An Application of Risk-Constrained Optimization® (RCO) to a Problem of International Trade

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Volume 16, *Number* 4
December 2010, *pp*. 415-465

The complexity, uncertainty, and perils of the 21st century generate a large number of crucially important complex and long-term socio-economic and technical problems. Solving these problems requires the application of advanced analytical tools that combine computers and sophisticated mathematical models. Using such a combination demands, however, embedding it in an ensemble of techniques that would neutralize potentially dangerous miscalculations.

Risk-Constrained Optimization® (RCO) provides the necessary ensemble of many novel concepts, models and methods that are critical to each other's success. Perhaps the most important of them is imposing on optimization models an additional function of self-filtering, so that they become very efficient "optimizing filters." Possibly with some modifications, all these techniques, associated with seven diverse disciplines, appear to be necessary components of any dependable methodology of decision making for non-trivial (complex and long-term) problems.

Thus, for the first time in more than 60 years, RCO legitimizes the high-level analytical use of a "computer-optimization model" combination. Describing that function of RCO is the first goal of the present paper.

Also, RCO is the only currently existing methodology for strategic *risk management. (The second goal.) RCO constructs a set of robust and flexible, reasonably good and safe long-range candidate strategies. The final strategy is selected from that set subjectively. As with any protective equipment, RCO could reduce the need for knowledge about the future.*

Then, as an inseparable component of the outlined above ensemble, RCO introduces a new paradigm of economic decision making -- "catastrophe avoidance," which replaces the current paradigm of utility or profit maximization. Also, economics should be nudging people and organizations toward making socially beneficial decisions. RCO -- or some its equivalent, if it appears and is better -- should become an important part of a badly needed radical transformation of the theory and practice of economics, Operations Research, and adjacent disciplines. (The third goal.)

This paper demonstrates the RCO methodology on the problem of USA-China trade under conditions of radical uncertainty. It is a problem of enormous complexity; we can barely start dealing with it here, in an article focused on RCO. Nevertheless, the approach taken is dismissing the incredibly dangerous *assumptions of abstract theory of international trade that, applied in the real world, have destroyed the beneficial social balance, created with enormous difficulties in progressive societies in the last 200 years. (The fourth goal.)*

Keywords: Paradigm of economic decision making, Decision making under uncertainty, Risk management, Scenario planning, International trade, Political economy.

1. Introduction

The best principle of science was probably formulated by Albert Einstein: "Make everything as simple as possible, but not simpler." That commandment would be particularly appropriate as a general epigraph to this special issue of the journal, devoted to decision making in complex systems. The epigraph would constantly remind us that violating the principle might court disaster. That is exactly what happened in economics and adjacent disciplines, such as Operations Research and Decision Science: their current paradigm is simplistic and they are therefore unable to address any complex and long-term problems. These disciplines can only deal with short-term issues, such as "rearranging chairs on the deck of Titanic."

Much of that primordial sin of oversimplification goes back to the 18th century, to the proposition that economic theory adopts the maximization of utility as one of its foundations. In that approach the decision maker became no more than an abstract construct, and the decision problem was short-term and simple, basically coming down to the selection of goods and services to be consumed. It was assumed that the utility of a decision could be calculated, and that nothing else but the value of utility (subject to the relevant constraints) determined the decision.

In the framework of a mathematical abstraction, and under these rudimentary assumptions, it was correct to consider the one-dimensional maximizing behavior of the decision maker as "rational."

What is correct for the abstract Never-Never Land is not correct though for the human society. There are no absolutes in society, and there exist no rules of behavior or decision making that can be taken as axioms. There are only approximate rules of thumb, which sometimes are applicable and sometimes are not. But reduction of self-interest to a single one-dimensional goal is not even one of such rules of thumb: it is an abnormal behavior of a psychopath that may be considered an obsession, a fixed idea, monomania, paranoia. (An obsession can be noble and magnificent, too, but only when "Damn the torpedoes" is for the benefit of society.) Asserting that utility is not one-dimensional because it incorporates all needs and wishes of the decision maker does not help: such a declaration does not sound true and indeed is not. Utility obviously can be calculated only for a narrow field of short-term individual consumption (and as "acquired utility" of the corresponding production factors), rather than for a broad range of more general, long-range, or socially relevant items.

Moreover, even in terms of the individual self-interest, maximizing consumption does not maximize happiness (and its proxy, utility). As Murray convincingly argues, "If we ask what are the institutions through which human beings achieve deep satisfaction in life, the answer is that there are just four: family, community, vocation, and faith. " [Murray 2009] Conspicuous consumption – that is, basically, consumption above the primary needs of the Maslow's hierarchy [Maslow 1943] – plays a minor positive, and often negative, role in all four institutions. People do not consume what they really need: they consume "…what they *think* they need, and are willing to pay for" [Akerlof and Shiller 2009, 26], and that brings them no more than a very passing pleasure.

And woe to society that prefers fat to muscle. Folk wisdom – from "Nothing in excess" of ancient Greece, that nation of philosophers, to bushido – always was against lavish consumption. Orwell considered even decent consumption the prime cause of social instability; that is the real theme of "1984." [Orwell 1949].

In short, I think that, in the real world, "rationality" of utility maximization belongs in the "emperor's clothes" category, even for an individual. Moreover, society is much more than a simple sum of individuals, and the individualistic paradigm should be replaced by a more socially relevant criterion. (It should retain though its individualistic format, but the decisions should be "nudged" in the proper direction by, most likely, price signals that contain the necessary societal information. For consumers, pleasure of eating cherry or blackberry for breakfast may be the same, but if we want to prevent, say, demolition of cherry orchards, the price of cherries should be lower.)

Like every living organism, a society has a goal – *long-term sustainable survival in an acceptable state*. Every human decision has a social impact, even if is just a small "butterfly effect"; every decision produces some externality, some effect on general welfare. Thus there are no purely economic and purely individualistic decisions; even the decisions that appear to be such are just socio-economic decisions with the social part deliberately overlooked.

There is no workable social welfare function. (Even simple interpersonal comparison of utilities immediately opens a Pandora box of unpleasant questions.) Calculation of a social utility is therefore impossible not because of lack of data, but *in principle,* even for the short-term and even in simple situations. Moreover, every long-term problem, in addition to being more complex *per se*, as a rule is incomparably more difficult to solve because of radical uncertainty of outcomes. (We do not know how to translate the potential outcomes of our decisions, even if we knew them, into social utility. But neither do we know these outcomes now. Uncertainty is at least "squared." Determining utility for long-term problems is therefore incomparably harder and obviously is absolutely out of question.)

But, in distinction from animals, humans are still known to make sometimes decisions for complex and long-term problems (which, for brevity, we may from here on call "non-trivial"). *Homo economicus,* the presumed rational know-all super-being, who – to choose A over B – still needs some utility function to maximize, is as helpless here as a babe in the wood; he would deprive us of that distinction. It is a *homo sapiens,* a person of common sense, who is able to make the decisions. How, in absence of utility as a guide, does he do it? Is there any other maximand, an approximate parameter that he can maximize, as proxy of utility? Or should there be a completely different paradigm, an alternative to maximization?

The abstract theory of the firm often assumes maximization of profits. But, because of radical uncertainty (see below), calculation of long-term profits is as well impossible. (It also has been rigorously proven that the profit maximization criterion leads to bankruptcy of the firm at some finite time, with probability one [Radner and Shepp1996]; see also [Masch 2004a, 436]). Moreover, as usual, the bad drives out here the better, so "profit" becomes replaced by "short-term profit." After less than thirty years of infatuation with short-term profits, we already have the current economic crisis (see Section 4).

Behavioral versions of economics and finance criticize the mainstream versions of those disciplines. Both move in the right direction, but take only timid steps. It would seem that the *behavioral* versions should pay great attention to the *behavior* of decision makers, to the cardinal disparity between their assumed (maximizing) and real behavior. But most proponents of those disciplines stay within the framework of the maximization paradigm and, accordingly, do not offer any breakthroughs ([Akerlof and Shiller 2009], [Shleifer 2000]). The gurus of behavioral finance in [Bernstein 2007] often lacked long-term risk management skills. For instance, in the end of 2008 the Yale endowment, admired in a whole chapter of that book, lost in 2008 almost $6 billion, or a quarter of its principal [Kaminski 2009].

There also exists a "bounded rationality" approach that assumes limited mental capabilities of the decision maker and limited availability of data [Simon 1982]. But the real issue is not those limitations that can -- conceptually -- be avoided, say, by use of computers instead of human brain. The issue is that if abstract "rationality" is -- in plain English -- paranoia, who needs "bounded paranoia"?

As for the currently fashionable search for robust solutions, it may be good as a supplementary tool, but only if the main paradigm is right. A solution based, say, on maximizing short-term profit could be absolutely robust – and fundamentally wrong. As for also fashionable robust control, it is not relevant here -- control does not deal with long-term problems.

With no good proxies or other options left in maximization, we have to switch to a different paradigm. I propose an approach alternative to maximization, consistent with the hierarchy of human needs introduced by Maslow [Maslow 1943]. The lower, mandatory levels of his pyramid of needs involve survival of the individual; the present and possible future events related to these levels should not threaten his existence. In other words, potential outcomes should not be catastrophic. It also is important that -- in this approach -- the decision maker sees the dangers to his community as dangers to himself. He may still be self-interested, but his interests are now assumed to be quite comprehensive. And that is good both for him and for everybody else.

Mankind has employed the "catastrophe avoidance" approach for millions of years. But it is much older than that – it is inherent in the behavior of any animal and has been used by the animal kingdom for hundreds of millions years. In full agreement with evolution theory, a pack of wolves does not attack the biggest bull, trying to maximize its consumption of meat. It pursues instead a young or sick antelope to avoid the catastrophe of starvation. A "rational" maximizer Mowgli would fare much worse: he would attack the bull and be gored. And that would serve him right: do not fix what ain't broken; do not try to impose a simplistic and myopic abstract theory onto the complex real world where it does not belong.

I call the catastrophe avoidance approach "natural" [Masch 2004a]. I see this approach as having, in its original form, only three operations: (a) identification or development of decisions or strategies; (b) screening out of any strategy that has – under some possible future conditions – a clearly unacceptable outcome in any risk type; (c) subjective final selection of one strategy out of the remaining subset of candidates. None of these operations requires any formal or sophisticated methods. The survivability and universal applicability of the “natural” process are wholly explained by the simplicity of these operations, which require an absolute minimum of intellect.

This simple sequence has, however, serious limitations. It becomes “… increasingly deficient as problems grow more complex, as the environment changes more rapidly, and as the number of decision-makers increases.” [Weil 2009]. Of course, it would be a major breakthrough if we go beyond this sequence and succeed in combining the wonderful simplicity of “natural” decision making with the wonderful complexity of modern technology; that was not done in the past 60 years. The big question is – how to combine the best features of the old and the new without being overwhelmed by the negatives of modernity?

We have developed powerful computers that perform billions operations per second, and mathematical programming models and algorithms that can deal with millions of constraints and variables. But they never are employed where they are desperately needed and where they should bring real benefits – as high-level analytical tools in long-range social and business strategic planning and decision making. And our present economic crisis – crisis that destroyed many trillions of wealth, many millions of jobs, and is far from ended -- confirms that sad conclusion. In other words, our technology has created two new Wonders of the World, but – outside the Information Revolution in short-term operations -- we are using them like Neanderthals, to crack nuts.

Senge proposed a most helpful idea. He suggests that a major breakthrough results only from combining of a special ensemble of efficient "component technologies” that come from diverse fields of science or technology, and only when all necessary components of that ensemble come together [Senge 1990]. He strongly emphasizes that the power of the ensemble comes mainly not from the individual components, but from their combined impact within the process. In his words, they form an inseparable ensemble and “ ... are critical to each others’ success” [Ibid. 6]. In other words, we need a *yin yang* of technologies. Our task is to discover whether a set of technologies with such an inestimable property does exist in our field, and if it does -- to develop and combine all its components.

I’ve been fortunate to be able to develop an ensemble of models and methods that has that property and exactly meets both the necessary and reasonably sufficient requirements. *I strongly believe that all these models and methods -- possibly with some modifications, nothing in this world is perfect -- are absolutely necessary components of any dependable methodology of decision making for complex and long-term problems.*

In spite of its anti-maximization and risk prevention spirit, the RCO ensemble extensively uses optimization (mathematical programming) models, because the too risky candidate strategies developed by these models are eliminated, modified, or scaled back by a succession of efficient filters. Exactly as required by Senge, models and filters are inseparable and “... are critical to each others’ success.” Filtering includes “strong screening” by risk-limiting constraints in stochastic multiscenario models of special structure, and “weak screening” by a range of “synthetic” decision criteria, applied within the framework of a “strategic frontier” (see Section 7). The role of models is relegated from top-level selection of an optimal strategy to auxiliary analysis in generation of candidate strategies. Change of paradigm of economic decision making from maximization to catastrophe avoidance is a crucial part of the RCO ensemble.

In my opinion, the most valuable technique is “strong screening,” that imposes on optimization models an additional function of *self-filtering*, so that they become *very efficient “optimizing filters.”* Among other uses, they might become the prototypes of novel *techno-economic filters* (when technical parameters may vary).

RCO incorporates yet another major idea. The decision maker has to be actively involved not only in the final selection of the strategy, but also in the whole process of generation, evaluation, and screening of the candidate strategies. That avoids misinterpretation of his knowledge, perceptions, and preferences, and transforms standard tools into realistic customized models.

Also, the philosophy of RCO is that protective equipment reduces the need for knowledge about the future. Therefore it can construct extra robust and flexible strategies – of course, if that is consistent with the risk attitude of the decision maker. For that purpose, RCO tries to detect dangers lurking behind not only the *probable*, but also the *possible* (zero probability, which is even smaller than the minuscule probabilities of “black swan”) scenarios, and protect the projected strategy from these dangers, too.

The RCO ensemble provides the possibility of a fundamental overhaul of the methodology of decision making in economics, OR, and adjacent fields. The need and importance of such an overhaul and a switch to an alternative paradigm can hardly be overstated. A behavioral and institutional economist, Shiller, has said that "Historically, economic thinkers have been limited by the state of relevant risk management principles of their day" [Shiller 2003, ix]. Basically, he is saying that economics is not a long-term discipline. (And what, after all, is *risk management*, if not an application of the “catastrophe avoidance” paradigm?) Since these principles have just begun to be properly formulated now, the inference is unambiguous: a novel, revolutionary approach is required, both for real-world economic theory and for making decisions in socio-economic problems. *Economics must become a moral discipline, taking into account externalities and”nudging” people and organizations to make socially beneficial decisions* [Masch 2009a]. RCO (or some its equivalent, if it appears and is better) should become an important part of a badly needed theoretical revolution.

In the 21st century, an enormous worsening of uncertainty aggravated the impact of economic blunders made. The uncertainty external to any long-term decision problem has become much more important than the uncertainty internal to the problem. The harmful outcomes under the external scenarios dwarf those of internal scenarios, and the likelihood of such outcomes is quite high. This is caused by the combined impact of geopolitical disturbances, including terrorism and possible use of weapons of mass destruction, deterioration of the planet's environment, potential pandemics, and so on. The future may drastically worsen even in a matter of days or hours. We do not know when, where, what might happen, and of what intensity. We do not know the future, even in the short-term, even in probabilistic sense. Consequently, even some short-term problems should now be treated as happening under radical, "uninsurable" uncertainty. (I relax the definition given in [Knight 1921] and define *radical uncertainty* as a situation where the probabilities of future scenarios cannot *be reliably* known.)

Let us face it: we are in the 21st century. The human race grows like on yeast, in wrong places. Everybody wants to live better; nobody wants to live worse. But the Planet Earth's capacity is limited, while the social balance, lovingly created and carefully nurtured for 200 years, has been fecklessly destroyed. We may be close to a catastrophe if we do not successfully find socially beneficial solutions of a number of crucially important interrelated long-term problems, from corporate governance, to managing the disbalanced world economy, to measures that may define the very fate of the planet. We have to do that simultaneously and immediately, which makes it even more difficult. Traditional economics and adjacent disciplines are of little help there: their current paradigm and their techniques, especially dealing with radical uncertainty, limit their use to short-term simple problems. In dealing with the long-term, employing an RCO-type methodology should be a must.

But what about the USA-China trade, which begets one of those crucially important problem? As of now, it has been dealt with inexcusably badly. The country has to apologize to millions of American workers that have already been sold down the river by business and political elites for their self-interest. Sustainable "Chimerica," for heaven's sake! (Without any doubt, this term derives from Chimera, that ancient monster.) To paraphrase Krugman [Krugman 2009], a great many bad actors made their political careers or enormous financial fortunes through activities that were socially destructive. And those activities were fully blessed by crowds of "mainstream" American academic economists (7 out of 8); see Section 4. "Free trade above all!" – while closing their eyes to all violations of that principle. "In their obsession with getting government out of economic life" [Skidelsky 2009], wishing to maximize profits, or to help – perhaps – people in the developing countries, they are ready to sacrifice a lot. Very noble and Nobel. A lot of other people, of course.

Any absolute dogma is a bad bedfellow for a society or an economy, be it sleeping on the left or the right side of the bed. The Soviet Union (on the left) and free trade (on the right) are good examples. If they do not *fire at you*, they *fire you.*

To avoid any misunderstanding, let me be completely clear. *I am all for capitalism, free market, free trade, and globalization. But we need to save them from their currently employed -- running amok, extremist and unbridled variations.* No society or economy can prosper with extremism. Even anything good –- and especially anything "free", such as "free fall", "free love", "free lunch", "free speech", "free medicine," "free trade", or "free market" –- should still be used in moderation. *Anything "free" is only as good as its set of constraints.*

In Section 4 I replace by realistic goals and constraints the usual, somewhat tarnished lately, absurd assumptions of abstract theory of international trade. Those assumptions are among the main causes of the current economic catastrophe and exemplify the possible dangers. The main culprit is refusal to admit that healthy balance-of-payments, strong middle class, powerful manufacturing base, and achieved geopolitical goals of the country are incomparably more important than reducing the price of underwear by a couple of dollars – and incomparably more important than trying to resuscitate simplistic and outdated economic principles and "laws," as dead as the dodo.

One of the most important legacies of Keynes is the concept that lower level (micro) market activities should be controlled and constrained, at a higher (macro) level, by a non-market entity. In accordance with that principle, saving all these institutions should involve proper control and regulation.

As for the RCO model of this problem, does it recommend any particular strategy? Of course not, it is a problem of enormous complexity; we can barely start approaching it here, in an article focused on RCO. The model is not based on real data; it is here just to demonstrate the techniques of RCO modeling of complex problems and the RCO process. Nevertheless, the approach taken has already dismissed a set of socially destructive, incredibly dangerous assumptions of abstract theory of international trade, as it has been currently applied in the real world. Also, the business of RCO is merely to provide a lot of additional information, not available from any other system, so that the decision maker could make a subjective, but well-informed and prudent decision.

This paper is intended to serve four purposes. First, I am attempting to legitimize employing computers and optimization models in high-level complex and long-term problems that face society. Second, RCO may become a reasonably reliable protective (risk management) device; in our extremely interesting times, we do need an honest risk management system. Third, I am trying to show that economics, OR, and adjacent disciplines are at a dead end and badly need a drastic overhaul, with RCO suggested as a part of an alternative approach. Therefore I cannot avoid being somewhat polemical. Fourth, I am dismissing from the model of the USA-China trade a set of absurd and extremely dangerous -- from both socio-economic and political point of view -- assumptions of abstract theory of international trade.

If the proposed approach is accepted and successfully replaces the current methodologies, we might kill four formidable Goliaths by one RCO stone. Or not. (That is to mitigate unavoidable accusations of being too ambitious and dogmatic.)

Isn't it surprising that one tool creates breakthroughs in so many important and diverse directions? I think not. This attests to the extraordinary power of an ensemble, if its components critically contribute to each other's success. Also, computers and models strengthen here *a natural* way of making decisions. Results come easy to *a natural.*

To facilitate understanding and to speed up potential acceptance and application of RCO, I am describing its methodology in as much detail as possible. But I have to cover several enormous fields. Due to space limitations, many important issues covered in [Masch 2004a] are omitted here; that article is a complement to the present paper. Some other issues, such as computational algorithms of RCO and its methodology of calculating quasi-utilities, have yet to be described elsewhere.

In conclusion, let me again remind the reader that I consider RCO-type methodology highly advisable, and sometimes even mandatory, only for complex and long-term problems. These include socio-economic and political problems, and that explains why I have not been able to maintain a detached academic style, which would be advisable to minimize unnecessary discussions. We are dealing here not with dry OR subject, like decomposition or taboo methods. Among other disciplines, economics is involved, and Keynes has said, “Economics is a moral and not a natural science” [Skidelsky 2009]. Very true, except that he should have said “a moral discipline”: “a moral science” is an oxymoron.

2. Moving to Basic Innovation in Use of Computers and Mathematical Programming

As mentioned in Section 1, the current use of computers in important problems never rises above the data processing precursors to decision making.

Instead they could have been used in combination with another marvel of technical perfection -- “optimization” (mathematical programming) models. Such models may include millions of constraints and scores of millions of variables; they can describe in detail large and complex systems and problems and find refined solutions – solutions that would be perfect if we knew the future, at least probabilistically, and if the model is correct. The model’s goal, the “objective function,” is not at all dependable: it indicates the proper direction of search – at best, very approximately, and at worst very badly, maybe even opposite to the correct direction. The “constraints cages” are, however, much more reliable. (Even if we have introduced some constraints that are tighter than it is strictly necessary, that might only be to the better. Extra protection rarely hurts: it is better to be safe than sorry.) The human brain is not capable of such extraordinary feats, such sophisticated and far-reaching exploration of every potential avenue of improvement, such comprehensive search for a lurking danger or for any opportunity to protect the outcomes under a precarious scenario.

Optimization models have another huge advantage. We are drowning in an ocean of data – redundant, irrelevant, imprecise, incomplete, conflicting, and possibly wrong. How can one extract from that ocean some meaning, some scraps of useful information? The models help: they have data about the whole enormous multidimensional area of feasible solutions, but focus our attention on just one of its points – the point of model’s solution.

And yet, like computers, these methods never have been applied successfully in high-level problems. Even in business management, leading journals, such as Harvard Business Review, stopped publishing articles on optimization about 30 years ago. The main reason for that failure is obvious: the more powerful a tool is, the more dangerous it may become in unskilled hands or when wrongly applied. (See the avalanche of literature about the current financial meltdown.)

These models can be extremely dangerous [Masch 2004a, 433-34, 447-49]. They also have other drawbacks. They are impersonal, completely focusing on the problem and not taking into account the knowledge, opinions, and preferences of the decision maker. Even if they try to reflect these opinions, the methods to do that are and always will be inadequate, so that every attempt to insert a model (really, a modeling analyst) between a problem and a decision maker may lead to severe mishaps. The analyst probably has no idea how important are those factors and considerations that he has *not* included in the model, while they may be of paramount importance for the decision maker.

Another major flaw is conceptual inconsistency: the deterministic version of such models presupposes knowing the future, and even a less demanding stochastic version presupposes reliable knowledge of at least the probability functions or probabilities of future events or scenarios. The concept of radical uncertainty nullifies, however, the very possibility of any such knowledge.

Finally, the "natural" approach precludes even the very existence of "the best decision" in any serious problem. The "natural" approach should exclude therefore the attempts to find "the best" there by any means, including the use of "optimization" (really "extremization") models -- which are based on maximization, too.

Summing up, mathematical programming is the most powerful *decision making* methodology in the world – for well-defined problems. For other problems, these models and algorithms can provide, however, only *extremal*, not *optimal*, solutions that are too risky; they cannot be employed without extensive screening. It might remain, however, a very powerful *analytical and filtering* methodology, and the purpose of RCO is to make that happen.

In the 21st century, we have many crucially important problems that may define the fate of the humankind. Given the gravity of these problems, getting help from computers and mathematical programming might be tantamount to a "basic innovation" (Senge 1990, 6), perhaps no less important than the very creation of these tools.

Senge classifies as "basic innovations" creation of the telephone, the digital computer, or commercial aircraft -- major technological or scientific breakthroughs. He describes creation of the commercial aircraft in the following terms: "… [D]iverse 'component technologies' come together. Emerging in isolated developments in separate fields of research, these components gradually form an 'ensemble of technologies that are critical to each others success.' … [T]he McDonnell Douglass DC-3, introduced in 1935, … , for the first time, brought together five critical component technologies that formed a successful ensemble. They were: the variable-pitch propeller, retractable landing gear, a type of lightweight molded body construction called 'monococque,' radial air-cooled engine, and wing flaps. To succeed, the DC-3 needed all five; four were not enough" [Ibid.].

Senge was also absolutely correct in insisting on the need of work in several diverse fields of science or technology. For instance, as a multitude of others, Dantzig paid enormous attention to "planning under uncertainty" [Horner 1999]. But he tried to deal with radical uncertainty in the framework of stochastic programming, that is, mere Operations Research. No wonder that these attempts were unsuccessful: without being placed into an RCO-type ensemble, a stochastic model produces only one strategy, and that prevents subjectivity of selection. RCO just starts where stochastic programming ends.

What do we want from an ensemble? Our goals are: (a) To obtain useful information from an ocean of irrelevant data; (b) To identify or to construct seemingly good decisions or strategies on the basis of that information; (c) To reduce or eliminate the misinterpretation hazards that may arise with insertion of a model between a decision maker and a decision; (d) To discover hidden dangers, possibly associated (under some conditions) with these strategies; (e) To protect from these dangers by screening out the risky strategies and by preparing contingency plans to deal with those dangers, would they arise.

RCO forms an ensemble that meets these requirements out of components that are associated with seven disciplines: Economics, Operations Research/Management Science (OR/MS), Scenario Planning, Decision Science, Risk Management, Utility Theory, and Portfolio Theory, with a brief digression into the eighth field – Psychology. In each of the seven fields, RCO introduces novel concepts, models and methods. All components are interconnected and are absolutely necessary for successful work of the ensemble. The development of RCO took about 30 years, from the 1960s to the 1990s, which, according to Senge, "is a typical time period for incubating basic innovations" [Ibid.]. Work on RCO continues.

How RCO moved to its present state explains to a large extent, I think, its composition and methodology. Therefore I describe it in detail.

More than 50 years ago it was already shown that none of the then known strategy comparison criteria for objective decision making under radical uncertainty could be deemed "the best" that is, both theoretically correct and good under any conditions ([Arrow 1953], [Arrow and Hurwisz 1972]; [Luce and Raiffa 1957, 278-306]); none can be used as a solitary guide. We have to evaluate candidate strategies by several criteria, which may lead to contradictory conclusions and needs subjectivity. Maximization *per se* becomes impossible.

In the 1960s, a substantial advance in the field was made by a group of Russian scientists from the USSR energy industry, which, under the influence of [Luce and Raiffa 1957], used this concept to develop a scenario planning system called "the Zone of Uncertainty" [Makarov and Melentyev 1973]. The "Zone" was a set of candidate strategies; to select a strategy, the cost behavior of these candidates had to be evaluated on a large range of scenarios.

In "the Zone of Uncertainty" system:

- A number of single-scenario "What if" linear programming models is constructed and these models are solved;
- Groups of similar model solutions are clustered into a number of candidate strategies;
- Single-scenario linear programming models are constructed for all "strategy vs. scenario" combinations and these models are solved;
- The obtained values of the objective function (cost) are used as payoffs in a payoff matrix;
- The strategies are screened by applying to the payoff matrix the several decision criteria described in [Luce and Raiffa 1957];
- If different criteria lead to different selection conclusions, the final choice is made subjectively.

For its time, "the Zone of Uncertainty" approach proved enormously progressive. The methodology included an excellent mathematical description of the behavior of dynamic energy systems, as well as other novelties. Candidate strategies were developed, checked against up to1500 scenarios, and screened by several then known criteria. The results were good, robust regional compromises between scenario-specific extremal solutions in choosing among different fuels. In 1970, many of the derived results were used in the plans for the development of the USSR energy industry [Makarov and Melentyev 1973, 115-257]. (As far as I know, the methodology is not in wide use now, if it is used at all.)

That approach introduced three important ideas (see a more detailed outline in Section 7):

- Splitting variables into "strategic" and "operational" groups and thus clearly delineating each strategy;
- Constructing contingency plans and evaluating candidate strategies by the totality of their "post-contingency-plans" outcomes for the whole range of scenarios;
- Using several decision criteria for filtering out the worst candidates, rather than for selecting the best (follow-up from [Luce and Raiffa 1957]).

In 2006, a group of RAND scientists declared that "no systematic, general approach exists for finding robust strategies using the broad range of models and data often available to decision makers" [Lempert 2006, 514]. This methodology claimed to be such a general approach, but it did not include even the three extremely important ideas of "the Zone of Uncertainty" listed above. Contrary to ([Arrow and Hurwisz 1972], [Luce and Raiffa 1957]), it used, for instance, a single criterion of minimax regret. In a private communication it was also revealed that the authors were not aware of Risk-Constrained Optimization®, description of which was already published in 2004 [Masch 2004a].

As mentioned above, work on RCO started in the 1960s. The embryonic version of RCO, named "Robust Optimization" and expanding ideas of "the Zone of Uncertainty" and [Luce and Raiffa 1957], was drastically improved in the 1990s. In 1999 RCO was granted an USA patent [USA Patent 1999].

The major improvements included: the change of paradigm; introduction of special stochastic multiscenario models; "strong screening" by risk-limiting constraints within these models; development of algorithms for speedy solving of huge mathematical programming models; introduction of multidimensional outcome matrices; development of methods of converting heterogeneous outcomes into "quasi-utility" payoffs; addition of several "synthetic" criteria for "weak screening"; introduction of "strategic frontiers"; and development of contingency plans for a large range of scenarios within multiscenario models. Every one of these improvements is a necessary component of the whole ensemble, as required by Senge. *I strongly believe that, on the one hand, the three ideas of "the Zone of Uncertainty" and, on the other hand, their listed above major improvements introduced by RCO, are (maybe with some modifications) absolutely necessary components of any dependable methodology of decision making for any long-rang and complex problems.*

Consider the iron logic that directed forming the RCO ensemble. It is that logic that, I believe, allows me to make the dogmatic statement above, as well as other equally dogmatic statements throughout the paper:

- Subjectivity in making long-term decisions is unavoidable. To make subjective selection possible, we need multiple candidate strategies.

- Because of non-linearity and possible inflections, large number of scenarios is necessary to evaluate the behavior of each candidate strategy under a wide range of conditions.
- "Catastrophe avoidance" is a natural and common-sense, real-world paradigm, fully consistent with both psychology and theory of evolution. It is especially necessary under dangerous conditions of the 21st century.
- Separation of the model variables into *strategic* and *operational* is necessary for differentiating between switching from one candidate strategy to another, on the one hand, and operating modifications of the same candidate under the impact of different scenarios. Multitudes of distinct strategies cannot be built without this separation.
- Multiscenario stochastic models (not necessarily the special RCO models) are the best tools for developing robust and flexible candidate strategies that include interscenario compromises. They can start the iterative RCO process.
- A combination of common multiscenario stochastic models with risk-limiting constraints in the framework of the special RCO multiscenario models is the best way to ferret out dangers hidden in individual scenarios, both probable and possible, and a good way to protect from these risks. It allows creating trade-offs and resulting trees of candidate strategies. It also facilitates creation of contingency plans and evaluations of strategies in their "post-contingency-plans" state. *It imposes on optimization models an additional function of self-filtering.* "Strong screening" is here to stay.
- Each of a number of heterogeneous outcomes has to be protected from a catastrophe under each individual scenario. The usual stochastic multiscenario models are not interested in scenario values of these outcomes; in RCO, it becomes necessary to create additional variables defining those values.
- For easy revealing of unacceptable scenario outcome values, they should be presented in a format of multidimensional (at least three-dimensional, "scenarios vs. candidate strategies vs. types of outcome") outcome matrix,
- Additional "weak screening" of strategy payoffs provides auxiliary filtering of candidates, is in a different field from the mathematical programming models and methods employed, and is therefore highly desirable. It is already widely used (in its narrow, pre-RCO form) and also is here to stay (in the new format).
- "Weak screening" is possible only on homogeneous values. Heterogeneous values of outcomes have to be converted into homogeneous quasi-utility "payoffs" by approximate methods.
- "Single criterion" methods for comparing payoffs of candidate strategies are just special cases of more general "synthetic criteria"; moreover, they are shown to be inadequate for good analysis.
- A joint use of several "synthetic criteria," one at a time, leaves room for subjective choice, while facilitating that choice by filtering out the worst and riskiest strategies.
- The "strategic frontier" approach is more general and obviously better than using a single value of an optimism-pessimism (or any other) index.

- Contingency plans provide the basis of evaluation of candidate strategies and, prepared in advance, should substantially improve the execution of the selected strategy. A solution of a multiscenario model contains these plans for the whole range of scenarios; they just have to be extracted from that solution.
- The contingency plan for that scenario that actually comes into being becomes the basis for a new round of RCO, which might be performed after monitoring the evolving future and adapting to it.

In other words, models beget filters, and models themselves become strong filters, and filters legitimize models, and together they generate a multitude of candidate strategies, each with a set of contingency plans for a range of scenarios; for more detail, see Section 7. Models and filters constitute an inseparable ensemble, although in principle both may be modified and improved in comparison with the proposed RCO versions. There are other good analytical methods besides mathematical programming; they may further enrich RCO.

In our gradual advancement towards "basic innovation" of proper use of computers and mathematical programming, RCO is not the *end of the road* that makes "… a further breakthrough no longer possible, although, of course, much is still to be done by way of elaboration and application of the new … [methodology]; in other words, by way of 'normal science,' as distinct from revolutionary science" [Popper 1992]. (I replaced here words "quantum mechanics" by "methodology" – the situation with RCO seems very similar, although, of course, this does not mean at all that RCO is in the same category as the ideas and systems of the two giants, Bohr and Heisenberg.)

I rely on [Lempert 2006] in their survey of literature and do not repeat it. I have no doubt, however, that both the change of paradigm and rest of the ensemble of models and computational methods used in RCO are currently unique. Even "the Zone of Uncertainty" methods of the 1960s are unknown and not used in the West, not to speak of their cardinal improvement by RCO.

3. Risk-Constrained Optimization® -- General Comments

The sophisticated, computer-based version of the "natural approach" has to meet a number of rigorous requirements; they are listed in [Masch 2004a, 436-38] and are not repeated here. All these requirements are satisfied in RCO. In one of its roles, *RCO is a system of planning and* strategic *risk management under radical uncertainty that searches for the most acceptable (not "the best"!) compromise between improving results and reducing risk in our decisions.*

RCO is especially useful when uncertainty comes in two categories, from "internal" and "external" factors, with the "external" uncertainty dwarfing the internal one. Any serious strategic decision problem of the 21st century would almost certainly fit into this category. Under these conditions, the problem qualifies to be under radical uncertainty, but still has initial weights (probabilities) attached to individual internal scenarios. In the process of RCO, the decision maker subjectively overrides these probabilities.

RCO is purged (I hope) from all dangerous misconceptions and does not contain a single unwarranted, unrealistic assumption, such as predictability of the future (in particular -- applicability of normal distributions, with or without "fat tails"), reliability of historical correlations, and disconnectedness of events.

RCO consists of five major parts: (a) construction of a large number of scenarios: (b) generation of multiple candidate strategies that are reasonably good, flexible, robust, and protected from risk; (c) identification of a few most suitable candidates; (d) subjective selection of one of them as the strategy to be implemented; and (e) providing contingency plans of modifying the selected strategy under a range of scenarios.

The main version of RCO includes the following more detailed stages:

(i) Constructing a large number of "internal" scenarios of the future and performing the initial "What if" analysis.

(ii) Formulating a special stochastic multiscenario MILP model and using the model solution as a starting point for an iterative process of generating a number of alternative candidate strategies.

(iii) Recording the scenario outcomes for any candidate strategy in a three-dimensional "outcome matrix,": "scenarios vs. strategies vs. risk types."

(iv) Obtaining a number of alternative candidate strategies by re-running the model, in an iterative process, each time with a different set of "cutting planes", or "risk-limiting constraints" imposed to prevent any unacceptable outcomes.

(v) Converting the multidimensional "outcome matrix" with heterogeneous outcomes into a two-dimensional "payoff matrix" with homogeneous payoffs: "scenario vs. strategy."

(vi) Screening out the worst alternative candidate strategies by joining several decision criteria in a framework of "strategic frontier," leaving for final consideration a small subset of the best and safest candidate strategies.

(vii) Making from that subset a final, subjective, but well-informed and reasonably safe, selection of the strategy to be implemented.

(viii) Deriving for the selected strategy a set of contingency plans over the whole range of scenarios.

(ix) Monitoring the evolving situation and adapting the accepted strategy in accordance with the contingency plan for the coming scenario (if available).

(x) If warranted, starting the RCO process anew for the changed conditions and the new initial state of the system.

Four characteristics of RCO should be particularly emphasized.

First, the literature search in [Lempert 2006] confirms my conclusion that RCO is the only currently existing approach allowing *strategic* risk management - where we not only assume radical uncertainty, but also jointly construct both the long-range strategy and its scenario-specific modifications under the impact of different conditions (scenarios) of the future. In contrast, most other risk management systems consider the strategy as a given and just determine its operational modifications. (Let alone that many such systems, especially in finance, do not go beyond short-term at all.)

Moreover, RCO evaluates and selects the long-range strategy on the basis of its structure being already transformed under the impact of these modifications (contingency plans). This "post-contingency-plans" or transformed structure is found by using special multiscenario models and computational methods. (Optimization is used here not for finding "the best," but primarily for ferreting out potential dangers lurking in individual scenarios and protecting from these dangers. Protection from risk dominates in RCO over maximization of advantages. The formal optimization models and methods, such as mathematical programming models, not reliable enough to find "the best" alternative strategies, are still considered good enough for an easier task - to screen out the worst. These tools are tolerated because their output is filtered through five diverse layers of risk protection.)

Second, RCO generates, systematizes, and presents in an orderly and convenient manner two new types of information, helpful and important for making subjective strategy-selection decisions: information about the behavior of every candidate strategy under a broad range of future scenarios, and information about good contingency plans to be prepared in advance for each candidate strategy under the whole range of these scenarios.

Third, RCO underlies a specific philosophy of long-range decision making, intended to neutralize risk that is introduced by both “known unknowns” and “unknown unknowns”: the less we know about the future, the stronger and more flexible has to be the projected system. *As with any protective equipment, RCO reduces the need for knowledge about the future.*

For that purpose, following Keynes, RCO considers not only *probable*, but also *possible* scenarios of the future. (Keynes' theory of probability included radical uncertainty concerning events, to which no probability distribution, cardinal or ordinal, can be assigned, as well as events with non-numerical probabilities, about which one can only say "more or less likely" [Keynes 1921]). If the initial probability of a scenario is zero, but you still wish to be protected from its impact, that means that subjectively you assign to that scenario a non-zero probability.

RCO assumes that we do know something from the past. We have some more or less sound expectations about the future, expressed as probable internal scenarios.

RCO initially builds the best plan it can to use the opportunities and to protect against the threats arising under these probable scenarios, with their “guesstimate” probabilities. Then it asks, “The probability of the world flood is zero, and your house is 20 yards above sea level. Do you still want to protect the house against that threat?” If we do, we build a house with, say, a solid-cast plexiglass foundation and walls.

But we really have also done more than just protect against flood. We have built an extra strong and flexible construction, which may withstand, say, a nuclear explosion too. We want not more accurate and reliable data, which do not exist anyway: we want stronger constructions. That’s what RCO is about, and that’s what is needed -- in economics, finance, decision making, and risk management -- in these extremely interesting times.

Fourth, RCO is much more than just a methodology of dealing with uncertainty and constructing a long-range risk-protected strategy. RCO demonstrates the need, and shows the way, of changing the general paradigm of economic decision making. Instead of maximizing (very likely, incorrectly) satisfaction of our needs and wants, this approach deals with a simpler, easier to solve, more realistic and pressing problem -- how to avoid a catastrophic outcome in any of multiple risk factors. RCO negates any notions of *homo economicus* and utility (or profit) maximization as the ultimate bases for selecting a strategy.

The methodology and techniques of RCO are demonstrated below on the problem of USA-China trade -- of course, in an extremely simplified manner.

4. The USA-China Trade Problem – General Description

Similar to maximisers, Marx was an obsessed man. His monomania was, however, social revolution, and he evaluated from that point of view everything, including international trade. He voted "in favor of free trade" because "…. the free trade system is destructive. It breaks up nationalities and pushes the antagonism of the proletariat and the bourgeoisie to the extreme point. In a word, the free trade system hastens the social revolution."(Marx 1982, 224)

In 1965, Lowe analyzed the dialectic approach of Marx and found it unduly deterministic, but still brilliant and comprehensive [Lowe.1965, 180-193]. There was only one major flaw: he declined to see the unavoidable consequences of economic and technological revolution "that was undergoing before his own eyes." These consequences were: "the change of social stratification with the shift of political power to the middle classes, the rise of strong labor unions with a membership intellectually disciplined by general education and capable of making their growing aspirations felt under a system of widening franchise, not only democratized the spirit of modern government but created the new administrative key positions for a progressive Control of economic by political forces." [Ibid. 192]. In short, Marx missed emergence of a beneficial social balance between "countervailing power" of business, labor, and government [Galbraith 1952].

But that was long ago. Since the 1980s, a large number of the USA people – presidents and other politicians, CEOs and denizens of Wall Street, media pundits, and economic geniuses -- turned out to be "closet Marxists." They want to show that Marx has indeed been a prophet, that his predictions are coming true, in spades, and that all roads – not only of his prophesied class struggle, but also of market fundamentalism -- lead to social revolution. With such friends, we do not need enemies. Just in 30 years, they recklessly destroyed the fragile social balance, created in the West with enormous difficulties in the last 200 years. Scenarios of a North American Venezuela became highly likely [Masch 2007a, 1], [Masch 2007b, 10].

In a penetrating analysis, Palley argues, "Before 1980, economic policy was designed to achieve full employment, and the economy was characterized by a system in which wages grew with productivity. This configuration created a virtuous circle of growth. Rising wages meant robust aggregate demand, which contributed to full employment. Full employment in turn provided an incentive to invest, which raised productivity, thereby supporting higher wages." [Palley 2009, 3-4].

Of course, there were troublesome spots in this Eden, too. Penny-wise and myopic trade union leaders missed an opportunity to translate their dominance into political power and strong labor protection. They opted instead to grab unreasonably large wage increases, which, together with the oil shock, created unbearable inflation. It could be suppressed by sound, even if difficult, means. Instead, to the accompaniment of heart-rending screams about FREEDOM!!!, the "mainstream" Anglo-American school of economics switched to wholesale market orthodoxy.

"Voodoo economics" is the right name for that whole branch, not for just its napkin sub-variety.

Since 1980, the economic paradigm is based on following features: "asset price inflation (equities and housing); widening income inequality; detachment of worker wages from productivity growth; rising household and corporate leverage ratios measured respectively in debt/income and debt/equity ratios; a strong dollar; trade deficits; disinflation or low inflation; and manufacturing job loss." [Ibid. 4-5]. Workers were pressured on four sides: by globalization, reduction of the size of government, increase of labor market flexibility, and retreat from full employment [Ibid. 9]. Labor laws were weakened and not followed; membership and influence of trade unions were sharply reduced; government was weakened. *Business became the sole prevailing power*. In short, Marx couldn't dream of having better henchmen than the American and international elites of the last 30 years.

The end result of that Ponzi paradigm is easily predictable: "The problem with the model is that it is unsustainable. Maintaining growth of spending on consumption requires continued excessive borrowing and continued reduction in savings rates. Continued excessive borrowing requires ever increasing asset prices and debt/income ratios; hence, the systematic need for bubbles (which eventually burst). Meanwhile, when the savings rate hits zero, little further reduction is possible. Consequently, both drivers of demand eventually exhaust themselves." [Ibid. 14]. And "the policy triumph of corporate globalization accelerated the process and transformed it into a financial crash." [Ibid. 16] Finita la comedia.

I will not dwell here on the mental capacity and morals of the new paradigm crowd, really committed to turning the wheel of history sharply back, around 200 years. What I am saying is one of few voices crying in wilderness, anyway. But, at least, *the incredibly dangerous socio-economic and political blunders of the "mainstream" neo-liberal economists of the Anglo-American school* ***must*** *be corrected wherever possible. I am trying to do that in the following RCO model of the USA-China trade.* Of course, the problem is dauntingly complex, and in an article mainly focused on RCO I can only scratch its surface.

Described below is the problem of managing the activities of the segment of the US economy, directly involved in the USA trade with China. I deal here with the economic policy decisions of one country, the USA, and therefore consider all potential improvements from the point of view of that country.

The economic policy of a country should be based on the totality of its societal and economic needs and desires, that is, both the short-term and long-term goals and constraints of society. As a first approximation, eight main social objectives and constraints can be listed. Five of them are primarily short-term (sufficient satisfaction of needs and wants of population, low unemployment, sufficient growth, stable prices, and a healthy balance of payments). Three are long-term ones (the preservation of industrial base, the preservation of the middle class, and the attainment of geopolitical goals).

In the trade problem, while increasing the current consumption, the economic activities -- in this relevant USA segment and within the planning horizon -- should also contribute to long-term sustainable survival of the American society as a whole in an acceptable state. In our simplified formulation, the objective is to increase the value of the "long-term well-being" variable, which contains here three weighted components:

- Consumption - a positive component, representing the trade-related standard of life of the US society.
- GNP - a positive component, representing the production of the specified trade-related segment of the US manufacturing.
- Social costs - a negative component, covering here just the cost of the trade-caused US unemployment.

The three components reflect the activities throughout the planning period, but they also approximately represent the sustainable future activities beyond the planning horizon (GNP represents here the future production potential of the trade-related USA industry segment).

I make the following assumptions about international trade, each of them directly contradicting the corresponding assumption of existing theory of trade

- Unemployment is not excluded; trade may bring an increase in unemployment and thus lead to an increase in social costs.
- Transferring workers from one industry sector to another involves re-training, relocation, and readjustment. All these processes generate costs.
- Trade does not necessarily lead to adjustments of prices, wages, and currency rates, and even more so - to immediate adjustments.
- Trade may lead to trade surpluses and deficits, as well as to transfers of capital and technology.

Furthermore, I use the concept of "compensated free trade" [Masch 2004b; Masch and Perlman 2005; Masch 2007a; 2007b; Masch 2008; Masch 2009b]. In accordance with that concept, the USA sets annual trade deficit limits for each of our trading counterparts –- countries or groups of countries. If a country wants to exceed its limit, its government pays the US Treasury a stipulated percentage (up to the full amount) of the excess deficit. The allowed amounts of intergovernmental payments may be capped.

“The first rule of holes” asserts, “When in hole, stop digging!” Due to a multitude of factors, we cannot fully follow this sound rule now. We can limit, however, the maximum depth of the hole. That is the role of the concept.

Accordingly, I assume that:

- Trade deficits with China are capped.
- If done, intergovernmental China-US compensation payments raise the caps.
- Intergovernmental payments may be limited.

I introduce two types of uncertainty, "internal" and "external" uncertainty. Internal uncertainty is generated both by inherent unpredictability of a creative and dynamic economy, and by our incapability to elucidate deterministic values of the “known unknown" parameters of even a statistically predictable economy. External uncertainty comes from both "known unknown" and "unknown unknown" factors, which are not explicitly covered by the model: quickly changing and unpredictable geopolitical environment, terrorism, planet habitat, pandemics, global financial and economic crises, and other disturbances. The external uncertainty dwarfs the internal one; combined, these two categories clearly imply radical uncertainty.

The first factor of internal uncertainty is technical progress, both in the US and China. Technical progress in China is defined as probable. It is represented by raising the productivity of workers in each industry sector. "Guesstimate" probabilities are given for each level of productivity increase, but the causes of those increases are of no interest for us and therefore are not explored.

For the US, however, the technical progress is shown as a consequence of our R&D decisions, which cost money: if an industry sector performs a specified amount of R&D, it may or may not - again, with a given probability (possibly, also "guesstimate") -- make an invention that raises the productivity of its workers. If the industry sector performs no R&D, its productivity stays constant. R&D takes much time, so the decision whether to undertake it or not has to be made immediately, before we know the actual level of technical progress in China.

The second factor of internal uncertainty is that we do not know enough about the Chinese economy - in particular, about the qualified-labor resources of its trade-related part.

External uncertainty is represented by that, as mentioned above, we can make only very approximate guesses about the impact of the components and costs above on the "long-term well-being" of the USA society.

5. The Special Multiscenario RCO Model

Although RCO is a non-maximization process, the main analytical tool of its sophisticated form is a special stochastic multiscenario MILP (mixed integer linear programming) model. To understand better the problem, its input data, and the RCO approach to solving it, I will start demonstrating RCO by formulating a possible version of that model.

The multiscenario MILP model (1)-(21) is formulated as follows:

$$\text{Max } z = \sum_{i=1}^{ns} scen\_prob[h] * zsc[h] - addcost \qquad (1)$$

st

$$zsc[h] = wt[1] * cons[h] + wt[2] * gnp[h] - wt[3] * socost[h]$$

$$+ wt[4] * compens[h] \quad (h = 1,ns); \qquad (2)$$

$$cons[h] = \sum_{i=1}^{np} price[i,h] * y[i,1,h] \quad (h = 1,ns); \qquad (3)$$

$$x[i,1,h] \,/\, prod[i,1,h] = labu[i] + \sum_{i=1}^{np} retr[j,i] - \sum_{i=1}^{np} retr[i,j] - unemp[i,h]$$

$$(i=1,np;\ h= 1,ns); \qquad (4)$$

$$retr[i,j] <= retin[i,j] \quad (i=1,np;\ j= 1,np); \qquad (5)$$

$$\sum_{i=1}^{np} retr[i,j] <= retout[i] \quad (i=1,np;\ h=1,ns); \tag{6}$$

$$\sum_{i=1}^{np} x[i,2,h] / prod[i,2,h] <= labc[h] \quad (h = 1,ns]; \tag{7}$$

$$y[i,1,h] = x[i,1,h] + t[i,2,1,h] - t[i,1,2,h] \quad (i=1,np\text{-}1;\ h=1,ns); \tag{8a}$$

$$y[i,2,h] = x[i,2,h] + t[i,1,2,h] - t[i,2,1,h] \quad (i=1,np;\ h=1,ns); \tag{8b}$$

$$gnp[h] = \sum_{i=1}^{np} valadd[i,h] * x[i,1,h] \quad (h = 1,ns]; \tag{9}$$

$$def[h] = \sum_{i=1}^{np} exprice[i,2,h] * t[i,2,1,h] - \sum_{i=1}^{np} exprice[i,1,h] * t[i,1,2,h]$$

$$(h = 1,ns]; \tag{10}$$

$$def[h] <= limit * gnp[h] + compens[h] \quad (h = 1,ns]; \tag{11}$$

$$compens[h] <= limcomp * gnp[h] \quad (h = 1,ns]; \tag{12}$$

$$addcost = coef\_retr * \sum_{i=1}^{np} \sum_{i=1}^{np} retcost[i,j] * retr[i,j]$$

$$+ coef\_res * rescost * wres; \tag{13}$$

$$socost[h] = uncost * \sum_{i=1}^{np} unemp[i,h] \quad (h = 1,ns]; \tag{14}$$

$$mindem[i,k] <= y[i,k,h] <= maxdem[i,k] \quad (i=1,np;\ k=1,2;\ h=1,ns); \tag{15}$$

$$t[i,k,,h] <= x[i,k,h] \quad (i=1,np;\ k=1,2;\ h=1,ns); \tag{16}$$

$$t[i,1,h] <= w[i,1,h] * maxdem[i,2] \quad (i=1,np;\ h=1,ns); \tag{17a}$$

$$t[i,2,h] <= w[i,2,h] * maxdem[i,1] \quad (i=1,np;\ h=1,ns); \tag{17b}$$

$$\sum_{k=1}^{2} w[i,k,h] <= 1 \quad (i=1,np;\ h=1,ns); \tag{18}$$

$$x[np,1,h] <= wres * maxdem[np,1] \quad (h = 1,ns); \tag{19}$$

$$w[i,k,h] \ (0, 1) \text{ integers} \quad (i=1,np;\ k=1,2;\ h=1,ns); \tag{20}$$

$$wres \ (0, 1) \text{ integer.} \tag{21}$$

Parameters of the model (1)-(21) are:

ns – number of scenarios;

np -- number of products;

scen_prob[*h*] – “initial” probability of scenario *h*;

wt[*i*,*h*], (*i* = 1, 4) -- weights of the four components *i* of "long-term well-being" under scenario *h*;

prod[*i*,*k*,*h*] - productivity of a worker in industry *i* and country *k* under scenario *h* (for US *k*=1, for China *k*=2);

maxdem[*i*,*k*] - the maximum market demand for product *i* at *k*;

mindem[*i*,*k*] - the minimum market demand, that must be met, for product *i* at *k*;

price[*i*,*h*] - the retail US price of product *i* under scenario *h*;

valadd[*i*,*h*] - the US value added per unit of product *i* under scenario *h*;

labu[*i*] - the initial number of workers in the US industry *i*;

labc[*h*] - the number of workers in the international trade-related part of the Chinese economy under scenario *h*;

retcost[*i*,*j*] - the cost of re-training one US worker from industry *i* to industry *j*;

retin[*i*,*j*] - the maximum number of the US workers of industry *i* that can be re-trained for work in industry *j*;

retout[*i*] - the maximum number of "re-trainable" US workers in industry *i*;

uncost - the unemployment cost per worker;

exprice[*i*,*k*,*h*] - export price of product *i* from country *k* under scenario *h*;

limit - the maximum allowed trade deficit, as fraction of US GNP;

limcomp -- the maximum allowed compensation of trade deficit, as fraction of US GNP;

rescost - fixed cost of R&D research;

coef_retr - "coefficient of relevance" of non-recurring labor re-training costs;

coef_res - "coefficient of relevance" of non-recurring research costs.

The variables of the model (1)-(21) are:

z -- the value of the objective function of "long-term well-being";

zsc[*h*] -- the "scenario component" of "long-term well-being" under scenario *h*;

addcost -- optional non-recurring cost of re-training and R&D;

cons[*h*] - trade-related "standard of life" in the US (consumption of all traded products) under scenario *h*;

gnp[*h*] - the production of the trade-related segment of the US economy under scenario *h*;

socost[*h*] - the cost of unemployment under scenario *h*;

x[*i*,*k*,*h*] - output of industry *i* at *k* under scenario *h*;

y[*i*,*k*,*h*] - consumption of product *i* at *k* under scenario *h*;

retr[*i*,*j*] - the number of the US workers, re-trained from industry *i* to industry *j*;

unemp[*i*,*h*] - unemployment in industry *i* under scenario *h*;

t[*i*,*k*,*h*] - export of product *i* from country *k* under scenario *h*;

def[*h*] - the US trade deficit under scenario *h*;

compens[*h*] - compensation for the excess trade deficit, paid by China to the US Treasury, under scenario *h*;

wres - integer (0, 1) variable that defines the decision to perform or not to perform the R&D work;

w[*i*,*k*,*h*] -- integer (0, 1) variables that prevent the possibility of "cross-haul" exports of the same product from both countries under scenario *h*.

The model (1)-(21) is used to substantiate under uncertainty the two decisions that affect the trade-related segment of the economy - to determine the levels of, first, re-training of the American workers and of, second, R&D. These decisions should maximize the expected (weighted average over all scenarios) "long-term well-being" of the US. The decisions have to be made immediately, therefore the values of the corresponding variables remain identical over all scenarios.

The meaning of model (1)-(21) is as follows. There exist *np* "tradable" products, manufactured in each country by *np* single-product industries.

For simplicity, we assume that the US technical progress is possible only in one, the last, or *np*th, industry sector. So, if we decide to spend money on R&D, a new, *np*th, industry is created, where an invention may be made that would lead to a new product. (The production capacity of the Chinese *np*th industry thus equals zero.)

The model (1)-(21) has only one limiting production factor - the size of the available labor force; it is a one-factor model. For the US economy, we consider the starting labor force known for each industry sector. We know less about China, so we consider just an overall estimate of the labor force available in the "trade-related" part of the Chinese economy.

As mentioned in Section 4, we got rid of several absurdly unrealistic concepts of the traditional international trade models -- such as a "no unemployment" assumption, and a worker homogeneity assumption, where each worker of the US was a "jack-of-all-trades", skilled enough to work without re-training in any industry sector.

Individual constraints of the model have the following meaning (limited, wherever appropriate, to individual scenarios).

The value of the objective function (1) is a weighted (by “initial” scenario probabilities) sum of its “scenario components,” minus a specified fraction of non-recurring costs of R&D and labor re-training.

Equation (2) forms each “scenario component” of "long-term well-being" as a weighted total sum of standard of life, production potential, compensation from China (all positive), and social cost (negative) in the US segment. Equation (3) defines consumption.

Equality (4) expresses the relationship between the needed and available labor force in each industry sector of the US. We assume that, similar to the research decision, the re-training decisions have to be made immediately. Equality (4) defines the trade-created unemployment, too. Constraint (5) limits the number of workers in industry *i* who could be re-trained for work in industry *j*, and constraint (6) - the total number of re-trained workers of industry *i*.

Inequality (7) limits the possible employment in the "trade-related" part of the Chinese economy by the total available labor resources.

Equation (8a) establishes the relationships between the US output of each product, its export, import, and consumption. Equation (8b) performs the same function as (8a), but for China.

Equation (9) defines GNP of the trade-related US segment, and equation (10) -- the trade deficit of US. As proposed in the "compensated free trade" system (e.g., [Masch 2007a]), constraint (11) limits the trade deficit to a specified percentage of GNP; China is allowed, however, to export more, if its government pays to the US Treasury a compensation for the excessive export. Constraint (12) limits that compensation.

Equation (13) defines the additional costs, resulting from a more intensive R&D and labor re-training decisions, taking into account "relevance" of these non-recurrent costs for the static economy of indefinite length, and equation (14) -- the social costs of unemployment. Two inequalities (15) set upper and lower consumption bounds for both countries.

Inequalities (16) define physical limits on exports for both countries, so that they cannot exceed the domestic output. Inequalities (17) in combination with (18) eliminate the possibility of "cross-haul" exports, that is, simultaneous exports of the same product by both countries. Finally, constraint (19) limits the output of the new *npth* US industry: if we decide not to invest in R&D, the industry's production capacity equals zero. Constraints (20) and (21) define several (0, 1) integer variables.

6. The Numerical Example

The numerical example of the MILP model (1)-(21) outlined in Section 5 stems from the general lines of the three-product example of [Samuelson 2004]. It is modified and expanded in several directions.

The values of some parameters of the model (1)-(21) may be known with sufficient reliability; in that case, they are considered single-valued or deterministic and are shown in Table 1.

The absence of workers in industries 2, 3 and 4 means that new production capacity must be added to the existing facilities, in industries 2 and 3 -- with an old technology and old products, and in industry 4 -- with a new technology and a new product, both of which have yet to be invented.

Uncertainty in this example is introduced as follows. For each factor that contributes to uncertainty (an "uncertainty generator") we introduce a number of its values (or states, if it is expressed qualitatively) that represent its important alternatives - say, the alternatives that may lead to inflection points in the value of the objective function. Probabilities of these alternatives can be quite approximate.

A scenario is formed by taking one alternative of each "uncertainty generator." If a factor *r* has *n*[*r*] alternatives, the total number of scenarios equals the product of all *n*[*r*]. (It should be pointed out here that, for reasons explained in Section 7, we should not be concerned, due to computational capability, about the large number of scenarios emerging.) As emphasized there, we can also add any other scenario we might be concerned about, including any possible (zero probability) scenario. No zero probability scenario is added in this example. (Scenarios may be deleted, too.)

Table 1 *Parameter Values of the MILP Model (1)-(21)*

Product	1	2	3	4	Total
maxdem US	300	100	100	100	
maxdem China	200	100	100	50	
mindem US	50	10	10	0	
mindem China	0	10	10	0	
prod US	2.0	0.5	1.0	2.5	
labu	100	0	0	0	
retout	30	0	0	0	
retinmax	0	15	20	30	
retcost	0	16	8	10	
price	22	40	26	19	
valadd	15	23	25	18	
exprice US	18	35	22	17	
limit					0.03
limcomp					0.05
coef_retr					0.5
coef_res					0.5
uncost					20
rescost					110

There are five "uncertainty generators" in this example, each with two alternatives. Let us consider the first one an external generator, and the rest ones – internal.

1. With probability 0.5, *wt*[*i*][*h*] for the USA consumption, production, social costs, and compensation may be equal either (0.45, 0.35, 0.15, 0.05) or (0.25, 0.40, 0.28, 0.07). In the second case, non-consumption goals are considered more important.
2. The Chinese industry 3 may double its labor productivity from 0.1 to 0.2 with probability 0.25. Accordingly, *prod* [*i*, 2, h] in three industries of China (the country does not have the fourth industry) equals (0.05, 0.2, 0.1) or (0.05, 0.2, 0.2). China's export price for product 3, *exprice*[3,2,*h*], is in the second case reduced from 15 to 9. The prices of three products are then either (25, 16, 15) or (25, 16, 9).
3. Similarly, the Chinese industry 1 may raise its productivity from 0.05 to 0.16 with probability 0.3. In that case, its *exprice*[1,2,*h*] is reduced from 25 to 15.
4. If the US invests 110 monetary units in R&D, its industry 4 may invent its new product and new technology with probability 0.55. If it succeeds, its *prod*[4,1,*h*], *maxdem*[4,1] and *mindem*[4,1], price[4,*h*], valadd[4,*h*], and

exprice[4,1,*h*] will be as shown in Table 1, that is, 2.5, 100, 50, 19, 18, and 17. If it fails, the values of these six parameters equal 0. (The industry 4 parameters are known, but whether it will exist is not.) Moreover, not only the R&D investment will be lost, but the economy will also suffer additional losses: the workers of industry 4 will become unemployed. Per each unit of unemployed labor in industry 4 we will lose 5 monetary units of retraining and 20 monetary units of social costs.

5. With probabilities 0.6 and 0.4, *labc*[*h*] may be equal either 400 or 300.

7. Stages of RCO - Internal Uncertainty

Stage (i): Scenarios and the "What if" Analysis

Uncertainty is embodied by scenarios. The "internal scenarios" are relatively easy to generate; we will use them during the whole process of formulating and solving the problem. The "external scenarios" are additional scenarios that complement the internal group whenever that is considered necessary.

In the end of Section 7 we have introduced five "uncertainty generators" with two alternatives for each "generator." At this and the next four stages, RCO uses in this example only the last four "uncertainty generators", which give rise to 16 scenarios; see Table 2 below.

Table 2 *"Uncertainty Generators" Alternatives in 16 Scenarios*

Scenario / **Uncertainty Generator**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
2	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
5	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2

The values of the probabilistic model parameters are determined accordingly. For instance, scenarios 1-8 implement alternative 1 and scenarios 9-16 -- alternative 2 for "uncertainty generator" 2. This defines the value of *prod*[3,1,2] as 0.10 in scenario 1 and as 0.20 in scenario 9. The 16 scenarios are presented in Table 3.

A very important point should be emphasized here. *Creating scenarios, we do not have to worry about correlation of factors in the problem. Correlation influences only scenario probabilities.* (And, later in the RCO process, we subjectively override them, anyway. As explained in this section, Stage (ii), this is very good.)

The "what if" analysis consists in solving 16 mutually independent MILP problems, one for each scenario, and compare their results. (The models of all problems have the same structure and dimensionality, but the values of their parameters differ. Each model has 65 constraints, 40 continuous and 9 integer variables.) If the results of all problems all similar, satisfactory, and do not give rise to objections from the point of view of risk management, further RCO steps are not necessary. *The "what if" analysis is thus the first filter of RCO.*

Table 3 *Scenario Parameter Values*

Scen \Par	***prod* [*41*]**	***price* [*4*]**	***valadd* [*4*]**	***exprice* [*4*]**	***labc***	***prod* [*12*]**	***exprice* [*12*]**	***prod* [*32*]**	***exprice* [*32*]**	***scen_prob***
1	0.00	0.00	0.00	0.00	400	0.05	25	0.10	15	0.1417
2	0.00	0.00	0.00	0.00	300	0.05	25	0.10	15	0.0945
3	2.50	35.00	300	31.00	400	0.05	25	0.10	15	0.1732
4	2.50	35.00	300	31.00	300	0.05	25	0.10	15	0.1155
5	0.00	0.00	0.00	0.00	400	0.16	15	0.10	15	0.0607
6	0.00	0.00	0.00	0.00	300	0.16	15	0.10	15	0.0405
7	2.50	35.00	300	31.00	400	0.16	15	0.10	15	0.0742
8	2.50	35.00	300	31.00	300	0.16	15	0.10	15	0.0495
9	0.00	0.00	0.00	0.00	400	0.05	25	0.20	9	0.0473
10	0.00	0.00	0.00	0.00	300	0.05	25	0.20	9	0.0315
11	2.50	35.00	300	31.00	400	0.05	25	0.20	9	0.0577
12	2.50	35.00	300	31.00	300	0.05	25	0.20	9	0.0385
13	0.00	0.00	0.00	0.00	400	0.16	15	0.20	9	0.0203
14	0.00	0.00	0.00	0.00	300	0.16	15	0.20	9	0.0135
15	2.50	35.00	300	31.00	400	0.16	15	0.20	9	0.0248
16	2.50	35.00	300	31.00	300	0.16	15	0.20	9	0.0165

In this example, however, the results for different scenarios are not similar; there are 8 distinct groups (pairs) of scenarios, where the value of *z* varies from 3607 to 4064. Still more important, solutions differ in their two major decisions: in some solutions, R&D is used, in others it is not; in some solutions, workers of industry 1 are re-trained to work in industry 3, in some others - in industry 4, in yet others - in both of these industries, while in remaining scenarios there is no re-training at all. We therefore proceed to Stage (ii).

Stage (ii): The Multiscenario MILP Model

In the beginning of the strategy generation part, RCO constructs a multiscenario stochastic MILP model (1)-(21), which, in contrast to stage (i), considers the whole range of scenarios jointly. These models have a great advantage over the single-scenario models: the latter are not able to find any "interscenario compromise" solutions, which are correct answers for most problems (Masch 2004a, 440).

In addition, not only RCO, but also all multiscenario models remove a major conceptual difficulty mentioned in Section 1 – about using optimization methods, that presuppose some knowledge of the future, in problems with radical uncertainty that deny any such possibility. Namely, the optimization methods in essence are used in scenario submodels, and each submodel knows the future perfectly well: for that submodel, the future is the underlying scenario.

The RCO multiscenario model is of a new special type: see Figure 1. (The currently existing types of stochastic models are insufficient here.) The main distinction of the RCO model – it recognizes that not all decisions are created equal. RCO therefore classifies all decision variables of the model into "strategic" and "operational" (or “tactical”) variables. "Strategic variables" are a small subset of variables that correspond to the most important decisions. These include, but are not limited to, immediate and irrevocable decisions. For instance, in a problem of plant location the strategic variables are limited to, say, the 0-1 variables that define whether or not a plant will be constructed at a given city, and the integer variables that define the total production capacity of a plant projected at that city (say, 100, 500, or 1,000 units). All other variables, such as technologies, raw materials, and transportation modes used, are operational ones.

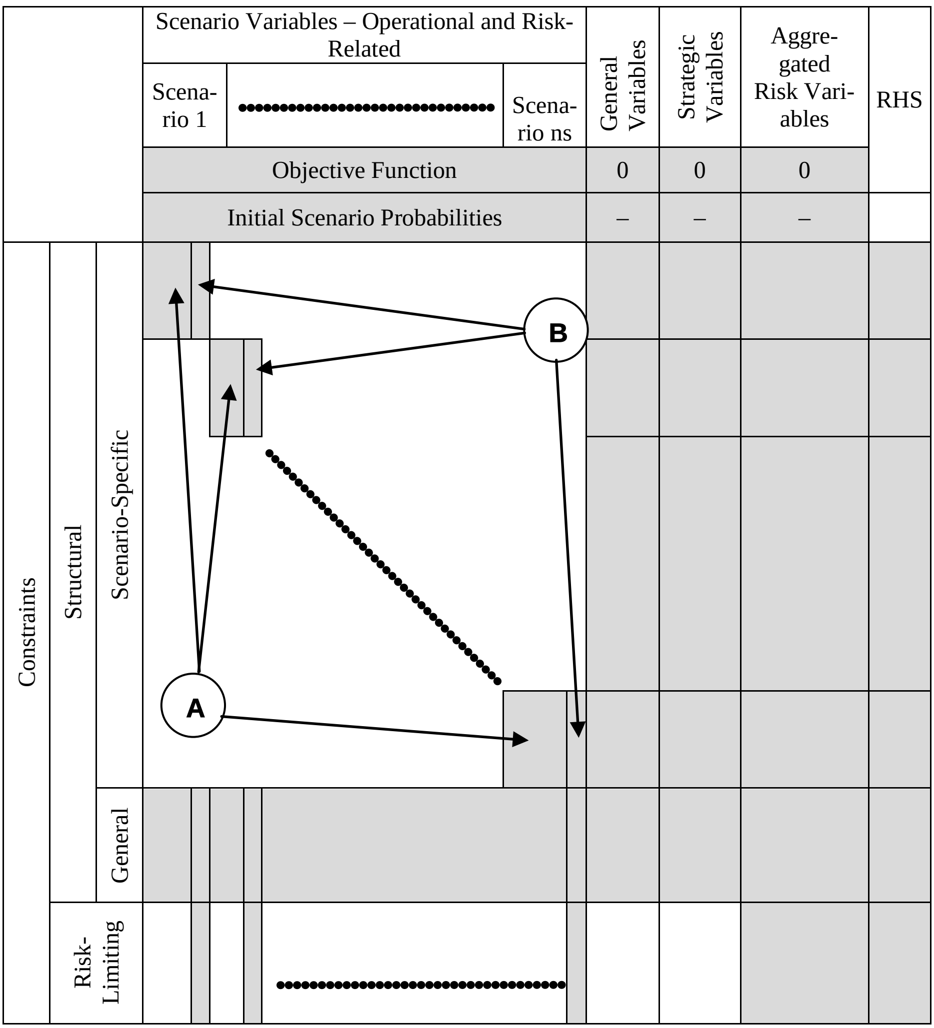

Figure 1 *RCO Matrix (A – Operational Scenario Variables, B – Risk-Related Scenario Variables)*

Under each scenario, the values of a strategic variable either remain invariant or change within narrow bounds. Accordingly, a “candidate strategy” is defined by the set of solution values of all strategic variables of the model.

In distinction from the usual approach of Operation Research, where a strategy is associated with the whole optimal solution of the optimization model and is vaguely portrayed by the values of a zillion of its variables, this technique clearly defines each strategy in a unique manner.

It should be emphasized that, as explained in more detail in Stage (iv), this approach provides the "post-contingency-plans" outcomes, that is, results of the strategy's reactions to each of the various scenarios. A strategy is evaluated on the basis of the totality of outcomes of its contingency plans over all scenarios.

In the second distinction from the current stochastic programming, which is interested only in the total value of the objective function of its model over the whole range of scenarios, RCO calculates the "bookkeeping" scenario components of this function, as well as the scenario-specific outcome values of each risk type, such as market share or environmental damage. RCO would need all these values at Stage (iv). In Figure 1, these variables are called “Risk-Related” (additional explanations of Figure 1 see in Stage (iv)).

In a multiscenario model, scenario inputs and results have to be weighted. The scenario weights (which are overridden later) are derived here by combining the internal probabilities of different alternatives of "uncertainty generators" that we are using at this stage; we do not need yet the external ones. For example, the probability of scenario 1 equals 0.75 x 0.7 x 0.45 x 0.6 = 0.1417. (For simplicity, we do not take into account in this example the possible correlations between the different "uncertainty generators," which might change the scenario probabilities.)

It should be pointed out that the historical values of the correlation coefficients are extremely unreliable. In any crisis situation these values change drastically. Since the historical values are the basis for calculating the “initial” scenario probabilities, it is very good that these probabilities are overridden in the iterative process of RCO.

It must be reminded that RCO works under radical uncertainty, that is, on the basis of incomplete, unreliable, fuzzy, non-quantifiable, contradictory, and often wrong information. We should not expect accuracy from forecasts and other input data used in the models. Most importantly, RCO should not treat the input data as reliable information. The immediate consequence of that premise is that the methodology should alleviate, as much as possible, the impact of the poor quality of the input data on the quality of solutions. In other words, the methodology should be, to some degree, self-correcting. Not only RCO, but also all multiscenario models are, to some degree, self-correcting; see [Masch 2004a, 441]. (A second consequence is that both the computational complexity of the models and the speed and accuracy of algorithms used to solve them should be commensurate with the quality of the data.).

It also should be pointed out that the enormous size of the multiscenario models that emerge with a large number of scenarios should not be a matter of great concern: due to the “anti-maximization” character of the process and the structure of these models, a very efficient special algorithm allows to solve problems of any number of scenarios. It uses ideas of alternate clustering and de-clustering.

Finding the extremal solution of this multiscenario MILP model is the end of the stochastic programming process as it is practiced now, but it is just the beginning of the iterative part of the RCO process. *This model is the second filter of RCO.*

The 16-scenario MILP model has 958 constraints, 565 continuous and 129 integer variables. Out of these 694 variables, four variables are set as "strategic variables": *retr*[1,2], *retr*[1,3], *retr*[1,4], and *wres*. The solution of this problem is presented in Table 4. We will call it Strategy 0. This solution contains "scenario sub-solutions" for each of the 16 scenarios - that is, the strategy proper, and its 16 reactions ("the contingency plans") for all scenarios.

Table 4 *Strategy 0*

Scenario	**Outcomes**
alpha	0.00
minprod	0.00
z	3466
addcost	205
wres	1
retr12	0
retr13	0
retr14	30

Scen	***zsc***	***cons***	***gnp***	***socost***	***compens***	***netdef***	***x11***	***x21***	***x31***	***x41***	***scen_prob***
1	2439	3975	2100	600	105	63	140	0	0	0	0.14
2	2255	3566	2100	600	105	63	140	0	0	0	0.09
3	4728	6364	4650	0	233	139	140	0	0	75	0.17
4	4499	6355	4650	0	233	78	140	0	0	75	0.12
5	2439	3975	2100	600	105	63	140	0	0	0	0.06
6	2255	3566	2100	600	105	63	140	0	0	0	0.04
7	4728	6364	4650	0	233	139	140	0	0	75	0.07
8	4499	6355	4650	0	233	78	140	0	0	75	0.05
9	2656	4458	2100	600	105	63	140	0	0	0	0.05
10	2472	4049	2100	600	105	63	140	0	0	0	0.03
11	4956	7370	4650	0	233	139	140	0	0	75	0.06
12	4758	6931	4650	0	233	139	140	0	0	75	0.04
13	2656	4458	2100	600	105	63	140	0	0	0	0.02
14	2472	4049	2100	600	105	63	140	0	0	0	0.01
15	4956	7370	4650	0	233	139	140	0	0	75	0.02
16	4758	6931	4650	0	233	139	140	0	0	75	0.02

As stated above, a strategy is a set of major decisions (that is, of the values of the four "strategic variables"), which are identical for all scenarios. In Strategy 0, both R&D and re-training of workers (from industry 1 to industry 4) are used, so that the values of the four strategic variables are as follows: *retr*[1,2] = *retr*[1,3] = 0, *retr*[1,4] = 30, and *wres* = 1. The values of *z* and *addcost* are also unique for a strategy; in Strategy 0 they equal 3466 and 205, respectively. (The re-training of 30 labor units for industry 4 costs 300 and the R&D investments -- another 110 monetary units, for the total of *addcost*, with *coef_retr* = 0.5 and *coef_res* = 0.5, equal to 205.)

Any decision maker has multiple, diverse and conflicting goals and factors of concern; we will uniformly call them "risk types". In addition to *z* and *addcost*, we are concerned here with 10 "risk types": "scenario components" of "long-term well-being" *zsc*[*h*], its four components (the overall US production *gnp*[*h*], consumption *cons*[*h*]), social cost *socost*[*h*], trade deficit compensation *compens*[*h*], "net deficit" *netdef*[*h*] = *def*[*h*] - *compens*[*h*], and the US production of four products *i* (*x*[*i*,1,*h*]).

Table 4 presents the values of *z*, *addcost*, and the values of 4 strategic variables (all unique for a strategy), as well as the values of 10 operational scenario components that correspond to 10 "risk types" (10 values for 16 scenarios each).

The values of *zsc*[*h*] for different scenarios vary widely, from 2255 to 4956. That is because the invention of the new product and the new technology for industry 4 turn out to be very lucrative: in spite of heavy penalties in eight scenarios with the total weight of 0.45, where industry 4 produces nothing and suffers unemployment, the extremal solution still favors creating this industry, training its workers and investing in its R&D.

In contrast to strategic variables, the values of all non-strategic (operational) variables under each scenario depend on the alternatives involved and on the specific values of the scenario parameters. True, in every scenario the remaining 70 labor units of industry 1 make the same 140 units of product 1, and there is no unemployment there. But, depending on the production and price patterns, the US sells to China different quantities of product 1 and product 4 -- from 0 to 40 units, and from 0 to 8 units, respectively. Accordingly, in exchange, we receive from China for our consumption from 10 to 50 units of product 2 and 10 units (uniformly) of product 3.

In eight scenarios where the invention process is successful, *gnp* equals 4650 monetary units and the social cost does not exist; in the remaining eight scenarios these numbers are 2100 and 600, respectively. When we are unlucky with the invention, the standard of life (consumption) dips precipitously, more than twice -- from the maximum of 7370 to the minimum of 3566. The differences between the scenario subsolutions are quite sharp, so the strategy is very risky.

Dependent on the size of *gnp*, the total deficit varies within the 168 to 372 range; it is compensated, however, by the intergovernmental payments from China to the US of 105 to 233 units, so that the "net deficit" is from 63 to 139 units. It rises with increases in *gnp* and never exceeds 3% of it.

We can go now to Stage (iii).

Stage (iii): The "Outcome Matrix"

The three-dimensional outcome matrix "scenarios vs. strategies vs. risk types" thus consists of 10 two-dimensional submatrices, one for each operational "risk factor"; each submatrix has 16 rows and the number of columns equal to the number of strategies. At this stage of the process, we have only one Strategy 0; the submatrices are therefore 16 x 1 columns.

The unique characteristics of each strategy that are identical for all scenarios (the values of *z*, *addcost*, the strategic variables, and the parameters of "risk-limiting constraints", see below) are presented in the beginning of the outcome matrix. *The matrix is the third filter of RCO*; it allows subjective analysis and elimination of risky strategies.

We can proceed to Stage (iv) now.

Stage (iv): "Risk-Limiting Constraints"

As is usual in extremization problems, the solution activities are concentrated, as much as possible, in the "best" industry, in this case - industry 4; the remainder of the trading sector stays in "the second best" industry 1. Industries 2 and 3 get no growth. But such unbalanced, risky (with much unemployment and social cost), one-track development is hardly likely to be good for any economy, especially for such a multifaceted one as the economy of the USA. Therefore let us try to develop the US manufacturing in a more balanced, coordinated, less risky way, so that industry 2 produces no less then *minprod*[2] units and industry 3 produces no less than a certain fraction *alpha*[3] of the outputs of industries 1 and 4, combined. To assure such an outcome, we add to the model (1)-(21) constraints (22a) and (22b):

$$x[2,1,h] >= minprod[2] \quad (h = 1,ns]; \tag{22a}$$

$$alpha[3] * (x[1,1,h] + x[4,1,h]) - x[3,1,h] <= 0 \quad (h = 1,ns]. \tag{22b}$$

Inequalities (22) are "cutting planes" -- "risk-limiting constraints" mentioned in Section 7(ii), and in a sense similar to "cutting planes" of R. Gomory [Gomory 1963]. If, after any iteration of the RCO process, the decision maker is not satisfied with any outcomes for any risk types under any scenario or group of scenarios, he adds to the multiscenario model some "risk-limiting constraints," imposed directly on poor outcomes or their combinations. (The capability to improve outcomes for individual scenarios was created by introducing the "bookkeeping" variables for scenario outcomes and the outcome matrix, which makes seeing them easier.) The constraints should improve these outcomes. The more additional constraints the model has, the more its solution differs from the initial solution of the process, that is, from the solution of the multiscenario stochastic MILP model described at Stage (ii). *Risk-limiting constraints are the fourth, strongest filter of RCO.*

Since the constraints are imposed not on the "structural" variables of the model, but rather on the "bookkeeping" variables that reflect only the model results or "outcome variables," the decision maker needs no modeling skills to impose these constraints; neither must he understand the internal structure of the model. It is quite sufficient to know the risk types and scenarios, and to know what one does not like. Imposing on a model a special set of risk-limiting constraints, he can "customize" the model.

The risk-limiting constraints are shown in the lower part of Figure 1; they involve only the risk-related scenario variables and, possibly, their aggregates.

In our case, suppose that *minprod*[2] = 7 units and *alpha*[3] = 0.10. So we just add into the input file of MILP the constraints (22a) and (22b) with those values of *minprod*[2] and *alpha*[3]. Now the model will implicitly split all possible strategies into two categories: the "good" strategies that satisfy those conditions, and the "bad" ones that do not. The constraints (22) exclude from consideration all "bad" strategies, but do not exclude a single "good" strategy. The previous extremal solution certainly belongs among the "bad" strategies and is excluded.

The model is re-run and a new solution is found with the outcomes reaching the requested levels if they are feasible. Of course, such partial improvements demand sacrifices in other parts of the solution, so the solution as a whole worsens - its total value of the objective function is less than that for the previous solution. It now is no better than that value for the previous "second best" solution. This "Dutch auction" process for a single candidate strategy is complete when either the decision maker is satisfied or further improvement becomes impossible. After the last constraint for this candidate is imposed, the new region of feasible solutions is some truncated, "safe" inner portion of the initial region of feasible solutions of the model.

Within a trade-off, from one constraint set to another, the definition of the "good" and "bad" strategies constantly changes, with the area of feasible solutions being truncated differently. If there exist no strategies with *minprod*[2] = 7 and *alpha*[3] = 0.10, we may grope for a feasible answer, asking the model if there exist any strategies with the pair (6, 0.10) and what sacrifices are needed in various operations or in other scenarios to reach that solution. On the other hand, if the pair (7, 0.10) is reachable, we may try for (8, 0.10) -- or, say, for (7, 0.15). Each branching of a set of constraints leads to a different trade-off.

The risk-limiting constraints imposed upon the multiscenario model reflect both the decision maker's propensity for risk and his attitude toward various risk types and optimality criteria. The strategy generation process can be repeated many times, branching out at different points, on different risk types, with different types of constraints, or with different bound values, and resulting in one or more "trees" of candidate strategies with different trade-offs.

Figure 2 illustrates how the risk-limiting constraints work in reducing risk. It shows the effect of RCO on the distribution of outcomes over the whole range of scenarios. "A" summarizes the solutions of single-scenario "What if" "optimization" models over that range. "B" shows how the situation changes with the introduction of a multiscenario model, which generates a single compromise strategy. "C" depicts the same strategy after risk-limiting constraints are added.

In “A,” single-scenario models have no mutual impact, so the good scenarios lead to the highest returns and the bad ones -- to the lowest. As a compromise, "B" has more modest results for good scenarios and is also less risky. Finally, the risk-limiting constraints in "C" cut off all elements that lead to poor outcomes under bad scenarios, so the distribution of returns is truncated on the left. The distribution in "C" is ” is greatly compressed, and, extremely important, the volatility of returns is decreased.

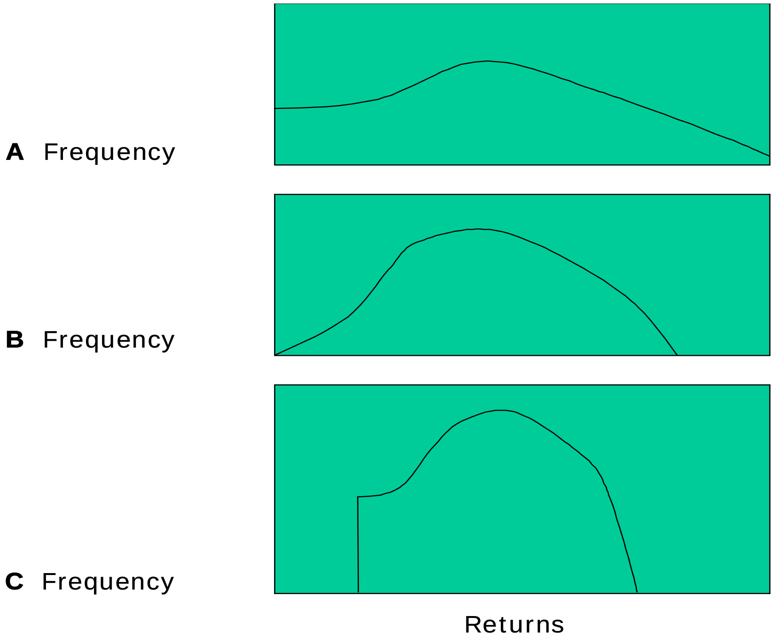

Figure 2 A-C *Distribution of Outcomes over the Range of Scenarios*

A *Optimal solutions of single-scenario models.*
B *Compromise strategy, optimal for multiscenario model.*
C *Strategy B after "risk-limiting constraints" are added.*

Systematic use of risk-limiting constraints, especially the constraints based on scenario-specific outcomes, is a novel, extremely fruitful risk-management concept introduced into the toolkit of the Operations Research/Management Science techniques by RCO. The constraints perform several functions. They allow:

- Screening out ("cutting off") the unacceptably risky solutions, while not excluding any good strategy.
- Thus performing the main function of risk management -- full or partial prevention of undesirable outcomes.
- Customizing the standard extremization models in accordance with the specific needs of the decision maker,
- Exploring tradeoffs.
- Overriding the initial scenario probabilities and thus implicitly introducing new sets of probabilities.
- Developing a number of trees of alternative candidate strategies.

Sum up: *risk-limiting constraints impose on optimization models an additional function of self-filtering.* "Guesstimated knowledge" is filtered by personal intuition.

It is important to note that every candidate strategy constructed at this stage is "strongly pre-screened" and thus "pre-approved": it is already reasonably good and reasonably protected from risk, at least - from internal risk. That feature substantially improves reliability of the "weak screening" process described in Stage (vi[b]) below, that is, of the commonly used strategy comparison procedure under uncertainty that is, for instance, the subject of Chapter 13 of [Luce and Raiffa 1957]. (As shown in Section (vi[b]), RCO greatly improves that procedure, too.)

We also have to add here an important new approach that further increases the potential of risk-limiting constraints. As mentioned in Stage (ii), in a crucial distinction from the conventional stochastic multiscenario models, RCO has a small number of strategic variables, their values remaining unchanged, or staying within specified bounds, under each scenario. Sometimes - for instance, in the multiscenario model of Stage (ii) or in the above model with additional risk-limiting constraints (22a) and {22b) -- the values of all variables, both strategic and operational, are "optimized" on a more or less equal footing. But in other cases we can fix the values of some or all of the strategic variables.

As soon as we find a candidate strategy worthy of exploration, we can construct for it a separate multiscenario model, with the values of some or all of its strategic variables being fixed -- at the values specific for that candidate. All non-fixed strategic variables and all operational variables remain free to be optimized. The "free" variables thus form optimal contingency plans that show the reaction of the fixed part of the candidate strategy to the whole range of scenarios.

If we have fixed the values of all strategic variables, we get the contingency plans for each scenario in the range. If we have left some or all values of strategic variables non-fixed, the new solution may, in turn, beget a new tradeoff candidate strategy and its contingency plans. (In both cases, we assume that some set of risk-limiting constraints may be imposed on the model.)

This technique allows exploring in detail the behavior of each candidate strategy and its contingency plans, as well as any candidates further derived from them. As we find a new promising candidate, we construct for it a new MILP with different bounds on the strategic variables, and so on. Thus we get “trees” of candidates.

And yet another, very important point. It was mentioned in Section 2 that optimization models focus our attention on just one point of the immense multidimensional area of feasible solutions. But the information about this point still can contain, say, values of millions variables of a large model. Splitting the variables into strategic and operational groups allows the decision maker to concentrate his attention, instead of possibly millions, on just few data that really matter – on the values of a *small set of strategic variables*, on what *new strategy* he has to pursue, as well as on *dynamics of the main factors* that influence the selection of that strategy.

This issue is far from trivial, especially if decisions have to be made at real time. For instance, van Cleveld emphasizes the impact of “flood of data.,” describing “… an explosion in the amount of data processed in any given command system to carry out any given mission. As the quantity of data grew, the difficulty of interpreting it in preparation for decision-making grew, causing staff to be piled upon staff and computer upon computer.” [Cleveld 1985, 3]. RCO can treat the possible enemy’s moves as parameters of scenario formation and present, in real time, very concentrated picture of the developing situation and of the strategies evolving.

Let us return to our problem now. Solving the model (1)-(22) for values of *minprod*[2] and *alpha*[3] equal to 7 and 0.10, we obtained a new Strategy 1, shown in Table 5.

Table 5 *Strategy 1*

Scenario	**Outcomes**
alpha	0.10
minprod	7.00
z	3084
addcost	176
wres	0
retr12	14
retr13	16
retr14	0

Scen	***zsc***	***cons***	***gnp***	***socost***	***compens***	***netdef***	***x11***	***x21***	***x31***	***x41***	***scen_prob***
1	3327	5309	2661	0	133	80	140	7	16	0	0.14
2	3143	4900	2661	0	133	80	140	7	16	0	0.09
3	3323	5299	2661	0	133	80	140	7	16	0	0.17
4	3139	4890	2661	0	133	80	140	7	16	0	0.12
5	3327	5309	2661	0	133	80	140	7	16	0	0.06
6	3143	4900	2661	0	133	80	140	7	16	0	0.04
7	3323	5299	2661	0	133	80	140	7	16	0	0.07
8	3139	4890	2661	0	133	80	140	7	16	0	0.05
9	3364	5391	2661	0	133	80	140	7	16	0	0.05
10	3180	4982	2661	0	133	80	140	7	16	0	0.03
11	3359	5381	2661	0	133	80	140	7	16	0	0.06
12	3175	4972	2661	0	133	80	140	7	16	0	0.04
13	3364	5391	2661	0	133	80	140	7	16	0	0.02
14	3180	4982	2661	0	133	80	140	7	16	0	0.01
15	3359	5381	2661	0	133	80	140	7	16	0	0.02
16	3175	4972	2661	0	133	80	140	7	16	0	0.02

Let us analyze that strategy. The value of *z* equals 3084; R&D and re-training for industry 4 are not used; re-training is 14 for industry 2 and 16 for industry 3. Production for industries 1 to 3 is 140, 7, and 16 units for all 16 scenarios. For all scenarios *h*. *gnp*[*h*] = 2661, there is no unemployment, and *netdef*[*h*] = 133. Consumption *cons*[*h*] varies within the range 4890 to 5391. The US trades 18 to 40 units of product 1 and 6 units of product 3 for 42 to 66 units of product 2.

Clearly, industry 2 is a burden: its production stays at its lower bound 7. That immediately suggests branching out into a better tradeoff: reducing this bound. Let us set *x*[2,1,*h*] >= 5 for all *h*, with *alpha*[3] still equal to 0.10, which will give as Strategy 2 shown in Table 6.

The value of *z* equals here 3198. R&D and re-training for industry 4 still are not used; re-training is 10 for industry 2 and 20 for industry 3. Production for industries 1 to 3 is 140, 5, and 20 units for all 16 scenarios. For all scenarios *h*. *gnp*[*h*] = 2715, there is no unemployment, and *netdef*[h] = 136. Consumption *cons*[*h*] varies within the range 5087 to 5505. The US trades 20 to 38 units of product 1 and 10 units of product 3 for 50 to 70 units of product 2.

Table 6 *Strategy 2*

Scenario	Outcomes
alpha	0.10
minprod	5.00
z	3198
addcost	160
wres	0
retr12	10
retr13	20
retr14	0

Scen	***zsc***	***cons***	***gnp***	***socost***	***compens***	***netdef***	***x11***	***x21***	***x31***	***x41***	***prob***
1	3434	5505	2715	0	136	81	140	5	20	0	0.14
2	3250	5097	2715	0	136	81	140	5	20	0	0.09
3	3430	5495	2715	0	136	81	140	5	20	0	0.17
4	3246	5087	2715	0	136	81	140	5	20	0	0.12
5	3434	5505	2715	0	136	81	140	5	20	0	0.06
6	3250	5097	2715	0	136	81	140	5	20	0	0.04
7	3430	5495	2715	0	136	81	140	5	20	0	0.07
8	3246	5087	2715	0	136	81	140	5	20	0	0.05
9	3434	5505	2715	0	136	81	140	5	20	0	0.05
10	3250	5097	2715	0	136	81	140	5	20	0	0.03
11	3430	5495	2715	0	136	81	140	5	20	0	0.06
12	3246	5087	2715	0	136	81	140	5	20	0	0.04
13	3434	5505	2715	0	136	81	140	5	20	0	0.02
14	3250	5097	2715	0	136	81	140	5	20	0	0.01
15	3430	5495	2715	0	136	81	140	5	20	0	0.02
16	3246	5087	2715	0	136	81	140	5	20	0	0.02

Strategy 2 is obviously better that Strategy 1 and is more stable than Strategy 0. As expected, the more restrictive is the constraint (22a) -- that is, the higher is the value of *minprod*[2] -- the lower is *z*. The constraint (22b) undoubtedly follows the same rule. We could continue developing new tradeoffs, but, for the purpose of demonstrating the RCO techniques, these three strategies (0 to 2) are sufficient. We present them in the *outcome matrix* of Table 7. The outcome matrix combines all 10 submatrices and provides, in the beginning of each column, the pertinent general information about the three strategies. For space considerations, Table 7 demonstrates only a part of it – the values of strategic variables and the submatrix of *zsc*.

We can proceed now to the next step of the RCO process, Stage (v).

Stage (v): Calculating "Utility" Payoffs

As noted in (Masch 2004a, 444), if, in addition to the "strong" screening of Stage (iv), we also want the commonly used "weak" screening of strategies, we must transform the three-dimensional matrix of outcomes into a two-dimensional payoff matrix - in other words, to calculate "quasi-utility" of such different and complex risk types as (in our example) the US consumption, production, social cost, and deficit compensation.

Table 7 *Outcome Matrix*

Var\Strat	**0**	**1**	**2**
alpha	0.0000	0.1000	0.1000
minprod	0.0000	7.0000	5.0000
z	3466	3084	3198
addcost	205	176	160
wres	1	0	0
retr12	0	14	10
retr13	0	16	20
retr14	30	0	0

(*ZSC*)

Scen\Strat	**0**	**1**	**2**
1	2439	3327	3434
2	2255	3143	3250
3	4728	3323	3430
4	4499	3139	3246
5	2439	3327	3434
6	2255	3143	3250
7	4728	3323	3430
8	4499	3139	3246
9	2656	3364	3434
10	2472	3180	3250
11	4956	3359	3430
12	4758	3175	3246
13	2656	3364	3434
14	2472	3180	3250
15	4956	3359	3430
16	4758	3175	3246
max	4956	3364	3434
min	2255	3139	3246
av	3671	3260	3358
nav	3595	3251	3340

We will use the simplest, but reasonably reliable, method of conversion (Ibid.): applying several sets of conversion coefficients. We have two such sets related to the first “uncertainty generator”, (0.45, 0.35, 0.15, 0.05) and (0.25, 0.40, 0.28, 0.07). Quasi-utility *util*[*h*][*j*] of Strategy *j* under scenario *h* and the coefficient set *r* is calculated by (23):

$util[h][j][r] = coef[1][r] * cons[h][j] + coef[2][r] * gnp[h][j] - coef[3][r] * cons[h][j]$
$+ coef[4][r] * compens[h][j] \quad (h = 1, ns; j = 0, 2; r = 1, 2)$ (23)

The number of scenarios increases to *ns* * *num_set*, or 16 * 2 = 32: scenarios 1 to 16 for the first set of coefficients and scenarios 17 to 32 - for the second set. To get weights of new scenarios in the payoff matrix, we specify the "guesstimate" probability of each set of coefficients -- say, *prob_set*[1] = 0.6 and *prob_set*[2] = 0.4. Payoffs and regrets for 32 scenarios are shown in Table 8.

We can proceed to Stage (vi [a]).

Stage (vi[a]): Decision Criteria

Now each candidate strategy is defined by a set of "payoffs" – quasi-utility values under the whole range of scenarios, expanded to (*ns* * *num_set*) scenarios. To select a strategy, we need to compare the values of some strategy range aggregates of these payoffs. There are four major possible "single" range aggregates for each strategy: (a) the weighted average payoff and (b) the non-weighted average payoff over all scenarios, (c) the maximum ("best case") payoff under a single scenario, and (d) the minimum ("worst case") payoff under a single scenario that is, (*av*), (*nav*), (*max*), and (*min*). Four similar "regret" measures can be calculated as well. ("Regret" is a derivative of payoff that measures the opportunity lost. For each scenario, the regret for Strategy *s* is calculated as the difference between the best payoff under that scenario and its payoff of Strategy *s*.) As mentioned earlier, the "scenario vs. strategy" values of utility payoffs, regrets, and the eight aggregates listed above are shown in Table 8.

Chapter 13 of the seminal [Luce and Raiffa 1957] book offers four criteria of comparing payoffs, one ("minimax regret") of comparing regrets, and one (the "pessimism-optimism index") criterion of L. Hurwicz, which we call a "synthetic" criterion. A "synthetic" criterion means a weighted average between a more optimistic and more pessimistic outlook, the latter being represented by the "worst case" payoff or regret, respectively. (In the Hurwicz criterion the weighed averages are calculated between the "best case" and the "worst case" payoffs.) As far as I know, the later work in Decision Science (except RCO) still continues to use the same six comparison criteria.

RCO increases this number from one to six "synthetic" criteria, combining the eight "single" criteria into six pairs, three for payoffs and three for regrets; the pessimistic end is represented by the "worst case" payoff or regret, respectively. The weights used in these averages reflect our subjective evaluation of the chances of "good vs. bad" outcomes, which approximates the risk attitude. They also reflect our trust in the reliability of the input data ("confidence" of [Keynes 1921, 148-9]).

As shown, however, in ([Arrow and Hurwicz 1972]; [Luce and Raiffa 1957]), no single criterion is "uniformly good" under radical uncertainty. That conclusion left only one usable "synthetic" criterion - the Hurwicz criterion.

The "synthetic" payoff criteria are: "index of pessimism-optimism" ("PO index") of Hurwicz; "partial ignorance index" ("PI index"), for an average between the weighted average payoffs and the "worst case" payoffs; and the "insufficient reason index" ("IR index"), for an average between the non-weighted average payoffs and the "worst case" payoffs. The regret criteria are similar, with the regret values instead of payoffs. "Single" criteria thus become merely the narrow special cases of more comprehensive and meaningful "synthetic" criteria.

Table 8 *Payoff and Regret Matrix*

Scenario	**Payoff Strategy**			**Regret Strategy**			*scen_prob*
	0	**1**	**2**	**0**	**1**	**2**	
1	2619	3327	3434	815	107	0	0.0850
2	2435	3143	3250	816	107	0	0.0567
3	4728	3323	3430	0	1405	1298	0.1039
4	4499	3139	3246	0	1360	1253	0.0693
5	2619	3327	3434	815	107	0	0.0364
6	2435	3143	3250	816	107	0	0.0243
7	4728	3323	3430	0	1405	1298	0.0445
8	4499	3139	3246	0	1360	1253	0.0297
9	2836	3364	3434	598	71	0	0.0284
10	2652	3180	3250	598	71	0	0.0189
11	4956	3359	3430	0	1596	1526	0.0346
12	4758	3175	3246	0	1583	1512	0.0231
13	2836	3364	3434	598	71	0	0.0122
14	2652	3180	3250	598	71	0	0.0081
15	4956	3359	3430	0	1596	1526	0.0149
16	4758	3175	3246	0	1583	1512	0.0099
17	2009	2401	2472	463	71	0	0.0567
18	1907	2299	2370	463	71	0	0.0378
19	3592	2398	2469	0	1194	1123	0.0693
20	3465	2296	2367	0	1169	1098	0.0462
21	2009	2401	2472	463	71	0	0.0243
22	1907	2299	2370	463	71	0	0.0162
23	3592	2398	2469	0	1194	1123	0.0297
24	3465	2296	2367	0	1169	1098	0.0198
25	2130	2421	2472	342	50	0	0.0189
26	2028	2319	2370	342	50	0	0.0126
27	3719	2419	2469	0	1300	1249	0.0231
28	3609	2317	2367	0	1292	1242	0.0154
29	2130	2421	2472	342	50	0	0.0081
30	2028	2319	2370	342	50	0	0.0054
31	3719	2419	2469	0	1300	1249	0.0099
32	3609	2317	2367	0	1292	1242	0.0066
max	4956	3364	3434	816	1596	1526	
min	1907	2296	2367	0	50	0	
av	3397	2901	2987	283	780	694	
nav	3246	2805	2880	277	719	644	

The conclusion of ([Arrow and Hurwicz 1972]; [Luce and Raiffa 1957]) can easily be generalized: no criterion, single or synthetic, is "uniformly the best" under radical uncertainty. This conclusion has been only strengthened by our introduction of multiple "synthetic" criteria. In other words, any problem may have several "best" solutions, based on different criteria. Therefore RCO uses all six "synthetic" criteria - jointly, but in turn; "single" criteria are not used at all. (The "synthetic" criteria can also be jointly used *under risk*, when scenario probabilities are sufficiently reliable, instead of the weighted averages, providing a more versatile and reliable comparison.)

Six "synthetic" criteria, combined with the “strategic frontier” of Stage (vi[b]), provide for a "weak", but still very important fifth filter of RCO. In contradistinction to the risk-limiting constraints, these methods are not connected with the MILP model used to generate the candidate strategies. They help therefore compensate, to some extent, for possible flaws in the model.

The crucial advantage of the "synthetic" criteria is that four out of six do not need scenario probabilities at all, while the other two are only weakly connected with them. This frees RCO from almost any reliance on probabilities, which are the weakest part of the input data. Instead, RCO focuses on *possibilities*.

This also makes RCO an honest system: manipulation of probabilities is the favorite technique for distorting the comparison of the strategies. It is much easier to change subjective probability than, say, the cost of a contingency measure. Choosing a wrong range of scenarios is a variation of the same manipulative technique: it is equivalent to assigning zero probabilities to undesirable scenarios. That is what Enron used to do -- for strategic decisions, it thoroughly analyzed up to 1,000 scenarios (DeLoach, 2000, 194). All scenarios were taken, however, from an overly optimistic range.

An additional benefit of "synthetic" criteria is that, like many of the "mass customization" technologies used in industry, they offer possibility of delaying the most difficult (or, in our case, the most controversial) operation until the very end of the process, or until such a time when its introduction will inflict the least harm. "The most controversial" operation here would be the use of subjective estimates of the decision maker's optimism.

Stage (vi[b]): "Strategic Frontier"

Moreover, RCO uses the "synthetic criteria" in such a way that they become much more than just a better technique for comparing strategies. They are embedded into a framework of a novel "strategic frontier," which is a major part of *the fifth filter of RCO*, not connected with the "optimization" model. This "strategic frontier" could not be applied with any "single" criteria.

The frontier incorporates the following valuable information about the relative merits and faults of any strategy:

- The composition of the subset of strategies that form the frontier.
- The width of the interval supporting each frontier strategy.
- The order of the frontier strategies on the optimism-pessimism spectrum.

- The difference between the frontier strategy and each other strategy, which shows the possible impairment of results in choosing a non-frontier strategy.

The "strategic frontier" allows us to apply subjective estimates in a more prudent, convenient, and less demanding way (that is, the decision maker does not need to specify in advance his degree of optimism). Specifically, the frontier replaces hard-to-estimate "point" indices by index ranges. For instance, the current user of the "PO index" criterion may ask the question: "Which strategy, B or C, is better if our estimated value of the index equals 0.8?" This means that we compare the strategies at precisely 0.8 probability of the "bad" outcome and 0.2 of the "good" outcome. Instead, when we use the strategic frontier, it is sufficient to say that Strategy C is preferable if the value of the index is no more than, say, 0.768, and Strategy B otherwise.

The "synthetic" criteria and strategic frontiers do not select the strategy to be implemented. They just shrink the list of the "finalist candidates" to a few reasonably most acceptable and safest strategies, leaving the final selection to the decision maker. Similar to the risk-limiting constraints, they do not find the best - they eliminate the worst, which is easier.

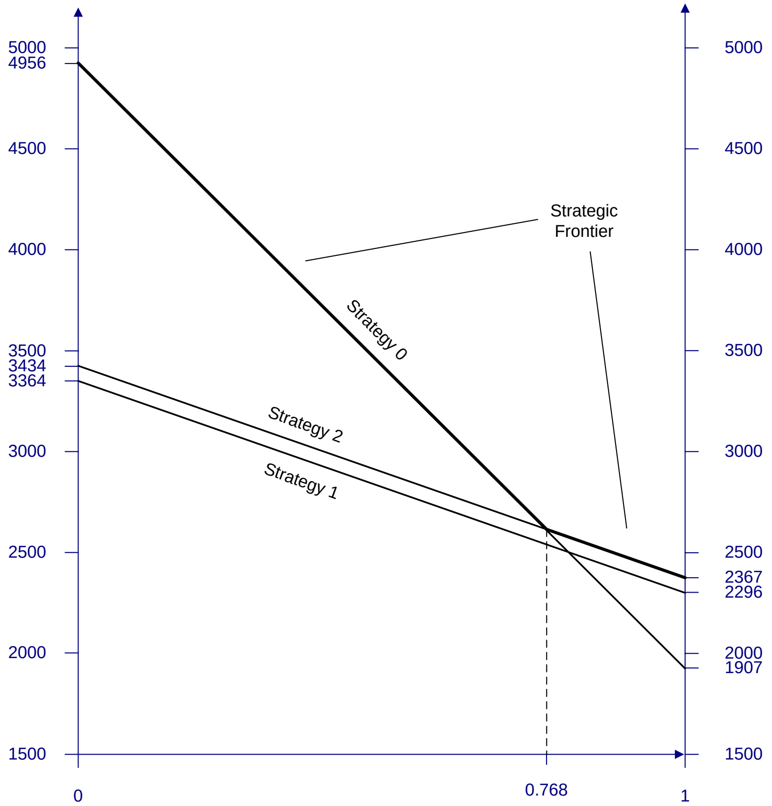

Figure 3 *Strategic Frontier for the Payoff "PO Index"*

Strategic frontiers for three "synthetic" criteria are demonstrated above and below. Figure 3 shows the strategic frontiers for the payoff "PO index", Figure 4 -- for the payoff "PI index", and Figure 5 - for the regret "PI index".

For the payoff "PO index" criterion shown in Figure 3, we need two numbers for each strategy: the "best case" and the "worst case" payoffs. As follows from Table 8, for Strategy 0 these numbers are 4956 and 1907, for Strategy 1 - 3364 and 2296, and for Strategy 2 - 3434 and 2367. The zero value of the PO index corresponds to complete optimism; the 1.0 value, to complete pessimism. For each strategy, the "best case" value is plotted on the left vertical axis, the "worst case" value, on the right vertical axis. These two points are then connected by a straight line. The upper segments of these straight lines on the [0, 1] range of values of the PO index form the "strategic frontier."

According to Figure 3, this frontier (bold lines) lies with Strategy 0 at the index values from 0 to 0.768, and with Strategy 2, from 0.768 to 1. This means that, according to the "PO index", Strategy 2 is preferred only in a small, most pessimistic portion of the possible index values.

As may be expected, the Strategy 1 is worse than Strategy 2 on the whole [0, 1] range of the PO index values.

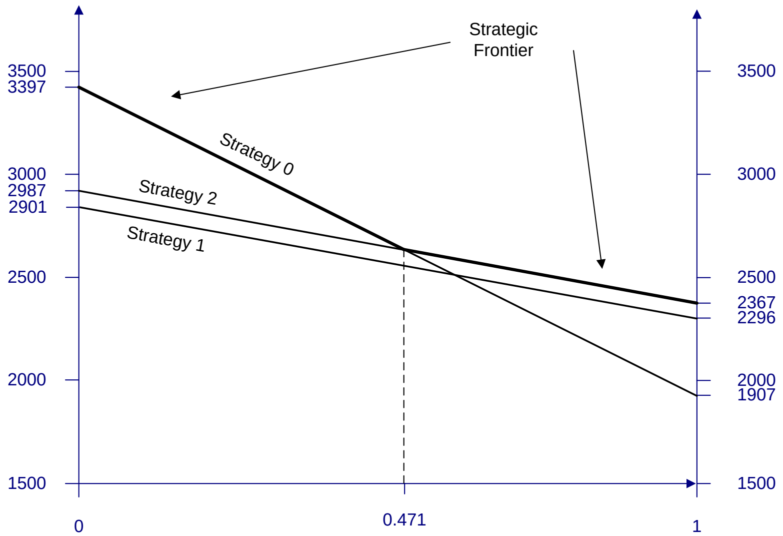

Figure 4 *Strategic Frontier for the Payoff "PI Index"*

The strategic frontier of Figure 3 has an important distinction from the "efficient frontier" of portfolio theory. The strategies that form the strategic frontier move from left to right, from more optimistic to more pessimistic. Since the more optimistic strategies start higher and decline more steeply (otherwise they would not intersect with the next strategy), the strategic frontier for payoffs -- in contrast to the "efficient frontier" -- is always concave upward.

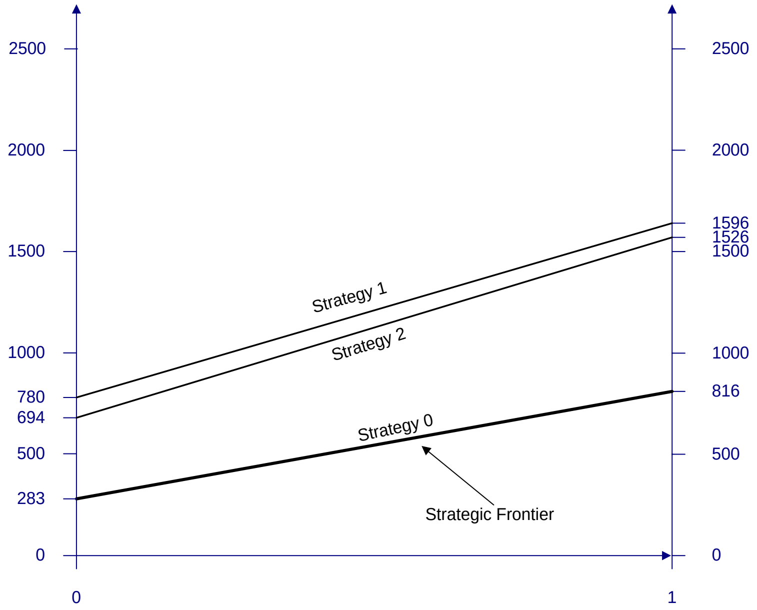

Figure 5 *Strategic Frontier for the Regret "PI Index"*

The PO index has many advantages, the main one being complete independence from the scenario probabilities; instead of "probability," it explores "possibility." (In this example, the picture in Fig. 3 does not change if we alter scenario probabilities.) However, this criterion has a significant fault: it might be too optimistic, especially if, as in this example, we do not take correlation into account: the very best scenario may be difficult or practically impossible to achieve.

The second criterion, the "PI index," assumes, instead, that the best that we can expect is not the "best case" payoff but, rather, the weighted average payoff.

For each strategy, this average value (see Figure 4) is plotted on the left vertical axis, while the "worst case" value is plotted on the right axis. Otherwise, these two criteria are similar. For each strategy, we again need two numbers: the weighted average and the "worst case" payoff.

For Strategy 0, they are 3397 and 1907, for Strategy 1 -- 2901 and 2296, and for Strategy 2 -- 2987 and 2367. Again, Strategy 0 is the best in the optimistic part of the [0, 1} interval, and 2 - in the pessimistic part. According to Figure 4, Strategy 2 is preferable over Strategy 0 on a broader part of the PI index values interval now -- from 0.471 to 1.

In the regret "PI index" diagram (Figure 5), the less is the value of regret, the better. For the worst result, we use the maximal regret of a strategy. The strategic frontier is concave downward. But in this problem Strategy 0 is the best on the whole range from 0 to 1; its straight line does not intersect with the line of two other strategies.

But this "numbers-driven" point of view does not necessarily prevail in Decision Science, where the Tortoise is often preferred to the Hare. We have presented various decision criteria and strategic frontiers to demonstrate the RCO techniques, but considerations of stability and balanced growth of the economy should carry more weight in this problem.

In this problem, Strategy 0 is extremely risky; in half of scenarios all workers of industry 4 become unemployed, and so on. If industry 4 is successful, however, its results are spectacular. The maximum and average payoff values are therefore much higher for Strategy 0 than for Strategies 1 and 2, while the regret values for Strategies 1 and 2 are much higher than for Strategy 0. This is a good demonstration of possible inconsistency and unreliability of numerical criteria, both single and synthetic.

Stages (vii) and (viii): The Final Selection and the Contingency Plans
The need to use jointly several mutually contradictory criteria confirms that Decision Science can make the comparison of candidate strategies systematic, consistent, and orderly, but not objective. The best it is able of is to screen out bad and risky strategies. The final selection of a strategy to be implemented is largely a matter of subjective choice.

The decision maker subjectively selects the final strategy, taking into account the most acceptable combination of the outcomes for all risk types under all scenarios, as well as other considerations (in this case -- of stability, social costs, and the need for a balanced growth of the economy).

The model solution for this strategy is then used to derive more detailed and specific information, including contingency plans for each scenario. We already have these plans as the scenario components of that solution (see Tables 4 to 6), so we have only to extract and fully utilize these results. As mentioned before, the basis for evaluating each strategy is the totality of outcomes for the contingency plans over the whole range of scenarios. Having good contingency plans ready in advance of any thinkable crisis is the contribution of RCO to executing the selected strategy.

Stages (ix) and (x). Monitoring, adaptation, and starting the RCO process anew.
Issues of monitoring evolving conditions, comparing them with the projected scenarios, and adapting the strategy to these conditions – that is, implementing the corresponding contingency plan – deserve serious consideration. Lack of space prevents, however, from doing that.

8. The External Turmoil

Seventy years ago, Keynes said: "We have, as a rule, only the vaguest idea of any but the most direct consequences of our acts. ... Thus the fact that our knowledge is fluctuating, vague and uncertain, renders wealth a peculiarly unsuitable subject for the methods of classical economic theory. ... By 'uncertain knowledge' ... I do not mean merely to distinguish what is known for certain from what is only probable. ... The sense in which I am using the term is that in which the prospect of a European war is uncertain, or the price of copper and the rate of interest twenty years hence, or the obsolescence of a new invention, or the position of private wealth holders in the social system in 1970. About these matters there is no scientific basis on which to form any calculable probability whatever. We simply do not know" (Keynes 1937). As Skidelsky observed, "Keynes is saying that his own theory is what the classical theory would have had to be had it taken uncertainty seriously" (Skidelsky 1992, 618). The post-Keynes economics also did not take uncertainty "seriously" and did not develop the necessary methodology to deal with it.

As observed in Section 1, in the 21st century even many short-term activities, such as operations of international supply chains, are subject to substantial uncertainty, since these operations would be severely curtailed in the case of a terrorist act on the US territory. The "external uncertainty", generated by geopolitical instability, terrorist threats, warming of Earth, pandemics, price of oil, and the state of the world's economy, dwarfs the "internal uncertainty" described by the model (1)-(23) and the data, scenarios, and results presented in Section 7 above.

Because we do not know, for instance, where, when, what type and how large would be the next terrorist act, we do not really know what is the worst scenario and how the possibility of the external turmoil worsens the "internal" scenarios. The worst, the best, and all in-between scenarios become "movable" - as a rule, down. The size of that shift can only be "guesstimated".

If we believe that there exists a possibility that none of the external factors would severely change the internal scenarios, these scenarios may remain valid. In that case, the external uncertainty is represented by additional "external scenarios", and we would repeat the RCO process - perhaps considering the obtained earlier set of candidate strategies as given. In that case, for each candidate strategy, we just need to solve a MILP again, with fixed values of strategic variables that are specific for that candidate. After getting the values of the resulting outcomes for all risk types and under all scenarios, internal and external, we proceed again to Stage (v) and on, taking into account both "internal" and "external" results.

If, however, we consider that some external turmoil would unavoidably impact the economic entity considered in the problem, we may need to repeat process from the very beginning. If the problem is important enough, we may repeat the RCO process under different assumptions about the timing or geography or intensity of the "external factors" involved.

But we also have to take into account the worst possible scenario (that is, of a catastrophe happening in your backyard). In this case, the worst payoff goes down so far that any strategic frontier becomes very close to a vertical line and using any of our criteria becomes, in a sense, meaningless (although the strategies retain their relative strength). Again, we have to jack up the worst value. By how much? The decision is purely subjective.

All that once again confirms our conclusion, reached at Stage (viii): the most that we can achieve is an orderliness of the process. A subjective final selection of a strategy to be implemented is absolutely necessary.

Possible Scenarios

It is easy to create possible scenarios with zero probability: add to some "uncertainty generator(s)" an alternative or alternatives with zero probability. Of course, any arbitrary scenario we are interested in can be additionally included, too.

When inserted in the multiscenario model, the possible scenarios do not impact the extremal solution. They show, however, the outcomes that would happen under each such scenario. That would allow imposing on the model additional risk-limiting constraints that would prevent the undesirable outcomes. The decision maker can thus implement a very cautious, "super-hedging" risk attitude.

It was such attitude that was needed in finance, to avoid the current financial crisis. No bonuses would be paid though.

9. Conclusions

1. The complexity, uncertainty, and perils of the 21st century generate a large number of crucially important complex and long-term socio-economic and technical problems. Solving these problems requires the application of advanced analytical tools that combine computers and sophisticated mathematical models.
2. This article describes a methodology, Risk-Constrained Optimization® or RCO, that, for the first time in more than 60 years, legitimizes analytical use of computers and sophisticated models in high-level, complex and long-term problems. This is achieved by embedding computers and models into an ensemble of concepts, models, and methods that neutralize the potentially dangerous miscalculations.
3. In combination with computers, RCO merges in such an ensemble technologies that are associated with seven fields: Economics, Operations Research/Management Science (OR/MS), Scenario Planning, Decision Science, Risk Management, Utility Theory, and Portfolio Theory, with a digression into the eighth field – Psychology. In each of the seven fields, RCO introduces novel concepts, models and methods. These include: change of paradigm, introduction of special stochastic multiscenario models; development of algorithms for speedy solving of arising huge mathematical programming models, "strong screening" by risk-limiting constraints; introduction of multidimensional outcome matrices, development of methods of converting heterogeneous outcomes into quasi-utility payoffs; addition of several "synthetic" criteria for "weak screening," introduction of "strategic frontiers," and development of contingency plans for a large range of scenarios within multiscenario models. *I strongly believe that, maybe with some modifications, all these items are absolutely necessary components of any dependable methodology of decision making for complex and long-term problems.*
4. A great abstract theory still will lead to a crisis, when applied in the real world, if its basic assumptions are simplistic and therefore wrong. Perhaps the main wrong assumption of the "mainstream" economics, Operations Research, and adjacent disciplines is the paradigm of maximizing behavior of decision makers. I propose an alternative paradigm of "catastrophe avoidance," that corresponds to real evolutionary behavior of mankind and animal kingdom, as well as to the Maslow's hierarchy of human needs.
5. RCO is a system of planning and *strategic* risk management under radical uncertainty that searches for the most acceptable (not "the best"!) compromise between improving results and reducing risk in our decisions. It is especially

suitable for conditions of the 21st century, when the "external" uncertainty is much more important than the uncertainty "internal" for the problem.

6. Four definitive characteristics of RCO are as follows:
   - RCO is completely purged of unwarranted assumptions, which is important for protection from crises. It considers not only probable, but also possible scenarios of the future.
   - RCO jointly constructs both long-term candidate strategies and ranges of scenario-specific contingency plans that reasonably protect the candidates from catastrophic outcomes. Candidates are evaluated on the basis of their "post-contingency-plans" state. RCO is used not to select "the best" candidate strategy, but rather to screen out the worst ones. Optimization models are used in RCO primarily for ferreting out potential dangers and protecting from them; protection from risk dominates in RCO over maximization of advantages.
   - RCO generates, systematizes, and presents two important types of information: description of behavior of several best risk-protected candidate strategies under a broad range of future scenarios, and a set of contingency plans for the candidate strategies under that range. The strategy to be implemented is selected subjectively from that set of candidates.
   - RCO demonstrates the need, and shows the way, of changing the general paradigm of economic decision making. Instead of maximizing the arbitrarily aggregated satisfaction of our wants, this approach deals with a simpler, easier to solve, more realistic and pressing problem -- how to avoid a catastrophic outcome in any of multiple risk factors.
7. RCO provides results in several important directions. This attests to the extraordinary power of an ensemble of models and filters, if these components are critical to each other's success. Also, computer and sophisticated models strengthen here *a natural* way of making decisions. Results come easy to *a natural.*
8. This paper presents a reasonably realistic (but still very simplified) RCO formulation of the USA-China trade problem under radical uncertainty, a formulation that attempts to eliminate three major faults of the theory of international trade, namely:
   - Consideration of the US economy in isolation from the country's societal goals;
   - Unrealistic and harmful assumptions of free trade theory; and
   - Absence of a methodology of dealing with radical uncertainty.
9. As a first approximation, I consider eight main social objectives and constraints. Five of them are primarily short-term (sufficient satisfaction of needs and wants of population, low unemployment, sufficient growth, stable prices, and a healthy balance of payments). Three are long-term ones (the preservation of industrial base, the preservation of the middle class, and the attainment of geopolitical goals).
10. I make the following assumptions about international trade:

- Unemployment is not excluded, and trade may bring an increase in unemployment, and thus lead to an increase in social costs.
- Transferring workers from one industry sector to another involves re-training, relocation, and readjustment. All these processes generate costs.
- Trade does not necessarily lead to adjustments of prices, wages, and currency rates, and even more so - to immediate adjustments.
- Trade may lead to trade surpluses and deficits, as well as to transfers of capital or technology.

11. Also, in accordance with the concept of "compensated free trade," I assume that
    - Trade deficits with China are capped.
    - If done, intergovernmental China-US compensation payments raise the caps.
    - Intergovernmental payments may be limited.
12. The RCO model develops several reasonably good and safe candidate strategies. It does not recommend the final choice, but provides valuable information about the behavior of these candidates under a broad range of scenarios and about possible contingency plans, so that the decision maker could make a subjective, but well-informed and prudent decision.

Acknowledgements: I would like to acknowledge extremely constructive suggestions and criticism made by the editor of the special issue, Professor Shih-Kung Lai, as well as by two anonymous reviewers. Dr. M. Liwshitz and Dr. Victor V. Masch provided most useful comments and helped in editing the article. Needless to say, I am fully responsible for the remaining faults, including repetitions.

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He founded the Russian school of modeling multistage “supply chains,” formulating the models and solving the long-range planning problems of several industrial sectors. The most important, both by its scope and the results achieved and implemented, was the coke coal industry. He also headed a 15-scenario study of locating (in Togliatti) the automobile plant to be built by FIAT. His recommendations led to four decisions made by the Soviet Government, GOSPLAN of the USSR, and Presidium of the Academy of Sciences of the USSR.

In the USA (since 1974), he worked initially at Bell Laboratories, and then as an independent scholar and consultant. He is working on the theory and tools of “Socio-Economic Sustainability”; RCO is its part.