely explain the varying vulnerability reduction in the system (see Sect. 5.4.1). With regard to the dynamics of vulnerability, other factors describing the micro level of agents, behavioural strategies as well as relationships were explored in the simulation experiments. By conducting simulation experiments, further details of the processes inside the system leading to the dynamics of vulnerability have been revealed. The simulation results illustrate that heterogeneous agent attributes and preferences, autonomous agent decisions as well as different human-environment and micro–macro relationships can influence the system development (see Sect. 5.4). The agent-based simulation allowed tracing the process of vulnerability reduction and assessing how agent actions, interactions and feedback effects form and alter the system development. Thus, the simulation also emphasises the importance of social dynamics for the whole system development.

Complex systems research is about how systems evolve; by so-called trajectories the changes in the system can be described over time (see Sect. 3.1.4.2). The vulnerability baseline trajectory of the ABM (see Fig. 5.24) showed how the vulnerability on macro level decreases in the system over the simulated time period. By comparing agents with differing preferences for the self-protection strategies the model revealed further possible system trajectories (see Sect. 5.4.2). The simulation experiments facilitated to explore the system behaviour under different (initial) conditions[1] and over the considered time period. The self-protection preferences of the agents are important for the system development as the offered self-protection strategies can “attract” the system to less vulnerable states over time. As a result, less vulnerable groups of agents evolved in the model. The self-protection strategies represent an attractor comparable with the example of political parties which attract votes and thus represent attractors (Mainzer 2008, p. 95). Whereas for the recognition of attractors a phase portrait of the system and its dynamics is necessary (see Mainzer 2007, p. 377), here only observations about a relatively short system development are possible. In consideration of these restrictions, however, it could be observed during the simulation that agents with preferences for three or four strategies were attracted to lower vulnerability levels/states over the simulated time period than agents with less or without such preferences (see Fig. 5.36). The influence of the attractor(s) was explored again by simulation experiments. It allowed comparing the decrease of vulnerability between different agent groups over the short-term system development, e.g. between agents with two preferred strategies or with heterogeneous vulnerability profiles (Sect. 5.4.2).

The mechanism leading to dynamics of vulnerability in the first experimental set (Sect. 5.4.2) are the decisions of the agents. The system’s vulnerability changed during the simulated time period as a consequence of positive agent decisions towards better self-protection strategies (Sect. 5.3). The changes in the system thus resulted from individual decisions. But they can lead to a further positive feedback

[1] Although agents can persuade other agents in the course of the model, all preferences are derived from empirical data and read as behavioural rules at the beginning of the simulation.

mechanism in the system, i.e. that the change tendency is amplified. Agents with positive decisions towards self-protection can persuade other agents and thus amplify the change tendency towards better self-protection, but in the considered system merely weakly. The positive feedback loop functions only inside the local agent collectives and over the relatively short system development. As indecisive agents rather represent a small part of the agent system, the feedback effect occurs not very often, e.g. in the insurance strategy and it could be shown in the simulation experiment with changing network sizes (see Fig. 5.50). Furthermore, a negative feedback mechanism can change the dynamics of the system under study. The lack of awareness increased during the simulation (see Table 5.9) as the time period between the last events in agent memory and the reference year (2011) of the model increases.[2] The negative feedback mechanism results in a further time delay of the scheduling and thus in the dissemination of self-protection strategies in case of the sample of Münsterdorf (Sect. 5.3). Although the simulated time period is not able to show long-term system development, the influence of short-term feedback effects affecting only small parts of the whole system could be regarded in the developed ABM.

Due to the connectivity in complex systems, every change in the relationships between elements or between the agents and their environment can result in different system behaviour (see Sect. 3.1.2). Complex systems research reminds us to focus on these connections and relationships in systems. Thus, various simulation experiments were conducted to test the influence of the human-environment relationship and the micro–macro relationship in the agent-based system (see Sects. 5.4.2, 5.4.3). By comparing the vulnerability baseline trajectory (see Sect. 5.4.1) with the trajectories resulting from differing relationships, the sensitivity of the system to these relationships could be demonstrated. It could be shown that a favourable human-environment relationship can lead to different system trajectories (see Sects. 5.4.2, 5.4.3). A favourable human-environment relationship, i.e. with low lack of awareness values and trust values results in a quicker vulnerability reduction over the simulated time period as shown in the agent sample of Kellinghusen (see Fig. 5.39). A relative effect of a favourable human-environment relationship on the level of vulnerability reduction occurred also concerning the agent attributes evaluation, perception and expectations (see e.g. Fig. 5.46). The vulnerability reduction of agents with risk perception and evaluation and in particular of agents expecting an increase of risk in the future is higher in comparison to agent types without such attributes.

In the same way, also for the micro–macro relationship, different experiments were conducted that demonstrate the importance of focussing on relationships in systems. The micro–macro relationship of agents determines the agent's social interaction and might lead to increased acceptance of self-protection measures

[2] Whereas the positive feedback effect depends on local relationships inside the model, i.e. between the agents in their collectives, the negative feedback effect depends on the temporal relationships inside the model, i.e. based on the simulated time steps.

by persuasion. The micro–macro relationship had a lower impact on the system's dynamics than the human–environment relationship and the preferences for self-protection strategies. The simulation experiments conducted with regard to the micro–macro relationship showed that the initial network size at the beginning of the simulation is not of major importance (see Sect. 5.4.4). Yet, the simulation experiments exploring the micro–macro relationship revealed, regarding the level of vulnerability reduction, that the most vulnerable agent types at the beginning are not necessarily the most vulnerable at the end (see Fig. 5.51). Concerning the human–environment relationship, this effect could not be observed over the simulated time period.

A system cannot be fully understood as a whole by simply analysing its elements (properties) (Cilliers and Preiser 2010). Behaviour is not always possible to be explained by a single dominant cause such as in the case of a billiard ball moving due to the impact from the cue ball (see Sect. 3.1.5). By varying the conditions of the simulation run, it was possible to explore the effects of different relationships and attributes on the vulnerability trajectories. The developed ABM allowed assessing how relationships and interactions in systems as well as individual behaviour can either facilitate or constrain changes in the system properties. By considering different levels of analysis, the possible processes and interactions inside the system leading to a vulnerability reduction were simulated. For analysis of behavioural complexity, focus should be on the relationships and interactions—as they are relevant for system dynamics and behaviour changes (see Sect. 3.1.3). The simulation experiments thus provided various answers to the third research question about possible vulnerability trajectories evolving in the considered system.

Other than in many physical systems, the interconnections between the elements in social systems are not physically visible. Yet, by means of the ABS experiments, the relationships and interactions were made more comprehensible by the resulting system trajectories. In case of different perceptual thresholds in the agent collectives vulnerability reduction was delayed due to a rather unfavourable human–environment relationships, e.g. in the sample of Borsfleth. Another important capacity in social systems is that individuals contain (subjective) representations of processes inside the system. By implementing subjective aspects of risk handling in the model, the simulation tried to emphasise the relevance of a subjective and contextual representation of the environment. The decision processes were considered as contexts influenced by perceptual, individual and relational aspects of the agents (see Fig. 5.21). In this way the ABM respects that different perceptions of reality can result in different behavioural patterns (Sect. 3.1.5). Not only with regard to complex systems research, but also with regard to socio-ecological approaches, the ABM enables to look at the human–environment relationship, not solely at the environment as a physical space per se.

The simulation method enabled a prospective process tracing of vulnerability. The simulated time period is not able to show long-term system development, only the short-term system development can be explored in the developed ABM. Therefore, the simulation cannot show a whole phase portrait of the system in order to recognise bifurcations state changes and nonlinear behaviour (Sect. 3.1.4.2). Other than in retrospective analyses, where possible states might be identified by analysing e.g. the historical processes or phases since World War I (see Mainzer 2008, p. 97). In this approach the status quo of vulnerability in the reference year is known, i.e. at the beginning of the simulation. But it allows exploring possible system trajectories resulting from the empirically based preferences, attributes and relationships. The simulated system development can be regarded as one state that started by introducing self-protection strategies at t = 0 and the levels of vulnerability stabilise over the 25 time steps. By “stimulating” the system with self-protection strategies, the observed dynamics were achieved, yet after the 25th time step the state of vulnerability reduction cannot be changed anymore under the assumed system conditions. Further stimulations would be necessary to keep the system in a change process, e.g. by changing the control parameter.

The system under study can only simulate an extract of the complex social world. It is reduced to the degree of accuracy needed for the scope of the assessment. But the simulation approach emphasises the importance of understanding interrelations for the system’s development. Thus, the agent-based vulnerability approach is looking at the issue in another way; in a more context-sensitive and dynamic way. The ABM aimed at exploring the detailed dynamics of the system under study by focusing on different levels of analysis in the simulation experiments. ABMs emphasise the importance of the micro dynamics for the macro dynamics (see Fig. 3.1). Hereby, the approach also emphasises on outliers—from a statistical point of view—as they might follow a very different trajectory. Pyka and Grebel (2006, p. 24) argue that ABMs “aim at the isolation of critical behaviour”, in this approach it aimed at the critical behaviour affecting vulnerability. The conducted simulation experiments focused on depicting the agents, their relationships and the processes governing the transformation towards a less vulnerable system. Yet, a considerable reduction of vulnerability or a “culture of prevention” can only *emerge* from a combination of individual preferences, favourable human–environment relationships and further interactions inside the system as shown in the example of agents that prefer all four self-protection strategies (see Fig. 5.36).

6.2 Relevance (of the ABS) for Risk Research

Agent-based modelling approaches can show how collective phenomena come about and how the interactions of the autonomous and heterogeneous agents lead to the genesis of these phenomena (Pyka and Grebel 2006, p. 24). Here, the ABM approach aimed at the social phenomenon of vulnerability. The developed ABM included the perceptual and social context in which decisions are taken, and the subjective (e.g. awareness, trust in official risk management, risk evaluation) and objective (e.g. exposure, occurrence of event) aspects that may influence self-protective behaviour and vulnerability of individuals. The developed ABS thus offers to analyse the detailed dynamics of vulnerability—including various dimensions of vulnerability (individual, relational and spatial aspects) and levels of analysis ranging from micro, macro, human to environment as well as the respective relationships and interactions. Whereas the last chapter focused on the relevance of the ABS for the meta-theoretical level of complex system research, the results are now reflected with regard to their relevance for risk research.

For a comparative study about vulnerability in the five communities, it was necessary to make "the un-measurable measurable" (Birkmann and Wisner 2006). Although agents are virtual entities, they are created based on empirical data—from a household survey in the coastal zone of Schleswig–Holstein. The model rules were either directly transferred from empirical data or supported by statistical analyses. The expressed preferences of respondents for self-protection measures were implemented in the model. Besides the preferences, agents act according to their perception of the environment (human–environment relationship). The model served as an observational and experimental apparatus for exploring the prospective process-tracing of vulnerability reduction. It produces a picture of the vulnerability futures in 2015, based on the assumed scenario of disseminating self-protection strategies, i.e. the system is "stimulated" by the dissemination of self-protection strategies to agents.

The model results demonstrated how the vulnerability of the agents decreases while they take their decisions to implement self-protection strategies. The mean potential vulnerability is dropping slowly from 10.1 to the final vulnerability level of 7 (see Fig. 5.26). The vulnerability level is decreased by 0.12 on average each time step over the simulated period between 2011 and 2015; yet in the model the decrease does not occur consistently. From the model trajectory different "phases" of vulnerability reduction can be observed. Transferred to the temporal frame of the simulation run, in the first year (reference year: 2011) vulnerability drops quite considerably. Also in the following years (2012–2014) a reduction of vulnerability occurred, even though more slowly and with a period of stagnation approximately in the year 2013. From the 19th time step onwards (around 2015), the vulnerability level stagnates at the level of 7.0.[3] With regard to the system development the dynamics of vulnerability reduction could be observed: due to the dissemination of self-protection strategies to the agents and the micro dynamics, the vulnerability on macro level also decreases over the simulated time period.

Further inferences for risk research can be made on the macro level considering the state of acceptance of self-protection strategies. By analysis of the model outcome (see Fig. 5.28), the state of acceptance cannot completely explain the varying vulnerability reduction in the system. With regard to the dynamics of vulnerability, other factors describing the micro level of agents, their behaviour and relationships thus were explored in the simulation experiments. Regarding the dynamics of vulnerability, it is essential to know what drives the system towards

[3] The last "phase" of stagnation still was documented in the model results to indicate that no vulnerability reduction can be assessed from this point onwards.

a lower vulnerability level: individual, relational and spatial aspects affecting vulnerability. In order to understand the detailed dynamics in the considered coastal system, the simulation experiments were conducted focusing on preferences for self-protection strategies, human–environment relationship, micro–macro relationship as well as to further individual attributes of agents (see Sects. 5.4.3–5.4.5).

Concerning the individual aspects, the influence of self-protection preferences and agent vulnerability attributes could be observed by means of the ABM. Agents with preferences (e.g. for the information strategy) were able to considerably decrease their vulnerability level in comparison to agents without such preferences. In the simulation, agents preferring the information strategy for example reduced by a level of 5.3 in vulnerability. The empirical study revealed furthermore that a certain percentage of respondents are uncertain about the issue of self-protection. For risk research it might be useful to especially focus on these groups, e.g. for providing more information about the strategies and the advantages (or disadvantages) of implementation. In the model this role is taken over by the social network of agents. In case of the insurance strategy, indecisive agents still were able to decrease their vulnerability level quite considerably (by 3.9). In the model these agents were convinced by other agents that already applied the strategies, i.e. due to a positive feedback effect.

Yet, from a risk research perspective, the implementation of more than one self-protection strategy should be focuses. The aggregated effects of preferences for two and more strategies were explored in the simulation model to see the particular effects of certain combinations. From the resulting trajectories it could be inferred that preferences for three or all four strategies indeed result in lower vulnerability levels. Yet, also the combinations of at least two strategies still lead to a considerable decrease in vulnerability—occurring in 65 of the 100 cases. Thus, for risk research, also preferences for at least two strategies can lead to a considerable decrease in vulnerability (see Fig. 5.37).

Agent-based simulations are concerned with dynamics and change in social systems. The change in the system is driven by individual behaviour; vulnerability decreases while the households decide to implement self-protection measures. Yet, this decision process towards better self-protection of the agents is simulated in the model including the perceptual and social context. Expressed in the agent's micro–macro and human–environment relationships, agents in the model act on local information in their collectives. In order to assess the individual dimension of risk and the wider decision context, bounded rationality and subjective aspects of risk handling played an important role in the development of the ABM. In uncertain situations, i.e. under risk conditions, people decide on the basis of bounded rationality (Mainzer 2008, p. 101). Whereas bounded rationality occurs due to incompleteness, inaccurateness and coincidence in the human cognition of problems and situations (see Ibid. 2008, p. 101).

Considerable differences in the awareness of risk and trust in the official risk management could be identified in the coastal communities. The survey revealed further differences in the vulnerability attributes evaluation of flooding risk and expectations concerning future risk (see Sect. 5.4.3). A comprehensive risk management should also consider these subjective aspects shaping risk conceptions of individuals (see e.g. Tapsell et al. 2010; Bankoff 2001). Hence, the model incorporates subjective aspects, e.g. lack of awareness and trust in the official risk management. These aspects result in a delayed scheduling of strategies. In consequence of the differences in the human–environment relationship, the trajectories in the sample of Büsum indicated a later decrease in vulnerability as in the sample of Kellinghusen (see Fig. 5.39). Due to the high trust and lack of awareness values in the sample of Büsum and even higher values in the samples of Wewelsfleth and Münsterdorf (see Fig. 5.40) the decision processes for self-protection measures were prolongated. The resulting trajectories in the simulation reveal how local conditions and perceptual aspects led to a very different vulnerability development in the agent collectives over the simulated time period. For risk research and management, these differences can only encourage taking subjective aspects into account, as they may decide about the success or failure of strategies for better self-protection of private households. Mainzer (2008, p. 101) as well as Mitchell and Streeck (2009) argue that the results of studies taking bounded rationality into account have to be included in management decisions in order to prevent institutions and authorities from wrong rationality models.

The differences in the communities regarding the last event remembered, e.g. 9 years in Wewelsfleth and 1 year in Kellinghusen (see Table 5.4), observed during the empirical survey were translated into a negative feedback effect during model development. Accordingly, the negative feedback effect in the model led to a further decrease in the decision processes towards better self-protection measures. It reminds us to take advantage of the "window of opportunity[4]", as it slows down the change tendency towards better self-protection with further distance from the last event in the sample of Münsterdorf (see Sect. 5.4.3). The simulation experiments conducted with regard to the social network size (see Sect. 5.4.4) showed that the positive feedback effect has a small amplifying effect on the system change. With more agents participating in the social network, a few more agents could be persuaded and applied the respective strategies (see Fig. 5.50). Ass the network size increases dynamically in the simulation due to the acceptance of the information strategies, the initial network size at the beginning is not as important as assumed. For the convincing of further agents, the model postulates that agents already implemented successfully the respective strategy and that both agents are connected to the same network. Meaning that, besides the quantity of agents in the network the qualitative aspects inside the network have can influence the number of accepted strategies. The model furthermore implies that only indecisive agents can be persuaded.

The experiments conducted with regard to individual, relational and spatial aspects of vulnerability allowed to see possible trajectories in the vulnerability of the social simulation. Under changing initial conditions the trajectories either

[4] Shortly after a disaster the motivation to implement risk reducing measures is higher than with further time distance from the event (see Steinführer and Kuhlicke 2007, p. 97).

drifted apart (see Fig. 5.31), converged (see e.g. Fig. 5.54) or ran parallel to each other (e.g. Fig. 5.42), indicating a rather positive, negative or neutral influence of the considered factor. Some trajectories started at similar levels of vulnerability, some at very different levels. In some trajectories the changes in the vulnerability level occurred right at the beginning of the simulation; some trajectories stagnated at the beginning and vulnerability decreased later in the simulation run (see Fig. 5.39). For risk research these results indicate to consider vulnerability as a dynamic phenomenon, as the social dynamics can lead to considerable differences in the system development. Besides the individual aspects influencing the vulnerability trajectories, also the spatial and relational aspects showed influences, i.e. the human–environment or the micro–macro relationships (see Sects. 5.4.3, 5.4.4). With regard to the simulated trajectories, the agent-based model facilitates to see the various influences of social dynamics on the system development and to explore the range of possible system developments. Regarding the coastal zone of Schleswig–Holstein, the simulation projected the status-quo of vulnerability to the future and traced the changes in the system. For risk research and management, these results can only encourage taking the multiple factors vulnerability (dynamics) into account. Furthermore, it emphasises the importance of the individual dimension of risk, i.e. the way of how people live, think and act. As the combination of factors influences the dynamics of vulnerability and self-protective behaviour, they may also decide about the success or failure of policy strategies for better self-protection of private households. Behaviour is not possible to be explained by a single dominant cause. It is also shaped by the context in which the decisions are taken, proving the context-sensitivity of vulnerability. By the combination of an empirical study important attributes could be identified, such as the attitude towards self-protection measures, which then could be further explored in the simulation experiments concerning the system's vulnerability development.

6.3 Conclusion

Agent-based models "force" the researcher to systematically analyse the system under study as the agents, their attributes and behavioural rules, relationships and interactions are reconstructed in a computer model. The developed ABS aimed at understanding the detailed dynamics of vulnerability in the considered system. The relevance of the approach for complexity science and risk research (see Sects. 6.1, 6.2) could be shown with regard to simulation experiments. The ABM offers a different methodological approach for vulnerability assessment. Yet, not only the simulation experiments, but the whole process of system analysis (see Chap. 5) provided a different, agent-based view on the social phenomenon of vulnerability. The model approach focused on the equivalent consideration of a theory-based conceptual model as well as on the empirical calibration of the computational model.

The examination of vulnerability dynamics has been based on a broad theoretical research framework (see Sects. 3.1, 3.2), whereas the complexity perspective provided the general framework to assess dynamics and behaviour in systems. Agent-based simulations and complexity theory are concerned about dynamics and change in social systems—yet the former constitutes a methodological and the latter a theoretical approach. Chapura (2009, p. 464) characterises complexity theory more as “a meta-theory than a [as] theory *per se*”, providing a schema and vocabulary for analysis. In this approach not complexity itself is the object of research, but complexity theory is used in order to lead to a different perspective on the research target. It requires a translation process in which the language of complexity research is applied to the specific research context. In this research approach the method of agent-based modelling has been applied as a “translator”, i.e. to provide an appropriate epistemological concept (see Sects. 2.1, 2.3) for the assessment of vulnerability dynamics.

In complexity research, the assessment of systems can be related to the structure of a system as in the case of compositional complexity or as in the case of behavioural complexity to the kind of relationships and interactions that are relevant for the behaviour and dynamics in systems (see Sect. 3.1.3). Thus, systems thinking involve besides the description of the system’s structure and boundary, the examination of relationships and the analysis of interrelating processes between the elements, subsystems and between the system and its environment (see Sect. 3.1.2). To develop a complex systems view on the research target of vulnerability and self-protective behaviour, the schema and vocabulary for analysis and tools for assessment (see Sect. 3.1.5) were taken into account. Complexity theory (see Sect. 3.1) and the agent concept (see Sect. 2.3) allowed assessing those features of vulnerability such as dynamics or different levels of analysis (see Sects. 3.2.2, 3.2.3). Based on this theoretical foundation (see Chap. 3), further examination of the social phenomenon by means of an agent-based model approach was possible. Although the model building required a reduction of the real-world phenomenon, the abstraction process here has been handled on the basis of complex systems thinking. Despite this necessary reduction, the assessment of dynamics of vulnerability was possible in an “isolated” model system based on a case study. Yet, the approach can only simulate an extract of the social reality.

The agent concept allowed an integration of different disciplinary perspectives (see Sect. 5.1); making agent-based simulation an interesting “integrating tool” (Sect. 2.1). According to the first research question, different disciplinary risk/vulnerability approaches could be reconciled with the agent concept. In order to assess the dynamics of vulnerability, the identified components of ABM and vulnerability can be combined again in various ways depending on the researcher’s perspective. The developed general conceptual model of vulnerability dynamics (see Sect. 5.1) resulted from the identification of ABM and vulnerability components and can be implemented into an ABS according to the researcher’s perspective as discussed in Sect. 5.1. Here, the general conceptual model served for the assessment of vulnerability dynamics in an agent-based system for the coastal zone of Germany. Hereby, ABM proves to be a very flexible approach applicable with various theories or concepts. Of course also the various indicators for vulnerability assessments (see Sect. 3.2) had to be reduced according to the scope of assessment; but the resulting individual agent is vulnerable in a multidimensional way due to its relationships and various individual attributes. For a descriptive usage of the model, i.e. for investigating the detailed dynamics of the system under study, the model has been further adapted to the regional context (see Chap. 4 and Sect. 5.1).

In this approach two types of relationships influencing the system dynamics and system behaviour were focused: the human–environment relationship and the micro–macro relationship (see Sect. 3.1.2) which were related to the model target of social vulnerability (see Sects. 3.2.2, 6.2). Based on these levels of analysis—micro, macro, human and environment—individual, relational and spatial aspects influencing the dynamics of vulnerability were considered. By using the agent concept, the disciplinary boundaries were "dissolved" and "translated" into relationships found in an agent-based system, e.g. the human–environment relationship or the micro–macro relationship of agents. Although this translation process implies a reduction, this reduction might help focusing on the kind of relationships and interactions that are relevant for the behaviour and dynamics in systems (behavioural complexity).

According to complexity theory, the research interest lies in the understanding of how the elements interact with each other to form the system itself. In ABMs the dynamic relationships between agent actions and interactions at the micro level leading to the emergence of patterns and structures on the macro level of agent system can be explored. In order to assess the detailed dynamics of social vulnerability in the coastal zone, empirical input data was used in the computational model. By assigning agents with empirically based vulnerability attributes and behavioural rules related to vulnerability, it was possible to explore the vulnerability dynamics of the model system. According to the second and third research question, the research approach focused in the empirical study on the agent types concerning agent types and risk behaviour, in the computational model it tested the different trajectories evolving in the system by means of simulation experiments. The empirical study revealed that certain attributes are relevant with regard to the case study region, such as the attribute attitude. Other aspects vary between the communities and might only become relevant under local conditions, e.g. rejection of the incentives strategy that differ between 80 % in Münsterdorf and 19 % in Kellinghusen (see Fig. 5.19). The empirical study allowed to derive these agent types (see Sect. 5.2), transfer them into a computational model with vulnerability attributes and behavioural rules for agents (see Sect. 5.3) and trace the macro level effects of the micro level decisions in a simulation model (see Sect. 5.4).

From a methodological perspective, the bottom-up approach of agent based modelling allowed to explore how system properties evolve from agent interactions. The developed agent-based simulation shows the short-term consequences of the dissemination of self-protection strategies; it allows tracing the process of vulnerability reduction under the assumption of better self-protection measures. The system property of vulnerability is related to the agent attributes as well as to the agent behaviour, i.e. to the decisions to implement self-protection measures. By running the model under different initial conditions and by focussing on relationships and interactions inside the system, the system development could be explored from various perspectives and levels of analysis (see Sect. 5.4). Although the decision process is based on multi-stage condition-action rules, all agent attributes are empirically based and the behaviour rules concerning self-protection were statistically tested before applied in the model. The ABM thus permitted to study how rules of individual behaviour give rise or "map up" to macroscopic regularities (Epstein 2006, p. 4). Yet, a critical aspect of these types of models based on "real" agents is that although individuals have been interviewed, in the ABM households are modelled (see also e.g. Seidl 2009, p. 233). In the questionnaire survey it has been attempted to reduce this problem by addressing the household's decision maker.

The lack of self-protection in Germany and the lack of motivation for self-protective behaviour has been characterised rather as an underlying problem of awareness and perception of the topic (see further BBK 2006; Goersch 2010). By focussing on dynamics of vulnerability—both depending on individuals′ attributes and self-protective behaviour—facilitated a vulnerability assessment that allows further exploration of determining processes, influences and trajectories (see further Birkmann 2006). The developed ABM emphasises that vulnerability is shaped by human self-protective behaviour but also regards individual aspects of the subjective risk concept e.g. awareness, trust and perception. Concerning the consequences, ABMs in a way respect that different perceptions of reality can result in different behavioural patterns (Janssen 2002, p. 407). As self-protection measures are not very common in German (yet), the questions dealing with self-protection preferences were purposely formulated as assumption or scenarios. It intended addressing the operational level (*Handlungsebene*) of the households with regard to self-protection. Based on the empirical data, the short-term consequences of these assumptions for the overall system can be explored by the model results. As each agent represents a household in exposed areas of the selected communities and as the model attributes and rules are calibrated empirically, further implications and inferences about the dynamics and the development of the considered system in the coastal zone of Schleswig–Holstein can be drawn (see Sect. 6.2). Hereby, the agent-based simulation allowed a different vulnerability assessment, namely a prospective process tracing of the dynamics of vulnerability that result from individual risk behaviour. But to what extent can the model results encourage an adaptive risk management?

Adaptive means to continually observe the system's development in order to respond with adequate management strategies (see Sect. 3.1.5); by recognising the amenable key variables and interactions as well as by identifying critical fluctuation or changing conditions, it may help to modify the system trajectory. In the developed ABM, simulation experiments concerning the self-protection preferences revealed that most agents are attracted by the information strategy. Hereby, agents are able to reduce their vulnerability level. But it also revealed that the higher the preferences, e.g. for three or four strategies are, the higher is the decrease in vulnerability. In general, these results emphasise the importance of the individual and of understanding how vulnerability is rooted in the behaviour or action of individuals; yet to regard the individual dimension of risk represents a considerable and challenging aspect in an adaptive (and comprehensive) risk management (see e.g. Bründl et al. 2009; Downing et al. 2006). The decrease in vulnerability in the model system required a consecutive offering/dissemination of self-protection strategies; whereas not the whole system responded immediately with vulnerability reduction as shown in the delayed schedule in certain agent samples (see Fig. 5.39).

The developed ABM emphasises the importance of the detailed dynamics in systems. The simulation experiments showed various influences on the dynamics of vulnerability instead of focusing on single determining factors. Although based on other research methods, also in other approaches no linear relationships could be found e.g. between awareness and protective behaviour or responses of individuals (see e.g. Tapsell et al. 2010; Steinführer et al. 2009). Instead—as shown in the simulation experiments—for a vulnerability assessment the whole context should always be considered: the vulnerability profile of the household, its relationships and the decision context as well as the spatial/local situation. It could be illustrated in the simulation results that differences in the initial conditions can lead to very different vulnerability trajectories (see Sect. 5.4).

The agent-based simulation allows a reflexion of the dynamics on the (macro) system level but the change process can also be traced on the micro level of the households; allowing a reflexion on the individual household level. The empirical study revealed that the majority of the residents in the low lying regions do not feel sufficiently informed or are unsure about self-protection measures (see Fig. 5.7). By further analysis of the empirical data concerning the information strategy it could be followed that e.g. uninformed agents prefer the information strategy. As the acceptance of the information strategy in the model, foster positive feedback effects on the agent profile, e.g. on the level of information, the social network, the attitude towards self-protection strategies it decreases the vulnerability in the agent system. Thus, for changing the condition of self-protection in Germany, the information strategy could be viewed as an attempt to increase the implementation of self-protection measures—at least for which many households are open and which could decrease the vulnerability of households in the coastal zone by behavioural measures (see Sect. 3.2.4). In comparison to the information strategy preferred by 51 % of the households in the empirical study, the preferences for the self-protection strategies insurance and incentives accounted for 33 % and 37 %. Migration was only preferred by 13 %.

The simulation showed that the iterative actions of agents can change the system trajectory. But the simulation experiments imply that vulnerability should be *understood* as a context-sensitive social phenomenon, as different individual self-protective behaviours can drive the system into different trajectories of vulnerability. More importantly, vulnerability should be *assessed* as a context-sensitive and dynamic phenomenon. By changing the levels of analysis and by prospective process tracing, the simulation can help to find critical initial conditions leading to very different vulnerability trajectories. And it could be observed that the most vulnerable agent type of today must not necessarily be the most vulnerable tomorrow, e.g. in the experiments conducted with regard to the micro–macro relationship.[5] The simulation revealed that also "subjective"thresholds have to be overcome—and that these require further knowledge of the local conditions as they vary considerably in the five communities. Agent households in the sample of Kellinghusen for example benefit from lower vulnerability values at the beginning and relatively high preferences for self-protection strategies, but also from low lack of awareness and trust levels with regard to the official dike protection. It is the combination of individual factors and the human–environment and the micro–macro relationships that lead to the emerging of a "prevention culture", as it could further be shown in case of agents affecting all four strategies (see Fig. 5.36). An adaptive risk management thus should refer to these individual, relational and local aspects, as it might help to positively affect the system trajectory. The developed ABS demonstrated that vulnerability can be assessed including its dynamic and context-sensitivity and emphasised the role of individuals and cross-level effects for vulnerability reduction in society.

The development of the simulation model, allowed including various dimensions of vulnerability and levels of analysis into the agent concept. The results discussed in Sect. 5.4 are based on simulation experiments. By running the model, agents take decisions and interact on the micro level. The ABS facilitates to trace the process of autonomous and heterogeneous agent behaviour and decisions affecting the macro system level. For the understanding of vulnerability it offers a processual investigation of the social phenomenon in the agent system. Besides this processual perspective, the simulation experiments can be changed according to the selected level of analysis, e.g. the individual, relational or spatial aspects of vulnerability. Due to the connectivity of the system in particular relationships, e.g. between agent and environment can be modelled. Furthermore, it allows both—zooming into the individual level and out to macro system level.

Whereas the model focused on the social dynamics, due to climate change and probable adverse effects on coastal regions also the dynamic changes of temporal and spatial hazard conditions could be further included in more detailed spatial models. The simulation can only represent one possible starting point for more explorative agent-based vulnerability assessments based on empirical surveys. Another way of representing the context in which individuals make their decisions involves role-playing games and companion modelling (see Janssen and Ostrom 2006). In such way models represent a medium for discussion, not for prediction (see further Janssen 2002, p. 408). As we deal with an open social system, the model results can only show possible system trajectories of the considered system in this simulation. While process simulation and ABM can lead to a further understanding of the dynamics in the social complex world, it does not change the unpredictable development of reality. For an adaptive management approach, Geyer and Rihani (2010, p. 187) point out that from "a complexity perspective, there are no final orders, no happy endings and no ultimate resting points.

[5] Even though, only positive effects of the self-protection strategies were included.

Struggle, tension, difficulties and challenges are all a part of the process. They will never go away in human complex systems because they are a fundamental part of what we are. Learning, adapting, uncertain advances and unpredictable mistakes never end". By imitating the change processes and detailed dynamics, agent-based simulation is a necessary tool for developing a complexity perspective. As complex systems research is not providing a justification for doing nothing; it is rather underlining the importance of including a multitude of agents in planning processes and the communication about future development (Ratter 2011, p. 98).

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Appendix

A.1 Questionnaire

1. Which hazard do you consider as most important for your community?
   - ☐ environmental pollution
   - ☐ too much tourism
   - ☐ storm surges and climate change
   - ☐ industry and energy production
   - ☐ river flooding
   - ☐ car and ship traffic
   - ☐ economic decline
   - ☐ other ___________________

   [Only included in the Stör region:]

2. The river *Stör* is a tide dependent river in the coastal lowland of the Elbmarsh region. In the river catchment measures were taken against coastal storm surges as well as against river flooding from the hinterland.

   Do you personally consider the risk of flooding following a storm surge at the coast as relevant or rather river flooding from the hinterland?
   - ☐ storm surges at the coast
   - ☐ river flooding from hinterland
   - ☐ both
   - ☐ don't know

3. How would you evaluate the risk of flooding/a storm surge in your community?
   - ☐ very high
   - ☐ high
   - ☐ medium
   - ☐ low
   - ☐ very low
   - ☐ not at all

4. Do you live in a flood-prone area, i.e. an area that could be flooded in case of a dike breach or due to the failure of flood barriers?
   - ☐ yes
   - ☐ no
   - ☐ don't know

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5. Have you ever personally experienced impacts of a flooding event/storm surge?
 □ yes, once □ yes, more than once □ no

 If YES, when did you experience the last event [year] and what happened [short description]?
 ____
 ____

6. Are you the owner or the tenant of the house/apartment you live in currently?
 □ owner □ tenant

7. Have you (whether owner or tenant) personally taken measures against flooding/storm surges?
 □ yes □ no

8. Considering the following three options of self-protection measures, have you personally applied one or more of these measures? [multiple answers allowed]
 - □ I applied structural measures: e.g. my house is build on higher grounds or without a cellar, doors and windows can be sealed in case of flooding, I decided against the installation of an oil heating system or protected it against flooding, etc. [structural measures]
 namely:____
 - □ I have taken preparations for a flooding/storm surge event and know what has to be done [behavioural measures]
 - □ I hold an insurance policy [financial risk transfer]
 - □ no, none of these measures
 - □ no, I applied other measure(s):________________________________

9. Where did you learn how to protect yourself against flooding/storm surges? [multiple answers allowed]
 - □ from my own experience with flooding/storm surges
 - □ by talking to others affected by flooding (e.g. in citizens initiatives)
 - □ by media coverage (mail circulars, brochures, radio, television, etc.)
 - □ by public informative events (e.g. of the community or of the local water boards)
 - □ I don't know exactly how to protect myself

10. Do you feel sufficiently informed by the local authorities on the occurrence of flooding/storm surges and possible prevention measures?
 □ yes □ no □ don't know

 Please outline your answer____

11. Do you think that you can personally diminish the impacts of flooding/storm surges effectively by self-protection measures?
☐ yes ☐ no ☐ don't know

If YES, by what kind of self-protection measures?
____

12. Do you think that losses due to flooding/storm surges will increase in the future for you personally?
☐ yes ☐ no ☐ don't know

13. Assuming that the risk of flooding/storm surges increases in the future, then I would . . . . .
☐ still live here
☐ migrate to less exposed areas
☐ other ____

14. Are you interested in events that inform you about self-protection measures?
☐ yes ☐ no ☐ don't know

If YES: How much time would you spend on it?
☐ one event each month ☐ one event every six months
☐ one event every three months ☐ one event each year

15. Assuming that the risk of flooding/storm surges increases in the future, would you choose to be insured against losses?
☐ yes ☐ no ☐ don't know

16. Assuming that the risk of flooding/storm surges increases in the future, would you implement measures if incentives/subsidies were given by the government?
☐ yes ☐ no ☐ don't know

17. Assuming that the risk of flooding/storm surges increases in the future, to what extent do you agree with the following statement?
"Due to the dike protection in the community no further measures of self-protection are necessary."
☐ I fully agree ☐ I rather not agree
☐ I rather agree ☐ I do not agree at all

18. Which other measures do you consider to be effective in reducing the impacts of flooding/storm surges — here in your community?
   □ dike heightening
   □ better flood barriers
   □ adaptation of land use in flood-prone areas
   □ better self-protection of residents
   □ better scientific findings
   □ better early warning by responsible authorities
   □ other comments: ______________________________

A.1.1 Statistical information:

You are:	male □ female □
You were born in the year:	19__________
Your postcode is:	__________
Since when have you lived in your house/apartment?	________ [year(s)]
How many people live in your household (including you)?	________ [person(s)]
who are ≤ 15 years old:	________[person(s)]
who are ≥ 65 years old:	________ [person(s)]
What is your highest school qualification?	__________

A.2 Characteristics of Survey Locations

Community/ District	Location	Community Size (2010)	Area at risk from flooding	Selected area for survey	Number of valid question-naires	Response rate	Last Event remembered by residents in the year ... (2010)
Kellinghusen/ Steinburg	at tide dependent river Stör, approx. 55 km upstream	7,843	Coastal Flooding: all areas below + 6.5 m GOL based on a bicentenary storm surge event; River Flooding: legally binding flood plain based on a bicentenary flood event (HQ 200)	Streets adjacent to flood plain of the river Stör: Birkenallee, Mittelstr., Brauerstr., etc.	36	20 %	2010
Münsterdorf/ Steinburg	at tide dependent river Stör, approx. 38 km upstream	1,965		Street adjacent to flood plain of the river Stör: Itzehoher Str./Hujer Weg	5	19 %	1962
Wewelsfleth/ Steinburg	at river mouth of the tide dependent river Stör, a tributary of the river Elbe; Wilstermarsch	1,511		Streets adjacent to flood plain of the river Stör: Außendeich, Dammducht, Hollerwettern, Deichreihe, etc.	20	22 %	2002
Borsfleth/ Steinburg	at river mouth of the tide dependent river Stör, a tributary of the river Elbe; Krempermarsch	812		Streets adjacent to flood plain of the river Stör: Büttel, Dorfstr., etc.	7	23 %	1962
Büsum/ Dithmar-schen	at Meldorf Bight, directly located behind the primary North Sea dike	4,984	Coastal Flooding: all areas below + 6.0 m GOL based on a bicentenary storm surge event	centre of Büsum	32	personal interviews	1976

Sources: MLUR 2010; Statistisches Amt für Hamburg und Schleswig-Holstein 2010; MLUR 2007; own survey data
MLUR (2010) Informationen zur Einführung einer Küsten- und Hochwasserschutzabgabe. Ministerium für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein, Kiel. http://www.schleswig-holstein.de/cae/servlet/contentblob/954478/publicationFile/InfoEinfKueSchuAbg.pdf. Accessed 30 May 2011
MLUR (2007) Generalplan Binnenhochwasserschutz und Hochwasserrückhalt Schleswig-Holstein. Ministerium für Landwirtschaft, Umwelt und Ländliche Räume (MLUR), Kiel. http://www.schleswig-holstein.de/cae/servlet/contentblob/419008/publicationFile/GP_BinnenHW.pdf. Accessed 3 March 2011
Statistisches Amt für Hamburg und Schleswig-Holstein (2010): Bevölkerung 2010. http://www.statistik-nord.de/publikationen/publikationen/statistische-berichte/bevoelkerung-und-gebiet/. Accessed 30 May 2011

A.3 Java Code: Human.java

```
package strinfo;

[…]
public class Human extends SimpleAgent {

	// Agent vulnerability parameter
	private int initialvul;
	private float perception;
	private int assets;
	private int measures;
	private int information;
	private float experience;
	private float attitude;
	private float expectations;
	private int network;
	private float evaluation;
	private int agentid;
	private String location;

	// Preferences
	private float p_information;
	private float p_insurance;
	private float p_incentives;
	private float p_migration;

	// further state variables
	private float lackOfAwareness;
	private float trust;
	private float p_timeRate;

	// Initial model assumptions
	public Human(int agentid, boolean exposure, int initialVul) {
		this.agentid = agentid;
		this.exposure = exposure;
		this.initialvul = initialVul;
	}


	// to assess potVul from "C:\\Program Files\\RepastSimphony-1.2.0\\workspace\\Behaviour100_values.csv":

	/**
```

```
 * This method calculates the potential vulnerability of each agent.
 *
 * @return PotVul
 */
public int getPotVul() {
        int ret = initialvul;

        if (evaluation >= 0.5)
                ret--;
        else
                ret++;

        if (perception == 1.0)
                ret--;
        else
                ret++;

        if (assets == 1)
                ret--;
        else
                ret++;

        if (measures ==1)
                ret--;
        else
                ret++;

        if (information == 1)
                ret--;
        else
                ret++;

        if (network == 1)
                ret--;
        else
                ret++;

        if (attitude == 1.0)
                ret--;
        else
                ret++;

        if (expectations == 1.0)
                ret--;
        else
                ret++;
```

```
		if (experience >= 0.5)
			ret--;
		else
			ret++;

		return ret;
	}


	/*
	 * ================ Behaviour ==================
	 */
	[…]

	// 1 = information; 2 = insurance; 3 = incentives; 4 = migration;
	// 5 = pause and start again at 1
	private int executeCounter = 0;

	//delayed execution
	private int numberOfStrategyByLocationAddition = 0;


// this method is called every simulation time step
	// Step method
	@ScheduledMethod(start = 1, interval = 1)
	public void step()
	{
		// gets the current tickCount and gets the schedule on which the
		// current run's events are scheduled for execution of strategies

		int tick_complete = (int)RunEnvironment.getInstance().getCur-
rentSchedule().getTickCount();
		int tickCount = tick_complete % 5;

		[…]

		boolean log = true;

		// is the strategy offered at my location?
		int numberOfStrategyByLocation = calculateNumberOfStrategy
ByLocation(lackOfAwareness, trust, numberOfStrategyByLocationAddition);

		TimeStep.addNumberOfStrategyByLocation(numberOfStrategy
ByLocation, tickCount);
```

```
        //delayed scheduling of strategies:
        numberOfStrategyByLocationAddition++;

        if (numberOfStrategyByLocation == 1 && executeCounter<4)
        {
                executeCounter++;

                //execute strategies:

                if (executeCounter==1)
                        strategy_information(log);

                if (executeCounter == 2)
                        strategy_insurance(log);

                if (executeCounter == 3)
                        strategy_incentives(log);

                if (executeCounter == 4)
                        strategy_migration(log);

        }
        else if (numberOfStrategyByLocation==1 && executeCounter>=4)
        {
                //reset ExecuteCounter and increase lackOfAwareness
                executeCounter = 0;
                numberOfStrategyByLocationAddition = 0;

                lackOfAwareness += 0.1f;
        }
}

/**
* Is the strategy offered at my location? Calculation of perceptual
threshold
 *
 * @param lackOfAwareness
 * @param trust
 * @param addition
 * @return 1=strategy is applied, 0=strategy is refused
 */
```

```
	private int calculateNumberOfStrategyByLocation (float lackOfAware-
ness, float trust, int addition)
	{
		/*
		 * (step-1), do not add at first step
		 */
		float numberOfStrategyByLocation = 1 − (lackOfAwareness +
trust) + (addition);

		if (numberOfStrategyByLocation >= 0.5f)
			return 1;
		else
			return 0;

	}


	//**** strategy information

	//FLAG
	private boolean appliedStrategyInformationFlag = false;

	//FLAG
	private boolean addSocialInfluenceFlagForInformation = false;

	//INFORMATION
	private void strategy_information(boolean log)
	{
		//INFORMATION (appliedStrategyInformation/agent = p_infor-
mation + p_timeRate >= 2.0f)
		float appliedStrategyInformation = p_information + p_timeRate;
		// test the preference and the preferred time rate

		//Handling of SocialInfluenceForInformation

		//SocialInfluenceFactor
		if (appliedStrategyInformation<2.0f && addSocialInfluenceFlag
ForInformation)
		{
			//Special case START
			if (p_information==1.0f && p_timeRate==0.5f)
			{
				//Special case
				if (information==0.0f)
					appliedStrategyInformation += 1.0f;
```

```
                    }//Special case ENDING

                    appliedStrategyInformation += getSocialInfluenceFor
                    Information();

          }

          addSocialInfluenceFlagForInformation = !addSocialInfluenceF-
          lagFor Information;


          appliedStrategyInformationFlag = !appliedStrategyInformation
          Flag;

          //positive effects of strategy information on agent profile
          if (appliedStrategyInformation>=2.0f && p_information!=0.0f)
          {
                    information = 1;
                    network = 1;
                    attitude = 1.0f;
                    perception = 1.0f;
                    measures = 1;


                    TimeStep.addAppliedStrategyInSystem(1);

                    if (log) System.out.printf("%s: executed strategy\t\t\
tINFORMATION\n", this.toString());
          }
          else
          {

          }
}


/**
 * Check social Influence for Strategy information
 * @return 1.0 if social influence in other cases 0.0
 */
private float getSocialInfluenceForInformation()
{
          if (network == 1)
          {
           Iterator it = ContextUtils.getContext(this).iterator();
```

```
                    while (it.hasNext())
                    {
                              try
                              {
                                        Human aktuell = (Human)it.next();

                                        if (aktuell == this)
                                                  continue;

                                        //My Network??
                                        if (aktuell.getNetwork() == 1 && location.
equals(aktuell.getLocation()))
                                        {
                                                  if ((aktuell.p_information+aktuell.p_
timeRate)>=2.0)
                                                            return 1.0f;
                                        }
                              }
                              catch (ClassCastException cce){}
                    }
                    }
                    return 0.0f;
          }



          //**** strategy insurance

          //FLAG
          privatebooleanaddSocialInfluenceFlagForInsurance = false;

          //INSURANCE
          private void strategy_insurance(boolean log)
          {
                    //Insurance (appliedStrategyInsurance/agent = p_insurance −
experience )
                    float appliedStrategyInsurance = p_insurance − experience;
                    // test the preference and the correlating attribute experience

                    if (appliedStrategyInsurance <= 0.5f && addSocialInfluenceF-
lag ForInsurance)
                    {
                              appliedStrategyInsurance += getSocialInfluenceFor
Insurance();
                    }
```

```
			//FLAG –  every second time step
			addSocialInfluenceFlagForInsurance = !addSocialInfluenceFlag
ForInsurance;


			//positive effects of strategy insurance on agent profile
			if (p_insurance!=0.0f && appliedStrategyInsurance>0.5f)
			{
				attitude = 1.0f;
				measures = 1;


				TimeStep.addAppliedStrategyInSystem(1);

				if (log) System.out.printf("%s: executed strategy\t\t\
tINSURANCE\n", this.toString());
			}
			else
			{

			}
		}

		/**
		 * Check social Influence for Strategy insurance
		 * @return 2.0 if social influence in other cases 0.0
		 */
		private float getSocialInfluenceForInsurance()
		{
			if (network == 1)
			{
			 Iterator it = ContextUtils.getContext(this).iterator();

			 while (it.hasNext())
			 {
				try
				{
					Human aktuell = (Human)it.next();

					if (aktuell == this)
						continue;

					//My Network??
					 if (aktuell.getNetwork() == 1 && location.
equals(aktuell.getLocation()))
```

```
                                        {
                                                    if    ((aktuell.p_insurance-aktuell.
experience)>0.5f)
                                                         return 2.0f;
                                        }
                                }
                                catch (ClassCastException cce){}
                        }
                        }
                        return 0.0f;
        }



        //**** strategy incentives

        //FLAG
        privatebooleanaddSocialInfluenceFlagForIncentives = false;

        //INCENTIVES
        private void strategy_incentives(boolean log)
        {
                //Incentives (appliedStrategyIncentives/agent = p_incentives +
p_insurance)
                float appliedStrategyIncentives = p_incentives + p_insurance;

                if (appliedStrategyIncentives < 2.0f && addSocialInfluenceFlag
ForIncentives)
                {
                        appliedStrategyIncentives += getSocialInfluence
ForIncentives();
                }

                //FLAG - every second time step
                addSocialInfluenceFlagForIncentives = !addSocialInfluenceFlag
ForIncentives;

                //positive effects of strategy incentives on agent profile
                if (p_incentives!=0.0f && p_insurance!=0.0f && appliedStrateg
yIncentives>=2.0f)
                {
                        attitude = 1.0f;
                        measures = 1;
```

```
                              TimeStep.addAppliedStrategyInSystem(1);

                              if (log) System.out.printf("%s: executed strategy\t\t\
tINCENTIVES\n", this.toString());
                    }
                    else
                    {

                    }
          }

          /**
           * Check social Influence for Strategy incentives
           * @return 1.0 if social influence in other cases 0.0
           */
          private float getSocialInfluenceForIncentives()
          {
                    if (network == 1)
                    {
                     Iterator it = ContextUtils.getContext(this).iterator();

                     while (it.hasNext())
                     {
                              try
                              {
                                        Human aktuell = (Human)it.next();

                                        if (aktuell == this)
                                                  continue;

                                        //My Network??
                                         if (aktuell.getNetwork() == 1 && location.
equals(aktuell.getLocation()))
                                        {
                                                  if ((aktuell.p_incentives>=1.0f &&
aktuell.p_insurance>=0.5f))
                                                            return 1.0f;
                                        }
                              }
                              catch (ClassCastException cce){}
                     }
                    }
                    return 0.0f;
          }
```

```
    //**** strategy migration

    //FLAG
    privatebooleanaddSocialInfluenceFlagForMigration = false;

    //MIGRATION
    private void strategy_migration(boolean log)
    {
        //migration (appliedStrategyMigration = p_migration − expectations)
        float appliedStrategyMigration = p_migration − expectations;


        if (appliedStrategyMigration <= 0.5f && addSocialInfluence
FlagForMigration)
        {
            appliedStrategyMigration += getSocialInfluence
ForMigration();
        }

        //FLAG - every second time step
        addSocialInfluenceFlagForMigration = !addSocialInfluenceFlag
ForMigration;

        //effects of strategy migration
        if (p_migration!=0.0f && appliedStrategyMigration>0.5f)

        {
            // but if p_migration >0.5, agents start migrating
            Context context = ContextUtils.getContext(this);
            context.remove(this);

            TimeStep.addAppliedStrategyInSystem(1);

            if (log) System.out.printf("%s: executed strategy\t\t\
tMIGRATION\n", this.toString());
        }
    }

    /**
     * Check social Influence for Strategy migration
     * @return 2.0 if social influence in other cases 0.0
     */
    private float getSocialInfluenceForMigration()
    {
        if (network == 1)
```

```
                {
                Iterator it = ContextUtils.getContext(this).iterator();

                while (it.hasNext())
                {
                        try
                        {
                                Human aktuell = (Human)it.next();

                                if (aktuell == this)
                                        continue;

                                //My Network??
                                if (aktuell.getNetwork() == 1 && location.
equals(aktuell.getLocation()))
                                {
                                        if ((aktuell.p_migration-aktuell.
expectations)>0.5f)
                                                return 2.0f;
                                }
                        }
                        catch (ClassCastException cce){}
                }
                }
                return 0.0f;
        }
        // potVul is calculated for allHuman (system level)
        public float getPotVulFromAllHuman()
        {
                int summe = 0;
                int anzahl = 0;

                Iterator it = ContextUtils.getContext(this).iterator();

                while (it.hasNext())
                {
                        try
                        {
                                Human aktuell = (Human)it.next();
                                summe += aktuell.getPotVul();
                                anzahl++;
                        }
                        catch (ClassCastException cce){}
                }
```

```
        return ((float)summe)/((float)anzahl);
}



//**********Getter and Setter***************
// getter and setter for agent parameters:
// agentID, location, exposure, initalVul, evaluation, perception,
// experience, assets, measures, information, network, attitude, expectations

publicintgetInitialVul() {
        return initialvul;
}

/**
 * @return the agentid
 */
public double getAgentID() {
        return agentid;
}

public String getLocation() {
        return location;
}

public void setLocation(String location) {
        this.location = location;
}

public float getPerception() {
        return perception;
}

public void setPerception(float perception) {
        this.perception = perception;

}

publicintgetAssets() {
        return assets;
}

public void setAssets(int assets) {
        this.assets = assets;
}
```

```
publicintgetMeasures() {
        return measures;
}

public void setMeasures(int measures) {
        this.measures = measures;
}

publicintgetInformation() {
        return information;
}

public void setInformation(int information) {
        this.information = information;
}

public float getEvaluation() {
        return evaluation;
}

public void setEvaluation(float evaluation) {
        this.evaluation = evaluation;
}

public float getExperience() {
        return experience;
}

public void setExperience(float experience) {
        this.experience = experience;
}

public float getAttitude() {
        return attitude;
}

public void setAttitude(float attitude) {
        this.attitude = attitude;
}

public float getExpectations() {
        return expectations;
}
```

```
public void setExpectations(float expectations) {
        this.expectations = expectations;
}

publicintgetNetwork() {
        return network;
}

public void setNetwork(int network) {
        this.network = network;
}

//setter for preferences:
public void setP_migration(float p_migration) {
        this.p_migration = p_migration;
}
public void setP_information(float p_information) {
        this.p_information = p_information;
}
public void setP_insurance(float p_insurance) {
        this.p_insurance = p_insurance;
}
public void setP_incentives(float p_incentives) {
        this.p_incentives = p_incentives;
}

// getter/setter for further state variables:

public float getP_timeRate()
{
        return p_timeRate;
}

public void setP_timeRate(float rate)
{
        p_timeRate = rate;
}

public float getlackOfAwareness()
{
        return lackOfAwareness;
}
```

```
	public void setlackOfAwareness(float lackOfAwareness)
	{
		this.lackOfAwareness = lackOfAwareness;
	}

	public float getTrust()
	{
		return trust;
	}

	public void setTrust(float trust)
	{
		this.trust = trust;
	}

	public String toString()
	{
		return String.format("%s (%d, %d)", location, agentid, execute
Counter);
	}
```

Index

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