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Evolutionary modelling of the macro-economic impacts of catastrophic flood events

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Abstract

This paper examines the possible contribution of evolutionary economics to macro-economic modelling of flood impacts to provide guidance for future economic risk modelling. Most macro-economic models start from a neoclassical economic perspective and focus on equilibrium outcomes, either in a static or dynamic way, and describe economic processes at a high level of aggregation. As a consequence, they typically fail to account for the complexity of social interactions and other behavioural responses of consumers and producers to disasters, which may affect the macroeconomic impacts of floods. Employing evolutionary principles and methods, such as agent-based modelling, may help to address some of the shortcomings of current macro-economic models. We explore and discuss the implications of applying consumer and producer heterogeneity, bounded rationality, network effects, social and technological learning, co-evolution and adaptive policy-making concepts into existing economic frameworks for the assessment of macro-economic impacts of floods.

Keywords: macro-economic models, evolutionary economics, flooding, agent based modelling

1. Introduction

The economic losses caused by natural disasters have increased significantly over the past decades (Munich Re, 2009). Many regions and economic sectors are vulnerable to increasing disaster risks because of a lack of resources to implement cost-effective loss-reduction and risk transfer measures. Several studies have attempted to estimate the economic damages associated with climate change and include them in integrated models, of which FUND (Tol, 2002a,b) and DICE (Nordhaus, 1992; 2008) are probably best known. Potential catastrophic events like floods are by far the most important factor in these total damages (Nordhaus and Boyer, 2000). However, indirect economic effects from increased extreme weather events and associated catastrophes are usually not included in existing integrated assessment models (Patt et al., 2010). There is increasing dissatisfaction with existing macro-economic models used for the assessment of flood damages and risks. They rely on assumptions of market equilibrium and behavioural rationality of market participants, which are not considered realistic in the context of catastrophic events.

In this paper, we explore the potential contribution of an alternative theoretical perspective and methodological tools from evolutionary economics to address some of the shortcomings associated with current macro-economic modelling approaches to study the impacts of floods. The focus on flood risk is motivated by the fact that floods have been identified as the most common hazard for the entire European area among different natural and technological disasters (Schmidt-Thome and Kallio, 2006). The unprecedented 2002 large-scale flooding in central Europe and other events have placed adaptation to climate change at the top of the political agenda (see, for instance, the EU White Paper on Adaptation COM 2009).

The main challenge ahead lies in integrating different types of non-economic knowledge and information, such as geophysical land use data, with economic data and equations related to changing risk perceptions and behavioural adjustments. Exposure to natural disaster risk such as floods, and ultimately economic damage costs, are a function of both an individual's private choices and government decisions over land use zoning and infrastructure investments (Hallegatte and Dumass, 2009; Boustan et al., 2012). Empirical studies emphasize the role of socio-economic factors (personal characteristics, risk perception, behaviour in relation to flood damage) in reducing flood damage, in addition to structural measures (Shaw et al., 2005; Botzen et al., 2009). However, heterogeneity of individual responses to perceived and actual risks cannot be easily incorporated into existing macro-economic models, which rely on aggregate equations and do not discriminate between different behavioural rules. This relates to the fact that these macro models entail a simplifying assumption that the diversity of agents within a specific sector can be described as one "representative" utility maximizing agent, whose preferences coincide with aggregate choices of individuals. This

simplification may be unjustified as the reaction of the representative to changes can be very different from the aggregate reaction of the individuals he ‘represents’ (Kirman, 1992).

In the paper, we discuss how employing evolutionary principles and methods, such as agent-based modelling, can help to address shortcomings of current macro-economic models. Evolutionary economics replaces assumptions of representative, rational agents, exogenous preferences and utility-maximization by populations of diverse, boundedly rational and interacting individuals, whose preferences evolve over time. As a consequence, it may provide a useful approach to study adaptation and mitigation policies aimed at stimulating changes in behaviour and technologies prior to and after the disasters. We provide an overview of evolutionary-economic building blocks for researchers working on disaster modelling, who may be interested, but not familiar with recent developments in evolutionary-economic modelling. Evolutionary models allow studying macro outcomes emerging from interactions of many agents on multiple markets. In particular, the agent-based modelling technique has been increasingly employed to model such interactions, for instance in financial (e.g. Arthur et al. 1996; Caldarelli et al. 1998; LeBaron 2001; Levy et al. 2000) or electricity markets (e.g. Bunn and Oliveira, 2001; Safarzynska and van den Bergh, 2011). In such models, behavioural rules of agents are deduced from empirical studies and psychology experiments. Agent-based models have proved to be capable of generating aggregate macro regularities, while allowing at the same time at the micro level of the individual decision maker to explore feedback mechanisms that underlie economic dynamics. In this context, providing macro models with explicit micro foundations enriches the analysis of economic outcomes and policies. Designing agent-based models for flood damage and risk assessments requires theory development, micro and macro data collection to validate model assumptions and to design behavioural rules of agents prior to and after disasters. Our paper aims to offer a starting point for such an endeavour and provide guidelines for future flood risk modelling.

The remainder of the paper is as follows. In Section 2, we discuss current approaches to integrated macro-economic modelling of flood risks and their theoretical underpinning. In Section 3, we present an overview of the key concepts and methods in evolutionary economics, while section 4 elaborates and further details the specific contribution of evolutionary building blocks to existing macro-economic systems to provide a more realistic account of economic dynamics during and after a catastrophic flood event.

2. Integrated macroeconomic modelling of catastrophic flood events

Integrated models of catastrophic flood events attempt to combine all relevant physical and economic aspects related to a water flow in a single framework. They provide a conceptual basis for the assessment of flood damages and cost-benefit comparisons of climate change mitigation and

adaptation measures (e.g. Zhu et al., 2007; Jonkman et al., 2008). In many of such models, economic analysis of flood protection measures is carried out at the expense of hydrological detail, while social and technological learning are rarely addressed (Brouwer and Hofkes, 2008). On the contrary, in Geographical Information System (GIS)-based models, the flood event is described in more detail and geographically linked to a set of financial and economic assets (e.g. houses, factories, infrastructure) based on available land cover and land use maps. These models are used to simulate alternative flood event scenarios, for which economic values of damages are then computed based on available land cover and land use data. In such frameworks, no assumptions about behaviour of economic actors (consumers or producers) are being made. This simplification is problematic as the value of economic losses is expected to be sensitive to flood protection and other adaptation measures undertaken by firms and households as a result of experience and learning along with changes in perceived flood risks.

Input-output and general equilibrium models predominate among economic approaches employed for assessing flood risk and damages. Input-output models enable modelling of the interdependencies between different sectors in the economy. Here, natural disasters are often conceptualized as a shock to technological coefficients. The input-output approach has been criticized for its lack of explicit resource constraints and responsiveness of economic variables to changes in prices (Rose, 2004). Moreover, it does not allow modelling of behavioural responses of consumers and producers to stochastic shocks or the substitution of inputs in production. These shortcomings can be partially addressed by general equilibrium models. Contrary to I-O models, general equilibrium models allow introducing more sophisticated dynamics, describing price-quantity relationships, supply-demand adjustments towards equilibrium, input substitution and trade relations.

In general equilibrium models currently used to assess the impacts of flood events, deterministic equations describe optimizing behaviour of a representative producer and consumer, whose activities are disturbed by flood events (e.g. Narayan, 2003). Typically, their behaviour is invariant to natural disasters, i.e. characterized as business as usual after a catastrophic event, and the analysis focuses on relatively small incremental changes towards equilibrium. However, disasters can be a source of long-term structural change and behavioural adjustment to post-disaster situations. For instance, the size and composition of the population may change (Vigdor, 2008), firms may upgrade their capital (Hallegatte and Dumass, 2009) or consumers may reduce demand as a sign of sympathy for individuals affected by disasters (Okuyama, 2004). Such behavioural responses and changes in the population and consumption patterns are not yet well understood, let alone modelled properly.

Typically, in input-output and general equilibrium models, natural disasters are modelled as stochastic shocks disturbing economic dependencies or exogenous changes in coefficients describing pre- and

post- disaster situations (Rose and Liao, 2005; Steenge and Bokarjova, 2007). To illustrate this with an example, the technological coefficients in the input-output model by Steenge and Bokarjova (2007) change in a post-disaster situation, so as to reflect losses of industrial capacities. Modifying the matrix of coefficients yields a new equation, describing relations between labour, output and prices, called the Basic Equation. Different adjustment pathways of consumption and production after the catastrophe can be analysed using this approach. The restoration path always involves a transition between two equilibriums. The Basic Equation has also been employed in Jonkman et al. (2008) to evaluate the indirect damage of flooding in the Netherlands. In the model, a hydrodynamic module generates input information that is translated into different flood scenarios. Estimation of the direct losses is based on the damage equation: $D = \sum_{i=1}^m \sum_{r=1}^n \alpha_i(h_r) D_{max,i} \eta_{i,r}$, where $D_{max,i}$ is the maximum damage for an object or land use category i , m is the number of damage categories, n the number of flooded locations in an area, h_r captures the hydraulic characteristics of the flood at a particular location, $\alpha_i(h_r)$ is a damage function that expresses the fraction of maximum damage for category i as a function of flood characteristics at a particular location r and $\eta_{i,r}$ is the number of objects of damage category i at location r . Here, damages are evaluated with reference to a static equilibrium, which does not allow accounting for behavioural and technological change occurring after the disaster. Okuyama et al. (2004) extend the I-O table with the sequential industry framework to introduce dynamic and spatial dimensions into the model.

Alternatively, scenarios are simulated with the help of hydraulic and hydrological models that are translated into different flood probabilities (e.g. Jonkman et al., 2008; Bouwer et al., 2009). In the latter case, flood probabilities can be used to compute expected economic damages based on land cover and land use maps. In particular, geographical information systems (GIS) can be used to map flood risk areas (Harou et al., 2009). For instance, in models developed by Tol and co-authors to assess the economic impacts of sea-level rise, GIS provides information on the type of land lost across regions for different climate scenarios (Darwin and Tol, 2001; Bosello et al., 2007; Tol, 2007). However, economic modules in such models are mostly deterministic, based on optimization procedures for a representative, rational agent, focusing on equilibrium outcomes. This ignores vulnerability and resilience of socio-economic agents, changes in their risk perception, and behavioural adjustments to disasters (Okuyama and Chang, 2004; Brouwer et al., 2007).

After giving a short introduction to evolutionary economics in the next Section 3, we will discuss in section 4 insights from evolutionary economics which can potentially provide hydro-economic models with a more realistic behavioural foundation so as to address some of the discussed shortcomings of current macro hydro-economic approaches.

3. Evolutionary thinking and modelling approaches

3.1. Evolutionary economics

In evolutionary economics, an economy is seen as a complex, hierarchical structure comprising various levels and subsystems linked together through feedback mechanisms (Potts, 2000). The micro interactions among heterogeneous elements (e.g. individuals, technologies) lead to the emergence of a higher structure, while variation and selection processes occurring in any of the subsystems affect changes in the total environment. Evolutionary-economic models do not impose assumptions of market clearing and perfect foresight. As a result, many processes occur out of market equilibrium, which is relevant for modelling catastrophic flood risk scenarios.

Contributions to evolutionary-economics are very diverse. They vary with respect to assumptions made about economic reality and concepts inspired by theoretical biology (Witt, 2008). Essential elements of any evolutionary system are: diversity, adaptation through selection and innovation. The more diverse the elements upon which selection for fitness acts, the greater the expected improvement in fitness (Fisher, 1930). In natural systems, fitness translates into survival chance or reproduction. In economic contexts, fitness can be defined in terms of utility, growth or profits. Adaptation through selection requires interactions of entities with the environment in a way that causes their differential replication. Selection reduces diversity over time. The process is counterbalanced by mechanisms of variety generation, i.e. innovation. Innovation is an essential force behind evolutionary dynamics. It may take the form of a series of incremental improvements in already existing designs or the introduction of a design radically different from original solutions. Without persistent diversity creation, an evolutionary system is likely to become locked-in to a single option or oscillate between solutions because of repeated selection.

Additional features of evolutionary systems are: bounded rationality, path dependence and lock-in, coevolution, and group selection (Safarzynska and van den Bergh, 2010a). Individuals are assumed to interact with others and their environment. They are boundedly rational and follow various heuristics instead of constantly optimizing their choices. The assumption of bounded-rational behaviour prevails in behavioural economics. However, the analysis in behavioural economics focuses on a decision-making process by a single individual, while models in evolutionary economics often incorporate insights from behavioural studies to study macro outcomes emerging from interactions of many boundedly rational agents. During social interactions, individuals learn about a state of the environment, their own and others' preferences, and the efficiency of various strategies. These interactions are characterized by feedback mechanisms and increasing returns, which can be a source

of lock-in and path dependence. The latter explains why, after a system follows a particular path of development, it may be difficult to reverse or alter the direction of system change. Co-evolutionary and multi-level dynamics underlie many economic processes. Co-evolution implies that two or more heterogeneous populations are linked together in such a way that each influences the evolutionary trajectory of the other(s) (van den Bergh and Stagl, 2004; Winder et al., 2005). Finally, selection can operate not only on individuals (e.g. behaviours, technologies, policies) but also on groups. A theory of group selection explains evolutionary processes based selection acting on multiple levels, namely of individuals and groups (Wilson and Sober 1994; Wilson 2002; Henrich 2004; Wilson 2006; van den Bergh and Gowdy 2009).

In evolutionary growth theory, an interplay of innovation, selection and diversity drives economic growth and technological change. The seminal evolutionary model of endogenous growth by Nelson and Winter (1982) has provided macroeconomic dynamics with explicit micro foundations, opening black boxes of firms' innovative activities. In their model, the population is composed of many firms using different production techniques. Firms constantly engage in search for new solutions. Profitability determines differential growth of firms. In particular, market shares of firms which generate above-average profits in the industry grow in size. Among more recent evolutionary growth models with explicit micro foundations, two distinct approaches can be identified (Kwasnicki 2007): (1) capital-vintage type of models (e.g., Silverberg and Verspagen 1994a,b; 1995); and (2) two-sector type of models (Chiaromonte and Dosi 1993; Fagiolo and Dosi 2003), where the single economy is divided into an industry fabricating inputs for production and an industry manufacturing final goods. For instance, Dosi et al. (2006) propose an evolutionary model of industry dynamics, which extends endogenous business cycles with Keynesian features. The framework describes an economy composed of heterogeneous firms and consumers. Firms are bounded rational in their expectations about future demand, their investments are lumpy and constrained by their financial structures. Firms search each period for new machines with improved labour productivity. The result of this effort is uncertain: firms can develop a new prototype characterized by a new level of labour productivity, which may be higher or lower than the one of the currently manufactured machines. Model simulations proved capable of generating self-sustaining patterns of growth characterized by the presence of endogenous business cycles. This framework offers an interesting starting point for framing economic dynamics in hydro-economic models for addressing stochastic shocks and subsequent adjustments on the labour markets.

3.2. Evolutionary modelling techniques

Evolutionary modelling techniques encompass (Safarzyńska and van den Bergh, 2010b): evolutionary game theory and selection dynamics (Hofbauer and Sigmund, 1998; Weibull, 1998; Sandholm, 2007), evolutionary computation (Back, 1996; Mitchell, 1996; Banzhaf et al., 1989; Goldberg, 1989; Beyer,

1998; Lazi, et al., 1998; Bull, 2004), and agent-based modelling (Wooldridge, 1999). In evolutionary game theory and evolutionary computation, individuals do not change over time but a population evolves due to selective replication and variation processes (e.g. Axelrod, 1987). In both approaches, individuals are carriers of simple strategies. Payoffs, associated with these strategies, determine the number of ‘offspring’ in the next population. In evolutionary computation, variation and selection operates on a large population of strategies. On the other hand, in evolutionary game theory, dynamics focuses on selection processes and omits structural innovations. A central concept in evolutionary game theory is the evolutionarily stable strategy, which denotes that strategies in an equilibrium are resistant to invading ‘mutant’ strategies (Samuelson, 1997). To study dynamic paths to reach equilibrium underlying evolutionary games, various dynamic equations have been proposed, referred to as population or selection dynamics (Hofbauer and Sigmund 1998). It is important to emphasize that evolutionary game theory and evolutionary economics are often considered to be two distinct fields in the literature (Witt, 2008; Hodgson and Huang, 2012). Nelson (2001) explains this by the fact that evolutionary game theory is less empirically oriented than evolutionary economics and it mainly serves to study the adjustment dynamics towards different equilibrium configurations.

Agent-based modelling is the most flexible of evolutionary modelling techniques, and may be the most suitable for addressing complexity of hydro-economic dynamics. The basic structure of an agent-based system involves specifying a large number of parameters and variables: time, the number of agents, micro states (actions) that can be endogenously modified by agents, micro parameters containing information about agents’ behavioural and technological characteristics, time independent variables governing the fixed technological and institutional setup, the structure of interactions and information flows among agents, and aggregate macro variables (Pyka and Fagiolo, 2007). Formally, agents can be defined as computational entities, situated in some environment, capable of undertaking flexible autonomous actions with the objective of meeting their goals (Wooldridge, 1999). Intelligent agents can exhibit goal-oriented behaviour, and interact with other agents. Their interactions are characterized by feedback mechanisms and increasing returns. The rules or mechanisms that underlie such interactions, and which enhance the performance of agents, are selected over time. Mechanisms causing system malfunctions are not selected. In addition, each intelligent agent (whether an individual, group or organization) has an internal model that allows him to anticipate future outcomes and choose an action accordingly, given a desired future state. These models can change as a result of innovations, or as individuals learn from experience. Farmer and Foley (2009) argue that the economy needs agent-based modelling as empirical statistical models fail to predict changes in the face of great change, whereas dynamic stochastic general equilibrium models rules out crises by assuming a perfect world. The flexibility of the agent-based method enables researchers to incorporate more realistic assumptions about the behaviour of consumers and producers, their spatial and temporal interactions, and coevolution of hydro-economic systems into hydro-economic models. So far, few agent-based

hydro-economic models have been proposed (e.g. Barreteau, 2004, Brouwers and Verhagen, 2001), also, in the context of water management processes (e.g. Tabara et al., 2007; Galan et al., 2008; Krykow et al., 2008). Despite the limited modelling efforts so far, this line of modelling opens a promising venue for future research.

4. Comparing conventional and evolutionary approaches to macroeconomic modelling of flood events

In this section, we explore potential contributions of evolutionary-economics to improve the design of current macro-economic models, with respect to firm and consumer behaviour, mechanisms of social interactions, technological learning and network effects for the evaluation of the economy wide impacts of flooding (Table 1). We will provide suggestions how these aspects can be improved in current modelling approaches, by providing more realistic, empirically grounded foundations, through evolutionary-economic methods and tools, linking the latter evolutionary economics building blocks to the specific characteristics of catastrophic flood events. We do not intend or pretend to be exhaustive in terms of discussing existing models, but merely aim to illustrate commonly used methods for modelling macro-economic consequences of flood events. More exhaustive overviews of formal conventional modelling methods of flood events are found in Okuyama (2004), Okuyama and Chang (2004), and Zenklusen (2007), and of natural disasters in general in West and Lenze (1994), Rose, (2004), Cavallo and Noy (2009), and Hallegatte and Przulski (2010).

INSERT TABLE 1 HERE

4.1.1. Firm behaviour in conventional models

In conventional input-output models, firms' (and consumers') behaviour is not modelled explicitly. Instead, such models examine interdependencies between different sectors in the economy. This allows estimating coefficients describing relations between supply of and demand for inputs and their flow in different sectors. In particular, a static input-output model describes the relationship between supply X_i of industry i and intermediate demand X_{ij} for industry's i product by industry j , and total final demand FD_i (Conrad, 2001):

$$X_i = \sum_{j=1}^n X_{ij} + FD_i = \sum_{j=1}^n \alpha_{ij} X_j + FD_i, \quad i=1, \dots, n,$$

where n is the number of industries and α_{ij} is a relative weight describing demand in industry i for input j to the total supply of input j .

Output levels X_j of primary input j are derived from equilibrium conditions:

$$PX_j X_j = \sum_{i=1}^n PX_{ij} \alpha_{ij} + PL \cdot \alpha_{Lj} + PK \cdot \alpha_{Kj},$$

where PX_j is the price of intermediate products X in industry j , PL is the price of labour L , and PK is the price of capital K , and α_{Lj} and α_{Kj} are the relative weights of demand for labour and capital respectively. Here, no assumption is made about behaviour of producers and consumers, and thus it is not possible to model their responses to a catastrophic flood event.

On the other hand, in general equilibrium models, profit-maximization determines production and investment decisions of firms. Production is often described by constant elasticity of substitution

(CES) production functions: $CES_j(PX_q, \dots, PX_m) = \left[\sum d_i^\sigma PX_i^{1-\sigma} \right]^{\frac{1}{1-\sigma}}$, where σ is the elasticity of substitution describing the ease with which one input can be substituted for another in production, and d_i is a weight attached to input X_i , with PX_i being its price. Alternatively, a Cobb-Douglass production

function $Y = A \prod_{i=1}^n X_i^{\gamma_i}$ can be employed, where X_i for $i=1, \dots, n$, describe different inputs in production,

A is the productivity coefficient and γ_i the elasticity of output, which measures the responsiveness of the level of output Y to a change in the use of input i . Note that the Cobb-Douglass function is a special case of the CES function for $\sigma=0$. Here, adjustments undertaken by producers with the aim of reducing disaster-related losses can be captured by changes in elasticities in production functions following the event. Alternatively, changes in inputs use following a catastrophe are derived as a solution to the optimization problem (e.g. cost minimization, profit maximization) given the limited availability of inputs, e.g. capital or labour in the case of a catastrophic flood event.

In the context of catastrophic flooding, we identify three main issues that are relevant for the macro-economic modelling of firm behaviour, which are difficult or in some cases not possible to capture in conventional models. This includes: the importance of the network structure on the spread of risk, the trade-off between R&D activities and investments in reconstruction/upgrading of capital following the catastrophe, and the impact of increased flood awareness on undertaking flood protective measures such as insurance or investments in damage reduction measures. Catastrophic flood events may result in business and supply chain disruption over extended periods of time and often require rebuilding destroyed capital stock. Such disruptions may have wider macroeconomic effects. A well-known legal case is, for instance, that of Tyson Foods, where undamaged perishable food had to be sold under market prices because of the disruption of the company's (international) logistic networks (shipping facilities at various ports used by the company) caused by Hurricane Katrina. The combination of the earthquake and tsunami in Japan in 2011 has had an immediate and direct impact on the northern region of the country where the disaster occurred. In addition, the financial and economic effects have spread throughout the Japanese, East Asia and rest of the world economy due to Japan's major role in

global supply chains, both as supplier of parts and producer of final products (Nanto et al., 2011). At the same time, flood risk awareness and perception may increase due to the experience and prevalence of catastrophic events and lessons learned in the past or elsewhere (e.g. the catastrophic floods in central Europe in 2002, the flooding as a result of hurricane Katrina in New Orleans in 2005 or the earthquake and tsunami flood in Japan in 2011), resulting in protective measures or upgrading of production technology to better withstand potential future flood risks or to increase the level of catastrophic flood risk preparedness. Protective measures may refer to very simple solutions, such as moving machinery to higher elevated places or keeping machinery in flood water-resistant, lockable compartments inside factories. Alternatively, business and contingent business interruption insurances can hedge firms against future losses. This topic has achieved much attention after Hurricane Katrina in 2005.

4.1.2. Possible applications of evolutionary economics approaches for modelling firm behaviour

The short and long term effects of floods are very different. In this section, we first discuss how evolutionary economics can contribute to modelling short-term consequences of floods, i.e. how floods affect routines of firms and how supply chains and networks of firms are disrupted after a disaster. In the longer run, the consequences are inter alia determined by the choice of technology when rebuilding the destroyed capital and how generally the search for innovation is affected by catastrophic events. This will be discussed in more detail in Section 4.2.2.

In evolutionary economic models, production can be described by a CES or Cobb-Douglas function, just as in neoclassical economic models. However, the level of output or capital expansion is not necessarily determined by profit maximization or cost minimization procedures. Instead, firms may follow various heuristics and routines. Nelson and Winter (1982) claim that firms operate to a large extent according to decision rules that are not consistent with profit maximization, but instead take the form of complex patterns of routinized behaviour. For instance, in Windrum and Birchenhall (2005) each firm j sets a target level of production y_{jt+1} for the next period as a weighted average of its current sales s_{jt} and actual demand d_{jt} : $\tilde{y}_{jt+1} = \zeta d_{jt} + (1-\zeta) s_{jt}$, where ζ and $(1-\zeta)$ are the weights assigned to sales and demand respectively, which may change drastically after a catastrophic flood event, hence allowing us to take into account drops in production following a catastrophic event. Heuristics and routinized forms of behaviour can also describe investment decisions. An example is the model developed by Dosi et al. (2006), where firms invest in capital expansion only if their level of capital is lower than some threshold level. Employing this approach to model the wider impacts of a catastrophic flood event would require specifying how these threshold levels change after a flood event or as a result of changes in flood risks.

A number of evolutionary-economic studies have analyzed behaviour of firms and strategic arrangements within specific networks (Malerba 2006). In the context of modelling floods, studying interactions of firms within networks is considered important for the assessment of the consequences of a flood event. It can provide insights into or help to identify drivers of ‘cascades of failures’. Floods typically destroy firms’ capital and thus their production capacities. This will result in delays in output delivery, which in turn will have an effect on firms employing this output as inputs. The severity of losses depends on the availability of other sources of input supplies and firms’ inventories (unless the latter are also irreversibly lost by the flood). Such interdependencies cannot be captured by the elasticities of substitution alone. This is because the structure of interactions between firms determines the severity of their losses. Weisbush and Battiston (2007) proposed a model to study under which conditions local failures to produce or to deliver output can result in an accumulation of shortages and bankruptcies. This approach allows for the modelling of a cascade of failures as a result of flooding, where the probability of failures can be expressed as a function of key hydro-geological conditions. Along similar lines, Henriot et al. (2011) propose a theoretical framework to investigate economic robustness to exogenous shocks such as natural disasters. Their model presents a regional economy as a network of production units through the disaggregation of sector-scale input-output tables. The results suggest that disaster-related output losses depend on both the heterogeneity of direct losses and the economic network structure.

In evolutionary-economic models, networks of firms do not need to have an explicit structure in the physical space. However, bringing a spatial dimension into evolutionary-economic models for the assessment of flood consequences can help identifying key factors to increase the resilience of the economic system to natural disasters. Non-service (i.e. primary and secondary sector) related production processes are usually highly dependent on existing infrastructure (the latter also determining substitution possibilities in case of catastrophic flood events) and are often located in or near urban areas. Resilient infrastructure ensures the continuity of critical production processes and services in the presence of natural disasters. In this context, Cagno et al. (2009) propose an integrated method for the assessment of resilience and vulnerability of infrastructure in urban areas. Their approach combines the input-output inoperability model (Haimes and Jiang, 2001) with topological and area risk methods (Egidi et al., 1995). The inoperability input-output model still uses Leontief-like matrices to capture interdependencies of infrastructures between different sectors. Matrices are in this case directly linked to detailed descriptions of the geographical areas served by the infrastructures so as to enable the study of economic losses as a result of a disruption to a specific sector.

Finally, heterogeneity in firms’ responses to disasters can be modelled explicitly with agent-based models. Recently, an agent-based model for the whole of the EU has been proposed as part of the EURACE project (Deissenberg et al., 2008). The framework represents in a simplified and stylized

way 27 European countries. It links GIS-based land use data to demographic and socio-economic data from Eurostat. The model is capable of simulating behaviour of over 10^7 heterogeneous agents in multiple markets of consumption goods, investment goods, labour, credit, and other financial assets. Individual behaviour is described in terms of routines and (wherever possible) empirically documented rules. Its main aim is to investigate how the distribution of skills influences the speed of technological change, employment and wage dynamics, and the growth rate. Thus far, the impact of climate change is not included in the model. The possible integration of hydrological conditions could generate novel insights.

4.2.1. Technology and technological change in conventional models

In input-output models, technologies are not described in any detail but implicitly incorporated in the input-output matrix coefficients at industry level. Technological coefficients can be static or change over time. Assuming fixed coefficients carries a risk of overestimating direct output losses from disruptions in input supplies such as capital and labour under catastrophic flood conditions. Alternatively, technological coefficients can be updated each period to reflect changes in input intensity in various industry sectors, other than cost or price driven improvements in technology. For instance, for a model with n sectors, the entries in the matrix $A(t)$ of technical coefficients can change according to (Pan, 2006):

$$A(t) = A(t-1)S^O(t) + A^N(t)S^N(t)$$

The elements of matrix $A(t)$ are $a_{ij}(t)$, which represent old $a_{ij}^O(t)$ or new $a_{ij}^N(t)$ processes. $S^O(t)$ and $S^N(t) = 1 - S^O(t)$ are the shares of sector j 's output produced by old and new processes respectively to sector j 's total output. Some models have attempted to endogenize the rate of change in technological coefficients as changing along a generalized logistic curve (Goulder and Schneider, 1999; Pan, 2006):

$$a_{ij} = a_{ij}^O + \frac{a_{ij}^S}{1 + e^{-I^{R\&D}(t)\alpha(t - (M / I^{R\&D}(t)))}}$$

with α being the average growth rate, a_{ij}^O the initial level, a_{ij}^S the saturation level of the coefficient, $I^{R\&D}$ the R&D index capturing R&D investments in new technology, which may be under severe pressure in times of catastrophic flooding due to necessary reconstruction investments, and M the maximum growth, which also may change as a result of a catastrophic flood event. Here, R&D activities may also shift the relative weights of technologies in the production process by developing new ‘‘climate change proof’’ technologies, anticipating increasing flood risks and thereby reducing the macro-economic impacts of future catastrophic flood events. In this context, natural disasters are still modelled as an external (exogenous) shock to technological coefficients. In reality natural disasters

may affect both the productivity of existing technologies and damages to the existing capital stock and investments herein.

In general equilibrium models, technological change is described in terms of exogenous or partially endogenous improvements in inputs or total factor productivity. Alternatively, it can rely on the replacement of old by new vintage capital technologies in production. The replacement of physical capital after a calamity like a flood event can compensate capital losses due to disasters. For instance, Japan's economy contracted substantially immediately after the catastrophic event, but was expected to partly offset this by rebuilding and reconstruction investment activities the years after (IHS Global Insight, 2011). Hallegatte and Ghil (2008) suggest differentiating between reconstruction investments and investments in the embodiment of new technologies to capture the role of upgrading technologies in overcoming the disasters, i.e. in terms of moderating their impacts and flood prevention. Here, achieving the desired production level after a flood calamity requires reconstruction investments I_r and investments I_n that increase productive capital K_o according to:

$$\frac{\partial K_o}{\partial t} = \frac{1}{\tau_{dep}} K_o + \frac{I_n}{\xi_k}, \quad \frac{\partial \xi_k}{\partial t} = \frac{I_r}{K_o},$$

where τ_{dep} is the depreciation rate of capital and ξ_k the proportion of potential productive capital K_o that has not been destroyed. This approach allows studying a productivity paradox, according to which disasters may induce positive economic consequences through the accelerated replacement of capital (Hallegatte and Dumas, 2009). The discussed approaches do not allow studying the effect of innovations, i.e. the emergence of new technologies, on economic growth and the impact of catastrophes on the innovative activities of firms. We will discuss this further in the next section

4.2.2. Possible applications of evolutionary economic approaches for modelling technology and technological change

In this section, we discuss potential contributions of evolutionary-economic models to the assessment of longer-term consequences of flooding. These longer-term consequences are linked to the search for and emergence of new technologies, and how technological change is affected by catastrophic floods and the perceived risk of these catastrophic events.

In evolutionary growth models, different approaches exist to conceptualize technological change in macro-economic models. For instance, innovations can be conceptualized as a stochastic process (e.g.

Poisson distribution) that results in structural discontinuity, a random or myopic search in a fitness (technology) landscape (Frenken, 2006), the emergence of a new vintage of capital (e.g. Iwai, 1984a,b; Silverberg and Lehnert, 1993; Silverberg and Verspagen, 1994a,b, 1995) or new technologies emerging from variations and recombinations of existing technological options (Weitzman 1998; Olson and Frey 2002; Tsur and Zemel 2006; van den Bergh 2008). These approaches deserve more attention in existing macroeconomic models aiming to simulate or predict the wider macro-economic consequences of large scale catastrophes like floods.

In particular, in the seminal growth model by Nelson and Winter (1982), opportunities of innovation can arise any time, as firms are constantly involved in search activities for better technological solutions. Here, heterogeneous firms produce the same homogenous product but with different techniques. Each firm is engaged in the search process for better solutions. The latter is modelled as a two-stage random process. In the first stage, imitation and innovation draws from a specified distribution density function determine the firm's probability of undertaking R&D activities. If a firm gets an imitation draw, then in the second stage it copies the industry's best practice. If it gets an innovation draw, it samples productivity from a distribution of technological opportunities. Both random processes may have different probability distribution functions, more directly related to actual behaviour observed after catastrophic events. Such distributions are typically fat-tailed (i.e. very high variance) and usually mathematically not well-behaved (e.g. Dash, 2004; Gray and Malone, 2008). In the specific context of catastrophic flood risks, the random search process underlying Nelson and Winter's model could be modified in such a way that R&D activities are undertaken with an eye on the possibility for future damage cost reductions should a catastrophic flood event occur. In this context, technological changes can moderate the economic impacts of a catastrophic flood event, but they do so in different ways and to different extents depending on the firm's technology pathway.

Immediately after the disaster, a firm needs to restore the destroyed capital. A firm may invest in restoring old capital to its previous level or invest in new, technologically upgraded capital, which would enhance its productivity in the long run. Reconstruction investments will compete with R&D investments unless firms are able to upgrade production capital using disaster loans, insurance coverage or national aid. The availability and conditions of loans would determine how fast the economy may recover after the shock. In reality, many disaster loans are intended to help firms to recover business to its pre-disaster conditions and only under certain circumstances for adopting mitigating devices or upgrading capital. Therefore, access to finance is a crucial determinant of the technological change following disasters.

More research in this direction is needed to better understand how fast the economy can recover after shocks. Evolutionary-economic models allow designing rules for heterogeneous firms in terms of investing in insurance or upgrading capital depending on firms' characteristics (capital endowments, profitability, perception of risks).

4.3.1. Household behaviour in conventional models

In general equilibrium models, on the demand side a representative consumer maximizes the discounted sum of intra-period utilities from consumption of goods and leisure, given his budget constraint (Conrad, 2001):

$$U_t = \sum_{\tau=t}^{\infty} (1+s)^{t-\tau} \frac{\sigma}{\sigma-1} (FC_s)^{\frac{\sigma-1}{\sigma}},$$

where σ is the inter-temporal elasticity of substitution, FC_s is total final consumption and s is a discount rate. The derived level of total consumption determines the quantity of necessary labour supply. This approach ignores changes in the population size and its composition due to economic growth or disasters.

We identify two main issues that are relevant for the macro-economic modelling of household behaviour in the context of flood risks. First, households' risk perception and valuation may undermine existing assumptions in conventional modelling of what is considered rational behaviour in expected utility theory (Kahnemann and Tversky, 1979; Slovic, 1987). Together with the risk culture and social learning (e.g. Beck, 1992; Douglas, 1992), this will determine to what extent households take self-protection measures (e.g. Shogren and Crocker, 1991) under typically low probability and high impact conditions and hence influence the extent of flood damage costs. Secondly, self-protection measures may include migration due to public perception where flood risk levels are considered unacceptably high (and as a result reduce self-protection costs, for instance in embankment systems, to zero). The attraction of living along the coast has encouraged, for example, many people in the past to move to areas at risk from flooding, increasing the economic costs of disasters (Boustan et al., 2012). Migrations away from affected areas can be an important adaptation strategy to changes in flood risks. It has been estimated that the large-scale displacement of people associated with natural disasters can render between 200 million to 1 billion climate change induced migrants by 2050 (Smith et al., 2010). Such scales of migration will inevitably either directly influence future damage costs to households and their property or indirectly through the labour market also production processes and therefore production output values in flood prone areas.

We will address these issues in more detail in the next section, and focus specifically on evolutionary economics perspectives, to better describe individual risk assessment and decision-making under uncertainty.

4.3.2. Possible applications of evolutionary economic approaches for modeling household behaviour

In evolutionary-economic models, agents often follow alternative rules of thumb and heuristics to maximizing utility. Instead of a representative consumer, the population is composed of many heterogenous interacting agents. In some evolutionary-economic models, behaviour of consumers in the population is described by utility functions, just as in neoclassical economics. Such utility functions typically include a social component which increases the attractiveness of products adopted by others (Jansen and Jager, 2002, Windrum and Birchenhall, 1998, 2005; Windrum et al., 2009ab, Safarzyńska and van den Bergh, 2010b) or accommodate an array of assumptions of bounded rational behaviour.

Individual and social learning drive changes in preferences or changes in rules. Evolutionary modelling provides an array of tools to conceptualize these processes (Dosi et al., 2003). For instance, in formal models, an agent selects a specific rule given environmental stimuli and after evaluating how well the rule performed in the past. Rules can change due to social interactions (imitation) or by chance. On the other hand, individual learning can be conceptualized as a cognitive mechanism entailing the construction of mental models and behavioural patterns in a changing environment. In evolutionary models, bounded rational agents are capable to tailor rules-of-thumbs to their environment and experience; they learn how to learn (Milgrom and Roberts, 1991). Societal learning relies on imitation, which can take the form of either copying the ‘the most successful’ or ‘the majority’ strategy (Boyd and Richardson, 1985; Henrich et al., 1999). Formally, the process of preference change can be conceptualized as threshold levels for product quality evolving towards their average values in the population. In the context of flood modelling, it is important to identify the relevant thresholds. For instance, depending on the number of individuals affected by the flood, other consumers may refrain from purchasing certain products (e.g. luxury products) as a sign of sympathy. In addition, catastrophic events may disturb daily routines of agents, as illustrated below.

Evolutionary economics allows studying outcomes emerging from interactions of many boundedly rational agents so as to study the consequences of social interactions and influences through networks on the consequences of floods, and vice versa the impacts of flood risks on society. The challenge lies in identifying behavioural theories which will account not only for the influence of social interactions on individual decisions but also for how individuals behave under risk and uncertainty. Individual household preferences for risk (risk aversion) can be reflected in the curvature of the utility function.

In the face of uncertainty with, for example, two possible states with or without a catastrophic event occurring in a specific year and known objective or subjective probabilities P , expected utility equals:

$$E(U(Y)) = \sum_{i=1}^n P_i * U(Y_i) = P_i * U(Y_1) + (1 - P_i) * U(Y_0)$$

where Y_1 refers to the situation with the catastrophic event and Y_0 to the situation without the catastrophic event. The subscript i is included to indicate that individual households may belong to different risk groups j ($i \in j$). In order to assess at what point an individual household is willing to pay for preventing, reducing or eliminating a catastrophic risk event (e.g. by buying risk insurance), the price (e.g. risk premium) p_i has to be identified that would make the individual indifferent between taking the risk and paying p_i to avoid the risk. To this end, expected utility without taking protective measures is set equal to expected utility with protective measures at the individual's current income level.

Under expected utility, risk aversion holds if utility is concave, corresponding to diminishing marginal utility of income ($U''(Y) < 0$), where an individual is willing to pay to avoid (a loss due to) a risky event: $E(U(Y)) < U(E(Y))$. However, Tversky and Kahneman (1992) propose an alternative convex utility function of the form shown below for welfare losses based on empirical evidence that the linearity embedded in standard expected utility models does not hold in typical low probability-high loss risk situations:

$$U(Y_i) = -\lambda(-Y_i)^\alpha$$

where λ is a loss aversion parameter and α reflects the degree of convexity of the utility function ($0 \leq \alpha \leq 1$). A value for α equal to one implies that the individual is risk neutral. This utility function is commonly used in experimental studies. In its general form the utility function can be written as:

$$U(Y) = \sum_{i=1}^n w(P_i) * (P_i U(Y_i))$$

where $w(P_i)$ is a probability weighting function reflecting the fact that an individual household values risks related to gains and losses differently, resulting in Tversky and Kahneman's (1992) empirically observed S-shaped utility function. Empirical evidence for the estimates of λ and α in the specific context of catastrophic flood risks is to our knowledge absent and require further testing to examine how alternative utility function specifications affect individual household risk perception and behavior.

The above utility functions can be easily incorporated into agent-based models. In addition, such utility functions can be further modified to account for the effect of information exchange and social influence on purchasing insurance against flooding, which has rarely been done so far (e.g. Brouwers

and Verhagen, 2001). Social influence has been shown to affect investment decisions in protection measures against natural hazards (Siergrist and Gutscher, 2008; Terpstra et al., 2009). Evolutionary-economic models offer an array of formal models to conceptualize and study social influence, which can be adapted to study decision-making under flood events. They allow for a description of individual imitating behaviour of earlier adopters (e.g., information cascades), of neighbouring sites in case of a game with a spatial dimension (agents are located on a grid), or of individuals who belong to the relevant social network (e.g. Jansen and Jager, 2002, Windrum and Birchenhall, 1998, 2005; Windrum et al., 2009ab).

Raid et al. (1999) show that social influence, together with risk perception and access to resources, is a major factor in decision-making over whether or not to evacuate from dangerous situations, which will ultimately affect the number of casualties. Their research suggests that a simple warning is often not enough in emergency situations. Along this line, Dawson et al. (2011) propose an agent-based model to study evacuation strategies of agents located in flood prone areas. The model integrates remotely sensed information on topography, buildings and road networks with empirical survey data to fit characteristics of specific communities. Agent-based simulations have been coupled with a hydrodynamic model to estimate the vulnerability of individuals to flooding under different storm surge conditions, flood warning times and evacuation strategies. In their model, a flood incident may interrupt a daily routine of commuting agents, who need to decide whether to evacuate to the nearest shelter or to continue with their routine as normal.

Modelling migration processes explicitly as a result of disasters is important as losses due to disasters are largely influenced by changes in population and their location (Hewitt, 1997). Makowsky et al. (2006) and Smith et al. (2010) model migration as an adaptation mechanism to natural catastrophes. Changes in population and household composition affect a society's vulnerability and exposure to natural hazards (Changnon et al., 2000). It can result in significantly higher macroeconomic costs (e.g. commuting costs) or bring benefits of inducing readjustments on the labour market such that the supply of labour more closely matches labour demand in a post-disaster situation (Vigdor, 2008). Kniveton et al. (2011) proposed an agent-based migration model to investigate the role of climate change in migration decisions using different scenarios of future demographic, economic, social political and climate change in Burkina Faso. Czaika (2012) has argued that migration decisions can be better explained using prospect theory instead of the standard neoclassical model of expected utility. 'Migration prospect theory' explains how prospects about migration-related outcomes are altered with respect to a reference point. According to prospect theory, people dislike losses more than they enjoy gains. Migration outflow is therefore expected to respond to bad news about economic situations in the origin countries more strongly than migration inflow to good news. Formally, the

utility function explaining migration decision x with respect to some reference point r can be formalized as follows (Czaika, 2012):

$$v(x|r) = \begin{cases} (x - r)^\alpha & \text{if } x - r \geq 0 \\ -\theta(-(x - r))^\alpha & \text{if } x - r < 0 \end{cases}$$

where α indicates diminishing sensitivity to good or bad news ($0 < \alpha < 1$), and θ is the coefficient of loss aversion. Modelling flood-related migration using agent-based models allows accounting for heterogeneity of reference points depending on socio-economic status of individuals and socio-economic prospects of the affected area and the area of destination.

5. Conclusions

Despite the large variety of approaches to macro-economic modelling of consequences of catastrophic events, current models share many features in common. Typically, analysis is carried out at a high level of aggregation, while technologies are not described in much detail. Technological innovations, social interactions, and adaptive policy and decision-making are often missing from the analysis. As a consequence, most modelling exercises do not allow assessing and comparing the full range of consequences of floods, adaptation and mitigation policies. Evolutionary modelling of decentralized interactions between large numbers of heterogeneous agents operating in multiple markets (labour, capital, goods, financial) is nowadays possible because of the recent advances in computer technology. They can provide new insights into the mechanisms underlying hydro-economic dynamics. Many complex phenomena emerge only in simulations of sufficiently large populations of agents.

Evolutionary economics, with its methodological tools, can contribute to modelling the complexity of macroeconomic impacts of catastrophic events such as floods and study the effectiveness of prevention, adaptation and mitigation measures of these impacts. We suggested that key features of current (neoclassical) hydro-economic models such as the use of a representative agent, deterministic dynamics, single objective optimization processes, and adjustment processes towards equilibrium outcomes might be replaced by evolutionary notions like heterogeneous populations, stochastic dynamics, rule-based heuristics, bounded rationality and co-evolutionary dynamics. In most hydro-economic frameworks, economic behaviour is described by the paradigm of profit/utility maximization. However, individuals may be incapable of perfectly assessing profitability of different projects or identifying the cheapest solutions, especially after a disaster, resulting in bounded rationality and a series of seemingly sub-optimal choices along an adaptive management and learning based development path.

Elaborating micro foundations of integrated hydro-economic models along evolutionary lines offers the opportunity to study different types of responses to increased flood risk due to climate change, including responses on labour or insurance markets. For instance, network effects and influences are important determinants behind investments in protection measures against natural hazards in general and flooding in particular (e.g. Brouwer and Akter, 2010). Disaster-related output losses depend directly on the economic network structure. Still, social influence through networks has been rarely acknowledged in formal hydro-economic frameworks. Nevertheless, it is important for damage reduction activities, and thus it can affect total damage estimations.

In evolutionary-economic models, behaviour of consumers and producers is described in terms of rules and routines, which allows more flexible tailoring of behavioural assumptions to empirical observations in pre and post disaster situations. Here, technological change occurs due to innovation activities and learning from experience by individual firms, and technology selection drives changes in aggregate output. On the demand side, social interactions and network externalities affect decisions of individuals, which can offer insights into diffusion of protection measures against natural hazards, including mitigation activities, also as a result of changing perceptions of flood risks. Furthermore, explicit modelling of household migration processes as a result of a flood disaster is important as this may significantly impact macro-economic costs as well as induce significant readjustments on labour markets. Finally, evolutionary dynamics can be studied in space using agent-based modelling, which allows linking of economic dynamics with GIS-data. Such exercises have already been conducted for modelling multiple markets in EU countries, but until now the impacts of climate change and increased flood risks on economic variables have been ignored. These are in our view the most promising areas that deserve more attention in future hydro-economic modelling of flood disasters in the context of climate change.

Evolutionary economics offers flexible tools and methods to conceptualise an array of processes and behavioural assumptions. In this paper we do not suggest to model more explicitly all possible mechanisms for the assessment of catastrophic flood consequences, but to replace existing ones by those mechanisms, which have been identified in the literature as essential for validly and realistically assessing macro-economic flood consequences. There is, as always, a clear trade-off between realism and tractability. Yet, choosing the appropriate level of simplification should not be predetermined by a set of axioms (e.g. market equilibrium, rational behaviour), but based on the identification of economic processes that are considered relevant in the light of new evidence, offering the opportunity to revise existing theories and models to generate and test new hypotheses.

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Table 1: Key characteristics of macro-economic flood models and possible integration of evolutionary concepts

	Current neoclassical models	Evolutionary approach
Firm behaviour	<p>profit maximization and/or cost minimization</p> <p>Forward looking expectations: rational expectations based on perfect information and foresight</p>	<p>satisficing behaviour, heuristics, routinized forms of behaviour</p> <p>Search for innovation and imitating best frontier technologies</p>
Technology and technological change	<p>Technology defined at the industry level, not described in detail</p> <p>Exogenous or partially endogenous improvements in productivity of inputs</p>	<p>Technologies and innovation process described at the level of individual firms</p> <p>Innovation processes conceptualized as a stochastic process that results in structural discontinuity; a random or myopic search in a (technology) fitness landscape; the emergence of new vintage of capital; variation and recombination of existing technological options</p>
Consumer behaviour	<p>Utility maximization</p> <p>Possible adaptation measures result from utility maximization</p> <p>Demand-supply adjustments occurs through price mechanisms, which ensures competitive market equilibrium</p>	<p>Heterogeneous groups of consumers with network effects in consumption (imitation) and social comparisons</p> <p>Adaptation measures depend on social influences within networks</p> <p>Coevolution between demand and supply determines the direction of technological progress</p>