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THE ROLE OF AMBIGUITY IN THE EVALUATION OF THE NET BENEFITS OF THE MOSE SYSTEM IN THE VENICE LAGOON

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Abstract

In this paper we apply the NEO-capacity framework [5] to assess the role of ambiguity in a specific decision making problem. We first describe the framework and propose a graphical representation of the decision making functional. Then we apply it to a specific problem, namely, the role of ambiguity in the evaluation of the net benefits of the MOSE, the mobile barriers aimed to protect the Venice Lagoon from the periodic flooding (*acqua alta*). We show that the estimated impacts crucially depend on the level of optimism and pessimism of the decision maker and they substantially differ from the one calculated on the basis of the expected value. We also calculate the implicit ambiguity attitude of the decision maker.

Keywords: Decision making under ambiguity, NEO-Capacity, MOSE, acqua alta.

JEL classification: D81; Q51; Q54.

1 Introduction

Many policy decisions impacting on the environment are surrounded by a consistent level of *ambiguity*, which arises whenever the analysis of future occurrences depicts several scenarios whose likelihood cannot be inferred on the basis of any (either subjective or objective) probability distribution. This happens if there is no clear definition of the problem, so that the description of the states of the world is known to be incomplete [14] or when there is no justification of the use of any *a priori* distribution [6]. Several possible criteria for decision making have been proposed to solve this problem, starting with the well-knonw *Max-Min* criterion [24] which has been advocated, at least since Rawls seminal paper [16], as the proper guideline to be followed under situations of complete ignorance. Hurwicz [11], [12] and Arrow and Hurwicz [1] have augmented it, proposing to evaluate the best and worst consequences according to a linear combination of them. Other scholars [18], [17] have gone further in developing a unifying framework within the *Choquet Expected Utility* (CEU) model, based on *capacities*, i.e. normalized monotone measures of ambiguity. It has recently been proposed in the literature [5] to adopt a peculiar capacity, named *NEO-additive*, which is additive on non extreme events. A specific CEU functional is derived that can be expressed as a linear combination of the expected value, the best and the worst consequence of a given decision, where the weights depend on the specific ambiguity attitude of the decision maker, namely, optimism or pessimism. This approach can be used to deal with environmental decision making problems under ambiguity, such as for instance the analysis of some specific economic consequences of climate change. This is the framework of our work. We show that the CEU functional that derives from *NEO-additive* capacities can be usefully applied to the assessment of the economic impact on the city of Venice of the MOSE mobile barriers system that has been aimed at protecting the Venice lagoon from the periodic rise in the tide level (*acqua alta*). Given the ambiguity that affects the possible forecasts of both the environmental parameters (the average sea level rise and the frequency of the *acqua alta* phenomenon) and the instrumental ones (the safeguarding level beyond which the system will be operated), its economic impact cannot be uniquely determined. More precisely, several scenarios can be depicted depending on the combination of various parameters that determine the frequency and the length of the operation of the MOSE.

In this paper we evaluate the economic impact of the MOSE on the city of Venice using data referring to all possible scenarios, and not just the worst (or the best) one. Doing so, we show that the CEU provides a viable tool for decision making problems under ambiguity. Moreover, we highlight that decisions taken as if there was no ambiguity can indeed be interpreted as decisions taken in ambiguous frameworks by decision makers who hold implicitly a specific ambiguity attitude.

The paper is structured as follows. In section 2 we briefly summarize the *NEO-additive* capacities framework [5] and propose a graphical representation of their decision making functional. Section 3 describes the *acqua alta* phenomenon in the Venice lagoon and the engineering solution adopted to protect the city, i.e. the MOSE system. In section 4 we calculate the net benefits that derive from the use of the MOSE, analyzing the twelve possible scenarios that arise and applying the decision making rule introduced in section 2. Conclusions, acknowledgments and references follow. The final appendix describes in greater details the metodology and the data used for our calculations.

2 The framework: CEU and NEO-capacities

The *capacity* notion is at the core of the *Choquet expected utility theory* (CEU) [18] which generalizes the subjective utility theory as a criterion of choice by utilizing the *Choquet integral* for non-additive measures. Let S be a non empty set of states of the world, E a σ-algebra of subsets of S, X an arbitrary non-empty set of outcomes. A capacity is a real-valued normalized and monotone function $\nu : E \longrightarrow \mathbb{R}$. The sum of the capacity of two subsets may be different from the capacity of the union of the same sets. If the sum is strictly less (more) than the capacity of the union and of the intersection, the capacity is said to be convex (concave). The *Choquet integral,* i.e., the integral of an act $f : S \rightarrow X \subset \mathbb{R}$ with respect to a capacity v is the following integral:

$$I(f) = \int_{-\infty}^{0} (v(f \geq t) - 1)dt + \int_{0}^{+\infty} v(f \geq t)dt \qquad (1)$$

When X is a space of utility, i.e. if there is a utility function that takes from consequences to reals (endowed with the usual properties of utility functions), the integral w.r.t. a capacity is called Choquet Expected Utility (CEU). From the CEU theory a new strand of literature emerged investigating the role of *optimism* and *pessimism* as relevant features of individuals' attitude towards ambiguity. Wakker [25] characterizes optimistic and pessimistic attitudes in terms of decision weights. Typically, optimistic attitudes overestimate the likelihood of good outcomes, while pessimistic attitudes overestimate the likelihood of bad outcomes. In the context of the CEU model, concave capacities reflect optimistic attitudes towards ambiguity, while convex capacities model pessimism. In other words, the decision weights used in the computation of the Choquet integral overweight high outcomes if the capacity is concave and overweight low outcomes if the capacity is convex.

Chateauneuf *et al.* [5] propose a specific weighting scheme to model ambiguity. They introduce the *NEO-additive* capacity, namely, a specific type of capacity which is a linear combination of an additive capacity, i.e., a probability, and a "special capacity that only distinguishes between whether an event is impossible, possible or certain" ([5], p. 540), named Hurwicz capacity after Hurwicz's criterion. Let the triple N, U, E^* be a partition of S, where N denotes the set of null events, i.e., events for which it is impossible for them to occur, U is the universal set, i.e. the set made by taking the complement of each element in N, and E^* the set of essential events, i.e. events that are neither null nor universal, $E^* = E \backslash (N \cup U)$. The Hurwicz capacity is the capacity attaching a zero measure to events that are null, one to events that are universal and a measure that equals $\alpha \in [0, 1]$ to essential events:

$$\mu_\alpha^N(A) = \begin{cases} 0 & if \quad A \in N \\ \alpha & if \quad A \notin N \, and \, S \backslash A \notin N \\ 1 & if \quad S \backslash A \in N \end{cases} \tag{2}$$

A Hurwicz capacity can be interpreted as a convex combination of two capacities, one of which, convex, reflects complete ambiguity in every event but a universal event and the second one, concave, reflects complete confidence in everything but the null event ([5], p. 541.) A *NEO-additive* capacity is then defined as a linear combination of a finitely additive probability distribution π defined over (S, E) and a Hurwicz capacity:

$$\nu(A \mid N, \pi, \delta, \alpha) = \delta \mu_\alpha^N(A) + (1 - \delta)\pi(A) \tag{3}$$

where $\delta \in [0,1]$. *NEO-additive* capacities are additive for events yielding non-extreme outcomes; they exhibit pessimism for some events and optimism for some other events. In [5], Lemma 3.1, it is proved that the CEU calculated w.r.t. to the NEO-additive capacity defined in Equation 3 assumes the following representation:

$$CEU_f = (1-\delta)\, E_\pi(f) + \delta(1-\alpha) \min\left\{y : f^{-1}(y) \notin N\right\} + \delta\alpha \max\left\{x : f^{-1}(x) \notin N\right\} \quad (4)$$

where clearly E_π denotes the expected value calculated w.r.t. π. Several decision making criteria may be interpreted as special cases of the Choquet integral in Equation 4. When $\delta = 0$ the CEU_f coincides with the *Expected Value*; when $N = \{\varnothing\}, \delta > 0, \alpha = 0$ there is pure pessimism and if $\delta = 1$ the CEU coincides with the *Max-min*; when $N = \{\varnothing\}, \delta > 0, \alpha = 1$ pure optimism arises and if $\delta = 1$ it collapse into the *Max-max*; when $N = \{\varnothing\}, \delta = 1, \alpha = (0,1)$ we are back to the *Hurwicz* criterion.

Parameters $\delta(1-a)$ and δa in Equation 4 represent the impact of pessimism and optimism, respectively ([5], p. 544). Let us rename them as $\lambda = \delta(1-a)$ and $\gamma = \delta a$. Moreover, denote the Min in Equation 4 as C_1, the Max as C_2. The CEU in Equation 4 writes: $CEU = \lambda C_1 + \gamma C_2 + (1-\gamma-\lambda)\, E_\pi$, where we have suppressed the symbol of the act function f for simplicity of notation. We can display an interesting graphical representation of this functional form in a 3-d space, as a function of the pessimistic and optimistic parameters λ and γ. See that $\Delta := \{(\gamma,\lambda) \mid \gamma \geqslant 0,\ \lambda \geqslant 0, \gamma+\lambda \leqslant 1\}$, i.e., the simplex in $\mathbb{R}^2$, constraints the set of the admissible ranges for γ and λ. Consider Figure 1:

[Figure 1 about here]

It is easy to identify the side of the triangle that represents the space of CEU taking into account its linearity in γ, λ, and setting $\gamma = 0$, $\lambda = 0$ and $\gamma + \lambda = 1$, respectively. The expected utility evaluation corresponds to the point for which $\gamma = \lambda = 0$. The set of pure pessimistic (optimistic) evaluations is given by the side of the triangle depicted in Figure 1, call it CEU_p (CEU_o), for which $\gamma = 0$ ($\lambda = 0$). It is given by the following equation: $CEU^p = \lambda(C_1 - E_\pi) + E_\pi, 0 \leq \gamma \leq 1$ ($CEU^o = \gamma(C_2 - E_\pi) + E_\pi, 0 \leq \lambda \leq 1$). The Hurwicz criterion corresponds to the side of the triangle for which $\lambda + \gamma = 1$, that is: $CEU^H = \gamma(C_2 - C_1) + C_1$. Let us denote as $\hat{\gamma}, \hat{\lambda}$, those values of γ and λ for which the CEU exactly equals the expected value and that are compatible with the Hurwicz criterion, (i.e. that lie along the hypotenuse of the CEU triangle). Call this pair the Expected Value Equivalent point, and denote the set of points equivalent to the Expected Value as the E(xpected) V(alue) E(quivalent) set:

$$EVE := \{\lambda \in [0.1], \gamma \in [0.1] | \lambda C_1 + \gamma C_2 + (1 - \lambda - \gamma) E_\pi = E_\pi, \lambda + \gamma \leqslant 1\} \tag{5}$$

This is the set of values of the parameters that give exactly the same evaluation of the ambiguous-free expected value. In other words, it defines the implicit values of the ambiguity attitude that a decision maker has unconsciously in mind if she takes the decision on the basis of the expected value only, i.e., if she is optimistic or pessimistic about it. In Figure 1, we have represented the EVE as the set of reals along the dotted straight[1] line that starts form the Expected Value point and that is equidistant to the λ, γ, simplex. See that it intersects the Hurwicz set (i.e, the set of CEU values for which $\lambda + \gamma = 1$) at $\hat{\lambda} = \frac{C_2 - E_\pi}{C_2 - C_1}$ $\hat{\gamma} = \frac{E_\pi - C_1}{C_2 - C_1}$.Therefore, just one of the follow-

[1] Along the EVE line the ratio $\hat{\gamma}/\hat{\lambda}$ is constant.

ing three couples is true: either $\left\{\hat{\lambda} < 1/2, \hat{\gamma} > 1/2\right\}$; or $\left\{\hat{\lambda} > 1/2, \hat{\gamma} < 1/2\right\}$; or $\left\{\hat{\gamma} = \hat{\lambda} = 1/2\right\}$. In the first case, when the decision maker decides without taking into account the ambiguity of the problem (i.e., calculating the expected value only), it is as if she had an implicit optimistic ambiguity attitude; the opposite would be true in the second case, while she would express ambiguity neutrality only if the value of pessimistic ad optimistic parameters were exactly equal along the EVE line.

3 The MOSE system

The lagoon of Venice is characterized by the phenomenon of *acqua alta*, i.e. the periodical high water event causing (partial) flooding of the historical centre of Venice.[2] Data[3] show that such a phenomenon is recently increasing both in its frequency and intensity. According to forecasts, global warming will induce a rise in the average worldwide sea level [9], [10], which will further worsen the phenomenon over the next century. Both mitigation and prevention measures have been implemented in order to reduce the high water impacts on architectural, artistic and cultural heritage and the economic damages to the population and its visitors. These include, *inter alia*, the much debated mobile barriers system (MOSE), expected to provide an en-

[2] *Acqua alta* is usually defined as a tidal event reaching quota of 80 cm above the 'Punta della Salute' Tidal Datum, which is the Venetian main reference tide gauge. At this quota, problems of displacements arise in the lowest parts of the city, but it is at +100 cm that these problems become relevant for most of the city. A tide of +140 cm identifies an exceptional high water episode, causing the flooding of about 90% of the city. Autumn and winter are the critical periods during which the interaction of astronomical and meteorological factors typically favours an increase in flood occurrence [3]

[3] See www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/3045

gineering solution to the problem of high water through a system of mobile gates installed on the sea floor of the inlets (Chioggia, Lido and Malamocco). This system has been planned to separate from a hydraulic point of view the lagoon from the Adriatic Sea every time the water level exceeds a certain *safeguarding level*. Such a parameter has to be decided and it will be probably tailored after the starting of the system. There has been a long debate about its optimal threshold level. Clearly, there is a trade off between fixing it at a low level which would force the system to be operated a large number of times with higher benefits, and setting it at a high level, which would minimize its costs but with more frequent and high flooding episodes of the city. More precisely, the higher the functioning frequency, the higher the benefits for both Venetians and tourists, in terms of both displacements expenses within the city and protection expenses of the cultural and artistic heritage, but at the same time, the higher the costs in terms of interferences with Venice harbour activities, still a relevant sector for the whole economy of the city.[4] For this reason, the definition of the safeguarding level is extremely important. In particular, it is possible to envisage two main reference levels for the threshold level: +100 cm or +110 cm above the 'Punta della Salute' tidal datum.[5] When a tide over +100 cm or +110 cm is forecasted,

[4]Even though the MOSE project was elaborated in order to minimize the negative consequences for the navigation, interferences of the mobile barriers operational functioning with port activities cannot be completely avoided. The building of navigation basins at the inlets may indeed reduce the delay in ship traffic due to the mobile barriers closure; however, its effect at the moment can not be exactly quantified.

[5]Indeed, it seems that there is a more general consensus about +110 cm as the proper safeguarding level. Notice that this is the limit that is referred to by the consortium that is building the infrastructures (Consorzio Venezia Nuova, see www.salve.it). However, the +100 cm limit has often been appealed by the "Magistrato delle Acque" (the public regulating authority of the venetian lagoon) as a precautionary threshold level that should

it is expected that the mobile barriers will be raised and emerge from the water, stopping the tidal flow and temporarily separating the lagoon from the Adriatic Sea. Given the frequency of the *acqua alta* phenomenon, the mobile barriers closures are indeed more frequent if the safeguarding level is set at the lower boundary rather than at the higher one and if an increase of the sea level is going to occur. The choice between these two thresholds therefore provides an example of a decision making problem under ambiguity due to the environmental parameters whose likelihood cannot be inferred on the basis of any probability distribution.[6] Thus it represents an interesting case to be studied under the specific decision making tool discussed in the previous section.

The simulation of MOSE activity is carried out through a model describing the hydrodynamics of the Venice lagoon and developed at the ISDGM-CNR [20], [21], [22], [23]. Given the water level at the inlets and wind over all the lagoon, at every time step (5 minutes) this model computes the water level, simulating the propagation of the tide inside the lagoon, and the barotropic current in all nodes of the numeric grid. Output variables of the simulation model include also the frequency of how often the water level exceeds the safeguarding level and the time of mobile barriers closure. For the considered period, we can simulate the water level inside the lagoon for twelve different scenarios, resulting from the hypotheses we assume about the relevant variables. In particular, we consider three possible different sea

be considered [13]. Therefore, it is not possible to be certain now about what will be exactly the safeguarding level that will be effectively implemented when the system will be operated.

[6]Notice that there is also a systematic source of ambiguity due to human behaviour. In our case, due to the behaviour of those institutions that will have to operate the MOSE once the system will be activated.

level increases (0, +30 cm, + 50 cm) reflecting the IPCC forecasts.[7] We take into account the two different safeguarding levels at which the mobile barriers procedure of closing can be activated (+100 cm, +110 cm). Finally, we include also a *security increment* (0, +10 cm) that can be set to compensate possible tide daily forecast errors of the sea level within the lagoon, according to the following rationale: the closure steering of the mobile barriers follows a precise procedure based on tidal and meteorological forecasts (as described in [13]). In particular, the closing procedure is activated whenever a forecast of the water level (with a four hours delay) reaches the safeguarding level. The security increment can thus be used (and indeed has been included as a working hypothesis within the ISDGM-CNR hydrodynamic model) as a tool to reducing the impact of erroneous forecasts on the prevention of *acqua alta* episodes, since it increases the forecasted water levels used to alert the system.

4 The economic assessment of the MOSE net benefits

Our analysis of net benefits from MOSE functioning is based on the impacts of *acqua alta* identified by [4]. We focus on buildings (and historical buildings protected by specific laws) repairing average avoided costs, old people and students displacements average avoided costs and tourists average avoided

[7] In absence of specific forecasts for the Adriatic Sea, we consider three different scenarios for the local impact of global warming on sea level, reflecting the IPCC surveys [9], [10]. 50 cm is the highest level, the null hypothesis corresponds to the *status quo*, i.e., no impact, while the 30 cm assumption is the intermediate one. Clearly, ambiguity implies that no prior probability distribution can be attached to these levels.

expenses.[8] Data provided by [4] on the consequences of flooding for people and buildings and the tide level forecasts obtained through the previously mentioned hydrodynamic model allow us to compute the quota of the city involved by the most serious episodes of flooding and the frequency of floods (see the Appendix for details).

Costs include two components: the operational and manintenance costs [7] and the estimate of the *direct* costs induced by MOSE functioning on the Venice harbour [15].[9] The latter, in particolar, are due to the longer period ships wait in roadstead and/or stay in wharf/quay when the mobile barriers are raised and inlets closed (see the Appendix for details).

The estimated costs, benefits and net benefits for each scenario are shown in Table 1, where each scenario is described by three entries: the possible sea level rise (00 cm, 30 cm or 50 cm), the safeguarding level (100 cm or 110 cm) and the security increment (00 cm or 10 cm). The twelve possible combinations are indexed by a letter tag, from A to L.

[Table 1 about here]

[8] We do not include avoided costs for business activities due to the lack of information, except for costs due to reduced expenditure of tourists. [2] provide an estimate of business costs, but their analysis is not consistent with our framework. In particular, they only assume a 10 cm sea level rise, while in our valuation exercise we consider different sea level scenarios.

[9] Our analysis does not take into account the *indirect* costs, corresponding to the foregone earnings due to the potential loss of navigation in favour of alternative ports. The existence of additional costs associated with MOSE functioning may indeed penalize the port of Venice with respect to other ports, which in that case would become economically more competitive.

We can see that net benefits increase if sea level rises, as expected, since the *acqua alta* episodes become more frequent. Similarly, MOSE operates more frequently when the security increment is added, which explains why benefits improve too. Finally, notice that the minimum level of net benefits (negative amount) corresponds to scenario B. Such a result derives from a partial failure of the mobile barriers' closing procedure: the system is not alerted due to a forecast error and therefore the tide reaches a high level (+ 144 cm w.r.t. Punta della Salute Tidal Datum).

In order to compare the different estimates of total benefits and costs and use them for policy considerations we need to distinguish between decision making variables and exogenous (environmental) ones. The formers are the two threshold levels (+100 cm or +110 cm) and the security increment (0, +10 cm); the latter is the sea level rise (0, +30 cm, +50 cm). Choices about variables are supposed to be made on the basis of the estimated net benefits associated to each scenario, weighted according to the decision criterion adopted by policy makers. We compare the results obtained from the application of the CEU described in Equation 4 under different values of the subjective parameters $\gamma = \delta(1 - \alpha)$ and $\lambda = \delta\alpha$ with the one arising from a decision framework without ambiguity, i.e. the expected value.

Let us consider first the expected net benefits of MOSE functioning. There is no objective probability measure that can be called on to evaluate it. Thus, the states of the world should be equally weighted according to a uniform probability distribution.[10] In our case, this implies that a prob-

[10] On te basis of the Bernoulli's Principle of Insufficient Reason, named also principle of Indifference. There is a vast debate in the literature about it, that we cannot report here because of space constraint. See [8], [19] and references therein. Notice, moreover, that our analysis would not be qualitatively affected by taking a different assumption, which leads to a different prior; simply, we would obtain a different value for E_π and a different

ability $p_i = \frac{1}{12}$ is associated to the estimated net benefits for each scenario: $E(c(MOSE)) = \sum_{i=A}^{L} p_i \cdot c_i$, where c_i denotes the net benefits of MOSE in scenario i. This criterion provides a benchmark corresponding to the situation with no ambiguity. In the case of MOSE, the expected value equals $214,841$ Thousands of Euro (Table 2).

[Table 2 about here]

The *Max-Min* criterion (C_1) considers only the worst outcomes associated with each possible decision, taking the decision corresponding to the less bad outcome among them. Recall that the decisions are about the safeguarding level and the security increment. The worst scenarios[11] (lowest benefits) refer to the possibility of foreseeing a null increase of the sea level, that leads to the lowest net benefits scenarios B, D, A, C. Net benefits range from $-6,490$ Thousands of Euro in case of scenario B, which corresponds to a threshold level of +110 cm and no security increment , to $178,159$ Thousands of Euro under scenario C (safeguarding level of 100 cm and 10 cm of security increment). The less bad outcome among them is associated to scenario C. Similarly, the most optimistic criterion, the *Max-Max* (C_2 in the previous section), considers only the maximum values. In our case, the relevant decisions about the threshold level and the security increment lead to the best outcomes (highest benefits) in the case of a sea level rise of 50 cm. These outcomes correspond to scenarios K, L, I and J. Among them, scenario K exhibits the best outcome, equal to $373,290$ Thousands of Euro. The evaluation of the net benefits of MOSE functioning derived from the application

set of $\hat{\gamma}, \hat{\lambda}$, but the value of E_π would still be encompassed between the Min and the Max.

[11] Given that the investment has already been planned and the MOSE system has to be operated, the scenarios inducing the lowest net benefits are the worst ones.

of the CEU defined in Equation 4 changes according to the subjective ambiguity attitude of the decision maker. For instance, if we fix $\gamma = \lambda = \frac{1}{2}$ the net benefits of MOSE functioning would be $\frac{1}{2}C_1 + \frac{1}{2}C_2$, which corresponds, according to our estimates, to $275,724$ Thousands of Euro, higher than the expected utility estimate**.** Different assumptions about the decision makers attitude towards ambiguity entail a different value of γ and λ. Substituting the values of C_1, C_2 and E_π with those calculated in the case of MOSE gives the following equations for the set of points showing pure pessimism, pure optimism and for the Hurwicz criterion, respectively (Thousands of Euro); $CEU^p = -\lambda(-36,683) + 214,841$; $CEU^o = \gamma(158,448) + 214,841$; $CEU^H = \gamma(195,131) + 178,159$. Finally, we can calculate the implicit ambiguity attitude: $\hat{\lambda} = 0.81$; $\hat{\gamma} = 0.19$. Thus, when deciding whether to finance the MOSE building, decision makers have implicitly shown pessimism, i.e., they have overevaluated the scenarios that provide the lowest benefits and have underevaluated those that induce the highest ones (thus following a precautionary approach).

5 Conclusions

Our application shows the relevance of ambiguity and ambiguity attitude in a real decision making problem. In all those circumstances in which an additive probability distribution cannot be associated to the different possible states of the world with certainty, different scenarios have to be taken into account and weighted according to a given decision criterion. The consequences in terms of the estimated outcomes associated to the various decision criteria may substantially differ. We apply the NEO-capacity framework [5] to the study of the net benefits of MOSE functioning for the city of Venice. A plus of the model is that it encompasses various decision making criteria as specific cases of the general decision making functional by just changing the value of the parameters expressing the optimism and/or the pessimism of the decision maker. Moreover, it allows to calculate the implicit attitude towards ambiguity of the decision maker who has to make the decision. To undertake our study, we identify different benefit components: avoided costs for repairing buildings from flooding damages, avoided costs for taking care of children at age of schooling and aged people forced to stay home by flooding and avoided reduction in tourists' expenses. For the costs, we consider the direct additional costs induced by the reduced frequency of shipping passages through the lagoon due to inlets closures. We derive, for the twelve different scenarios reflecting different assumptions on both environmental and anthropic variables an estimate of the net benefits of MOSE functioning and show the implications of the decision making criterion we consider. The estimated net benefits substantially vary according to the optimism and pessimism of the decision maker. Even assuming that decision makers have a symmetric attitude towards ambiguity (i.e., optimism and pessimism are equally weighted) net benefits are different from the ones that can be calculated on the basis of their expected value only. Moreover, the Expected Value Equivalent set shows that the decision maker has implicitly had a pessimistic (precautionary) approach when assessing the value of the benefits of MOSE system for the city of Venice.

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7 Appendix[12]

We describe here the methodology applied to calculate the net benefits of the MOSE system.

Two categories of costs are considered: operational and maintenance costs and direct costs due to the interferences with harbour activity. Data about the first category are obtained from the official report on MOSE described in [7]. They have been updated to take into account inflation and expressed at prices 2005; they equal 11,136 Thousands of Euro/year.

The second category has been derived from [15] and stems from the interruption of ship passages: when the mobile barriers are raised ships wait a longer period in roadstead and/or stay for a longer in wharf/quay due to the closure of inlets. These costs are calculated by summing two different components: *charter costs*, reflecting the additional time necessary to getting in and out of the lagoon; *mooring costs* depending on the additional time ships have to spend in docks. Charter costs capture the amount an individual has to pay to charter a ship. This amount is not fixed, but varies

[12] Data sets and regressions are available from the authors upon request.

according to contract clauses.[13] In the absence of detailed information, it is assumed that extra charter costs equal the ordinary charter costs.[14] Mooring costs include the costs for ships to stay in harbour; it derives from the official costs provided by the main maritime agencies operating within the Venice harbour: 'Venezia Trasporti Passeggeri' (VTP), for passenger ships; 'Terminal Intermodale Venezia' for all other ship categories.[15] Table 2 resumes the cost components expressed at market prices for each ship category.

[Table 3 about here]

Benefits are been calculated evaluating the impact of *acqua alta* on the city of Venice and people in and coming to the city. [4] identifies two different

[13] For crude oil tankers, for instance, *time charters* cover a long period of time, 10 or more years; *consecutive trips charters* (*COA*) specify the number of trips or the period of time (e.g. 1 year); *spot charters* refer to single trips between two specific harbours. Spot charters represent the 15-20% of the total transport needs and reflect the relationship between the short run demand and supply of crude oil tankers for single trips (www.eniscuola.net).

[14] Due to the lack of information on the charter type for each ship listed in our database it is not possible to make any specific assumption on how to calculate the extra costs due to the delay on ships passages induced by MOSE functioning. Charter contracts include several clauses on extra costs due to delay. Usually, if the delay is not caused by the fault of the charterer, no penalty is imposed, but daily costs may be reduced to a sum agreed by the owner and the charterer. This is typically the case of, *inter alia*, ice, dangers and accidents of the sea, collision or stranding, quarantine restrictions and act of war. If the delay is due to charterer responsibility, then it is likely that some extra costs are added, but the exact amount varies in each contract according to the specific agreements between ship owner and charterer. Even if at the moment it is not certain how the MOSE functioning will be treated, it is reasonable to imagine that it will be included among the causes of delay not under charterer responsibility.

[15] When expressed in USA dollars, costs have been transformed in Euro by using the average official exchange rate provided by the italian exchange bureau ('Ufficio Italiano Cambi, see www.uic.it) over the period January 2005 - May 2006.

categories of damages induced by *acqua alta*: damages to buildings, which can be subject to specific laws of protection on the basis of their artistic value, and damages to individuals (residents - elderly people, students - and tourists). We have adopted the following methodology: the first category refers to damages affecting the stock of real estate and thus it depends on the intensity of flooding; the latter affects the flow of services (touristic and personal) and therefore depends on the frequency of the flooding episodes. Thus, we calculate the benefits by deriving for each category the avoided costs, i.e., the cost saved thanks to the reduction in intensity and frequency of flooding due to the MOSE functioning in the following way.[16]

1. For buildings, high water causes damages to the walls,[17] which needs to be plastered after flooding. We assume that the renovation intervention is undertaken once, taking into account the highest tide experienced during the whole period considered for ships' traffic (2000-2002). We also assume that only the surface of walls that have been flooded is renovated. The surface is calculated setting the length[18] of the building surface involved by flooding as a function of the highest tide and multiplying it by a fixed height of 100 cm.[19] For buildings interested by specific laws of protection (historical buildings), the costs of renovation include also the costs for introducing a lead plate within the walls.

2. Avoided costs due to the displacement problems for Venetians include the avoided costs of caring for children in age of schooling and elderly

[16] All costs are expressed in 2005 prices; figures provided by [3], when needed, have been converted in Euro and upadted according to the OECD Italian Consumer Price Index.

[17] Damages to fornitures, apparels and systems are not included because of lack of data.

[18] The figure is obtained from a interpolation of the data about the length of buildings walls involved by *acqua alta* for different heights of floods, as described in [4].

[19] The rationale of such a height is explained in [4].

people. We used data provided by the official statistical bureau of the Municipality of Venice[20] for the distribution of cohorts. [4] shows that the 27% of children in age of schooling (from 5 to 19 years old) cannot reach their schools with a tide equal or above 120 cm. At the same tide, the 10% of the population from 75 to 84 years old cannot be cared of by their family. Therefore, we calculate the cost of interference on the personal services taking into account the opportunity cost of *acqua alta* for these people, namely, payments needed for baby-sitting and nursery services which occurs whenever the tide reaches + 120 cm over Punta della Salute Tidal Datum.

3. Data on the monthly tourist flow (during the period 2001-2007) come from the office of the Venice Municipality. An OLS regression is performed to calculate the number of tourists discouraged from coming to Venice as a function of the *acqua alta* (set equal or above 120 cm, including the months of the year as control variables).[21] Data on tourist average daily expense (for the period 2000-2002) come from the CISET Institute and is updated and used to convert figures of avoided tourists into avoided expenditures. Table 3 shows the different average unitarian costs.

[Table 4 about here]

Clearly, costs and benefits we consider are just a subset of the complete set, yet is the only one for which we could obtain data.

[20] See www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/1523

[21] On average, the presence of tourists in Venice is reduced by 3,516 units per every acqua alta episode (OLS regression, $t = -1.68$, $R^2 = 0.582$).

In particular, environmental costs (and benefits) are not taken into account too, since there are no clear estimates of them. We limit our analysis to the net benefits accruing to the historical part of the city of Venice only, excluding Mestre (its continental part), Lido, other islands and all other municipalities that are also affected by the *acqua alta* episodes in the lagoon. Moreover, we do not consider the expenditures of residents that can be affected by the displacement problems generated by flooding, except those of students and elderly people,[22] as well as any avoided cost due to the reduction in the damages to commercial and industrial inventories.

Finally, see that we do not take into account investment costs in our calculations. These are fixed (and sunk) costs, while we are interested in the evaluation of the net benefits of the MOSE due to the variation in the frequency of its usage. Thus, investment costs can be regarded as a scalar that could in principle be applied to our figures. However, it is not clear which exact amount should be used for it, since planned investment costs have been changing throughout the construction period (which is not yet terminated).[23]

[22] This is equivalent to suppose that all other Venetian residents's needs of displacement are not affected by *acqua alta*. This is clearly a simplifying assumption. The report of the international panel of experts [7] proposes a partial estimates of the effects of MOSE for Venetian. However, the methodology followed in that work is not compatible with our approach (it does not distinguishes between tourists and residents); moreover their data on displacement costs are not available.

[23] At present it equals 4, 271.63 MEuro (www.salve.it) .

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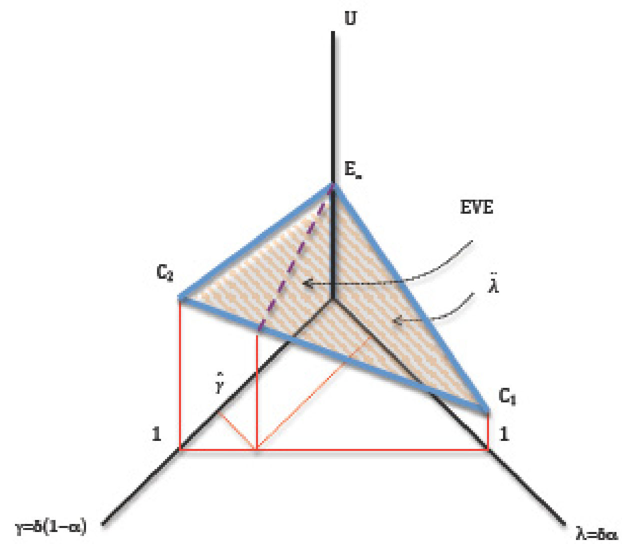

Figure 1: The CEU space in the γ, λ, simplex

Scenarios	Total costs	Total benefits	Net benefits
(A) 00_100_00	31,838	152,533	120,695
(B) 00_110_00	31,934	25,444	-6,490
(C) 00_100_10	31,669	209,828	178,159
(D) 00_110_10	31,862	152,533	120,671
(E) 30_100_00	33,588	268,182	234,593
(F) 30_110_00	32,080	230,794	198,714
(G) 30_100_10	35,485	268,182	232,696
(H) 30_110_10	33,024	231,238	198,214
(I) 50_100_00	41,383	369,152	327,770
(J) 50_110_00	36,277	306,543	270,265
(K) 50_100_10	45,084	418,373	373,290
(L) 50_110_10	39,522	369,041	329,520

Table 1: Total costs and benefits (Thousands of Euro/Year) for each scenario

Decision critierion	Net benefits
EU	214,841
Max-Min	178,159
Max-Max	373,290
CEU^p	$-\lambda(-36,683) + 214,841$
CEU^o	$\gamma(158,448) + 214,841$
CEU^H	$\gamma(195,131) + 178,159$
Implicit ambiguity attitude: $\hat{\lambda} = 0.81$; $\hat{\gamma} = 0.19$	

Table 2: Estimated net benefits: a comparison between different decision criteria

	Charter costs		Mooring costs
	Tons	€/Ton/Hour	€/Hour
Crude oil tanker	∀x[a]	0.03	1,333.33
Other oils tanker	x>1,000	0.13	1,333.33
	1,000>=x<1,500	0.12	1,333.33
	x>=1,500	0.11	1,333.33
LNG tanker	x<7,000	0.29	1,333.33
	7,000<=x<20,000	0.19	1,333.33
	x>=20,000	0.14	1,333.33
Container	x<15,000	0.03	1,000.00
	x>=15,000	0.02	1,000.00
Cargo	x>=4,500	0.01	1,333.33
Carrier	x<4,500	0.03	1,000.00
	x>=4,500	0.01	1,000.00
		€/Pass/Hour	€/Hour
Passenger ship		1.60	0.17
Yacht		46.77	0.45

[a] x refers to ships' gross tonnage.

Source: our elaboration from [15]

Table 3: Charter and mooring costs for ship category

Buildings	
Plastering: internal walls	2.77 €/1m 1cm high
: external walls	5.44 €/1m 1cm high
Artistic buildings	
Plastering: internal wall	2.77 €/1m 1cm high
: external walls	5.44 €/1m 1cm high
Lead plate: internal walls	20.11 €/m
: external walls	61.87 €/m
Aged people	
Caring	12.37 €/hour
Children in age of schooling	
Caring	12.37 €/1.5 hours
Tourists	
Tourist expense	85.96 €/day

Table 4: Avoided costs and expenses for category