Chapter 2
Harmonizing the Omnipresence of MCDM in Technology, Society, and Policy

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Abstract This paper presents historical perspectives on the evolution of the field and discipline of Multiple Criteria Decision Making (MCDM), followed by recognizing MCDM as a philosophy that inspired the development of theory, methodology, and practice of the art and science of MCDM. Except for a brief epilogue, the balance of the paper presents the following Ten Principles for the practice of MCDM: First Principle: MCDM as a harmonizing discipline in science, technology, society, and policy must be holistic; Second Principle: a common denominator bridges risk analysis and MCDM; Third Principle: models and state variables are central to MCDM; Fourth Principle: MCDM must account for risk of low probability with extreme consequences; Fifth Principle: MCDM must account for knowledge uncertainty and variability uncertainty; Sixth Principle: MCDM must account for emergent forced changes; Seventh Principle: multiple models are required to represent the multiple perspectives of a system; Eighth Principle: the imperativeness of selecting representative objectives and the time domain in MCDM; Ninth Principle: the MCDM process must be holistic, adaptive, incremental, and sustainable; and the Tenth Principle: Phantom System Models are required for the effective practice of MCDM, while building on and adhering to all nine principles.

2.1 Historical Perspectives

During the past four or five decades, the consideration of multiple objectives (criteria) in modeling and decision making has grown by leaps and bounds. The 1980s, in particular, saw more emphasis on multiple criteria decision making (MCDM) and a shift from the dominance of single-objective modeling and optimization toward an emphasis on multiple objectives. Indeed, most (if not all) real-world

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decision-making problems are characterized by multiple, non-commensurate, and often conflicting objectives. For most such problems, there exists a hierarchy of objectives, sub-objectives, sub-sub-objectives, and so on.

For example, the planning of water and related land resources in a river basin (or a region) is a vital element in the formulation of public policy on this critical resource. Such planning, adhering to the systems-gestalt-holistic philosophy, ought to be responsive to the inherent multiple objectives and goals and should account for the trade-offs among these objectives with respect to myriad objectives, including the following five categories of concern (Haimes 1977, 2009a):

1. Time horizon: short, intermediate, and long term
2. Client: various sectors of the public
3. Nature: aquatic and wildlife habitats
4. Scope: national, regional, and local needs
5. Other considerations: legal, institutional, environmental, social, political, and economic

There are many ways of identifying and classifying objectives and goals for such a planning effort. The U.S. Water Resources Council advocated the enhancement of four major objectives: (1) national economic development, (2) regional economic development, (3) environmental quality, and (4) social well-being.

The Technical Committee study (Peterson 1974) identifies nine goals, which have been divided into two major groups:

1. Maintenance of security: (a) environmental, (b) collective, and (c) individual
2. Enhancement of opportunity: (d) economic, (e) recreational, (f) aesthetic, (g) cultural and community, (h) educational, and (i) individual

In an environmental trade-off analysis, policies should be established to promote conditions where humans and nature can exist in harmony. Resolution of conflicts should be achieved by balancing the advantages of development against the disadvantages to the environment and the aquatic system. The process is one of balancing the total "benefit opportunities," "risks," and "costs" for people and the environment, where the well-being of future generations is as important as that of present ones. Fundamental to multi-objective analysis is the Pareto-optimum concept.

MCDM cannot be practiced effectively, if at all, without models (analytical, conceptual, or simulation). Models, experiments, and simulations are conceived and built to answer specific questions. In general, models assess what is Pareto optimal given what we know, or what we think we know, and where knowledge is needed for an effective decision-making process. Furthermore, mathematical models are the imperative mechanisms with which to perform quantitative MCDM. They are essential for helping analysts and decision makers to better understand and manage a system by relating to its subsystems and its relevant or critical interdependent systems. Modeling is also an art because successful models must build on the artistic traits of experimentation, imagination, creativity, independent thinking, vision, and entrepreneurship. In contrast to scientific knowledge, whose validity can and must be proven, mathematical models cannot always be subjected to such metrics.

In fact, the more complex is the system to be modeled, the lower is the modeler's ability to "verify" or "validate" the resulting models. Some scholars even argue that no complex model can be verified or validated, in part because of the dynamic and probabilistic nature of all natural and constructed systems. Heisenberg's principle is at work here as well; namely, once the system's model is deployed, the essence of the system has been changed.

Therefore, in modeling, it is important to identify this hierarchy of objectives and avoid comparing and trading off objectives that belong to different levels. This fact necessarily leads to the development of hierarchical models and methods that enable the decomposition of an overall system (problem) with its associated objectives into small subsystems, each with its associated sub-objectives. The resulting hierarchical multi-objective decision-making process, which mimics organizational structure, presents a more realistic modeling schema and acknowledges the complexity of the inherent hierarchical multi-objective trade-off analysis (Haimes et al. 1990). In such hierarchical MCDM structures, the subsystems (e.g., department in a major plant or subregions in a regional planning district) generate their own Pareto-optimal strategies and policy options, given the available resources and other constraints. This set of Pareto-optimal options associated with the sub-objectives is forwarded to the next level of the hierarchy of decision making as an input for trade-offs among the overall objectives.

2.1.1 MCDM as a Philosophy That Inspired the Development of Theory, Methodology, and Practice of the Art and Science of Decision Making

The theory, methodology, and practice of the field of MCDM, inspired by the philosophy underpinning MCDM, have experienced a revolutionary process during the past four or five decades. Indeed, MCDM has evolved from a conceptual-theoretical enterprise of interests practiced by a limited number of disciplines and individuals to a universally embraced philosophy. Today, MCDM is being practiced by almost every discipline, including engineering, medicine, economics, law, the environment, and public policy. Furthermore, MCDM has emerged as a philosophy that integrates common sense with empirical, quantitative, normative, and descriptive analysis. It is a philosophy supported by advanced systems concepts (e.g., data management procedures, modeling methodologies, optimization and simulation techniques, and decision-making approaches) that are grounded in both the arts and the sciences for the ultimate purpose of improving the decision-making process. This trend can be traced to the emergent and evolving professional embracing and practicing the gestalt-systems approach, with its appealing representation of the inherent multiple perspectives and comprehensive philosophy by the various disciplines. Consequently, this continuous evolution has necessarily created the need to address the eventual realization of the centrality of multiple objectives that characterize most systems. This is the evolving dominant role of MCDM in harmonizing the disciplines.

Practitioners in the field of MCDM know that an optimum for a single-optimization problem *does not exist in an objective sense per se*. An "optimum" solution exists for a model; however, in a real-life problem it depends on myriad factors, which include the identity of the decision makers, their perspectives, the biases of the modeler, and the credibility of the database. Therefore, a mathematical optimum for a model does not necessarily correspond to an optimum for a real-life problem. This premise also applies to models with multiple objectives in the context of MCDM, as will be discussed subsequently.

In general, multiple decision makers (MDMs) are associated with any single real-world decision-making problem. These MDMs may represent different constituencies, preferences, and perspectives; they may be elected, appointed, or commissioned, and may be public servants, professionals, proprietors, or laypersons; also, they are often associated or connected with a specific level of the various hierarchies of objectives mentioned earlier.

Solutions to a multi-objective optimization problem with multiple decision makers are often reached through negotiation, either through the use of group techniques of MCDM or on an ad hoc basis. The seminal book on the *Art and Science of Negotiation* by Raiffa (1982) is a classic example. Such solutions are often referred to as compromise solutions. However, the pitfalls of a non-win–win compromise solution must be recognized, because one or more decision makers must have lost in the voting or negotiation process. This fact is important because a decision maker in a losing group may be influential enough to sabotage the compromise solution and prevent its implementation. Behind-the-scenes horse trading is a reality that must be accepted as part of human behavior. If a stalemate arises and a compromise solution is not achievable (e.g., if a consensus rule is followed and one or more decision makers objects to a non-Pareto optimal solution that is preferred by all others), the set of objectives may be enlarged or the scope of the problem may be broadened. Finally, it is imperative that decisions be made on a timely basis – a "no-decision" stance could be costly.

What follows are ten Principles that encompass some of the major theoretical, conceptual, and methodological elements that over time have supported MCDM and made it a harmonizing discipline and a field equal to others.

2.2 Ten Guiding Principles for the Practice of MCDM

2.2.1 First Principle: MCDM as a Harmonizing Discipline in Science, Technology, Society, and Policy Must Be Holistic

The multiple perspectives of science, technology, society, and policy, which invariably intersect and often dominate each other, necessarily lead to multi-objective quantitative and qualitative models. This fact positions MCDM as an omnipresence harmonizing philosophy, theory, and methodology of the diverse disciplines. Furthermore, conflicting and competing non-commensurate objectives (criteria)

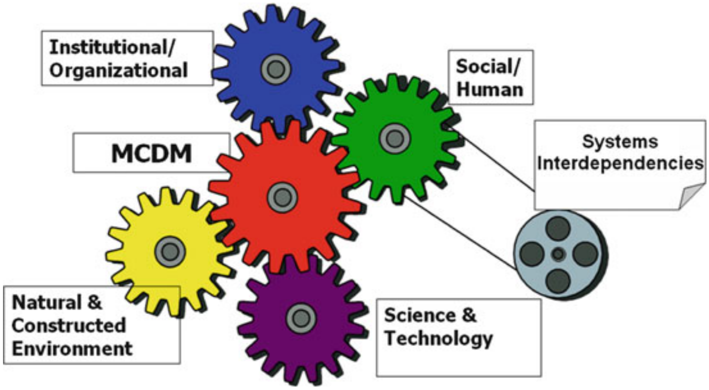

Fig. 2.1 The gestalt-holistic philosophy of MCDM as a harmonizing discipline in science, technology, society, and policy

characterize all disciplines, from engineering, medicine, architecture, agriculture, construction, politics, and education to public policy. MCDM theoreticians and practitioners can benefit from this diversity of users by building on the experiences gained through the domain knowledge of practitioners. The evolving wheels in Fig. 2.1 depict a sample of the multifaceted decision-making process, including the social/human dimension, institutional and organizational behavior, the natural and the constructed environment, and science and technology. All these, among other factors, are interconnected and interdependent systems; thus, the imperativeness of the gestalt-holistic philosophy embraced by MCDM. The analyses of the trade-offs that must be considered in all decision-making processes are depicted by the central wheel – the MCDM driving-force wheel.

2.2.2 Second Principle: A Common Denominator Bridges Risk Analysis and MCDM

The risk assessment and management process should be an integral part of the MCDM modeling effort, and risk management should be an imperative part of the multi-objective decision-making process – not an after-the-fact vacuous exercise. In risk assessment, the analyst often attempts to answer the following questions (Kaplan and Garrick 1981): What can go wrong? What is the likelihood that it would go wrong? What are the consequences? Here we add a fourth question: What is the time frame? Answers to these questions help risk analysts identify, measure, quantify, and evaluate risks and their consequences and impacts. Risk management builds on the risk assessment process by seeking answers to a second set of three questions (Haimes 1991, 2009b): What can be done and what options are available? What are the associated trade-offs in terms of all relevant costs, benefits, and risks? What are the impacts of current management decisions on future options?

The gestalt-holistic philosophy is the common denominator and probably is the most unique integrator and unifier that bridges MCDM with risk analysis. Both MCDM and risk analysis espouse the system-based, systemic, and comprehensive process. Assessing, managing, and communicating risk also means performing and balancing the trade-offs among the multiple conflicting, competing, and noncommensurate objectives and criteria associated with almost every system. By its nature, risk analysis is an integral part of MCDM and vice versa. They are two sides of the same coin – the complex and intricate decision-making process. In Fig. 2.2, MCDM is depicted as bridging the risk assessment and risk management processes through risk communication.

Figure 2.3 highlights the role of MCDM in harmonizing the inevitable decisions that must be made under conditions of risk and uncertainty, where the costs of current decisions associated with the risk assessment and management process are real and certain, but the corresponding beneficial opportunities resulting from reducing and mitigating expected future risks are uncertain.

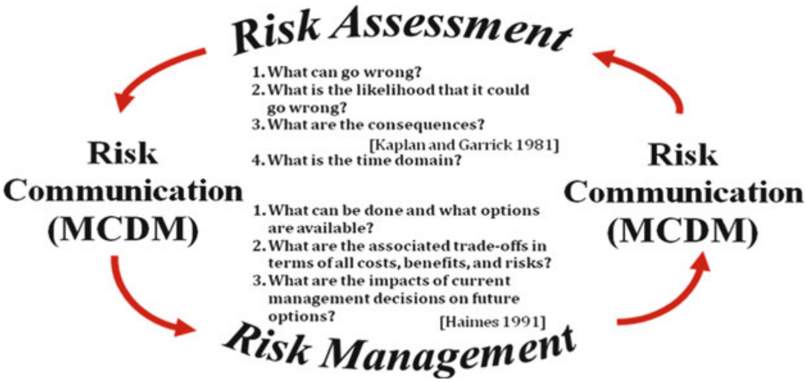

Fig. 2.2 Harmonizing risk assessment, management, and communication through MCDM

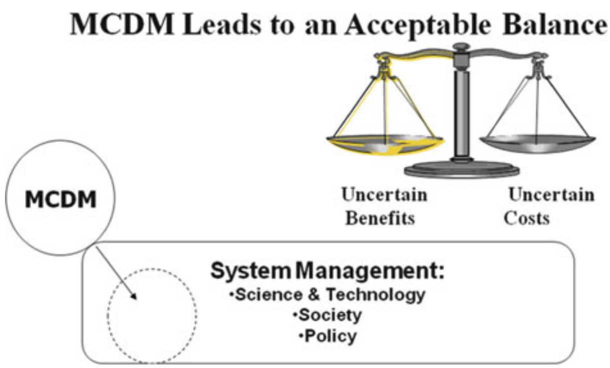

Fig. 2.3 MCDM harmonizes the acceptable balance between remaining residual risks with the costs of risk assessment and management

2.2.3 *Third Principle: Models and State Variables Are Central to MCDM*

Models are essential for quantitative and qualitative MCDM. Without models, decision makers and the MCDM community at large would be traveling blindly in unknown and often perilous terrains with dire consequences. The systems modeling process relies on the fundamental building blocks of mathematical models: *input, output, state variables, decision (control) variables, exogenous variables, uncertain variables*, and *random variables.* (Note that these building blocks may overlap; for example, *inputs* and *outputs* may be *random*.) Good managers desire to change the states of the systems they coordinate, manage, or control in order to support more effective and efficient attainment of the system's objectives. The choice of the model's state variables selected to represent the essence of the system is, to a large extent, determined and influenced by the model's purpose and the questions it is built to answer, and thus the choice of the decisions that will control the states of the system. Identifying and quantifying (to the extent possible) the building blocks of a mathematical model of any system constitutes a fundamental step in modeling, where the sine qua non is one building block – state variables. This is because at any instant the levels of the state variables are affected by other building blocks (e.g., decision, exogenous, and random variables, as well as inputs), and these levels determine the outputs of the system – primarily the system's objectives and criteria. For example, controlling the production of steel requires an understanding of the states of the steel at any instant – its temperature and other physical and chemical properties. Figure 2.4 depicts the model's building blocks of a farm. Note that at least two state variables are very critical for the optimal growth of the farmer's crops. Knowing the *state* of soil moisture would determine whether the farmer ought to irrigate the crops in non-rainy seasons, and knowing the *state* of soil nutrients would determine the level of fertilizer, if any, that is needed for an optimal growth of the crops. The centrality of state variables in modeling, within and outside the

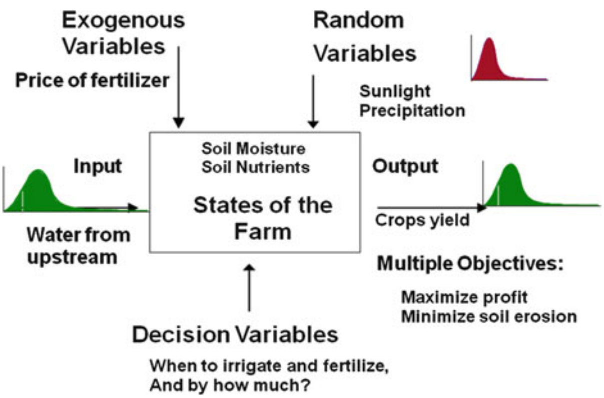

Fig. 2.4 Models and state variables are central to MCDM

MCDM community, has not been sufficiently emphasized. For example, both the vulnerability and resilience of a system are manifestations of the states of the system (Haimes 2006, 2009a, b, c). *Any model should be as simple as possible and as complex as required to answer the expected questions.*

2.2.4 Fourth Principle: MCDM Must Account for Risk of Low Probability with Extreme Consequences

The concerns of the public and most decision makers focus on events with dire and catastrophic consequences, even with low probabilities. Risk is commonly defined as a measure of the probability and severity of adverse effects (Lowrance 1976). With this definition of risk widely adopted by many disciplines, its translation into quantitative terms has been a major source of misunderstanding and misguided use and has often led to erroneous results and conclusions. The most common quantification of risk – the use of the mathematical construct known as the expected-value of risk metric – commensurates low probability of high-consequence events with high probability of low-consequence events – has been playing a decisive role in masking the criticality of these catastrophic events. It is probably the dominant reason for this chaotic situation in the quantification of risk. It is important to recognize the misuse, misinterpretation, and fallacy of the expected value *when it is used as the sole criterion for risk in decision making*. Moreover, the expected value of risk, which until recently has dominated most risk analysis in the field, is not only inadequate, but can lead to fallacious results and interpretations.

The partitioning multi-objective risk method (PMRM) (Asbeck and Haimes 1984; Haimes 2009a), which supplements and complements the expected value measure of risk, isolates a number of damage ranges (by specifying the so-called partitioning probabilities) and generates conditional expectations of damage, given that the damage falls within a particular range. *A conditional expectation is defined as the expected value of a random variable given that this value lies within some prespecified probability range*.

Two challenging questions – how safe is safe enough, and what is an acceptable residual risk? – underline the normative, value-judgment perspectives in risk-based decision making. No mathematical, empirical knowledge base today can adequately model the perception of risks in the mind of decision makers. In the study of MCDM, we clearly distinguish between the quantitative element in the decision-making process, where efficient (Pareto-optimal) policies and their corresponding trade-off values are generated, and the normative value-judgment element, where the decision makers make use of these efficient solutions and trade-off values to determine their preferred (compromise) solution (Chankong and Haimes 1983, 2008). In many ways, risk-based decision making can and should be viewed as a type of stochastic MCDM in which some of the objective functions represent risk functions. This analogy can be most helpful in making use of the extensive knowledge already generated by MCDM (witness the welter of publications and conferences on

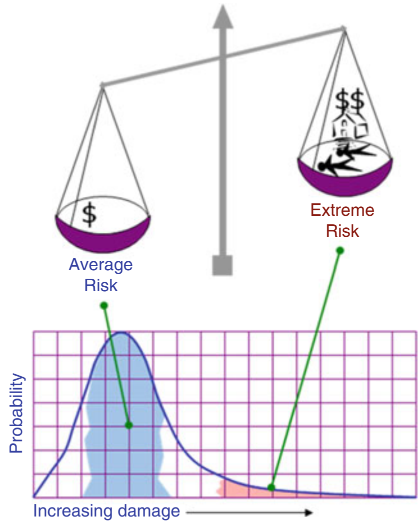

Fig. 2.5 MCDM must account for risk of low probability with extreme consequences

the subject). Probably the most important aspect of considering risk-based decision making within a stochastic MCDM framework is the handling of extreme events. Figure 2.5 depicts the importance of the philosophy, methodology, and practice of MCDM in balancing the average risk with extreme risk.

$$\text{Risk} = \textit{function}\,(\text{Likelihood, Consequences})$$

2.2.5 *Fifth Principle: MCDM Must Account for Knowledge Uncertainty and Variability Uncertainty*

Uncertainty, commonly viewed as *the inability to determine the true state of a system*, can be caused by *incomplete knowledge* and/or *stochastic variability* Paté-Cornell (1996). Two major sources of uncertainty in modeling affect MCDM and other professional fields: (1) *Knowledge Uncertainty*, which manifests itself among other sources in the selection of model topology (structure) and model parameters; and (2) *Variability Uncertainty*, which includes the incorporation into the modeling process of all relevant and important random processes, and other random events and emergent forced changes. Both types of uncertainties markedly affect the quality and effectiveness of the MCDM efforts.

Uncertainty can arise from the inability to predict future events; it dominates most decision-making processes and is the Achilles' heel for all deterministic and most probabilistic models. Clearly, both types of uncertainties markedly affect the quality and effectiveness of the MCDM modeling and analysis efforts and ultimately the decision-making process.

There is a fundamental difference between risk and uncertainty. Risk as a measure of the probability and severity of adverse effects represents an amalgamation of

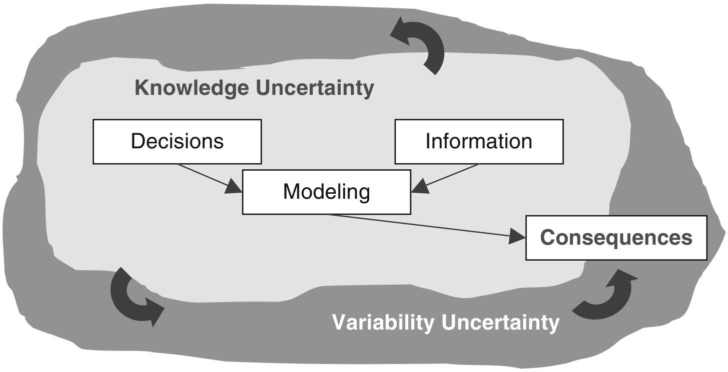

Fig. 2.6 Knowledge uncertainty and variability uncertainty in MCDM

both likelihood and consequences. The very term *risk* refers to a situation in which the potential adverse outcomes can be described in objectively known probability distributions. However, the term *uncertainty* refers only to the likelihood, and commonly refers to a situation in which no reasonable probabilities can be assigned to the potential outcomes.

A significant uncertainty, all too often ignored in the quest for quantitative predictive models, is how well the models used actually represent the real system's significant behavior. This uncertainty can be introduced through the model's topology (structure), its parameters, and the data collection and processing techniques. Model uncertainties will often be introduced through human errors of both commission and omission. In sum, uncertainty caused by variability is a result of inherent fluctuations or differences in the quantity of concern. More precisely, variability occurs when this quantity is not a specific value but rather a population of values. Figure 2.6 depicts the multiple sources of uncertainty.

2.2.6 Sixth Principle: MCDM Must Account for Emergent Forced Changes

Emergent forced changes must be anticipated, tracked, and their precursors be discovered with diligence, so that if and when they cross over (materialize), decision makers would be ready for such an inevitable reality. *The term "emergent forced changes" connotes external or internal sources of risk that may adversely affect the states of the system*, and thus affect the system as a whole. Figure 2.7 presents an example of emergent forced changes based on a 2008 report by the U.S. Department of Transportation, which projects that increased storm intensity due to climate change may lead to increased service disruption and infrastructure damage over the next fifty to one hundred years, and where in the U.S. Gulf coastal area "64% of interstates, 57% of arterials, almost half of the rail miles, 29 airports, and virtually all of the ports are below 7 m (23 feet) in elevation and subject to flooding and possible

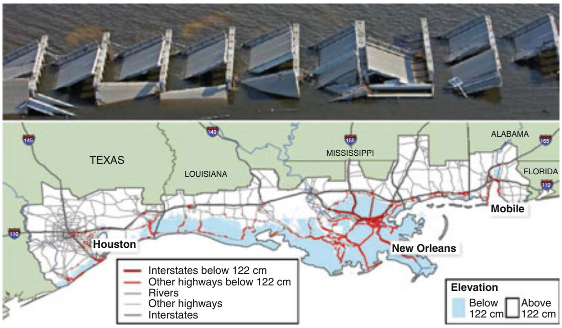

Fig. 2.7 An example of emergent forced changes: impacts of climate variability

damage due to hurricane surge." Addressing both time and uncertainty when studying emergent forced changes is a sine qua non principle that ought not to be violated by MCDM practitioners. Emergent forced changes may be manifested through a continuous spectrum of events, necessarily associated with mostly adverse effects. These may be caused by natural phenomena or malevolent human actions, including unintended disastrous consequences initiated through local, regional, or global public policy decisions and actions. Some emergent forced changes are occurring in today's world. Bayesian analysis constitutes an important element in modeling, estimating, and tracking over time the precursors to and the emergence of forced changes. Bayes' Theorem, which provides the basis for Bayesian analysis, translates probabilistically new knowledge, whether gained by direct observations or through expert evidence. It incorporates the new probabilistic acquired knowledge within the prior probabilistic assumptions. Scenario development constitutes a central role in tracking and estimating precursors to the occurrence of emergent forced changes. In scenario tracking, both the probabilities and consequences are considered when evaluating the importance of any specific scenario. The uncertain nature of emergent forced changes requires that appropriate metrics for the quantification of the risks and uncertainties associated with each objective function (and other parts of the model) considered in the MCDM process must be adopted and studied. Without such considerations the representativeness and effectiveness and the ultimate credibility of the entire decision-making process would be questionable.

One important demarcation line between a good or a great decision-making process is the extent to which the known and known-unknown future developments and emergent forced changes affecting the system enterprise are addressed. These forces, whose sources may be internal or external to an organization, must be anticipated and tracked, and their precursors discovered with diligence. Then, if and when they materialize, the decision makers and their tactical and strategic plans will be ready for such an inevitable reality. In other words, this is a sine qua non principle that should not be violated by risk analysts and practitioners.

Resilience, which is a manifestation of the states of the system and represents the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable composite cost and time, is an important concept in emergent forced changes (Haimes 2009c). This is because

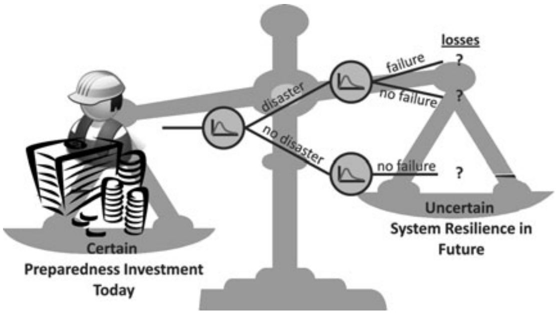

Fig. 2.8 Trade-offs are made between preparedness for emergent forced changes and future system resilience

the anticipation of and planning for emergent forced changes through preparedness and other risk management actions necessarily improve the resilience of the system. Figure 2.8 highlights the inherent trade-offs that must be made among certain investments today for preparedness in the quest to address emergent forced changes and the uncertain nature of either the realization of such forced changes or the expected future resilience of the system.

2.2.7 Seventh Principle: Multiple Models Are Required to Represent the Multiple Perspectives of a System

The interconnectedness and interdependencies within and among all large-scale and multi-scale systems defy a single model representation of the multiple systems' perspectives. The included and excluded systems' perspectives implicitly and explicitly affect the ultimate selection of policy options in the MCDM process. Indeed, most organizational and technology-based systems and all military systems are hierarchical in nature; thus their risk management is driven by this hierarchical reality and must be responsive to it. The risks associated with each subsystem within the hierarchical structure are likely to contribute to and ultimately determine the risks of the overall system. Hierarchical considerations and aspects of a system and the multiple objectives associated with that system are dual attributes that should be recognized as such in all serious modeling efforts, and particularly for risk-informed decision making. The ability to model the intricate relationships among the various subsystems and to account for all relevant and important elements of risk and uncertainty renders the modeling process more tractable and the MCDM process more representative and encompassing.

When modeling large-scale and complex systems such as dams and levees, more than one mathematical or conceptual model is likely to emerge; each of these models may focus on a specific aspect of the system, yet all may be regarded as acceptable representations of it.

It is impracticable to represent within a single model all the aspects of a large-scale system, such as physical infrastructure systems, that may be of interest at any given time (to its management, government, or regulators). Hierarchical Holographic Modeling (HHM) (Haimes 1981, 2009a) has emerged from a generalization of Hierarchical Overlapping Coordination (Haimes and Macko 1973; Macko and Haimes 1978). The name is suggested by holography – the technique of lensless photography. The difference between holography and conventional photography, which captures only two-dimensional planar representations of scenes, is analogous to the differences we see between conventional mathematical modeling techniques (yielding what might be termed "planar," limited-perspective models) and the more "multidimensional" HHM schema. In the abstract, a mathematical model may be viewed as a one-sided image of the real system that it portrays. In many respects, HHM is a holistic philosophy/methodology aimed at capturing and representing the essence of the inherent diverse characteristics and attributes of a system it attempts to model – its multiple aspects, perspectives, facets, views, dimensions, and hierarchies. Figure 2.9 presents two perspectives (decompositions) of the Maumee River Basin, within the Great Lakes Basin (Ohio, Michigan, and Indiana): Hydrologic (eight watersheds) and Political-Geographic (five planning subareas) (Haimes, 2009a).

The term *holographic* refers to having a multi-view image of a system when identifying vulnerabilities (as opposed to a single view, or a flat image of the system). The term *hierarchical* refers to the desire to understand what can go wrong at many different levels of the system. HHM recognizes that for the risk assessment to be complete, one must realize that the macroscopic risks that are understood at the upper management level of an organization are very different from the microscopic risks observed at lower levels. In a particular situation, a microscopic risk can become a critical factor in making things go wrong. In order to carry out a complete

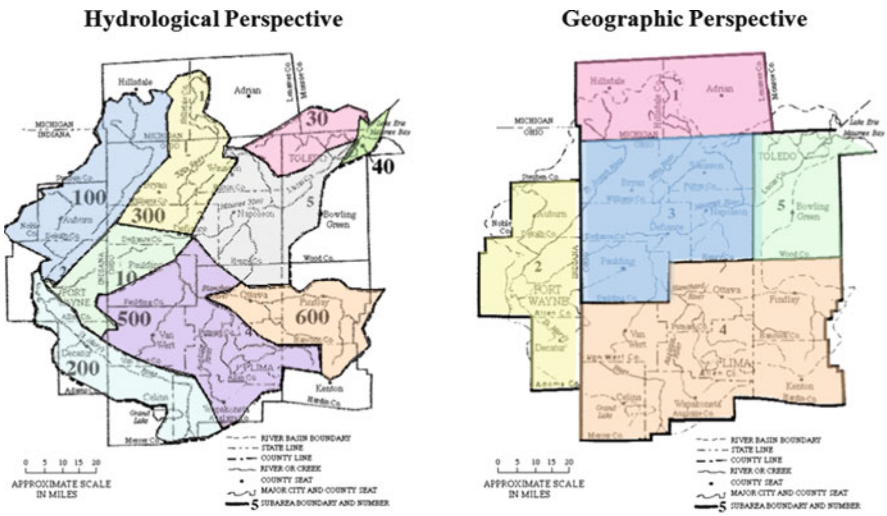

Fig. 2.9 Hydrologic perspective and political-geographic perspective

HHM analysis, the team that performs it must include people who bring knowledge from up and down the hierarchy.

HHM has turned out to be useful in modeling large-scale, complex, and hierarchical systems, such as defense and civilian infrastructure systems. The multiple visions and perspectives of HHM add strength to risk analysis. It has been extensively and successfully deployed to study risks for numerous government agencies. To counter the enormously large scenarios generated for both questions, the Risk Filtering and Ranking Method developed in 1990 for NASA was subsequently extended and modified (Haimes et al. 2002).

2.2.8 *Eighth Principle: The Imperativeness of Selecting Representative Objectives and the Time Domain in MCDM*

Today, more than ever, it is a mistake to try to optimize a set of objectives that are limited to present needs and aspirations or that are not responsive to emergent or future forced changes. In other words, for an adaptive, incremental, and sustainable MCDM process to be successful, future impacts of present decisions and policies must be incorporated and be an integral part of the trade-offs. Thus, a systemic approach to MCDM should be adopted to (1) continuously assess and evaluate precursors to potential forced changes, (2) balance present objectives with potential or perceived emergent needs and objectives, and (3) add more flexibility to present policy formulation to ensure against adverse emergent or unintended catastrophic or irreversible consequences. For example, evaluating the consequences and future flexibility of two preferred Pareto-optimal policies could dictate a distinct choice between two options presently perceived as seemingly equivalent. The importance of impact analysis is even more critical when considering the time domain that affects all systems – societal, organizational, and technological. Examples are the natural deterioration over time of all physical infrastructures, demographic changes, and advancements in technology. Each stage in this evolving dynamic world is characterized by multiple objectives, and trade-offs among the attainment of present objectives and future flexibility can be incorporated within the overall risk-informed decision-making process.

Should the systems modeler or decision makers always be satisfied with a single-perspective model of the system under study? The answer is no. Invariably single models as discussed in the previous principle cannot adequately capture the multifarious nature of large-scale water resources systems, their bewildering variety of resources and capabilities, their multiple non-commensurable objectives, and their diverse users.

Furthermore, the following too-often overlooked cases constitute major sources of misinterpretation or misuse of Pareto optimality:

1. The number of selected objective functions introduces an implicit bias in the ultimate outcomes generated through the MCDM process. To address this reality, concerted efforts must be devoted to assessing the sensitivity of the resulting

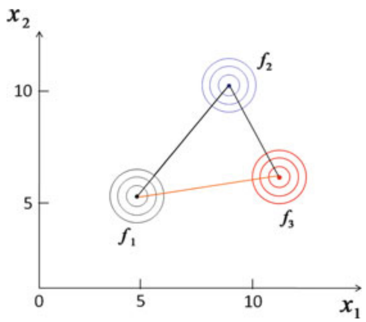

Fig. 2.10 Pareto optimality is dependent on the proper selection of the objective functions

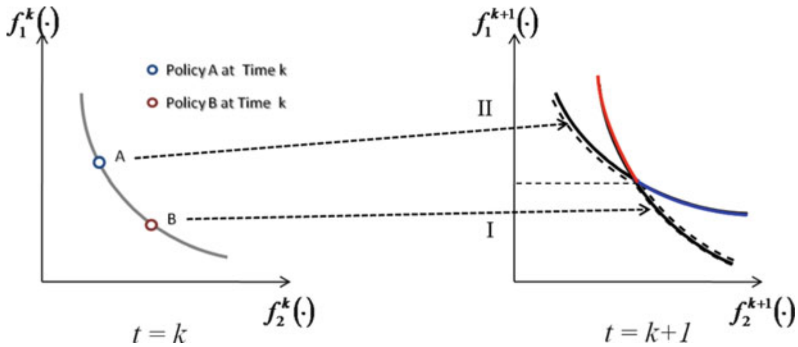

Fig. 2.11 Impact of policies at time $t = k$ on future options at time $k + 1$

policy options to the addition or deletion of one or more objective functions. Figure 2.10 presents three objective functions to be minimized in the decision space and the associated Pareto-optimal solutions (both Proper Pareto-optimal solutions in the interior triangle and Improper Pareto-optimal solutions in the boundaries of the triangle). Note that removing one of the three objective functions would eliminate a significant number of Pareto-optimal solutions, and vice versa.

2. Dynamic systems where the time domain is of paramount importance introduce another challenge to the theory and practice of MCDM. For example, ignoring the changes in the states of a safety-critical dynamic system as time progresses would render static-based decisions misleading, if not disastrous. Recognizing this fact, event trees, decision trees, and process control, among other methods, account for the impacts of current decisions on future options. Figure 2.11 presents impact of policies at time $t = k$ on future options at time $k + 1$, where the dotted line represents a new Pareto-optimal frontier generated at time $k + 1$. Note that if the decision maker were to prefer to operate during period $k + 1$ in Regime I, then Policy B would be inferior to A. Conversely, if the decision maker were to prefer to operate during period $k + 1$ in Regime II, then Policy A would be inferior to B. Clearly, the time domain is critical in the MCDM process.

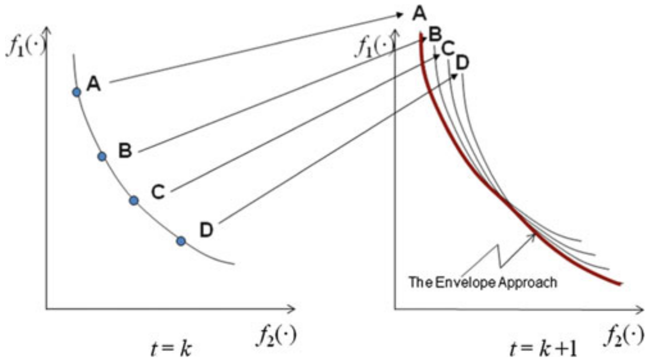

Fig. 2.12 The envelope of the combined Pareto-optimal frontier of policies A, B, C, and D for $k + 1$st period

The Envelope Approach was developed to account for the propagation of Pareto-optimal solutions from one period to another (Li and Haimes 1987). Figure 2.12 extends this concept through the Envelope Approach, where the Pareto-optimal frontier can be generated for n periods. Note that the solid-line outer curve represents the envelope of the combined Pareto-optimal frontier of policies A, B, C, and D for the $k + 1$st period.

Finally, the trade-offs among the multiple objectives must complement and supplement the determination of Pareto optimality in the MCDM process. The process of eliciting the decision makers' preferences must be systemic, repeatable, robust, and based on the evidence generated in the MCDM process. Several methods and approaches have been developed to generate the multiple trade-offs, including the Surrogate Worth Trade-off (SWT) method (Haimes and Hall 1974; Haimes 2009a).

2.2.9 *Ninth Principle: The MCDM Process Must Be Holistic, Adaptive, Incremental, and Sustainable*

Any characterization of a holistic and multifaceted decision-making process must address, at a minimum, its following attributes: it is dynamic; is fraught with myriad sources of risk and uncertainty, including emergent forced changes; involves a hierarchy of multiple decision makers; often must address multiple conflicting, competing, and non-commensurate objectives, goals, and aspirations; is driven by ever-moving requirements, demands, and targets; and, not least of all, it protects, adheres to, and promotes organizational core values. Thus, the decision-making process must be holistic, adaptive, incremental, and sustainable.

2.2.9.1 Why Holistic?

Can a decision-making process be considered effective and viable if only for randomly selected risks and opportunities, for a fixed time domain, and for only a subset of affected parties? Clearly, the complexity and multi-scale attributes of almost all organizational, societal, and the natural and built environment physical infrastructures require an encompassing and holistic MCDM process. The decision-making process cannot be addressed with a simplistic "one-fits-all" approach, because each system comprises its own unique characteristics and idiosyncrasies. Furthermore, once decisions are made, then the ways and means for *communicating* them to the stakeholders are often as important as the content and impacts of the decisions themselves. In addition, *not all decisions may go well or meet their intended functions.* Holism must be the hallmark of a decision-making process that is impeccable and above reproach.

2.2.9.2 Why Adaptive and Incremental?

Fundamental to the MCDM process is the consideration of present and future opportunities and risks associated with the decisions and trade-offs that are being made. Thus, if we accept the premise that all critical and important decisions are made under uncertain conditions, it follows that as we track the events over time and assess the consequences of the decisions made (positive or negative), some appropriate course correction and adaptation would be imperative. In his book *Good to Great*, Jim Collins (2001 p. 195) writes: "Enduring great companies preserve their *core values and purpose* while their business strategies and operating practices *endlessly adapt to a changing world*. This is the magical combination of 'preserve the core and stimulate progress"' [emphasis mine]. As a corollary, assessing and clarifying the viability of the decisions is dependent on the effectiveness of the MCDM process. In other words, an effective and viable decision-making process does not end when the decisions are made; rather, a systemic post-audit evaluation is required to continuously track the progress being made. *This would reveal future opportunities and unintended adverse consequences that might be encountered*. Furthermore, precursors to emergent forced changes, whose crossovers could adversely affect the system and might counter the original goals and objectives of the decisions being tracked, ought to be assessed and new actions adapted. These activities are commonly made incrementally with appropriate resources allocated for each tracked forced-change scenario commensurate with its projected impacts and consequences.

2.2.9.3 Why Sustainable?

The third edition of The Merriam-Webster New International Dictionary defines sustainability as: "maintained at length without interruption, weakening, or losing in power or quality." An MCDM process must also be sustainable and achieve sustainable results. This means it must maintain the planned and anticipated results from such decisions (in addition to the value derived from being holistic, adaptive, and

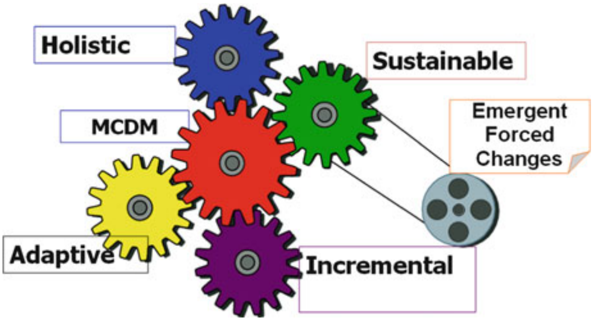

Fig. 2.13 The holistic, adaptive, incremental, and sustainable MCDM process

incremental). Fundamentally, a sustainable decision-making process shares many of the traits of a holistic process, because it also implies that the process must be strategic, encompassing, and well-balanced, involving and communicating with all concerned parties, and responsive to the uncertain world within which the results of the decision will be realized.

An appropriate model ought to be able to answer the following question: *Will the planned-for demands (or stress) on a system be dramatically exceeded by a potential emergent events that could produce a much higher critical demand (or stress) than planned for, thus resulting in extreme or catastrophic consequences?* For an informed confirmation of this scenario, we term this eventuality a "crossover." *Thus, in the context of modeling, crossovers connote situations where during the planning time horizon of a dynamic system, the projected extreme event (e.g., an emergent forced change) can cross from a state of too high an uncertainty to base designs upon to a forecasted state of too high a likelihood of occurring to ignore as an important factor of design*. In addition to focusing on model assumptions, *we must also continue our efforts to develop methods of modeling that can discover and illuminate crossovers, where the output of the model is highly sensitive to the shift in assumptions caused by external forced changes*.

Figure 2.13 depicts the holistic, adaptive, incremental, and sustainable MCDM process that is driven by and responsive to emergent forced changes, where holistic connotes systemic, comprehensive, and encompassing doctrine; adaptive connotes continuously updating the states of the system and the corresponding decisions, and where the time domain is of paramount importance; incremental connotes a step-by-step process that builds on new knowledge; and sustainable connotes a viable and repeatable process.

2.2.10 Tenth Principle: Phantom System Models Are Required for the Effective Practice of MCDM, While Building on and Adhering to All Nine Principles

This Tenth Principle encompasses all nine principles introduced previously. Consider the challenging tasks facing leaders and planners around the world to ensure adequate housing, supply drinking water of safe quality, and myriad other social and economic initiatives, given the emergent forced changes in climate, terrorism, and future population growth. These MCDM-based multi-scale complex systems are not "solvable" in any provable, cost-effective way. Like most complex systems, they require trade-offs across objectives and large-scale integration of scores of research efforts across many dimensions. Indeed, both cases share the urgent need to continue gathering and analyzing actionable information and incorporating it into an evolving policy. Horowitz (2007) provides a definition of multi-scale systems in the context of large-scale systems: "By their nature, large-scale and complex large-scale systems span a number of discrete levels from the highest system level to the lowest component level. As opportunities and risks present themselves, they may have different impacts and require different planned responses at different levels."

No single model can capture all the dimensions necessary to adequately understand, evaluate, and manage the above challenges. For example, it is impossible to represent in a single model all relevant state variables of large- and multi-scale systems. Furthermore, adhering to the nine principles discussed in this paper – and particularly the Ninth Principle, which calls for a holistic, adaptive, incremental, and sustainable MCDM process – requires a new modeling paradigm, referred to as Phantom System Models (PSM) (Haimes 2007, 2009a). (Note that the term PSM will connote the overall modeling philosophy, while PSMs will connote the modeling components.) Indeed, unprecedented and emerging multi-scale systems are inherently elusive and visionary – they are, by and large, phantom entities grounded on a mix of future needs and available resources, technology, forced developments and changes, and myriad other unforeseen events.

The PSM builds on and incorporates input from HHM (see Seventh Principle), and by doing so seeks to develop causal relationships through various modeling and simulation tools; it imbues life and realism into phantom ideas for emergent systems that otherwise would never have been realized. In other words, with different modeling and simulation tools, PSM legitimizes the exploration and experimentation of out-of-the-box and seemingly "far-fetched" ideas and ultimately discovers insightful implications that otherwise would have been completely missed and dismissed. In this sense, it allows for "non-consensus" ideas or an "agree-to-disagree" process for further exploration and study. The output of the HHM is a taxonomy of identified risk scenarios, or multiple perspectives of a system for modeling. Alternatively, the output of the PSM is a justification or rationalization for investment in preparedness or learning activities to protect against critical forced changes or emergent risks – investment that might not otherwise have been approved. *Through logically organized and systemically executed models, the PSM provides a reasoned experimental modeling framework with which to explore and thus understand the intricate relationships that characterize the nature of multi-scale emergent systems.* The PSM philosophy rejects dogmatic problem solving that relies on a single modeling approach structured on one school of thinking. Rather, its modeling schema builds on the multiple perspectives gained through generating multiple scenarios. This leads to the construction of appropriate models to deduce tipping points as well as meaningful information for logical conclusions and future actions.

The multi-model, systems-driven PSM approach can effectively address these emergent challenges at both the national strategic and local tactical levels. Such an approach must be capable of maximally using what is known now and optimally learn, update, and adapt through time as decisions are made and more information becomes available. In the context of the holistic, adaptive, incremental, and sustainable MCDM process, the PSM is a real-to-virtual laboratory for experimentation, a learn-as-you-go facility, and a process for emergent systems that are not yet completely designed and developed.

2.3 Epilogue

The complex social-, technological-, economic-, environmental-, and political-based challenges leaders and planners around the world experience necessarily require a holistic, adaptive, incremental, and sustainable decision-making process, where multiple non-commensurate, competing, and often conflicting objectives must be addressed and reconciled. During the past several decades, MCDM, by its philosophical underpinning and the theory, methodology, and practice that have been developed on the basis of its holistic philosophy, has served as a harmonizing agent in technology, society, and policy. The Ten Principles introduced in this paper are aimed at recognizing this harmonizing trend.

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