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Report on applicability of existing and improvement/development of new methods for decision making under uncertainty

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Executive Summary

The aim of the deliverable 4.2 is to analyze applicability of existing methods and suggest improvements and new methods and models for decision-making under uncertainty within the cli-mate change adaptation and risk management context. The overarching goal is to convey the importance of incorporation and treatment of uncertainties, risks, and policy measures in eco-nomic models for evaluation of climate change mitigation and adaptation strategies. The docu-ment covers main challenges related to problem of economic modelling and appraisal of measures for climate change adaptation, and as sub-goals specifically the methods addressing: deep, often unresolvable, uncertainties; long evaluation time horizons; analytically intractable and decisions-dependent systemic risks; integrated analysis and modelling of food-energy-water-environmental (FEWE) nexus, FEWE security considerations, risk of maladaptation and irrevers-ibility, synergies between mitigation and adaptation.

The deliverable explores potential drawbacks of commonly accepted economic models when applied specifically to an assessment of climate change adaptation strategies. Understanding these drawbacks is of key importance to avoid making potentially inappropriate decisions. The document discusses main methodological challenges associated with climate change uncertain-ties and risks and presents analysis of important shortcomings of such traditional approaches as cost-benefit analysis, expected utility, general equilibrium, traditional discounting, etc.

The deliverable illustrates approaches to robust management of uncertainties and risks being exploited and developed in various scientific communities and summarizes how these approach-es can be adopted and incorporated in economic models for climate change adaptation. With respect to uncertainties and risks induced by climate change, the cross-linking between scientific communities is important because of the need to account for cross-sectorial dependencies and interactions in order to hedge the systemic (interdependent) risks.

Another important aspect of the work presented in the document is a set of selected examples that illustrate feasibility and practical benefits from including considerations of uncertainty, risk, security, and robust solutions in economic models for appraisal of climate change adaptation measures. The examples demonstrate importance of modeling the nexus between anthropogen-ic and natural systems, the robust management of the emerging systemic risks and FEWE secu-rity, the evaluation of trade-offs between strategic (long-term) and operational (adaptive) deci-sions to treat maladaptation and irreversibilities in large-scale spatially-detailed multi-sectoral models. An example of trade market model illustrates the analysis of robustness of emission trading and reduction policies under asymmetric information and other multiple anthropogenic and natural uncertainties. In particular, the model shows important economic implications of un-certainties and risks that can change the structure and destabilize the market potentially affecting multiple enterprises. Another example is focused on economics of integrated catastrophic risk management and investigates the important role of insurance relevant to climate change adapta-tion context with a specific focus on a multi-layer disaster insurance program involving public-private partnerships. New approaches to discounting provide a powerful methodological tool for evaluation of climate change adaptation measures.

In addition to that, the report provides extensive references to original literature sources for more detailed information.

The deliverable discusses a variety of concepts and methods, whereas three economic models illus-trate feasibility and importance of explicit incorporation and treatment of inherent uncertainties and risks in large-scale models for effective and robust climate change mitigation and adaptation.

Stochastic version of the Global Biosphere Management Model (GLOBIOM model) is a large-scale dynamic recursive stochastic partial equilibrium model enabling integrated land use planning achieving food, energy, water, and emissions security goals. GLOBIOM accounts for interdepend-encies among main Land Use Systems (LUS) on global, national, and grid-cell levels. Food, water, environment (emissions) security constraints and biofuel targets introduce competition for limited resources (land and water). The supply of crops, i.e., agricultural production, has to cover final de-mands, livestock feed requirements, and biofuel production targets. Food consumption constraints have to be fulfilled under all circumstances.

In the stochastic GLOBIOM, systemic risks of various kinds are explicitly covered and can be ana-lyzed. The risks are characterized by the entire structure of the systems including distributions of risks shaped exogenously and endogenously by decisions of agents, costs structure, market pric-es, technologies, security constraints characterized by critical quantiles, Value-at-Risk (VaR) and Conditional Value-at-Risk (CVaR) risk measures, and feasible decisions of agents. The model incor-porates stochastic representation of crop yields facilitating analysis of induced systemic risks on crop production and food, energy, and water provision. Stochastic GLOBIOM is capable of treating cascading events in interdependent climate-agriculture-energy systems, e.g. a shock to corn pro-duction possibly leading to a deficit of important feedstocks for biofuels.

A stochastic model of the market-based emission abatement and trading investigates the role of economic instruments for environmental regulations in the face of various uncertainties and climate changes. At a project level, adaptation to climate change might be realized in the form of conforming to new regulations and/or adjusting to new market conditions induced by such regula-tions. This is where emission trading schemes and markets along with their development projections have to be taken into account. The developed multi-agent trading simulation system may function as a prototype of a real emission trading market. Various sources of emissions uncertainties are repre-sented and analyzed in the model. The model explores conditions of market's stability with respect to uncertainty by imposing appropriate safety constraints to control the level of admissible uncertain-ty which would guarantee cost efficiency of trades and safety levels of emission reduction targets (e.g., post-Kyoto pledge targets). Explicit treatment of uncertainties provides incentives for their monitoring and reduction before trading.

An integrated catastrophe risk management (ICRM) model focuses on the design of a flood-loss sharing program as a tool for climate change adaptation and risk hedging. The program can involve private insurance based on location-specific exposures, a mutual catastrophe fund, and a system of governmental compensations. It is demonstrated that a robust program designed with ICRM substantially reduces demand for other structural and financial risk mitigation and spreading mechanisms. The model consists of GIS-based flood model and a stochastic optimization procedure with respect to location-specific risk exposures. To achieve the stability and robustness of the pro-gram towards floods with various recurrences, the ICRM implies quantile-related risk functions of a systemic insolvency involving overpayments and underpayments of the stakeholders.

The deliverable provides an overview of state-of-the-art methods for decision-making under uncer-tainty and risks. While discussing particular approaches, we highlight the importance of integrated (cross-sectorial) analysis for robust management of food-energy-water-environmental security. Oth-er aspects we suggest for consideration within the adaptation context of the ECONADAPT project include: complex multivariate analytically intractable risk distributions, long horizons of evaluations, strategic and operational planning and management of risks, quantile-based risk adjusted perfor-mance indicators/goals/constraints, which can help derive robust solutions.

The provided methods overview is naturally far from being complete and does not cover all methods with the same level of detail. However, we carried out the analysis of the key methods specifically focusing on their applicability – their strengths and weaknesses within an adaptation context. To overcome critical deficiencies found, we suggest a range of improvements/new methods and illus-trate those with a few appropriate examples.

A special emphasis is put onto robust management of risks and evaluation of trade-offs. Supporting the discussion on a higher methodological level, special attention is given to several examples of integrated dynamic modeling for climate change adaptation. One of the central examples of treat-ment systemic risks and food-energy-water-environmental security is a stochastic version of the GLOBIOM model. Other examples illustrate integrated modeling of emissions trading and abatement under uncertainties, integrated management of catastrophic floods, and new approaches to dis-counting. These examples highlight feasible approaches for addressing the challenges of systems integration, methodological risk awareness, and solutions' robustness within a single modeling framework. In addition to that, we provide extensive references to original literature sources for more detailed information.

The fundamental messages coming out of the research communicate the need for:

- explicit inclusion of uncertainties and
- application of risk measures in adaptation projects to obtain
- robust solutions;
- emergence of systemic risk across sectors and scales and therefore
- the need for interdisciplinary research;
- sequential approach to decision making evaluating future flexibilities in
- operational decisions vs. strategic decisions.

Since many prominent economic assessment models are deterministic, they fail to account for the uncertainties and risks inherent in climate change. They are also unable to account for increasing variability and frequency of risks which currently dominate the climate change debates. Multiple studies and decision support models are based on deterministic scenario analysis and, hence, re-duce models with variable stochastic parameters to a set of their scenario-specific deterministic im-plementations assuming perfect information. This may lead to wrong policy implications with irre-versible consequences and lock-in states of developments, increase market volatility, and worsen situation with alarming issues of food, energy, water, and environment security.

Policy implementation based on methods ignoring risks may lead to unwanted results. For instance, interdependencies between land use systems constitute a complex network connected through economic demand-supply relations. If these systems are governed by incoherent policies, a serious disruption of the network may evoke systemic risks affecting food, energy, water, and environment security worldwide. To revert harmful consequences of inconsistent climate change adaptation measures, high investments and expensive projects might be needed to compensate for ongoing large scale human-made changes to ecosystems.

More concrete implications will be substantiated through ECONADAPT’s case studies.

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1 Introduction and framing of the problem of decision-making under uncertainty and risk in the ECONADAPT context

In deliverable D4.1 “A transparent overview and assessment of the relevant uncertainties for the main policy domains” we discussed the most critical aspects relevant to a very broad field of uncertainty as it relates to climate change (including climate variability) and adaptation to climate change. We presented and where possible compared with each other different views and approaches to understanding and modelling uncertainty and risk. We highlighted the concept of clustering present uncertainties into climate, socio-economic, and policy relevant ones. All those play an important role for long term adaptation, but not necessary in the short term. We presented examples relevant to several problem-areas to illustrate the material and help the reader see the practical implications of conceptual thinking.

The existing uncertainties and risks as reflected in modern scientific studies and strong interconnections at regional and global scales introduce systemic risk and highlight the importance of integrated cross-sectorial analyses. Therefore the methods of handling uncertainty and risk including the concept of strategic and operational planning of adaptation, which are further developed in the present document. Here we provide an exhaustive (but probably still not entirely complete) coverage of methods to cope with uncertainty and risk. The specific focus of this document is on the applicability of existing methods where their strengths and weaknesses are analysed and, where critical deficiencies are found, the improvements and/or new methods are suggested. These considerations are carried out within the project’s context of adaptation under climate change – decision making under uncertainty.

1.1 General challenges in relation to uncertainties and Climate Change adaptation

Much of the debate on climate change is based on a scientific understanding that the climate will change gradually and incrementally. Therefore, the majority of prominent economic assessment models are deterministic and fail to account for the uncertainties and risks inherent in climate change. What is also important is they are unable to account for the increasing variability and frequency of catastrophic risks which currently dominate climate change debates[1]. Multiple studies and decision support models are based on deterministic scenario analysis (see (Agarwal et al., 2002; Gielen et al., 2000; McCarl and Schneider, 2000) and hence, reduce models with variable stochastic parameters to a set of their scenario-specific deterministic implementations assuming perfect information. This may lead to wrong policy implications with irreversible consequences and lock-in states of developments, an increase in market volatility, and may worsen the situation with alarming issues of food, energy, water, and environment security (FAO, 2009; FAO et al., 2011). It seems that up to now there are only quite loose ties between the climate change community and other scientific communities dealing with uncertainties and risks, i.e., stochastic programming, operations research, engineering and reliability theory, real options analysis, hazard modelling, finance, insurance, etc.

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[1] Well known models in the literature include the DICE-model (Nordhaus, 1993) and the global 2100 model (Manne, 1992). Notable and more recent examples are (Mastrandrea and Schneider, 2001), in *Climate Policy*, and (Heal and Kriström, 2002), providing a nice literature review, both present rather stylized models and fail to model climate risk by appropriate stochastic processes.

Climate change might induce cascading catastrophes of an anthropogenic nature similar to a natural disaster triggering the nuclear catastrophe at the Fukushima nuclear power plant, which resulted from the hit of an extreme tsunami wave[2]. Another example is floods induced by hurricane Katrina caused by inadequate disaster prevention and mitigation decisions[3]. Less obvious, but vivid examples that are not connected to natural disasters are endogenous systemic risks propagating through land use systems. Various studies demonstrate that massive deforestation and increase of greenhouse gas (GHG) emissions in Indonesia, Malaysia, and Africa is due to rapidly increasing expansion of palm oil plantations being driven by biofuel targets in Europe (Coyle, 2007; Fitzherbert et al., 2008; Koh and Wilcove, 2007). This is an example of policy implementation based on methods ignoring risks and leading to potential maladaptation. Interdependencies between land use systems constitute a complex network connected through economic demand-supply relations. If these systems are governed by incoherent policies, a serious disruption of the network may evoke systemic risks affecting food, energy, water, and environment security worldwide. To revert harmful consequences of inconsistent climate change adaptation measures, high investments and expensive projects might be needed to compensate for ongoing large scale human-made changes to ecosystems (Butler et al., 2009; Koh et al., 2009; Wicke et al., 2011).

1.2 Key methodological aspects

Climate change adaptation involves the consideration of uncertainty and risks associated with different outcomes (scenarios) that may happen, and their costs. Due to spatial heterogeneity and interdependencies between natural and anthropogenic systems, the risks are characterised by analytically intractable complex spatio-temporal patterns challenging traditional risk modelling and management approaches. Assessment of such risks in an explicit analytical form is hardly possible, and the role of relevant integrated assessment models shifts from scenario-by-scenario projection and evaluation towards the design of robust strategies. Therefore, the aim of the ECONADAPT project lies not just within the scope of understanding of the nature of climate change uncertainties and risks. Ultimately the focus is on the development of models, methods, and tools, enabling the analysis of robust strategies that would help ensure stability of relevant systems, e.g., food, water, energy, and environmental security under a multitude of feasible future scenarios.

The project is focused particularly on treatment of uncertainties and risks in economic models for climate change adaptation. *Adaptation* for the purposes of this document is understood as actions that reduce and redistribute within a society the damages associated with climate changes. The discussion above suggests that economic analysis of climate change should include uncertainty and risks as a central feature. With a prominent position for uncertainty and risks, the understanding of proper risk perceptions and corresponding treatment of risk becomes critical for policy makers involved in climate change (CC) mitigation and adaptation. Attitudes towards risk, risk aversion, and risk measures are among the central aspects to be considered.

Some of the uncertainties can be potentially reduced (depending on their type to a different degree) through learning, leaving us with crucial questions: When and what will new information reveal? Will the society be able to react in time? Is it better to act now or to wait until the new portion of information is revealed? Given uncertainties, there is a trade-off between acting now

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[2] http://www.world-nuclear.org/info/safety-and-security/safety-of-plants/fukushima-accident/

[3] http://www.livescience.com/22522-hurricane-katrina-facts.html

and waiting for new information. The questions on how to address uncertainties, risks and learning in climate change decision analysis are discussed in the following sections.

In developing and supporting an adaptation strategy, there is a crucial role of financial, insurance and reinsurance industries, their capacity and instruments for pricing, absorbing, redistributing, and shifting potential losses. Institutions for risk transfer are important in particular, with respect to catastrophic interdependent risks. There is always a possibility that some of risks or changes are uninsurable or irreversible, which in the case of catastrophes is likely to happen. In this respect, in order to ensure robustness of policy conclusions, the currently existing economic models' notion of using truncated forms of uncertainty and treating it in fact as certainty (Arrow, 1996) needs to be given up.

There is a striking paradox of increasing losses from natural catastrophes: agreement that the global risk exposure is becoming unsustainable, and inability to stop the growth of human and economic losses. The main structural reasons for increasing losses are clustering of people and capital in hazard prone areas as well as the creation of new hazard-prone and hazard creating areas due to inadequate treatment of risks or risk ignorance. Current disaster trends are likely to continue undermining the markets and linkages between developing and developed countries. We argue that integrated catastrophic risk management approaches to treatment of interdependent endogenous systemic risks, as discussed in Section 3, may offer more coherent, comprehensive and robust policy analysis. Coherence is needed between economists, land use planners, natural scientists and disaster managers; comprehensiveness is required to identify policy gaps between the existing measures in place compared to those needed to guarantee economic development that is robust against shocks from potential systemic risks and catastrophes.

As highlighted in the literature, the time horizon of both climate change and catastrophic risks is very long (Tatiana Ermolieva et al., 2013; Ermoliev et al., 2010, 2008). Such time horizons undermine standard risk pricing mechanisms. Evaluation of adaptation projects has to account potentially for several decades or even hundreds of years, e.g., construction of a dike or a reservoir to protect against a catastrophic flood which may happen on average once in 300 or 500 years. However, this flood may happen today, next year, in 10 or 100 years, or not happen at all. How can the investments into mitigation efforts be justified, if they may possibly turn into benefits only over long and uncertain time horizons in the future? Long horizons of evaluation, uncertainties, and risks pose a challenge to the common thinking of investments and discounting.

1.3 Overview of the next chapters

In Section 2 we summarize traditional economic approaches, methods, and tools and investigate their applicability to address climate change adaptation challenges. Section 2.3 provides an overview of existing approaches that attempt to specifically address risks and uncertainties, and discuss their shortcomings with respect to climate change challenges. Also, we outline methodologies addressing risks and uncertainties in other areas, e.g., stochastic programing community, statistics, operations research, engineering, hazard management, insurance, finance, etc., and identify promising approaches enabling the analysis of robust climate change adaptation policies.

In Section 3, we discuss important improvements of methods in the adaptation context and further in Section 3.2 provide several examples of integrated models that incorporate most of the central issues in climate change adaptation such as interdependencies, possibility of systemic risks, abrupt catastrophes, treatment of irreversibilities and learning, safety and security requirements, and robustness of decisions.

Section 3.2.1 provides a preview of a stochastic Global Biosphere Management Model (GLOBIOM) (Ermolieva et al., 2015; Havlík et al., 2011) enabling integrated robust land use planning under systemic risks accounting for interdependencies among main land use systems on global, national, and grid-cell levels. The model incorporates stochastic crop yields[4] facilitating analysis of induced systemic risks on crop production and food, energy, water provision. The model is spatially detailed, and stresses the importance of geographic and temporal clustering of hazards, their implication for risk sharing and robustness of risk management.

Section 3.2.2 introduces a basic stochastic emission abatement and trading model allowing to analyse the robustness of emission reduction policies under asymmetric information and other multiple anthropogenic and natural uncertainties. This model studies the role of uncertainties on pricing emission permits. The model analyses if the knowledge about uncertainties may affect portfolios of technological and trade policies or structure of the market and how uncertainty characteristics may change the market structure.

Another example provided in Section 3.2.3 is dedicated to an integrated catastrophe management model. The model addresses the specifics of catastrophic risks: highly mutually dependent and spatially distributed endogenous risks, the lack of historical location-specific observations (unknown risks), the need for long-term perspectives and robust strategies, new approaches to discounting, and explicit treatment of spatial and temporal heterogeneities of involved agents such as farmers, producers, households, local and central governments, land use planners, water authorities, insurers, and investors. That GIS-based model explicitly accounts for the interplay between national and local ex-ante measures and ex-post measures, e.g., investment in prevention/mitigation measures (at levels of public authorities, citizens and insurance industry) and policies for sharing financial costs after disaster. This example provides an illustration of how identification and proper planning of land use policies for dealing with extremes may substantially decrease regional vulnerability and catastrophic losses which otherwise might have dramatic and long-term consequences for society.

Section 4 presents concluding remarks.

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[4] The model can include other stochastic parameters, for example; costs, resources, e.g. water availability or/ and requirements

2 Applicability of existing methods

In this section we highlight methods available for treatment of risks and uncertainties related to climate change. The UNFCCC's report on methods and tools (UNFCCC, 2008) classifies CC studies (approaches) according to the Methodology, Method, and Tool/models[5]. However, in (UNFCCC, 2008) decision-making approaches including uncertainty and risk are scarcely mentioned. Among the few methodologies explicitly referring to risk management is a framework of the United Kingdom Climate Impacts Programme (UKCIP) Climate Adaptation: Risk, Uncertainty and Decision Making[6], which gives general guidance as to the uncertainties and risk identified in climate change studies. Among other approaches, it offers methods and techniques for risk assessment and forecasting, options appraisal and decision analysis as tools to estimate climate change risk. According to UKCIP (Willows et al., 2003), techniques, tools and methodologies applicable for decision-making under climate change uncertainty and risk comprise, in particular, traditional or probabilistic cost-benefit and cost-efficiency analysis, multi-criteria analysis with the purpose to make a choice between adaptation alternatives; portfolio analysis for selecting adaptation portfolios; scenario analysis; cross-impact analysis, risk mapping, etc. A good review can be found in Markandya (2014).

In addition to sectorial studies, integrated Assessment Models (IAM) accomplish cross-sectorial studies involving climate component in the form of either simplified climate model (Nordhaus, 1992) or climate scenarios. Among well-known IAMs one can mention DICE, AD-DICE, RICE, AD-RICE, CLIMPACTS, ESCAPE, MAGICC, MiniCAM, SimCLIM, GLOBIOM, etc. The IAMs combine interdependencies among sectors to investigate effects of policies adopted in a set of sectors on other sectors. In this way, the IAMs integrate the bio-physical, sectorial and socio-economic dimensions of climate change scenarios to assess scenario-dependent mitigation and adaptation policy options (Weyant et al., 1996). Specific requirements and challenges associated with long-term modelling in the agri-food sector are discussed in the JRC report (Tonini et al., 2013). The report provides a review of the state-of-the-art computable general equilibrium and partial equilibrium models, and addresses a need for new methods which would allow a longer time horizon for planning, e.g. till 2050. As a possible extension of commonly used approaches, dynamic stochastic general equilibrium (DSGE) models and the use of approaches based on optimal control theory are discussed.

Recent studies in (Competence Center for Climate Change, 2013) explicitly identify scenario-by-scenario sensitivity analysis, as well as Monte Carlo approaches as means to treat uncertainties in economic models for climate change adaptation. There are also "supportive approaches" such as deterministic partial and general equilibrium models. Equilibrium

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[5] Here are the definitions used in the report:

Methodology /approach: a complete framework that prescribes an entire process for the assessment of vulnerability and adaptation and offers a broad strategic approach. An approach in some instances assembles certain methods and toolkits to support this process. Examples include: (Carter et al., 1994; Lim and Spanger-Siegfried, 2004; NAPAs Guidelines, 2002).

Method: A set and sequence of steps or tasks that should be followed to accomplish the task that represents a part of large framework. Method can be implemented through using a number of tools. Examples include: Methods for development and use of scenario data in the vulnerability and adaptation assessment, e.g. those presented in the (Feenstra et al., 1998) and (IPCC-TGCIA, 1999).

Tool (models): A means or instrument by which a specific task is accomplished. Examples include: RCMs, impact models, decision tools (cost-benefit analysis, MCA, TEAM, ADM, etc), stakeholder tools (vulnerability indexes, Livelihood Sensitivity Exercise, etc.).

[6] https://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5496.php

modelling facilitate analysis of interactions between climate change and markets. This is accomplished either at the global and/or national level (Chen and McCarl, 2009; Havlík et al., 2011).

A review of decision support tools (DST) for climate change adaptation has been undertaken by FP7 MEDIATION project[7]. The project (MEDIATION FP7, 2013) reviews and summarizes methodologies for assessing the costs and benefits of adaptation including their advantages and limitations as reproduced in Table 1.

Table 1: Methodologies for assessing the costs and benefits of adaptation. Source: (MEDIATION FP7, 2013).

Approach	**Description**	**Advantages**	**Limitations**
Economic integrated assessment models (IAM)	Global aggregated economic models that assess the costs of climate change and the costs and benefits of adaptation.	Provide headline values for awareness. Range of economic outputs. Used to provide economic information on global climate policy.	Very aggregated approach with highly theoretical form of adaptation, no technological detail. Insufficient detail for national or sub-national adaptation planning.
Investment and financial flows (IFF)	Early studies estimate costs of adaptation as percentage uplift. More recent national studies estimate cost of marginal increase needed to reduce climate risks.	Highlights scale of short term investment needs in sectorial or development plans.	Often little linkage with climate change scenarios, and little consideration of uncertainty.
Computable general equilibrium models (CGE)	Multi-sectorial and macroeconomic analysis of the economic costs of climate change, and emerging analysis of adaptation.	Captures cross-sectorial linkages across economy, including autonomous market adaptation. Can represent global trade effects. Can link to sector studies.	Utilizes aggregated representation of impacts and adaptation, no technical detail, no consideration of uncertainty. Omits nonmarket effects. Not suitable alone for detailed national or sector-based planning.
Impact assessment (scenario based)	Projects physical impacts and welfare costs from climate model outputs using impact functions, plus costs and benefits of adaptation options.	Sector-specific analysis of regional, national or sub-national scale. Physical impacts as well as welfare values. Can capture non-market sectors.	Not able to represent cross sectorial, economy-wide effects. Treats adaptation as a menu for technical options to defined scenarios. Medium to long term focus, thus less relevance for short-term policy.

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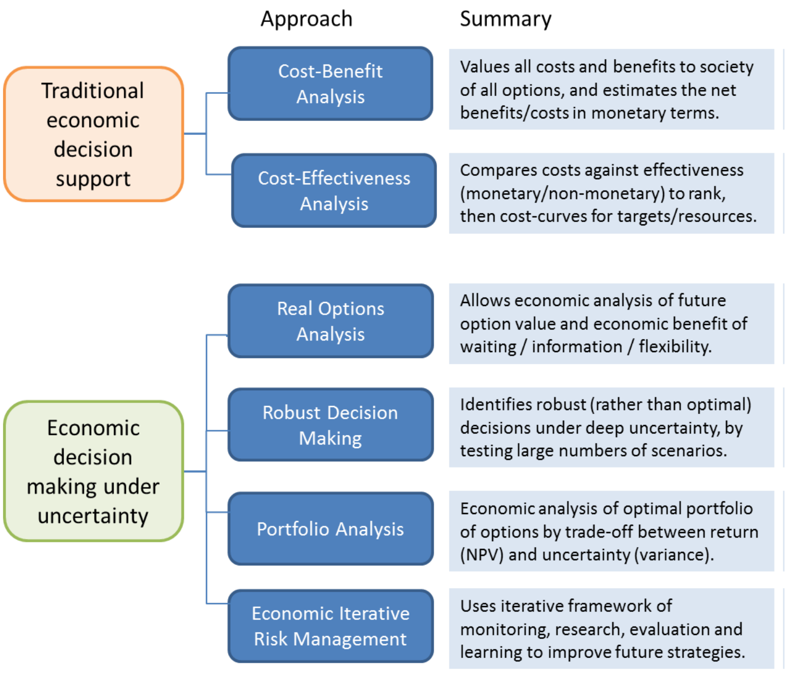
[7] http://mediation-project.eu/output/technical-policy-briefing-notes/

Impact assessment (extreme weather events)	Variation of above, using historic damage-loss relationships. Adaptation costs from replacement or analysis of options.	Consideration of future climate variability. Provides information on short-term priorities (with current climate extremes).	May be inappropriate to apply historical relationships to future socioeconomic conditions. Robustness limited by current high uncertainty in predicting future extremes.
Risk assessment	Risk-based variations include probabilistic analysis and thresholds.	As above, but risk-based context allows greater consideration of risk and uncertainty.	Risk-based approach introduces extra dimension of complexity with probabilistic approach.
Econometric based	Econometrics used for relationships between economic production and climate – applied to future scenarios.	Provides information on multiple factors and can capture autonomous adaptation.	Mostly focused on autonomous or non-specified adaptation. Simplistic relationships for complex parameters. No information on specific attributes.
Adaptation assessments	Economic analysis of adaptive management (iterative adaptation pathways).	Focus on immediate adaptation policy needs, soft and hard adaptation, and decision making under uncertainty.	Resource intensive.

Let us briefly discuss the methodological challenges relevant to some of the outlined methods applied in climate change adaptation studies.

Listed in Figure 1, the traditional economic decision support tools include cost-benefit and cost-efficiency analysis, which heavily rely on discounting and Net Present Value (NPV). Discounting is also involved in Real Options (RO) theory. The discounting imposes time preferences for investments to justify projects, e.g., mitigation efforts to prepare against a 300-year flood. Disadvantages of the standard deterministic discounted criterion are well known (Luenberger, 1998). In particular, it does not reveal the temporal variability of cash flow streams. Two alternative streams (e.g., associated with a system of river channels or a dam) may easily have the same NPV despite the fact that in one of them all the cash is clustered within a few periods, but in another it is spread out evenly over time.

This type of temporal heterogeneity is critically important for dealing with high losses from possible climate change related catastrophes (e.g., floods, hurricanes, etc.) which occur suddenly as a “spike” in time and space as it is discussed in (Ermolieva and Ermoliev, 2005; Ermoliev et al., 2008; O’Neill et al., 2006). An appropriate discount rate is especially difficult to define when decisions involve a time span beyond the planning horizon of the current generation, as market interest rates do not reflect the preferences of future generations (Arrow, K., 1996). A good review and some alternative views on discounting can be found in Zeckhauser and Viscusi (2008) and Chiabai et al. (2012) as it is discussed later in section 3.3.



	Approach	Summary
Traditional economic decision support	Cost-Benefit Analysis	Values all costs and benefits to society of all options, and estimates the net benefits/costs in monetary terms.
	Cost-Effectiveness Analysis	Compares costs against effectiveness (monetary/non-monetary) to rank, then cost-curves for targets/resources.
Economic decision making under uncertainty	Real Options Analysis	Allows economic analysis of future option value and economic benefit of waiting / information / flexibility.
	Robust Decision Making	Identifies robust (rather than optimal) decisions under deep uncertainty, by testing large numbers of scenarios.
	Portfolio Analysis	Economic analysis of optimal portfolio of options by trade-off between return (NPV) and uncertainty (variance).
	Economic Iterative Risk Management	Uses iterative framework of monitoring, research, evaluation and learning to improve future strategies.

Figure 1. Summary of Adaptation Decision Support and Appraisal Tools. Source: (Watkiss and Hunt, 2013).

The tools for economic decision making under uncertainty in Figure 1 include the approaches which address uncertainty and risk while choosing climate change adaptation options. For example, robust decision making (RDM) that is being used among others at RAND[8] refers to a rather loosely defined “framework that helps identify potential robust strategies, characterize the vulnerabilities of such strategies, and evaluate trade-offs among them[9]”. (Lempert et al., 2013) emphasizes that “RDM is not a model, but rather a method for improving quantitative uncertainty analysis and management”. There is no formal definition of “robust” decisions as well as no specification of criteria and procedures used in the analysis. Markandya (2014) argues in favour of 3 components for robustness approach: 1) It selects measures that are effective over the range of possibilities (no-regret); 2) it helps building flexibility into the adaptation measure so can be adjusted if needed in the future; 3) it builds flexibility into the decision process. In Ho Chi Minh City case studies, the RDM is a scenario-by-scenario evaluation of alternatives regarding flood mitigation decisions. A similar analysis of alternatives is performed in (Lempert and Groves, 2010). A decision or measure (or a combination of measures) which is not optimal in each of the individual scenarios can make the whole system better-off with respect to multiple scenarios (uncertainties). Assessment of alternatives can easily run into very large number of evaluations. For example, although floods are classified according to their recurrence periods (e.g. 100-, 500-, 1000-year floods), a 100 year flood may occur today, tomorrow, within the next 10 years, or not at all within a time span being explored. Developing scenario-trees for evaluating interplays among possible flood instances and policy measure responses is impossible in this case, especially accounting for potential conflicting criteria, uncertainty, and risks. In this sense, the choice of criteria and solution procedures defines the notion of “robustness” (some theoretical background to “robust estimates”, “robust solutions” is discussed in (Huber, 1973)). A key feature is the sensitivity analysis of decisions with respect to low-probability catastrophic events induced by climate changes (see, for

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[8] See e.g.: http://www.rand.org/pubs/external_publications/EP50282.html

[9] http://www.rand.org/topics/robust-decision-making.html

example, (Ermoliev and Hordijk, 2006). To achieve robustness of decisions, the model has to include proper risk-adjusted criteria, interdependencies and constraints of involved stakeholders.

Traditional Real Options (RO), very useful tools to build flexibility of adaptation measures, are similar to financial options in that both give the option holder the right, but not the obligation, to take a future action if doing so is advantageous based on future conditions. ROs exist when the underlying asset is a real asset such as land, a business opportunity, adaptation action, e.g., exercising land conversion or changing cultivar to alleviate the impacts of climate change. In RO it is assumed that uncertainty is likely to diminish over time. One of the practical limitations of RO analysis is that adaptation options are evaluated from narrowly-defined perspectives. This approach deals only with a given set of options that are not always evaluated together with other goals and constraints as in social planner models. The RO analysis is usually based on recursive optimization of discounted expected values (e.g. (Linquiti and Vonortas, 2012)). The decisions do not account for the variability of possible scenarios of stochastic parameters. The timing of uncertainties as well as policy updates is predetermined, no endogenous uncertainties which may depend on past or present actions. However, the RO analysis might prove to be well equipped to cope with features such as flexibility options of investments (uncertain returns, possibility to delay investments, alter the scale of the project, etc.) (Abadie and Chamorro, 2013) as it is discussed in section 3.1.1.

In probabilistic cost-benefit analysis, the choice offering highest expected value is selected. However, for a complete picture it is necessary to know all possible outcomes (cost, benefits) which follow from every potential option, and the respective probabilities associated with each outcome. Probabilities, costs, benefits depend on past, current and future policies. Since it may be impossible to explicitly determine costs and benefits, as well as the probabilities associated with future scenarios, it can be difficult to apply the maximum expected value approach, except by using subjective estimates of scenario probability leading to scientific uncertainty (see Section 3.1). Such approaches are generally not recommended (Competence Centre for Climate Change, 2013), but continue to be applied in the modern research.

Multi-criteria decision analysis (MCDA) deals with a multitude of goals (criterions) that are not always directly comparable to each other and involves the assignment of scores to each option on each criterion (see e.g. (Great Britain and Department for Communities and Local Government, 2009)). The incorporation of uncertainty adds even more complexity to the economic approach as well as to the interpretation and use of its results. However, speaking in terms of the approaches described above, uncertainty should be incorporated even given the danger that the results coming from application of the approaches will be less concrete and not necessarily straightforward. In other words, it would be inappropriate to design adaptation around a single future climate projection. If uncertainty is not taken into account, decision-making based on such analyses may not be robust enough. The next chapters present further elaboration on that.

2.1 Expected utility theory, the notion of risk aversion, and discounting

Decision making under risks has evolved since D. Bernoulli's formulation of expected utility theory (EUT) in the 18th century. The argument that people should use expected utility is even older, and was proposed by B. Pascal (1670) as "Pascal's wager" (Lengwiler, 2009). Later on, decisions based on "expected utility" became broadly accepted as "rational decisions", and "rational behaviour under uncertainty" was identified with "optimizing expected utility". The practical importance of the classic theory is underscored by the fact that US Congress requires its use in cost benefit analysis of any major budgetary decision (Chichilnisky, 2011). EUT is also involved in the analysis of climate change mitigation and adaptation policies, which might affect future generations. In this context, the crucial question is how EUT and relevant methods and concepts, e.g., Cost-benefit analysis (CBA), Probabilistic cost-benefit analysis (PCBA), Net present value (NPV), etc., are able to deal with cross-generational issues, uncertainties and catastrophic risks, inherent to the climate change debate. A practical issue is the development of robust policies under uncertainties and risks associated with climate change that are potentially of a catastrophic nature. Catastrophic risks are rare events with major impacts, for example, weather-related catastrophes (floods, hurricanes, droughts, etc.), cascading catastrophes (black-outs in power supply networks), etc. Under catastrophic risks, the principle of (expected) utility maximization does not work. EUT evaluates projects according to average indicators (losses or gains), without accounting for possible catastrophic spikes which may ruin insurers, affect farmers, destroy infrastructure, cause outbreaks of epidemics, etc. Average indicators ignore the contribution of rare extreme events. There appears the need for safety, solvency, security, and stability constraints for the treatment of catastrophic risks.

According to the EUT theory, individuals should use the expected value of the utility (usefulness, usage) of different outcomes (gains, losses, payoffs) of their choices as a guide for making decisions. EUT states that the decision maker (DM) chooses between projects by comparing their expected utility values, i.e., the weighted sums obtained by adding the utility values of outcomes multiplied by their respective probabilities. Introduction of utility functions allowed to introduce the so-called DMs attitude to risks, i.e., *risk aversion*, *risk-neutrality*, *risk-seeking*. Risk aversion is the reluctance of a DM to accept a project with an uncertain payoff rather than another bargain with a more certain, but possibly lower, expected payoff. Risk aversion of a DM assumes a concave utility function. DMs may have different risk attitudes, e.g., risk-neutral (linear utility function), or risk-seeking (convex). In traditional utility theory, the degree of risk aversion is measured by Arrow–Pratt coefficient of absolute and relative risk-aversion, which assumes twice-continuous differentiability of the utility function. The attitude of DMs towards risk aversion (concave utility), or more generally their individual risk preferences, is underrepresented in most of economic models. Crucial in the discussion is that most of the economic models, including general equilibrium (GE) models, turn out to be too simplistic in terms of treating risk as there is e.g. no need for "insurance markets specializing in risks" (Geanakoplos, 2008). In reality, risk aversion preferences play a substantial role. A DM or a social planner (welfare maximizer) may be a risk taker for smaller amounts and a risk avoider when larger (e.g. catastrophic) amounts are involved. Thus, a DM may select layers of different risks to ensure stability of the portfolio.

In fact, it is argued that individual and “social planner” utility functions should be different. Many empirical studies make attempts to estimate utility functions of different DMs, e.g., of an investor, fund manager, etc. For example, (Friedman and Savage, 1948) argue that the utility function must include a convex segment, i.e. a segment with increasing marginal utility. In this case, the utility curve follows an S-shape. (Markowitz, 1952a) refines Friedman and Savage’s and reaches a similar conclusion regarding risk aversion: he claims that investors have a utility function with concave and convex segments. While Friedman and Savage and Markowitz make theoretical arguments regarding the shape of the utility function, (Kahneman and Tversky, 1979) conduct experiments to study this issue.

Based on their experimental results, they conclude that investors maximize the expected value of a function (of profit) with a convex segment for negative outcomes and a concave segment for positive outcomes. Further empirical studies indicate substantial difficulties in estimating exact shapes of utility function.

For almost as many years as EUT has existed, experimental and empirical evidence has questioned the validity of the expected utility model. With respect to climate change, traditional criticism comes from the fact that (expected) utility normally refers to behaviour of individuals, while a welfare maximizer or a social planner has to have a utility that is different from that of individuals. Here the choice of utility is an ethical choice concerning the society as a whole. This ethical dimension of EUT has much importance for real-life cost-benefit analysis when, as in the field of climate change policy (see e.g. (Stern et al., 2006)), the interests of future generations are to be given proper attention.

The above discussion is important because so far, most of the models that have been used to analyse the economics of climate change rely on general equilibrium (GE) principles implying both risk/utility and cross-generational issues involving time preference structure of investments, i.e., discounting. Many integrated assessment models (IAMs), are dynamic general equilibrium models, e.g., DICE (Nordhaus, 1992), RICE (Nordhaus and Yang, 1996), GLOBE and MAGNET (Tonini et al., 2013), etc. Though GE theory has been initially established as a fundamental framework for theoretical discourse (Ackerman, 2002), its influence continues to spread in policy applications, with the growing use of computable general equilibrium models. Applicability of GE in climate change is highly debated for several reasons. For example, non-convexities, such as increasing returns to scale in production or introduction of new technologies (Gritsevskyi and Nakićenovic, 2000), are common in reality. If they are allowed into the theory then the existence of an equilibrium is no longer certain. Some critics of GE say that the world is essentially not in equilibrium. According to (McCloskey and McCloskey, 1994) the whole category of general equilibrium theorizing is merely “blackboard economics,” exhibiting the “rhetoric of mathematical formalism”. There are some theorists who criticize GE for immensely aggregated critical heterogeneities. For example, (Saari, 1995) writes that “[T]he source of the difficulty – which is common across the social sciences – is that the social sciences are based on aggregation procedures... One way to envision the aggregation difficulties is to recognize that even a simple mapping can admit a complex image should its domain have a larger dimension than its image space... [T]he complexity of the social sciences derives from the unlimited variety in individual preferences; preferences that define a sufficiently large dimensional domain that, when aggregated, can generate all imaginable forms of pathological behaviour”. This is especially true with respect to inherent heterogeneity of people and places subject to climate changes. Most of the IAMs discussions thus far have assumed that most of the relevant parameters are known with certainty. This is useful for exposition but obviously highly unrealistic —particularly in the context of climate change policy.

Discount rate is one of the most important parameters defining CBA, PCBA, NPV, and dynamic GEs evaluations. All studies assume discount rate as exogenous to the economic problem, and its choice is an ethical act. Many studies assume the intergenerational discounting rate equal to the rate of return in the capital market, which means that for a modest interest rate of 3.5% the expected duration of evaluation time horizon does not exceed 30 years (Ermoliev et al., 2008). Thus this rate orients the policy analysis on a 30-year expected time horizon, which has no correspondence with expected, say, 100- or 300-year extreme events. (Ramsey, 1928) argued that to apply a positive discount rate to discount values across generations is unethical. (Koopmans, 1966) contrary to Ramsey argued that a zero discount rate would imply an unacceptably low level of current consumption. According to (Arrow et al., 1996) “the observed market rates of interest refer to how individuals are willing to trade off consumption over their own life. These may or may not bear a close correspondence to how a society is willing to trade off consumption across generations”. The “perspective” approach tends to generate relatively low discount rates and thus favours mitigation measures and the wellbeing of future generations. The “descriptive” tends to generate higher discount rates and thus favours less spending on mitigations and the wellbeing of the current generation. The constant discount rate has only limited justification (see further overviews in (Chichilnisky, 1997; Frederick et al., 2002; OXERA, 2002). The recent literature argues that discount rates vary with time. As a compromise (see discussion in (Cline, 1999)) between “prescriptive” and “descriptive” approaches there is an argument for a decline in time discount rate of 5% for the first 30 years, and 1.5% beyond this. There have been proposals for other schedules and attempts to justify the shape of proper decline. Papers (Newell and Pizer, 2003; Weitzman, 1999) shed some light on how uncertainty about the rate of return produces a certainty equivalent discount rate which will generally be declining with time. (Weitzman, 1999) proposed to model interest rates by a number of exogenous time dependent scenarios. He argues for rates of 34% for the first 25 years, 2% for the next 50 years, 1% for the period 75-300 years and 0 beyond 300 years. (Newell and Pizer, 2003) analysed uncertainty of historical interest rates by using data on the US market rate for long-term government bonds. They proposed a different declining discount rate justified for a random walk model.

It can be shown that the choice of discounting associates with the occurrences of a “stopping time” event, determining a finite random horizon of evaluation (Ermoliev et al., 2010, 2008). Extreme events might affect discount rates, which in turn alter the optimal mitigation efforts that ultimately close the feedback loop impacting on the frequency of extreme events. This endogeneity of discounting and induced complexity calls for exploration of equivalent undiscounted evaluations and stochastic optimization methods (Section 3.3). In this connection it is important to discuss the implications of uncertainties and catastrophic risks on the choice of discounting. Especially, this concerns catastrophic risks and projects protecting against these risks (e.g. floods – dams, reservoirs, etc.).

2.2 Challenges of dependent catastrophic risks

Risk carries many different meanings depending on the area of application. In financial, insurance, engineering, operations research, and extreme events management communities, decision making under risk has a long tradition. Unfortunately, it has developed independently from traditional economic theory. The standard economic theory is dominated by truncated models of uncertainties, represented by a finite manageable number of contingencies well known to the society, which can, therefore, be priced and spread over the whole society through markets. Under such assumptions of certainty, catastrophes pose no special problems (Arrow, 1996).

The increasing interdependencies and vulnerability of our society calls for new integrated approaches to economic developments and risk management with an explicit emphasis on a possibility of catastrophes. The possibility of increasing frequency of catastrophes is prominent in discussions on current global changes. In fact, one of the main points in climate change debates concerns the increasing frequency of extreme events: floods, droughts, heatwaves, and windstorms rather than the increasing global mean temperature which can be within the difference between the average temperature of cities and their surrounding rural areas. The reason for catastrophes to become more statistically dependent is connected to increasing interdependencies among different regions and countries, clustering of properties and population in hazard prone areas and creation of new hazard prone areas, a phenomenon that may be aggravated by a lack of knowledge and ignorance of the risks. Analysis of insurance companies shows that because of economic growth in hazard-prone areas, damages due to natural catastrophes have grown at an average annual rate of five percent (Froot, 1997) and compares our society with a busy highway where disruptions in one its part may lead to fundamental traffic jams in other parts.

Dependencies among systems in the absence of proper integrated systems analysis may lead to the emergence of so-called endogenous systemic risks with potential catastrophic outcomes. Often, these are catastrophes induced by a combination of natural disasters with man-made failure. Examples relevant to climate change include hurricanes and floods which are often triggered by high intensity or long duration of rain, in combination with inappropriate reservoir management, land use planning, maintenance of flood protection systems, and behaviour of various agents. Other examples may include secure food, water, and energy provision.

Catastrophes produce heterogeneous losses highly mutually dependent in space and time, which are not analytically tractable. Heterogeneity of catastrophic risks challenges the standard insurance risk theory. The central problem of this theory is modelling the probability distribution of total future claims (Grandell, 1991) which is then used to evaluate ruin probabilities, premiums, reinsurance arrangements, etc. This theory essentially relies on the assumption of independent, frequent, low consequence (conventional) risks, such as car accidents, for which decisions on premiums, estimates of claims and likelihood of insolvency (probability of ruin) can be calculated by using rich historical data. The frequent conventional risks also permit simple risk-pooling, i.e., ``more-risks-are-better'', strategies with simple ``trial-and-error'' or “learning-by-doing” procedures for adjusting insurance decisions.

Catastrophic risks challenge the standard extremal value theory (Embrechts et al., 2000). The law of large numbers does not work sufficiently well in that case (in general), and the probability of ruin can only be reduced not just by pooling risks, but only if the DM (e.g., risk manager) deliberately selects the fractions of dependent catastrophic risks they can manage. The existing extremal value theory deals also primarily with independent events assuming these events are quantifiable. Definitely catastrophes are not easily quantifiable events as they may have quite different spatial and temporal patterns, which cause significant heterogeneity of losses in space and time. These losses can be dramatically affected by risk mitigation decisions (by construction of a dike or a flood retention area) and loss spreading schemes within a country or on the international level through the insurance or financial markets.

The interdependency of catastrophes and the linkage between their occurrence, scale, and decisions made before their occurrence call for a design of integrated approaches combining catastrophe models with specific decision support procedures (see Section 3.1), e.g. Adaptive Monte Carlo approaches based on Stochastic Quasi-gradient methods. Such an integrated modelling framework for catastrophic risk management is being developed at the International Institute for Applied Systems Analysis (IIASA) for a number of risk management case studies including floods induced by dam breaks, windstorms, seismic risks, and livestock epidemics risks (Amendola et al., 2000; Ermolieva and Ermoliev, 2005; Y. Ermoliev et al., 2000; Y. M. Ermoliev et al., 2000). In a sense, this approach bridges decision oriented economic theory with risk theory and catastrophe modelling. The choice of decisions in the presence of endogenous catastrophic risks can be regarded as a spatially explicit and dynamic stochastic optimization problem combining goals and quantile-based security constraints of the agents. For dealing with long evaluation horizons of catastrophic events, (Ermoliev et al., 2008) proposes new approaches to discounting. In Section 3.2.3 we discuss in detail an integrated catastrophe management model for dealing with flood risks.

2.3 Risk measures. Modern Portfolio Analysis

In the finance industry the importance of risk treatment has been recognised especially in connection with market crashes. For the stability of financial institutions Markowitz (Markowitz, 1952b) suggested the evaluation of financial asset portfolios accounting for the fact that assets with high expected returns may also be characterised by larger variability – both positive and negative, i.e., large standard deviations (which is currently a de-facto basis for Modern Portfolio

Analysis). Markowitz suggested to use the standard deviation of returns as a measure (proxy) for risk, which is valid only if asset returns are normally (or symmetrically) distributed. The Markowitz model relies strictly on the assumptions that the returns of assets are multivariate normally distributed or investor's utility function is quadratic (Weng Hoe et al., 2010). In many practical situations, neither of these two assumptions holds true. Many studies such as (Brooks and Kat, 2001) show that returns from hedge funds are not normally distributed. According to (Pratt, 1964), quadratic utility function is very unlikely because it implies increasing absolute risk aversion. Another problem with that approach is that mean-variance estimates are not robust to new observations (Ermoliev and Hordijk, 2006; Huber, 1973). In many practical studies DMs naturally object to employing standard deviation as a risk measure because standard deviation gives equal weight to deviations above the mean and deviations below the mean, whereas investors are likely to be more worried about bad outcomes, i.e., "downside deviation" rather than "upside deviation." According to this view, the most relevant returns are returns below the mean, or below zero, or below some other "target" or "benchmark" return. This has led to a "downside risk" measures. For example, an investor may quantify risk in terms of a shortfall risk; the risk that a portfolio's value will fall below some minimum acceptable level during a stated time horizon.

Shortfall risk is one example of the larger concept of downside. Downside risk concepts include not only shortfall but such concepts as semi-variance and target semi-variance. The oldest shortfall risk criterion in financial applications is Roy's safety-first criterion (Roy, 1952). Roy's safety-first criterion (SFC) states that the optimal portfolio minimizes the probability over a stated time horizon that portfolio return will fall below some threshold level that the investor targets to meet or exceed. If the portfolios under consideration have normally distributed returns, Roy's SFC can be reduced to maximization of the safety-first ratio, defined by expected return, its standard deviation and the minimum acceptable return. Otherwise, if the returns are not normal, the criterion is difficult to optimize.

Roy's criterion received renewed attention with the official adoption of the Value-at-Risk (VaR) measure (probabilistic constraint) in the Basel capital accords and the attention for downside risk concerns in behavioural finance (Basle Committee on Banking Supervision, 1999). The Value-at-Risk (VaR) emerged in the late 1980s after the stock market crash of 1987. For a given probability and a given time horizon, VaR indicates an amount of money such that there is *that* probability of the portfolio not losing more than *that* amount of money over *that* horizon. For example, if a portfolio has a one-day 90% value-at-risk of USD 3.2 million, such a portfolio would be expected to not lose more than USD 3.2 million, nine days out of ten. VaR is an established risk measure used in banks and financial firms for reporting (Basle Committee on Banking Supervision, 1999). Most financial applications still assume normal distribution of asset returns. Straightforward optimization of VaR is difficult, especially when using scenarios. In this case, VaR is non-convex, non-smooth, and it has multiple local extrema (Uryasev, 2000). Pros and cons of VaR are well-known (Artzner et al., 1999; Rockafellar and Uryasev, 2000). VaR is easily comprehensible. It is heavily used in various engineering applications, e.g. (Marti, 2008), where VaR risk constraints are called chance or safety constraints on probabilities of failures or losses.

In some applications, the biggest disadvantage of VaR is that it does not inform on the losses exceeding VaR. From a computation point of view, VaR is difficult to optimize for non-normal distributions. VaR has been also classified as nonconvex, i.e., not sub-additive measure. This property is the mathematical equivalent of the diversification effect. For risk measures that are not sub-additive it may happen (Artzner et al., 1999, 1997) that the diversified portfolio of independent risks, which is commonly considered as a way to reduce risk, can lead to an increase of VaR. In this sense, VaR is not a good measure of risk. This is one of the reasons why other types of risk measures have been studied, however the crucial assumption here is the independency of risks. For the analysis of risk measures, (Artzner et al., 1999, 1997) have introduced an axiomatic classification of the so-called coherent risk measures. Coherency, in particular, implies the “good” sub-additivity property which VaR lacks. Examples of coherent risk measures include MINIMAX and Conditional Value at Risk (CVaR). CVaR accounts for losses exceeding VaR (Figure 2). However, CVaR has a number of pitfalls, especially in its treatment of catastrophic risks. For example, CVaR is sensitive (not robust) to addition of outliers (scenarios). While sub-additivity is required for independent risks, it may be a bad property for estimating portfolios with dependent catastrophic (systemic) risks, etc.

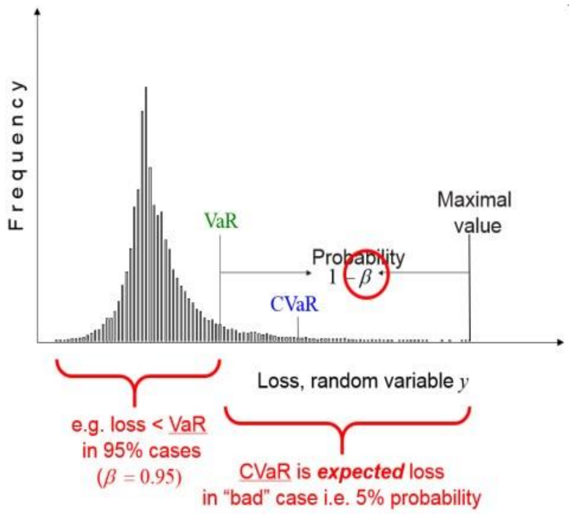

Figure 2. Conditional Value at Risk (CVaR) concept.

2.4 Treatment of risks and uncertainties in statistics, operations research, and engineering

Here we briefly discuss and summarize some notions and approaches, e.g., from statistics, operations research, stochastic programming, reliability theory, engineering communities, which we further transfer and apply in integrated models treating systemic risks in climate change adaptation (examples on floods management, emissions abatement and pricing, and land use planning are presented in the Section 3.2).

The idea to ensure the safe functioning of complex stochastic systems by a large probability, i.e. imposing a probabilistic constraint, comes from statistics and reliability theory. Sophisticated methods, e.g. the sequential analysis of Wald (Wald, 1945), contain the principle that the decision in favour of or against the hypothesis should be made by large probability. In reliability theory the correct functioning of one single part or a complete system is characterized by its probability and usually it has to be a number close to 1.

The need for including risks and uncertainty in complex decision models arose early in the history of mathematical programming. (Charnes and Cooper, 1959) developed a chance or probability constrained model. First two-stage models involving an action (ex-ante, anticipative decisions) followed by observation and reaction (recourse, ex-post operational decisions) appear in Beale (Beale, 1955) and (Dantzig, 1955). Both models originate from statistical decision theory (SDT) (Wald, 1950), but in contrast to SDT emphasize methods of solution and analytical solution properties.

In engineering, probability of failure characterizes functioning of one single part or a complete system. Such notions as “reliability” and “safety” relate to probability or chance constraints. In particular, reliability is defined as the probability that a technology or a construction, e.g., dam, reservoir, etc., will perform without failures for a specific time period under various scenarios.

Safety or reliability constraints in statistics and operations research motivates the development and application of advanced stochastic programming methods for risks and uncertainty treatment in interdependent economic, engineering, financial, environmental, technological systems, involving complex risks assessment techniques (Bowles, 2007, 2001; IAEA, 2001, 1992).

For example, safety of water treatment technologies (dams, reservoirs, channels) involves multiple safety goals of various agents, including non-engineering aspects (Tatiana Ermolieva et al., 2013). In particular, this relates to the so-called equity and ethical considerations, where the concerned parties are those who may be harmed if the dam is not constructed or if it fails. Here, there appears an essential dilemma. The dam is designed to withstand a specific probable maximum flood (PMF) to which corresponds a “maximum limit level of risk” (Bowles, 2007, 2001). The PMF criterion has become rather standard criteria for flood protection of major dams over the past decades (Jansen, 1988). The problem faced by the designers of dams and dam owners is to determine how much protection and maintenance should be provided to a dam considering the trade-off that rare high impact events can, but may not occur during the lifetime of a dam. Objectives of the evaluation of dams fall in two broad categories: economic efficiency and equity or ethics. The economic objective seeks to maximize benefits over costs, while equity objectives seek to find a balance between expenditures for dam construction (reinforcement and maintenance) of dam owners (and other parties, who may benefit from the dam) and those who might be potentially harmed in connection with the dam, e.g., farmers, households, infrastructure owners, etc.

Similar to engineering systems, safety and security requirements can be built in integrated economic, engineering, financial models for climate change adaptation involving multiple stakeholders. This may involve quantile-based chance (VaR) or CVaR type constraints, other forms of risk-adjusted indicators or functions enabling robust sustainable performance of interdependent systems, as it is discussed in Sections 3.1 and 3.2.

2.5. Transfer of risk and ambiguity aversion parameters

As a component of an adaptation strategy, the role of financial, insurance and reinsurance industries is crucial, especially their capacity and respective instruments for absorbing, redistributing, and shifting of potential catastrophic interdependent losses. Institutions for risk and ambiguity (uncertainty)-shifting and sharing will also be important in particular with respect to these catastrophic risks. There is a possibility, however, that some of the risks (changes) might turn out to be uninsurable (irreversible). In an adaptation context, risk perception, risk preferences, and their quantification and parametrization are needed for practical modelling and applications. The elaboration on this topic and more details are part of the forthcoming ECONADAPT deliverables D2.1-2.3.

2.6. Future learning and quasi-option values

The climate change uncertainty in quantification of impacts and adaptation costs and benefits can potentially be reduced with time and effort (called “learning”), which leads to a set of important questions: what needs to be done to resolve (if possible) the present uncertainties? To what extent can the uncertainties be resolved, is it better to act in the face of uncertainties or wait until additional information comes? How to address the trade-off between ex-ante decisions in the face of uncertainties and ex-post operational decisions when additional information becomes available? Given the possibility of future learning, issues of irreversibility may become salient.

The value of information – also known as quasi-option value – and existing methods for estimating the value of information in climate adaptation assessment can be explored in order to address the issue of ranking: which new data types or forms are most valuable. However, as the practice of estimating the value of climate risk information is in its infancy, this is a task among the most challenging ones on the agenda of adaptation-related quantification. The elaboration on this issue and more details are part of the forthcoming ECONADAPT deliverables D2.1-2.3.

2.7. Sequential decision making, learning, and maladaptation

Most state-of-the-art climate change mitigation and adaptation analysis tends to frame the climate change problem as a hit-or-miss type of decision making situation, in which a policy choice is made in a scenario-by-scenario manner. Acting with respect to a single (climate change or a catastrophe) scenario is associated with the risk of irreversibility and sunk costs (e.g., maladaptation) if a different scenario materializes. With respect to potential catastrophes, the analysis explicitly recognizes that the problem should be more accurately framed as sequential decision making under uncertainty. For example, one reflection is in a choice between acting now, either mitigating or adapting, or waiting until more information reveals (Chichilnisky and Heal, 1993; Dixit, 1994; Kip Viscusi and Zeckhauser, 1976; Pindyck, 2000; Ulph and Ulph, 1997; Webster, 2002; Wright and Erickson, 2003). This is a natural framing of the problem involving uncertainty, irreversibility and the potential for learning about climate change. Here, the main issue is how to properly factor in the irreversibility (sunk) costs (O'Neill et al., 2006). In economic literature the importance of irreversibility, learning and the concept of two-period decision making model was first introduced in connections with irreversible investments in land use change (Arrow and Fisher, 1974).

The term "two-period" or "two-stage" does not necessarily reflect just two consequent time intervals. Rather, these are two different types of decisions. First stage strategic decisions can be characterized as the decisions in the face of uncertainties (before "learning"). These are decisions which are costly to be altered (or even irreversible), e.g., land conversion or expansion, changing production structure, investing in an irrigation system, which may require huge up-front investments and long period of implementation and pay-back. Second stage decisions are executed when additional information on uncertainty is revealed (after "learning"), and the policies can be adjusted. These operational ex-post decisions aid strategic decisions. Inadequate modelling of interconnected strategic first-stage and adaptive second-stage decisions may lock a project (or the economy) in a wasteful use of resources and investments. (Fisher and Narain, 2003) analysed a two-period climate change learning model in a GHG abatement context using expected values of impacts. Setting a problem that way, however, is rather challenging as there is no explicit relation between the shape of uncertainties and decisions, what substantially restricts the analysis possibilities and may result in misleading conclusions (O'Neill et al., 2006).

The challenge of uncertainty, learning and the irreversibility (maladaptation) of decisions requires more rigorous approaches than "expected value", accounting for interdependencies between the first and the second stage decisions by using a criteria reflecting the variability of outcomes. Two-stage stochastic optimization approach naturally integrates the two types of decisions: strategic and operational decisions (risk preferences might be different at different stages). Therefore, the robustness of the decisions in a two-stage framework is achieved by combining two fundamental mechanisms for coping with uncertainty – anticipation and adaptation (Ermoliev and Wets, 1988). The robustness of the two-stage decision is also achieved with respect to different safety constraints and indicators reflecting the nature of the risks. A thorough discussion of two-stage STO is presented in (Ermoliev and Wets, 1988); an application of two-stage STO for the analysis of irreversibility and learning in climate change is presented in (O'Neill et al., 2006); application on catastrophic floods management is discussed in (Ermoliev et al., 2013).

3 Beyond the state of the art approaches

Section 1.1 discussed challenges arising in relation to climate change adaptation and Section 2 reviewed state-of-the-art economic tools and approaches to treat uncertainty in climate change analysis. In this section we suggest and introduce the methodological concept of integrated risk management in climate change adaptation extended with quantile-based criteria and robust solutions. We discuss the main advantages, challenges, and some technicalities of the suggested approaches.

3.1 Robust management of risks, evaluation of trade-offs

The notion of robustness in general decision problems differs from the notion of statistical robustness. A key difference comes from how sensitivity is considered with respect to low probability catastrophic events. Robust decisions in the presence of catastrophic events are fundamentally different from decisions ignoring them. Specifically, a proper treatment of extreme catastrophic events requires new sets of feasible decisions adjusted to risk performance indicators, and new spatial, social and temporal dimensions. Here is a simple example demonstrating that explicit treatment of risks enlarges a set of feasible solutions by including robust solutions, which are unattainable in scenario-by-scenario evaluations. Consider two crops A and B, and two states of nature, e.g., wet and dry season. Crop A outperforms crop B in a wet season, and B is better in a dry season. Production has to be planned before information about the season becomes known. A deterministic approach would lead to maladaptation if crop A is planted and the dry season occurs (same with crop B and the wet season). A robust solution may be crop C (or a combination of A and B), which is neither better than crop A in wet or crop B in the dry season, however, it is better in the context of uncertainties about the season. Thus, the robust solution minimizes costs associated with decisions taken before the uncertainties are revealed and the costs of correcting these decisions after information on uncertainties becomes available. The so-called *value of the stochastic solution* (VSS) (Birge, 1982) measures benefits of a robust solution compared to a solution of a deterministic model applied in a stochastic environment.

Another example demonstrates the shortcomings of scenario-based (Monte Carlo) uncertainty analysis, which produces a sample of outcomes dependent on a scenario run. A change in policy variable might affect probabilistic characteristics of simulated outcomes and therefore require a new set of Monte Carlo runs. The number of possible combinations of potential uncertainty scenarios and decisions increases exponentially. Thus, with only 10 feasible solutions, for example, levels of emissions reductions, i.e., 10, 20, …, 100%, in a given region, 10 regions, and 10 possible e.g. policy scenarios on top of that, the number of "what-if" combinations is 10^{11}. Thus, simulation-based approaches to evaluation of possible alternatives may easily run into nearly infinite number of decisions evaluations without ultimately giving a clue about the optimal one.

Contrary to these, Adaptive Monte Carlo stochastic optimization using stochastic quasi-gradient (SQG) procedures (Ermoliev, 2009a, 2009b) provides an efficient means for deriving robust optimal solutions without evaluating all alternatives, especially in the case of endogenous uncertainties, i.e., when uncertainties depend on solutions (Tatiana Ermolieva et al., 2013;

Ermolieva and Ermoliev, 2013; Ermolieva and Obersteiner, 2004; Ermoliev et al., 2013). An "Adaptive Monte Carlo" simulation is a technique that makes on-line use of sampling information to sequentially improve the efficiency of the sampling itself. The notion of "Adaptive Monte Carlo" optimization is being used (Ermoliev and Norkin, 2013) in a rather broad sense, where improvements of the sampling procedure with respect to the variability of estimates may be only a part of the improvements with respect to other goals of robust decisions.

The standard expected utility maximization model suggests two types of decisions in the response to uncertainty, either risk averse or risk prone decisions. These two options also dominate current climate change policy debates, emphasizing either ex-ante anticipative emission reduction programs or ex-post adaptation to climate changes when full information becomes available. Mitigation and adaptation measures to climate changes are discussed to a large degree independently one from another.

Clearly, a robust policy must include both options, i.e., the robust strategy must be flexible enough to allow for later adjustments of earlier decisions. The two-stage and multistage recourse models of stochastic optimization (Dantzig, 1955; Kall and Wallace, 1994) incorporate both fundamental ideas of anticipation and adaptation within a single model and allow for a trade-off between long-term anticipatory strategies and related short-term operational flexible adjustments of strategic first stage decisions once information about uncertainties becomes available ("learning" stage). Therefore, the adaptive capacity can be properly designed ex-ante, through investments in structural measures (e.g. dikes, irrigation systems, reinforcement of buildings), changing production structure, emergency plans and insurance arrangements. Robustness is also ensured by proper representation of interdependencies among uncertainties and decisions, adequate sets of feasible decisions and performance indicators, e.g., security constraints, characterizing main socio-economic, environmental, technological concerns.

3.1.1 Building robustness of adaptation measures: Real Option Analysis

As previously stated RO analysis can contribute to robustness by offering flexibility in adaptation measures. There are many situations where this can be very useful. A simple example would be a coastal area that can be protected against sea level rise by building a dyke of 1 metre high now or a 1 metre dyke with stronger foundations that allows raising the wall up to 2 or 3 metres should it becomes necessary (see Markandya, 2014).

Real options evolve from financial economics and are meant to deal with future uncertainties of a project's implementation (Zeng and Zhang, 2011).The concept of real option is relatively easy to understand; this is, when an investment decision is made, the entity doing it can obtain a right that can be used to buy or sell a physical asset or investment plan in the future (Myers, 1977).

In the context of adaptation economics, it can be said that Real Options Analysis quantifies the investment risk associated with uncertain future outcomes, being very useful when considering the value of flexibility of investments (Watkiss et al. 2013). "This includes the flexibility over the timing of the capital investment, but also the flexibility to adjust the investment as it progresses over time, i.e. allowing a project to adapt, expand or scale-back in response to unfolding events. The approach can therefore assess whether it is better to invest now or to wait – or whether it is better to invest in options that offer greater flexibility in the future." (Watkiss and Hunt, 2013).

This investment analysis tool has been gaining a lot of interest in the framework of adaptation economics as it "aligns with the concepts of iterative adaptive (risk) management, providing a means to undertake economic appraisal of future option values the value of information and learning, and the value of flexibility, under conditions of uncertainty. It can therefore justify options (or decisions) that would not be taken forward under a conventional economic analysis" (Watkiss and Hunt, 2013).

Relatively few applications exist for adaptation alternatives or investment projects. One of the exceptions is Kontogianni et al. (2014) where the alternatives to protect the Greek coast from sea level rise are analysed. They conclude that the analysis “through recognizing the uncertainty and keeping all the options open till uncertainty is resolved, provides an adaptation strategy that may be beneficial […] for the society”. Another interesting example can be found in Jeuland and Whittington (2013) with an application to water resource planning in Ethiopia for the construction of several large dams and operating strategy accounting for uncertainties due to climate change. And a third example is the work by Woodward et al. (2011) for flood risk management in the Thames Estuary. They conclude that “the results obtained demonstrate the potential for substantial cost savings under future uncertainties when Real Options are used instead of more traditional, precautionary approaches”.

The RO method is later applied in Work Package 6 in the Bilbao case study for flood protection alternatives.

3.2 Integrated dynamic modelling for climate change adaptation

With regard to climate change adaptation, the main concern is not only about the nature of uncertainty and risks, but even more - how these may impact on the well-being of humans who are dependent on food, water, energy, and environmental security, in a direct or indirect way. Researchers are concerned with the development of integrated models, methods, and tools, enabling the systems analysis of interdependent systems. The goal is to find solutions supporting the correct functioning of the systems independently on which scenarios occur. Below we provide an overview of the tools and models applied in selected studies of systemic risks induced exogenously (e.g. due to weather variability) or endogenously (by policy failures) and affecting food, energy, and water security.

3.2.1 Treatment of systemic risks in Stochastic GLOBIOM

Climate change challenges the world food system – a system that is supposed to feed everybody while ensuring the sustainable management of natural resources. Climate change, and particularly climate variability, have a growing impact on land use systems including agriculture. Unpredictable and severe weather patterns can destroy harvests, farmer’s livelihoods and seriously affect food supply. Integrated systems analysis of future land use changes induced by climate change and variability, socio-economic, population, and technological trends is important for global and regional decision makers for coping with inherent uncertainty. Increasing demands and sudden alterations of land uses triggered by various factor including but not limited to climatic drivers may have serious impacts on local water, soil, air, and increase health risks to humans. For example, the transformation of forest into cropland causes changes in water, soil, and air quality (Fitzherbert et al., 2008).

Stochastic version of the GLOBIOM model (Ermolieva et al., 2015; Havlík et al., 2011) is a large-scale dynamic recursive stochastic partial equilibrium model enabling integrated land use planning achieving food, energy, water, emissions security goals. GLOBIOM accounts for interdependencies among main Land Use Systems (LUS) on global, national, and grid-cell levels. Food, water, environment (emissions) security constraints and biofuel targets introduce competition for limited resources (land and water). The supply of crops, i.e., agricultural production, has to cover final demands, livestock feed requirements, and biofuel production targets. Food consumption constraints in the model are consistent with nutrition requirements (Joint FAO/WHO/UNU Expert Consultation on Energy and Protein Requirements, 1985; Joint

FAO/WHO/UNU Expert Consultation on Human Energy Requirements, 2004) and they have to be fulfilled under all circumstances.

Forestry resources are used for production of saw logs, pulp logs, and other industrial logs. Forest production also includes biomass for energy and traditional fuel wood. The energy biomass can be utilized through combined heat and power production, fermentation for ethanol, heat, power and gas production, and gasification for methanol and heat production. Furthermore, woody biomass for energy can also be produced from short rotation tree plantations. Agriculture and forestry sectors are bound among others by bioenergy targets and other policies (e.g. REDD) which introduce systemic risks among sectors in stochastic GLOBIOM. The model allows for endogenous conversions among land uses within the available total land constraint. Land use change alternatives are limited through explicit food, feed, energy, water, environment security constraints, as well as benefits, efficiency and potentials of conversion of one land use to another, and by linking land suitability criteria to production potentials. For details on the suitability analysis, the reader is referred to (Havlík et al., 2011), where all basic assumptions on exogenous drivers (i.e. parameters on population, economic, environmental, and technological developments, etc.) are presented.

In stochastic GLOBIOM systemic risks are characterized by the entire structure of the systems including distributions of risks shaped exogenously and endogenously by decisions of agents, costs structure, market prices, technologies, security constraints characterized by critical quantiles, Value-at-Risk (VaR) and Conditional Value-at-Risk (CVaR) risk measures, and feasible decisions of agents. The model incorporates stochastic representation of crop yields facilitating analysis of induced systemic risks on crop production and food, energy, and water provision. Stochastic GLOBIOM, for instance, is capable of treating cascading events in interdependent climate-agriculture-energy systems, e.g. a shock to corn production possibly leading to a deficit of important feedstocks for biofuels. To meet the biofuel targets, corn may be substituted by a costlier feedstock, for example, wheat, that would divert wheat from direct food and feed consumption, raising the prices both for biofuels and crops (for food and feed). That may, in turn, intensify production, destabilize market flows, and require additional storage capacities and trading possibilities. Stochastic GLOBIOM can be applied to designing robust land allocation, trade and storage decisions ensuring food, energy, water, environment security (FEWES) under systemic risks.

In (Ermolieva et al., 2015) it has been discussed that the current increase of grain price volatility and low grain stock-to-use ratios are consequences of disintegrated policies ignoring complex linkages and systemic risks in LUSs. For example, due to weather-related yield variability and high demand for corn bioethanol, the recent corn stock-to-use ratio has fallen below 15%. From January 2005 until June 2008, maize prices almost tripled (Mitchell, 2008). A sudden rise in corn prices has increased the prices of other agricultural commodities such as soya and wheat. Soybean and meat prices have risen. As corn is an important source for biofuel feedstocks, to fulfil climate mandates many countries of the world further encourage land grabbing to produce even more corn biofuels (GRAIN, 2013). In (Ermolieva et al., 2015) it has been shown that, contrary to a deterministic scenario-by-scenario analysis, the risk-adjusted two-stage decisions of stochastic GLOBIOM aid FEWES by hedging systemic production and consumption risks and ensuring market stability. In stochastic GLOBIOM land allocation among LUSs at global, national, and grid-cell levels is ex-ante strategic long-term decision. Agricultural land is divided between crops in different management systems: subsistent, intensive, irrigated. Trade and storages are operational scenario-dependent decisions serving to adjust the strategic decisions in each shock scenario. Food, (bio)energy, water, and environment security constraints push for a trade-off between the desire of producers (regions) to maximize their profits and to reduce the exposure to the risks that may jeopardize the security requirements. However, managing security criteria while controlling only land allocation and trade may require costly strategic solutions such as conversion of rain-fed into irrigated land to sustain rare-high impact shocks, e.g., a 100 year drought. For the case of catastrophic scenarios, availability of grain storages would allow to avoid expensive and possibly irreversible land transformations, and unnecessary technological investments. Robust long-term planning of land management in combination with trade and creating grain reserves reduces the losses associated with risk coping (e.g. ex-post purchasing) and meets consumption needs at lower prices.

Climate change impacts on agricultural systems vary between countries and regions. While increased heat waves and lower precipitation level, as predicted by climate change modellers, may shock production of major world grain producers such as Australia, Brazil, the USA; other countries and regions may win from projected climate changes. Stochastic GLOBIOM allows to investigate the redistribution of climate change risks among countries participating in agricultural markets and, thus, help to enhance world food security.

Many countries and regions often implement strict market strategies, e.g. bans, which in the presence of climate change risks will stimulate price increase, food insecurity, and instability in other systems. Stochastic GLOBIOM may serve as a tool for revealing and relaxing such “bottle necks” (tight dependencies) causing systemic risks in land use systems. For example, consider rice production in Japan. Rice prices in Japan are among the highest due to high demand and limited supply. Moreover, as a part of governmental control, rice imports are banned in Japan with the rationally that self-sufficiency in rice is important for food security. In the absence of imports, downward yield shocks lift prices. For example, rice production in 2003 was poor, “crop situation index” was about 90[10]. As a result, the rice price increased by 30% compared to the year 2002. This can be reflected in stochastic GLOBIOM where the model (given pre-defined set of decision variables) suggests to either change to low rice diets or to ease the import restrictions. In the latter case, introduction of storage may further reduce dependence on the ex-post imports.

Instead of traditional scenario-by-scenario analysis producing contradicting solutions for different single scenarios, stochastic GLOBIOM derives robust decisions, i.e., leaving us better-off independently of the scenario that occurs. Exposure to production and market risks motivates the reliance on domestic grain storages to smoothen consumption and lower prices. This happens especially in the presence of systemic risks when production shocks may be correlated across trade partners or/and if some markets are isolated or tightened by constraints and regulations, i.e., bans, subsidies, biofuel mandates, etc. Storages may prevent from undertaking costly investments, e.g., in irrigation capacities.

The stochastic GLOBIOM permits designing robust combination of strategic (e.g. land management) and operational (e.g. trades and storages) decisions within one common modelling framework. Land use planning is often confronted with decisions which are very costly to be reversed or altered (Arrow and Fisher, 1974). For example, conversion of peatlands and forests for biofuels production (Germer and Sauerborn, 2008; Parish, 2008) may cause a chain of cascading changes in different land use sectors making them exposed to possibly irreversible long-term systemic risks. For dealing with potential maladaptation and irreversibilities in LUSs, stochastic GLOBIOM distinguishes decisions in two stages – strategic long-term of the first (learning) stage and operational second stage decisions on future adjustments. The model illustrates why irreversible decisions have to be evaluated by non-smooth quantile-based risk functions. Endogenous demand, price, and trade flows are computed at the country level and/or aggregated world regions, while decisions on production and land use allocation are taken at the level of simulation units of about 50 km^2 resolution.

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[10] http://www.canon-igs.org/en/column/macroeconomics/20131001_2136.html

3.2.2 Integrated model of emissions trading and abatement under uncertainties

At a project level, adaptation to climate change might be realized in the form of conforming to new regulations and/or adjusting to new market conditions induced by such regulations. In the energy sector new investments into power generation capacities face the problem of technology choice and evaluation of future costs associated with potential payments for emitted carbon. This is where emission trading schemes and markets along with their development projections have to be taken into account. In this section we provide an overview of that topic.

The emission trading scheme was devised to lower the cost of achieving sets of greenhouse gas emission reductions for different countries with the price of tradeable emissions equal to the marginal cost of emissions reductions to meet the cap. However, emission trading was implemented through a market similar to financial markets. Disequilibrium carbon prices exhibit periods of high volatility. They react to and are the result of political decisions, information disclosure, speculations, financial bubbles, uncertainties around emissions and emissions reduction costs. The underlying actual cost of GHG reduction, i.e. the marginal costs of abatement technologies, under these circumstances is only of secondary importance. The existing emission trading, therefore, does not necessarily minimize abatement costs and achieve emission reduction goals. Lessons learned from the existing emission trading schemes point out to the need for changing the market's regulations to improve the overall emission trading efficiency.

Emissions cap and trade programmes (de Jong and Walet, 2004; Kerr, 2000) are economic instruments for environmental regulations which become popular both among policy-makers and scientific communities (Stavins, 2010). These programmes are now a key element in climate change policy negotiations establishing carbon prices and emission permits as a new asset type, a "new currency" (Kerr, 2000).The carbon prices are very sensitive to political decisions and information disclosure. For example, within two months, from January till April, 2006, European carbon prices went down from € 26/tCO_2 to € 10/tCO_2 after the data for 2005 was verified and adjusted emission levels revealed (see Figure 3).

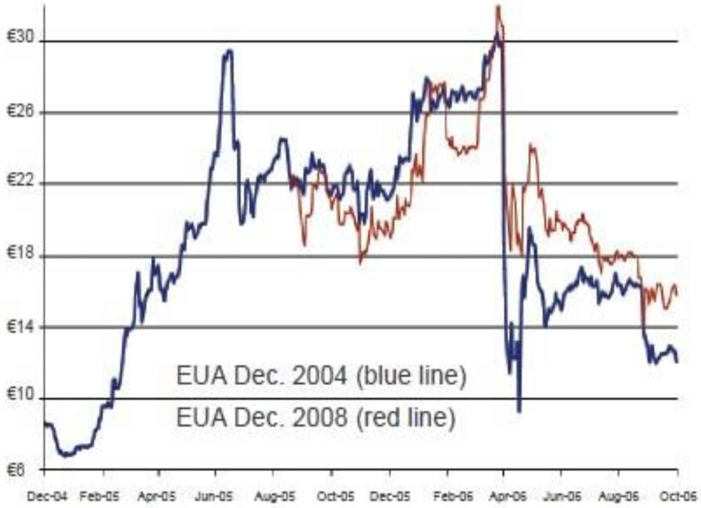

Figure 3. Carbon prices – European Union Allowances (EUA) in €/tCO2.
Source: www.pointcarbon.com, see also (Betz and Sato, 2006).

As studied by Potsdam Institute for Climate Impact Research[11] immaturity of the existing market policies triggered a major “dash for coal setting out on the construction of dozens of new coal plants. …”. Also, in the Netherlands, “…CO_2 emissions trading is a marginal consideration in the choice of fuel. Evidently, electricity producers are not too bothered about the price they pay for carbon emissions. The vast majority still favours coal, the worst carbon polluter. The reason is simple: the expected costs of emission rights are negligible compared to other investment outlays.” The building of coal-fired plants now may lock-in energy decisions for about forty years. Lessons learned from the existing emission trading (Betz and Sato, 2006) point out the need for environmental safety regulations in market instruments to smooth their performance (Cano et al., 2014).

The papers (Ermolieva et al., 2011, 2010; T Ermolieva et al., 2013) analyse cost-effective and environmentally safe carbon trading systems operating under uncertainty about emissions and their abatement and monitoring cost functions, asymmetric information, and irreversibility. These papers develop an integrated multi-agent emission trading and reduction model under multiple natural and human-related uncertainties. The model is an exploratory two-stage computerized multi-agent trading system (COMATS). It has important practical implications. It combines regulations (targets) on carbon emissions with a possibility of investing in emissions abatement and uncertainty reduction and redistributing the emissions permits through trading. The system may enhance real markets by analysing conditions for strategic robust trades and stable market’s performance. It explores conditions of market’s stability with respect to uncertainties by using safety constraints controlling verifiable uncertainties reductions, which guarantee cost efficiency of trades and safety levels of emission reduction targets (e.g., post-Kyoto pledge targets). The two-stage character of COMATS allows to cope with irreversibility, lock-in equilibriums, and private asymmetric information of decision making processes

COMATS is a computer-based modelling environment which allows trading “parties” to store in an anonymous manner their private information on cost functions, constraints, and other characteristics including specific characteristics of uncertainties. The procedure deriving equilibrium solution is the following: two parties are picked at random (“meet”) and exchange emission permits in a mutually beneficial way accounting for actual costs and uncertainties. At the next step, a new pair is picked and the procedure is repeated. At each step of the bilateral trading, the actual costs will differ between the sequential trades, but finally the trading converges to an equilibrium solution with marginal costs of all parties equal to an equilibrium price. COMATS determines emissions permits prices in a decentralized manner without requiring trading parties to reveal or exchange their private information. The pricing methodology is augmented with environmental constraints. The methodology of emissions pricing in the presence of uncertainties and incomplete information is a rather general scheme which has analogues with Walras law describing the dynamics of prices under specific market conditions, which finally converge to the optimal (equilibrium) prices. COMATS incorporates concepts of emissions detectability (verifiability) and discounting. Functioning of the robust market is illustrated with numerical results involving such countries as US, Australia, Canada, Japan, EU27, Russia, and Ukraine. The key questions the model addresses include: under what conditions is carbon trading environmentally safe and cost-effective in the long-term when considered in the context of a stochastic market; how the knowledge about uncertainties may affect portfolios of technological and trade policies of the parties; may uncertainties affect the structure of the market; what difference is there between marginal abatement costs calculated from technology parameters and the spot carbon price in the existing stochastic market; by how

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[11] http://thebreakthrough.org/archive/eu_emissions_trading_dash_for_coal

much may trading parties decrease the chances of lock-in solutions and “irreversible” trades at spot market.

As demonstrated in (Ermolieva et al., 2011, 2010; T Ermolieva et al., 2013), explicit treatment of uncertainties, as compared to simplified approaches, does significantly affect technological portfolios, trade policies, and permits prices, which in reality do highly depend on uncertain factors. Ignoring uncertainties leads to wrong policies, as it is illustrated with numerical experiments. Thus, without accounting for uncertainties, there is no mechanism for verifiability of emissions reductions, and countries with high emissions uncertainties may become major permit sellers. Under explicit treatment of uncertainties, these countries have to invest in uncertainty reduction and can offer less verifiable trade permits. When uncertainties are explicitly included in the trading, countries with low uncertainties may turn into permit suppliers. One of the main conclusions is that depending on abatement costs, exclusion or inclusion of additional players may have dramatic effects on the market. For example, traders with high emissions reduction costs will increase the carbon price, and the other way around.

3.2.3 Integrated management of catastrophic floods

This section is dedicated to the analysis of methodological relevance of approaches suggested earlier in this document and respective insights from flood management case studies. A discussion on the application of the Adaptive Monte Carlo procedure mentioned earlier in this document is carried out at higher level of detail.

Increasing losses from natural and human-induced catastrophes call for integrated approaches to risk management allowing, in particular, to demonstrate that investments in risk management is a welfare generating strategy. The importance of integrated approaches for management of financial risks is emphasized by (Doherty, 1984; Mayers and Smith Jr, 1983). Catastrophes represent new challenges. (Arrow, 1996) admits that rare catastrophic risks affecting large communities cannot be properly treated by standard economic models. Proper management of catastrophes calls for robust combinations of various ex-ante and ex-post risk management decisions, including deliberate selection of catastrophic risks for pooling by using appropriate stochastic optimization models. In other words, simple basic ideas of risk pooling in (Borch, 1992) are transformed into challenging stochastic decision-making problems (Y. Ermoliev et al., 2000; Y. M. Ermoliev et al., 2000) of catastrophic risk management. In this section we discuss an integrated catastrophic risk management model which is being developed and applied at IIASA for treatment of different catastrophes, e.g., floods, wind storms, earthquakes, livestock diseases. The main goal of this modelling effort is to address the specifics of catastrophic risks: highly mutually dependent endogenous risks, the lack of historical location-specific observations (unknown risks), the need for long-term perspectives, robust strategies, and explicit treatment of spatial and temporal heterogeneities of various agents such as individuals, governments and insurers. The model uses an Adaptive Monte Carlo procedure to deal with significant computational complexities of arising optimization problems.

The integrated model for management of catastrophic floods consists of five sub-models (modules): the "River" module, the "Inundation" module, the "Vulnerability" module, the "Multi-Agent Accounting System", and the "Variability" module. The River module calculates the volume of discharged water to the pilot region from different river sections for given heights of dikes, given scenarios of their failures or removals, and rainfalls. The latter are modelled by upstream discharge curves. Thus, formally, the River module maps an upstream discharge curve into the volume of water released to the region from various sections. The underlying sub-model is able to estimate the discharged volume of the water into the region under different conditions, for example, if the rain patterns change, if the dikes are heightened, or if they are strengthened or removed. The next module is the spatial GIS-based Inundation sub-model. This module maps water released from the river into levels of standing water and thus it can estimate the area of the region affected by different decisions. The Vulnerability module maps spatial patterns of released water into economic losses. This module calculates direct losses and may include possible cascading effects and their consequences. It may also include loss reduction measures, e.g., new land-use modifications, reinforcement of dikes, other flood preparedness measures. This module is able to indicate changes in economic losses from changes in risk reduction measures. The Multi-Agent Accounting System module maps spatial economic losses into gains and losses of agents. These agents are the central government, a mandatory catastrophe insurance (pool) and "individuals" (cells). Given sufficient data, the above-mentioned sub-models can generate scenarios of losses and gains at different locations for specific scenarios of failures, rainfalls, risk reduction measures and risk spreading schemes. However, there are still significant uncertainties and a considerable variability in these losses and gains (a statistical 50-year flood may occur in 5 days or in 70 years from now).

Insurers are especially concerned about variability since they may not have the capacity to cover large losses. In an attempt to maintain their solvency, they may charge higher premiums, which may result in overpayments by the insured parties. Alternatively, insurers may undercharge contracts. Insurers are also concerned about loss-reduction measures. A higher dike may fail and cause more damage in comparison to a dike without modification. The Variability module, a Monte Carlo model, transforms spatial scenarios of losses and gains among agents into histograms of probability distributions. For example, it derives histograms of direct losses at a location or a sub-region. It also calculates histograms of overpayments and underpayments for different agents.

The fundamental question concerns the evaluation of a desirable policy without the exact evaluation of all the options. The complexity of this task is due to analytical intractability of stochastic catastrophe models, generating only random values of goal functions and often requiring a large number of simulations for estimating outcomes of a single decision. The standard optimization methods imply that the goal (objective and constraints) functions are exactly calculated, i.e., for a given feasible solution these functions are calculated without an additional sampling procedure. Therefore, in general cases, one has to rely on the stochastic optimization methods, in particular, on the so-called Adaptive Monte Carlo Optimization (Y. M. Ermoliev et al., 2000; Ermoliev and Norkin, 2013). The Adaptive Monte Carlo Optimization model consists of three interacting blocks: Feasible Decisions, the Monte Carlo Catastrophe Model, and Indicators (see Figure 4).

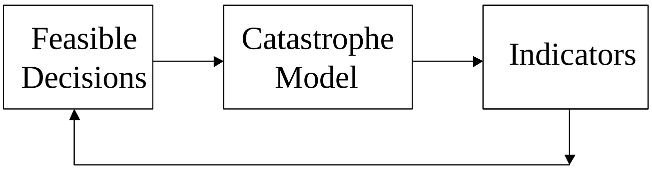

Figure 4. The concept of an Adaptive Monte Carlo Optimization Model.

The block "Feasible Decisions" represents all feasible policies for coping with floods. In general, they may include feasible heights of dikes, insurance coverage, land-use modifications, etc. These variables affect performance indicators such as profits of insurers, underpayments or overpayments by the insured, costs, insolvency and stability indicators.

The essential feature is the feedback mechanism updating decisions towards specific goals. The updating procedure relies on Stochastic Quasi-gradient (SQG) optimization techniques (Ermoliev, 1976; Ermoliev and Wets, 1988). Losses are simulated by the catastrophe model, causing an iterative revision of the decision variables after each simulation run. In a sense, the Adaptive Monte Carlo optimization simulates in a remarkably simple and evolutionary manner the learning and adaptation process on the basis of the simulated history of catastrophic events. Stochastic optimization provides a framework for the iterative revision of decisions embedded in the catastrophe model. These decisions influence the contribution of location-specific risks on the overall catastrophe losses. The model uses economically sound risk indicators leading to convex stochastic optimization problems strongly connected with a non-convex quantile-based insolvency constraint and Conditional Value-at-Risk (CVaR). The model enables simultaneous analysis of complex interdependencies among damages at different locations and robust prevention, mitigation, and adaptation (both structural and financial) measures.

Particularly challenging in management of catastrophic floods is a dilemma about the trade-off between the need for structural and financial measures in relation to protection against dam break floods and sharing potential dam break losses. One can argue that an increase of safety by means of additional investments into structural measures may completely eliminate the need in other measures. Let us consider a practical situation. In traditional dam management, for example, a typical goal is to reduce the probability of flooding induced by a dam break to below a certain value, the Probable Maximum Flood. Because of uncertainties around the estimate of the likelihoods, the investments into dam reinforcement may be essentially miscalculated. However, once effective measures are taken to protect against the targeted average event, it is precisely the variations around the estimate that may now pose the majority of the risk to the affected populations. The decision maker is in a quandary with pitfalls on either side. If the true likelihood of a particularly severe flood is quite high and no mitigation efforts are undertaken, massive damages might result. On the other hand, if the true likelihood is low and expensive mitigation measure are undertaken, then the resources used to implement the mitigation may have been lost if the event fails to occur. In the worst of all possible worlds, expensive mitigation measures could be implemented but would still fail when called upon to withstand the flood. In this case, losses are incurred both before the disaster (mitigation costs) and as a result of the disaster (in terms of damage to assets).

Due to the uncertainties, there is a need to find a portfolio of measures that may handle dam breaks. Investments into reinforcement can be effectively supplemented by insurance which provides an ex ante financial solution to cover or transfer the losses further to financial markets. Also, the need for mutual sharing of the risks calls for cooperation between the agents. In this case, individual involvement of each particular agent in the loss sharing program is analysed based on his exposure and safety constraints. The analysis of the exposures and the dependencies of exposures on newly implemented strategies is possible only with model-based approaches combining generators of potential catastrophes jointly with goals and constraints of the agents (including the dam owners, e.g., government).

Adding to that, the model permits the analysis of the implications of extreme events on the proper choice of discounting (Ermoliev et al., 2008) for evaluation of policies with long-term perspectives, e.g. climate change and catastrophe management projects such as construction and maintenance of dikes (Ermoliev et al., 2013). The misperception of catastrophe-related discounting may dramatically contribute to the alarming increase of regional vulnerability.

3.3 New approaches to discounting

The framework for integrated management of dependent catastrophic losses develops novel approaches (different from traditional ones discussed in section 2.1) to social discounting of long-term projects. These allow for endogenizing discount rates with respect to spatiotemporal patterns for key extreme event and risk management decisions. In (Ermoliev et al., 2010, 2008) it is shown that discount rates can be associated with the occurrences of irreversible "stopping time" events determining a finite "internal" discount-related horizon of the traditional "Net Present Value" criterion. The paper (Ermoliev et al., 2010) shows that the concept of stopping time and equivalent undiscounted random criteria allows inducing the social discounting that focuses on arrivals of catastrophic events rather than the lifetime of market products. Since risk management decisions affect the occurrence of disasters in time and space, the induced discounting may depend on spatiotemporal distributions of extreme events and feasible sets of related decisions. Discount factors can be linked to an irreversible "stopping time" extreme event which defines the internal discount-related horizon of evaluation. Expected duration of this horizon for discount rates obtained from capital markets does not exceed a few decades, and as such, these rates may significantly underestimate the results of long-term decisions. The explicit treatment of extreme events leads to dynamically adjusted discount rates, conditional on the degree of social commitment to mitigate or adapt to a risk. These new approaches still need to be implemented in risk management models.

Another approach to discounting has been developed by Chiabai et al.(2012). Given the multiple perspectives on discounting in the context of decisions which have an environmental impact, Chiabai et al. (2012) defined an ethically simple and intuitive rule to estimate the social discount rate for projects or programmes in which one of the options is to maintain or restore undeveloped land, which is either in or close to its natural state. The approach is based on the idea that any decision-maker should try to value equivalently and consistently a tract of land that is in its undeveloped (natural) state and another one which has been designated as appropriate for urban or industrial development. The long term value of preserving the undeveloped land should be at least equivalent to the value of similar land (located in the same area) with development rights. This "Equivalency Principle" implies giving the same value to both types of land and assumes that future generations would assign them equal utility and equal economic value. An additional advantage is that the use of this approach avoids making other uncertain assumptions about the expected welfare or growth rate of consumption of future generations, and the uncertainty associated with climate change impacts. The application of the Equivalency Principle is further assessed in Work Package 3.

4 Conclusion

In this document we provided and overview of state-of-the-art methods for decision-making under uncertainty and risks. While discussing particular approaches, we highlighted the importance of integrated (cross-sectorial) analysis. Other aspects we suggest for consideration within the adaptation context of the ECONADAPT project include: complex multivariate analytically intractable risk distributions, long horizons of evaluations, strategic and operational planning and management of risks.

The provided methods overview is naturally far from being complete and does not cover all methods with the same level of detail and references. We carried out the analysis of the methods specifically focusing on their applicability – their strengths and weaknesses within an adaptation context. To overcome critical deficiencies found, we suggested a range of improvements/new methods and illustrated those with a few appropriate examples stemming from current/previous research that is close to (but not necessarily the same as) the topic of the ECONADAPT project. A more detailed illustration and the application of the suggested new methods to selected ECONADAPT case studies still needs to be developed in the course of the project. These results will be presented in the forthcoming Deliverable D4.3 "An illustration of the application of the methods to cases, and recommendations on the implications for policy formulation, monitoring and revision over time".

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