The RCO/DN Approach to Planning of Urban Growth Boundaries

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ABSTRACT. Cities are faced with serious issues resulting from urban sprawl, and one way to manage this is through the implementation of urban growth boundaries (UGB). The complexity of cities makes long-term planning extremely difficult. The high level of uncertainty, currently inherent in any complex and long-term problem, makes this task even more formidable.

Decision Network (DN) methodology has been developed to deal with complexity and Risk-Constrained Optimization® (RCO) is a system for long-term planning and risk management under radical uncertainty. This study integrated the two systems in the form of RCO/DN, resulting in the creation of a powerful tool to deal with the problems of urban planning. RCO/DN is meant to enhance the effectiveness of planning by taking into consideration both its intended goals and undesirable unintended consequences. As a second function, RCO/DN prevents the overextension of urban resources, physical, technological, financial, and human.

RCO/DN presents the uncertainty associated with future events using multiple scenarios provided by city planners and simulations. Scenarios differ with regard to values of their parameters, such as annual land use or inflated costs of land within UGBs. Unfortunately, under radical uncertainty it is impossible to predict plan outcomes or reliably convert diverse outcomes into a single metric to allow a comparison of strategies. Finally, under such conditions there exists neither a “best solution”, nor a “best method” to select a solution.

The only option is to develop a number of reasonably good and safe strategies. These strategies can then be presented to decision-makers for final selection, which they make according to their preferences and their attitudes toward various forms of risk.

This approach seeks to identify good tradeoffs between various forms of risk, such as environmental, human safety-related, or financial. RCO/DN accomplishes this task by using an ensemble of novel techniques that includes enhanced stochastic multiscenario mathematical programming models, designed to reveal hidden dangers within unfavorable scenarios.

With regard to the planning of UGBs, RCO/DN is a risk management system that allows the combination of time-driven and event-driven approaches to reduce costs by shortening the planning horizon.

Simplified RCO/DN models can be standardized for small towns, while more complex models can be developed for large cities, in which UGBs are connected to multiple interrelated factors. This approach is particularly valuable in planning disaster mitigation actions as well as in dealing with economic crises. The more complex planning difficulties are, the greater the benefits of RCO/DN in realistic planning, risk management, and cost savings.

KEYWORDS. ***Stainability, risk management, urban planning, urban growth boundaries, decision-making under radical uncertainty, stochastic multiscenario models, complexity***

1. INTRODUCTION

Cities are facing serious issues resulting from urban sprawl, and one of the ways to manage this is through the implementation of urban growth boundaries (UGBs). A great many studies have investigated urban growth management; selective bibliographies on the subject are provided in a number of papers, such as those of Han et al. (2009) and Knaap and Hopkins (2001).

Urban growth boundaries are an attempt to control urban sprawl by designating the areas reserved for high- and low-density urban development. These designations generally span the entire urban area for use by local governments as a guide to zoning and land use decisions. According to Ding et al. (1999), in some jurisdictions, "UGB serves as a blunt instrument for rationing public service capacity". The area within a UGB is sometimes referred to as an urban growth area (UGA) or an urban service area.

Sound land use management requires an intelligent balance between developing urban sprawl and land and housing inflation. The conventional approach involves predicting the need for developable land within a horizon of 10 to 20 years. That amount of land is subsequently allocated and regularly readjusted (e.g. every five years), while taking into account the land use occurring since the previous review. This approach is regarded as "time-driven."

A number of "event-driven" methods to UGB planning have also been proposed (Knaap and Hopkins, 2001). This mode involves the adjustment of UGB when the availability of land comes close to a critical level, rather than at regular time intervals. This approach tends to be less costly, but also less convenient.

Urban growth is a dynamic process to which Knaap and Hopkins applied long-established principles of inventory control, as described in the works of MagGee and Boodman (1967) or Sippen and Bulfin (1997). Inventory control stipulates that stock be replenished at irregular times, triggered by the need to maintain sufficient safety supplies to prevent inventory exhaustion. Knaap and Hopkins demonstrated that such an event-driven approach is less costly than establishing UGBs using the time-driven method.

Han and Lai (2011) (2012) sought to apply the Decision Network methodology to the extension and reformulation of the inventory models of Knaap and Hopkins (2001). They confirmed that event-driven systems can indeed be more cost-effective than time-driven systems in the formation of UGB policy.

However, Knaap and Hopkins (2001) and Han and Lai (2012) adhered too strongly to a single methodology. Inventory control principles can be highly effective in manufacturing or trading enterprises, in which computerized systems provide data related to existing stock levels. In urban planning this approach is simply too expensive. Determining how much remaining land is available for development requires costly surveys, particularly inconvenient when they must be repeated more often than once every five years.

To overcome this difficulty, we propose combining time-driven and event-driven systems to enable the application of inventory control at regular time intervals.

If it were possible to predict how land would need to be used in the future, optimization via mathematical programming models would be the ideal tool for designing the UGBs. Linear programming is able to provide optimal results even with enormous models involving millions of equations. A relatively simple model to determine UGBs would not even require one thousand equations. Mathematical programming models (stochastic, linear or integer) can also be customized, providing the ability to link the establishment of boundaries to complex issues related to urban planning, such as environmental factors, concurrency with capital improvement and transportation projects, and changes in infrastructure. If systemic conditions were taken into account, this approach could also prevent an overextension of available resources, thereby providing a good multiperiod plan, specific to the city in question and integrated with proper time schedules for operations.

Nonetheless, optimization requires an adequate knowledge of the future – at least, in a probabilistic sense. Because obtaining such knowledge is impossible, allegedly “optimal” results often lead to grievous errors.

An unexpected turn of events may lead to erroneous inventory decisions in any enterprise. However, these errors are usually easily correctable, and any damage resulting from such decisions is limited. In urban planning, the consequences of erroneous decisions can have a profound effect on millions of inhabitants. In addition, the likelihood of making such errors is elevated, due to the increased uncertainty associated with systems as complex as modern cities.

The current concepts of a “smart city” and “urban sustainability” are often limited to short-term criteria, such as providing a healthy environment for inhabitants, furnishing a safe and reliable infrastructure, and maintaining a balanced relationship with local and global ecosystems. They should be drastically altered to take into account long-term risk management and to prevent overextension of resources. That would shift the prevalent approach to urban management.

2. UNCERTAINTY IN URBAN PLANNING

The socio-economic difficulties we are facing today are characterized by uncertainty and complexity. The goals of humankind have changed. Since time immemorial, a major goal of human endeavor has been to increase prosperity. Starting from the first Industrial Revolution, we have largely achieved this goal in many parts of the world. Unfortunately, progress in science and technology has led to the overwhelming possibility of human extinction – either by “natural” causes such as overpopulation and the subsequent destruction of the environment, or through willful mutual annihilation.

Mankind has faced numerous dark periods throughout history; however, the dangers were transient and not global. The challenges of today are global and appear to be worsening with time. This combination is without precedent.

The challenge of the 21st century is sustainability: We must find the means to skillfully and cautiously navigate between a wide range of potential dangers to ensure that the decisions we make are beneficial for the long-term survival of mankind.

Researchers in disciplines related to decision-making, such as economics, operations research, decision analysis, risk management, and game theory tend to overlook this, in their adherence to the paradigm of maximization. This 18th century notion is unnatural, artificial, and complicated, requiring information that is impossible to obtain. Worse, this mindset can have dangerous implications. The present degradation of the planet, human society, and the global economy are just the first indications of the difficulties that lie ahead.

In 1962, Thomas Kuhn published “The Structure of Scientific Revolutions”, one of the most influential books of the 20th century (Kuhn 1962). In it, he described how our ability to understand and deal with the real world evolves through a series of discontinuities. In a crisis current theories may crash, resulting in the birth of a new “incommensurable” paradigm, which may face a similar fate in the crises to follow. The current state of affairs poses innumerable perils and uncertainty; this is the Kuhn’s moment of ‘crisis’, when the needs of survival compel a shift in existing paradigms.

Considering the cost of failure, the new paradigm should follow the principle “safety first”, incorporated both in economic theory as well as the methodology of decision-making.

The current set of perils (natural, military, geopolitical, and economic) have resulted in an overwhelming increase in complexity and uncertainty regarding the types of changes we can expect as well as their scale, speed, and timing. Traditionally, “almost nothing” has been known about future events (even in the short-term). Now “almost” has disappeared, and we can only make guesses as to how the future will unfold. This is the state referred to as “radical uncertainty” (RU).

RU in the world as a whole is only one of the factors contributing to uncertainty in urban planning. In complex systems (such as cities), even a full awareness of individual components and the laws governing their interaction is insufficient to infer the properties and behavior of the system as a whole (Gell-Mann, 1994). The system imposes additional (“systemic”) conditions and constraints that are hidden from the observer.

In any business or organization, uncertainty is compounded by the “organized chaos” of the decision-making process, as well as by unavoidable disagreements between long- and short-term frameworks, or between the common goals (if they exist and are known) and personal ambitions of its members. In urban planning, conflicting or ambiguous goals have often been approached using untested technologies. A disorderly array of specialized and territorial governmental organizations often exacerbates this confusion by simultaneously introducing a multitude of uncoordinated or conflicting actions and programs (Christensen, 1999). On top of this, policy-makers and planners are subject to pressure from those who view goals as certain, agreed upon, and perfectly known, and technologies - as fully efficient (Ibid.), when in reality none of these conditions is true. The fact is that many individuals are afraid of being dismissed, if they do not propose policies that promise substantial benefits. These factors can often lead to considerable difficulties resulting from misguided social policy-making.

This raises the question of whether such mismatches between reality and policy can ever be avoided. The success of any such endeavor cannot be guaranteed, and RCO/DN is no exception. Like everything else in the world, it is highly uncertain. Nevertheless, RCO/DN does not promote exaggerated promises, and is therefore worthy of further investigation.

3. RCO/DN

The Risk-Constrained Optimization / Decision Network (RCO/DN) is a computerized multiscenario decision support system for long-term planning to facilitate the next generation of risk-protected strategies under conditions of RU. The main goal of RCO/DN is to achieve sustainability. It is devised to attain, as much as possible, the full purpose of planning - not only to achieve its planned, intended goals, but also to avoid undesirable, unintended consequences.

RCO/DN combines the Decision Network (DN) of Han and Lai (2011) with the Risk-Constrained Optimization (RCO) of Masch (2010). These two systems are integrated to generalize the methodology of policy-making for complex systems under conditions of RU. DN was originally developed for urban management, combining five aspects of cities (decision-makers, decision situations, problems, solutions, and locations) into a single entity. Thus, it explicitly imposes at least some of the above-mentioned hidden “systemic” conditions and constraints.

DN is meant to be used for policy-making in situations where the probabilities of future events are known; in long-term city planning, we do not have that knowledge. Thus, this study embedded DN in RCO to provide a long-range risk management system for policy-making under RU.

RCO is a comprehensive system comprising a wide range of novel components. However, to avoid distracting the reader from the application of RCO/DN in urban planning, it is described here as concisely as possible. A more detailed description can be obtained from (Masch 2010), available at rcosoftware.com. Please note: that paper is slightly outdated due to recent advancements.

RCO is a multistage process involving a series of mostly simple operations. The system comprises two parts, linked in the common goal of “catastrophe avoidance” – eliminating or mitigating unacceptable outcomes resulting from multiple forms of risk under any future scenario.

Catastrophe avoidance represents the new paradigm that RCO introduces to replace maximization. This paradigm is simple, natural, evolutionary, and cautious. It is a paradigm to guide decisions of an insider participant of the process of evolution; for an outsider, such as Darwin, it becomes “survival of the fittest.”

In the first part of “strong screening”, the scenarios are formed and numerous candidate strategies are developed. This task is performed by enhanced stochastic multiscenario (ESMS) mathematical programming models with risk-limiting constraints.

Scenarios are formed in a “combinatorial” manner. For each insufficiently known factor of future condition, we set two or more alternative values or states. A scenario is formed by taking one alternative for each uncertain factor. This often results in a very large number of scenarios. However, RCO employs clustering and de-clustering methods, which, combined with the paradigm of catastrophe avoidance, can handle these difficulties through.

The primary advantage of this approach is that an absence of knowledge regarding future conditions does not prevent the formation of scenarios. A lack of certain knowledge does not hinder process; it only makes it impossible to predict the probabilities. Each scenario has itself as a clearly defined future; however, if the probability of any scenario is infinitely small or zero, we can exclude it from consideration.

It should be noted that probabilities are the most questionable portion of input data. RCO/DN overcomes this difficulty in three ways. It allows ranges of probability (say, “0.1 to 0.6”) rather than precise measures (“exactly 0.4”). It also allows the altering of probabilities, which enables planners to play with them and evaluate their impact on resulting strategies. Finally, the initial probabilities of an RCO/DN model are overridden in its risk management operations.

The original (non-enhanced) stochastic multiscenario model is used to identify one strategy capable of providing the best contingency plan for each scenario, while also taking into account the whole range of scenarios under consideration as well as their initial probabilities. This model is currently the only possible way to achieve such ambitious results, therefore it is necessary. However, it is not sufficient, for its “optimal solution” may include unacceptable outcomes. This solution represents the end of stochastic programming, but is just the beginning of the RCO risk-management process.

If the decision-maker is dissatisfied with the outcome of any scenario(s), he can impose a risk-limiting constraint directly on that outcome. (For instance, “the output of pollutants under a particular scenario may not exceed 15 tons.") Constraints are imposed in accordance with a new principle: changing the overall solution of the model by altering the values of scenario-specific (rather than general) outcome variables. These operations, in conjunction with other novel methods, transform simple stochastic programming models into powerful self-filtering optimizers.

The ESMS model delivers pre-screened candidate strategies to the second part of "weak screening." We refer to that part as "weak" because no reliable methods can ever be developed to convert multidimensional outcomes associated with various kinds of risk into two-dimensional values of payoffs.

In that second part, RCO performs function of current Decision Analysis (DA), using though far more comprehensive and efficient methods.

In its current reductionist form, DA assumes knowledge of the exact value of payoffs and the existence of a best solution, so that decision-makers need only select the method best suited to attaining that solution. DA creates five aggregates of payoffs and regrets (a derivative of payoffs that measures lost opportunities): the best payoffs, the weighted and non-weighted average payoffs, the worst payoffs, and the worst regrets. The three first aggregates are optimistic, while the two latter are pessimistic. The decision-maker has six criteria with which to make selection: one of these five "single" aggregates or one "synthetic" combination of best payoff and worst payoff, called "the index of pessimism-optimism." The synthetic criterion combines the best and worst single aggregates at relative weights that are set by decision-maker arbitrarily.

RCO adds three additional single aggregates, best, weighted and non-weighted regrets, as well as five synthetic criteria (two for payoffs and three for regrets). The six synthetic criteria are used jointly but consecutively, one after another, to screen out the worst and riskiest strategies rather than to select the non-existent "best strategy."

The six synthetic criteria are not applied at a single, arbitrarily fixed value of the index, as is the current DA approach. Rather, strategies are compared on the entire [0, 1] range of values of the relevant index, in the framework of fundamentally novel "strategic frontiers". These frontiers look for hidden dangers over a broad horizon of scenarios, by replacing a narrow "point of view" by a broad "range of views." The frontiers additionally provide the following valuable information regarding the relative merits and faults of any given 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 whole [0, 1] index spectrum
- The difference between the frontier strategy and each other strategy, which shows the potential impairment of results in the selection of a non-frontier strategy.

RCO passes each strategy through five layers of strong and weak screening filters to neutralize the dangers of miscalculation. In this manner, RCO legitimizes the high-level analytical use of a "computer plus optimization model", for the first time since the inception of computing.

Despite the variety of novel techniques found in RCO, it is not the individual components of the system that matter most: it is their interaction within an ensemble of methods belonging to seven diverse disciplines. (These are: 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.) As shown in Senge (1990), major breakthroughs are currently possible only as a result of creating an ensemble of efficient and mutually supportive component technologies, derived from diverse fields of science or technology. The components of RCO, as well as its paradigm of "catastrophe avoidance", seem to fit together like yin and yang.

The use of RCO/DN reduces the need for exact knowledge regarding current or future conditions in the same way that the installation of a safety valve on a steam engine reduces the need to know the exact pressure of steam within the boiler. Previous analysis of complex issues related to urban planning required exact values for a wide range of characteristics related to the system in question. Furthermore, even when this information was available, the results were inconclusive. In contrast, the multiscenario approach of RCO/DN requires only approximated input data, thereby expanding the analytic possibilities.

In essence, the best that we can hope to achieve under RU is to obtain several reasonably good (and more importantly, safe) strategies and leave the final decision to decision-makers, while preventing them from underestimating the long-term risks.

The RCO/DN approach is a unique planning tool for managing urban land use, including situations in which the institutional structure of land management is extremely complex, uncertain, or unstable. The success of any plan cannot be guaranteed; however, RCO/DN emphasizes prudence and the avoidance of extremes, which should minimize the occurrence of errors and eliminate those that would be catastrophic.

4. AN EXAMPLE

In the following, we apply RCO/DN to the examples provided by Knaap and Hopkins (2001) and, Han and Lai (2012).

City planners sought to minimize the cost of establishing and adjusting the boundaries for the planning horizon from 2016 to 2035 (N = 20 years). The time-driven approach leads to the initial allocation of N * 2,000, or 40,000 acres of land at the end of 2015, where 2,000 is the previously forecasted land use of interval 0. Boundaries are readjusted every 5 years and, each time, the allocation (or contraction) of land is based on the forecasted need for the following planning horizon of 20 years at an annual use level, equal to the real land use during the first year of the five-year interval. The event-driven approach sees the adjustment of the UGB whenever and as much as necessary to avoid deficiencies.

The total cost of the system includes holding costs, order costs, and deficiency costs. The annual holding cost equals $1 per acre. The order cost is $1 per acre. The annual deficiency cost is $10 per acre of the difference between the stock of the developable land and the threshold level of 30,000 acres, whenever that stock dips beneath the threshold. Expansion and contraction orders are made at the beginning of the intervals, based on predictions derived from land use in the previous year. Land consumption is measured at the end of each year; land deficiency is evaluated at the midpoint of each year.

For each five-year interval between 2016 and 2040, city planners predicted one scenario of annual land use: 2,500, 1,500, 2,000, 1,700, and 2,000 acres per year. Changes in conditions at the end of 2015 cause a change in the interval 0 forecasts from 2,000 to 2,500 acres. As calculated by Han and Lai (2012), under this deterministic scenario the total cost for the 20-year planning horizon is as follows: time-driven - $1,030,000; event-driven - $830,000. The time-driven approach is much costlier, because it includes a deficiency cost of $250,000.

The RCO/DN approach poses the problem differently. It considers many diverse scenarios to determine which overall strategy would be least costly and least risky under all scenarios, considered jointly.

Scenarios may differ with regard to a number of problem parameters, such as annual land use and costs. These parameters can be provided by city planners or simulated. To keep the problem simple, we derived only the six scenarios in Table 1, in which each scenario differed only in the value of a single parameter, annual land use over five 5-year intervals between 2016 and 2040. The five values predicted by city planners were retained as Scenario 1; land use for the other five scenarios was simulated.

Table 1. Forecasted Annual Land Use Scenarios, in Acres

Interval\Scenario	Years	1	2	3	4	5	6
0	2016-20	2,500	2,500	2,400	2,900	2,500	2,400
1	2021-25	1,500	1,400	1,400	1,400	1,400	1,500
2	2026-30	2,000	2,200	2,000	1,900	2,300	2,300
3	2031-35	1,700	2,000	1,700	1,700	1,700	1,600
4	2036-40	2,000	1,900	2,000	2,400	2,100	1,900

Estimated probabilities of these six versions of land use are 0.4, 0.2, 0.1, 0.15, 0.08, and 0.07, respectively.

RCO/DN can define strategies in a variety of ways; however, for simplicity we will define a strategy according to only one variable, the length of the planning horizon N. Strategy 1 has N = 20, Strategy 2 has N = 19 years, and so on.

We constructed a six-scenario enhanced stochastic multiscenario (ESMS) optimization model. It is a linear programming model with 391 constraints (equations and inequalities) and 434 variables. It consists of six scenario "submodels" that have identical structure but differ in the value for annual land use. These submodels are connected by an objective function (a formula that pushes the solution to minimize the total cost of the plan), calculated as the sum of costs for the six scenarios, weighted by their estimated probabilities. Solutions of the six submodels (that is, how much land they add, contract, and hold in each 5-year interval) are dissimilar. Only one variable (N) has the same value in all scenarios.

For each scenario submodel and each time interval, the optimal plan can be obtained using two versions of UGB adjustment. In the first, land is allocated solely according to the length of horizon N, as in the time-driven approach. In the second version, land is allocated in accordance with the principles of risk management: the model determines whether to prevent deficiencies (as in the event-driven approach), or to permit them. RCO uses both methods. The best approach is then selected for that particular scenario and interval according to the overall multiscenario cost. In this manner, the RCO/DN model combines the time-driven and event-driven systems, while enhancing the latter by allowing deficiencies, should that be deemed beneficial to the overall plan.

Consider the planning of UGBs in interval 0 of scenario 1. When N = 12 years and an earlier prediction of initial annual land use is equal to 2,000 acres, the size of the order would be only 24,000 acres. Clearly, this would result in considerable deficiencies. Land deficiencies are evaluated at mid-year, and to avoid them would require no less than 30,000 acres after 4.5 years. With annual land use set at 2,500 acres, initial land allocation would require 41,250 acres (30,000 + 4.5 * 2,500). Consequently, 41,250, rather than 24,000, would be the land allocation in the model-derived plan.

It is important to note that as we advance in time, the impact of the forecasted parameter values, such as the annual land use, on the total cost of the plan, diminishes. This principle was implicit in the approach of Han and Lai (2012); however, it is explicit in the RCO/DN model. For instance, the forecast for interval 0 influences the plan approximately three times more than the forecast for interval 3. Because we assume the existence of RU, this feature is very valuable.

We performed several runs using different values for N (between 10 and 20 years). (Even using a typical laptop computer, the computing time for each run was a minuscule fraction of a second.) The flexibility of the RCO/DN model allows a reduction in N, because the resulting gap can be compensated for by risk-management constraints. In this example, the best N was 12 years, rather than the 20 years postulated by Knaap and Hopkins (2001) and Han and Lai (2012).

The total cost (weighted by probability) for all six scenarios at N = 12 years equaled $843,900; costs for individual scenarios range between $840,900 and $853,400. For N = 20, the total cost is much higher – $942,280. Risk management considerations prevail: due to the high annual cost of $10 per acre, no deficiencies were allowed in any interval, even in the worst-case scenario.

The total cost of the RCO/DN plan is 18 percent lower than that of the time-driven plan of Han and Lai (2012). The RCO/DN plan is slightly more costly than the event-driven plan of Han and Lai (2012); however, the RCO/DN plan provides also protection from risks stemming from uncertainty (the risks arising under any of six scenarios). Clearly, actual outcomes depend on the specifics, but these results are still a reasonable indication of the likely general trend.

Cost for Scenario 1 (the deterministic scenario provided by the city planners), would be $840,900. This scenario turned out to be the most favorable of the six.

5. POTENTIAL APPLICATIONS

A simplified multi-scenario RCO/DN model, similar to the one outlined in Section 4, could act as the initial model for planning UGBs under RU. A standard version of this model would be used mostly for small towns, while the model and the RCO methodology could be customized to deal with problems of greater complexity (inherent in large urban centers). This would require switching from linear programming to integer programming models of greater complexity.

Scenarios can be provided either by city planners or by Monte-Carlo simulation. The number of scenarios can reach into thousands or more; however, redundant scenarios could be screened out by planners. The system would protect against the risks associated with black swan scenarios (catastrophic scenarios with a minuscule probability of happening). Moreover, this approach can even protect against scenarios with forecasted probabilities of zero (beyond the ability of forecasts to predict).

In different runs of the model, planners would be able to "play" with probabilities and other input data, to explore its sensitivity to various factors and determine the best ways to manage risks.

The risk management capabilities of the RCO/DN approach are particularly valuable in planning actions to mitigate disaster in urban areas. These actions are designed to prevent a city from being damaged by disasters and to recover afterwards. This issue has become increasingly important due to vulnerability stemming from worldwide climate change.

Economic crises have also become more common and fluctuations in population levels make it dangerous to rely on the fact that previous growth was smooth, without sharp increases and decreases in the annual land use that tends to increase the cost of operations. Risk management is based on the tenet that it is better to be safe than sorry.

In complex situations, the benefits of RCO/DN are even more pronounced. RCO/DN can outperform other currently used models in formulating a new understanding of a “smart cities” and “urban sustainability.” In situations of great uncertainty, these benefits become crucial.

6. DISCUSSION

In complex systems, such as cities, even a full awareness of individual components and the laws governing their interaction is insufficient to infer the properties and behavior of the system as a whole (Gell-Mann, 1994). The system imposes additional (“systemic”) conditions and constraints that are hidden from the observer. To prevent an overextension of city resources (physical, technological, financial, and human) due to unforeseen systemic conditions, the proposed RCO/DN makes such conditions as explicit as possible.

Appropriate long-term risk management and the prevention of overextension are at the root of urban sustainability. As mentioned in Section 1, these issues extend far beyond current (often short-term) criteria, such as providing a healthy environment for inhabitants, furnishing a safe and reliable infrastructure, and maintaining a balanced relationship with local and global ecosystems.

A simple (“standard”) RCO/DN is limited to the development of strategies capable of balancing urban sprawl with inflation in land and housing prices, primarily in small towns.

This paper examines an application of the “standard” RCO/DN, as it pertains to UGB planning. We addressed both the “time-driven” and “event-driven” approaches outlined in Knaap and Hopkins (2001) and Han and Lai (2012). Our results demonstrate that RCO/DN is capable of combining the benefits of both approaches, while providing greater flexibility. Thus, the length of the “planning horizon” can be adjusted from 20 to 12 years: whenever this is insufficient for preventing deficiencies, risk-management techniques can be used to fill the gap.

In this example, the proposed scheme is 18 percent less costly than the “time-driven” plan of (Han and Lai, 2012) and has approximately the same cost as the “event-driven” plan. The RCO/DN plan provides protection from risks arising under a number of scenarios, while both the time-driven and event-driven plans of the previous authors are applicable only to one favorable scenario.

It is important to note that the further we advance in time, the less impact the forecasted parameter values have on the total cost of the plan. This was implicitly provided in (Han and Lai, 2012) and explicitly in the RCO/DN model. This feature is valuable because UGB planning is long-term and therefore performed under conditions of RU.

RCO/DN is not confined to the "standard" model. A customized model, intended for larger or more complex cities, can be used to connect UGB with multiple interrelated factors related to city operations to produce coherent plans and time schedules. This may be particularly valuable in planning urban disaster mitigation actions and in dealing with economic crises.

In complex situations associated with greater uncertainty, the benefits of RCO/DN are even more pronounced because they enable planning of greater realism, stronger risk management, and greater cost savings, all of which contribute to enhancing sustainability.

7. CONCLUSIONS

RCO/DN is a powerful long-range risk management tool capable of improving overall plans for the expansion of urban growth boundaries. This system enables planners to improve their analytic and policy-making capabilities, while drastically lowering costs and improving the management of risk, inherent in city operations. RCO/DN would make a considerable contribution to the operations and sustainability of cities.

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