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).

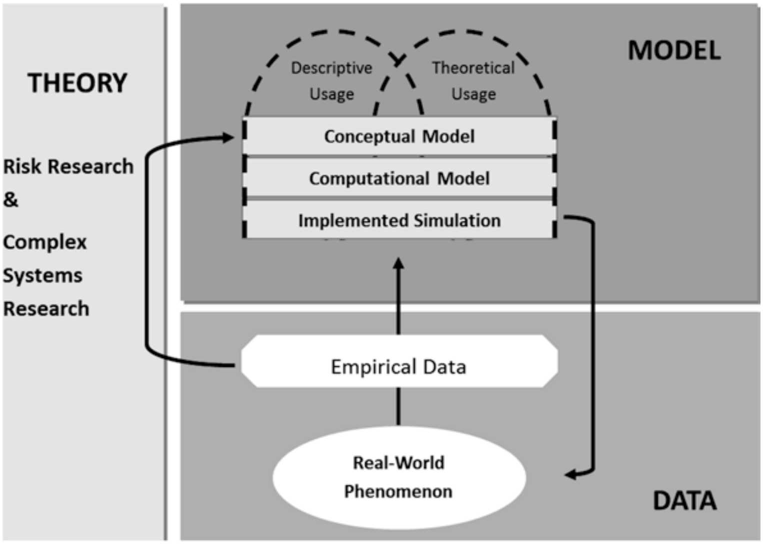

Fig. 2.1 Epistemological framework of research (adopted from Rossiter et al. (2010) on basis of McKelvey′s model-centred epistemology, reproduced by permission of Journal of Artificial Societies and Social Simulation)

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

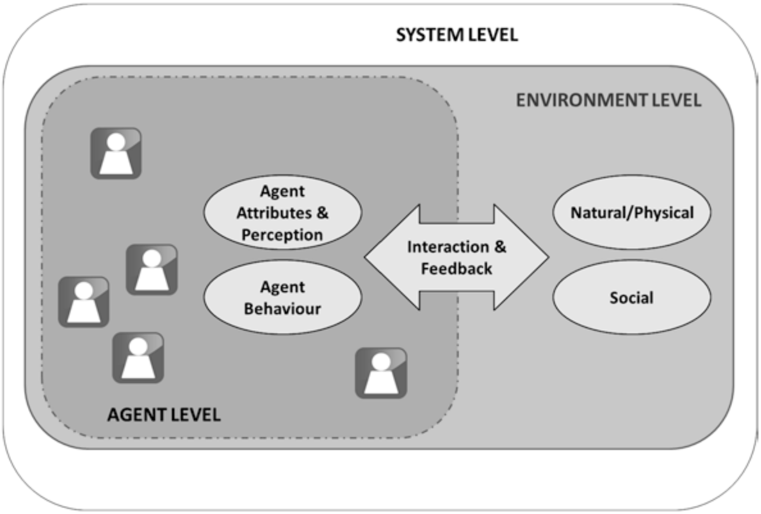

Fig. 2.2 Components of an agent-based model

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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