COMBINED MORPHOLOGICAL ANALYSIS AND SYSTEM DYNAMICS APPROACH IN URBAN DISASTER MANAGEMENT

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Abstract

Disaster Risk Reduction (DRR) in urban settlements is a multi-dimensional, wicked problem that requires knowledge and experience from a wide range of disciplines. It also requires a methodology which can collate and organize this knowledge in an effective and transparent manner, in order to develop a prototype multi-hazard disaster reduction model. The paper will present several models for enhancing existing urban settlements to be better prepared to confront natural and man-made hazards. For that purpose, first a Morphological Analysis (MA) model is generated, which enables identification and comparison of scenarios, i.e. risk reduction strategies, preparedness and mitigation measures, for different types of hazards. We continue with System Dynamics (SD), which offers a detailed insight into the system’s behaviour, but it meets an impasse when it tries to push its simulation run more than a few years into the future. MA scenarios can be developed using the standard MA model framework. Further optimization of the number of scenarios may be performed optionally. The simulation could be run in segments, with inputs to SD model modified as the inferences from the MA scenario being used as a continuously changing inputs fed into the SD simulation, against time. The inclusiveness of MA and the distinctiveness of SD seem to complement each other, potentially overcoming each other’s disadvantages. Such merging of the two methods may be significantly more powerful than either serving alone on long-term anticipations in disaster management in urban settlements.

**Keywords**: Disaster risk reduction, Urban Settlements, Morphological Analysis, System Dynamics, Resilience.

**Topics:** Resilience of places

# INTRODUCTION

The world is undergoing the largest wave of urban growth in history. More than half of the world’s population now lives in towns and cities, and by 2030 this number will swell to about 5 billion. (UNFPA, 2017) Key aspects of social, economic, technological and natural systems function differently in urban areas than in rural or camp settings. Urban systems have specific features due to the density, diversity and dynamism of cities. (WVI, 2017)Rapid urbanization is also inducing uncontrolled and densely populated informal settlements in hazard-prone areas. The lack of capacity of cities and local governments to regulate building standards and land use plans exacerbates the risk of those living in vulnerable conditions. Not only cities and local governments, but in the first place their citizens, need to increase their capacity to reduce both the damage and the recovery period from any potential disaster. Disasters capacity building starts with individuals taking responsibility for their actions and moves to entire communities working in conjunction with local, state, and federal officials, all of whom need to assume specific responsibilities for building the national quilt of *people safety*. (Keković et al, 2016)

Disaster Risk Reduction (DRR) in urban settlements is a multi-dimensional, complex problem requiring knowledge and experience from a wide range of disciplines. It also requires a methodology which can collate and organize this knowledge in an effective and transparent manner, in order to develop a prototype multi-hazard disaster reduction model. This paper present models for enhancing existing urban settlements urban resilience , in order to be better prepared to confront natural and man-made hazards. For that purpose, the joint use of Morphological Analysis (MA) and System Dynamics (SD) models is proposed, which may enable identifying and comparing scenarios, i.e. risk reduction strategies, preparedness and mitigation measures, for different types of hazards.

SD model offers a detailed insight into system behaviour, but it meets an impasse when it tries to push its simulation run into the future. MA scenarios can be developed using the standard General Morphological Analysis (GMA) model framework. The simulation could be run in segments, with inputs to SD model modified as the inferences from the MA scenario being used as a changing inputs fed into the SD simulation against time. Such merging of the two methods may be significantly more powerful than either of them serving alone for disaster management assessment and planning in urban settlements.

**DISASTER AS A WICKED PROBLEM**

The challenges contemporary society faces are characterized by great uncertainty and complexity. The hyper-connectedness that characterizes our globalized world makes it hard, if not impossible to clearly isolate causes and effects of any given threat. (Duijnhoven and Neef, 2016) With consideration of emerging and systemic risks and inherent uncertainty associated with surprising events, planning for and managing risk, crisis and disasters requires understanding of the space of possibilities in order to avoid unrealistic expectations that can influence the management of disasters and catastrophes. (Masys, 2012)

Disasters can be triggered by natural or human causes. What we learn from terrorist attacks is that scenarios must look beyond threat, vulnerability and impact and include a more ‘systemic view of the terrorist space’ with the intent of ‘designing’ intervention strategies that are holistically applied. (Masys, 2016) Natural disasters such as floods and fires show similar complexity traits.

The inherent interactive dynamic complexity associated with wicked problems illuminates the shortcomings of a linear, reductionist approach. A more inclusive and holistic understanding of the problem necessitates multiple perspectives from partners and stakeholders. This requires a type of thinking capable of grasping the big picture, including the interrelationships between the full range of causal factors and strategic objectives. In terms of intervention strategies, every action or intervention causes changes to the overall system that must be recognized and managed.

The concept of wicked problems stems from the work of Rittel and Weber (1973) and their paper “Dilemmas in a General Theory of Planning”. The wicked problems we face in society are so challenging because they are both unsolved and unstructured. Rittel outlined the ten characteristics of wicked problems, which sets out the basis for collective participation and argumentation:

1. Wicked problems have no definitive formulation, but every formulation of a wicked problem corresponds to the formulation of a solution.
2. Wicked problems have no stopping rules.
3. Solutions to wicked problems cannot be true or false, only good or bad.
4. In solving wicked problems there is no exhaustive list of admissible operations.
5. For every wicked problem there is always more than one possible explanation, with explanations depending on the Weltanschauung of the designer.
6. Every wicked problem is a symptom of another, “higher level”, problem.
7. No formulation and solution of a wicked problem has a definitive test.
8. Solving a wicked problem is a “one shot” operation, with no room for trial and error.
9. Every wicked problem is unique.
10. The wicked problem solver has no right to be wrong—they are fully responsible for their actions. (Rittel, 1972)

Framing the problem space in terms of ‘wicked problems’ acknowledges the inherent interconnectedness and complexity, and thereby calls upon novel approaches that challenge traditional linear thinking mindsets. What emerges from the recognition of wicked problems is the necessity to actively engage with it by building up an understanding and knowledge of interdependent dynamic systems, feedback loops, emergent features and surprises assessing the impacts and employing reflective practices.

# APPLICATION OF GENERAL MORPHOLOGICAL ANALYSIS IN DISASTER RISK REDUCTION

Analyzing and modeling complex social, organizational and political (i.e. policy driven) systems presents us with a number of difficult methodological problems. Firstly, many of the factors involved are not meaningfully quantifiable, since they contain strong social, political and cognitive dimensions. Secondly, the uncertainties inherent in such problem complexes are in principle non-reducible, and often cannot be fully described or delineated. This includes both so-called agonistic uncertainty (conscious, self-reflective actions among competing actors) and non-specified uncertainty (for instance, uncertainties concerning what types of scientific and technological discoveries will be made in the future). (Ritchey, 2011:7)

“Morphological analysis” refers to the analysis of structural relationships within the particular scientific discipline where this term is used. In the 1940s and 50s, Fritz Zwicky, the Caltech astrophysicist, *generalized* the “morphological approach” as a method for structuring and analyzing *any type* of multi-dimensional, essentially non-quantified problem complex. (Alvarez & Richey, 2015) According to Zwicky: “Attention has been called to the fact that the term morphology has long been used in many fields of science to designate research on structural interrelations – for instance in anatomy, geology, botany and biology. ... I have proposed to generalize and systematize the concept of morphological research and include not only the study of the shapes of geometrical, geological, biological, and generally material structures, but also to study the more abstract structural interrelations among phenomena, concepts, and ideas, whatever their character might be.” (Zwicky, 1969, p. 34) Therefore, General Morphological Analysis (GMA) is a method for identifying and investigating the total set of possible relationships contained in a given problem complex. This is accomplished by going through a number of iterative phases which represent cycles of analysis and synthesis – the basic method for developing scientific models.

The method begins by identifying and defining the most important *parameters* of the problem complex to be investigated, and assigning each parameter a range of relevant *values* or *conditions*. This is done mainly in natural language, which can be utilized to specify the set of elements defining the discrete *value range* of a parameter.

A morphological field is constructed by setting the parameters against each other in order to create an n-dimensional configuration space. A particular *configuration* within this space contains one ”value” from eachof the parameters, and thus marks out a particular state of, or possible formal solution - scenario to, the problem complex. (Ritchey, 1998)

The point is to examine all configurations in the field, in order to establish which are possible, viable, practical, interesting, etc. and which are not. In doing this, we mark out in the field a relevant *solution space*. Obviously, in fields containing more than a handful of variables, it would be time-consuming – if not practically impossible – to examine all of the configurations involved. For instance, a 7-parameter field with 6 conditions under each parameter contains almost 280,000 possible configurations. The solution space of a morphological field consists of the sub-set of all the possible configurations which satisfy some criteria. The primary criterion is that of *internal consistency*.

Thus the next step in the analysis-synthesis process is to examine the *internal relationships* between the field parameters and "reduce" the field by weeding out configurations which contain mutually contradictory conditions. In this way, we create a preliminary outcome or solution space within the morphological field without having first to consider all of the configurations as such. (Alvarez & Ritchey, 2015)

This “reduction” is achieved by a process of *cross-consistency assessment* (CCA). All of the parameter values in the morphological field are compared with one another in the manner of a cross-impact matrix. As each pair of conditions is examined, a judgment is made as to whether – or to what extent – the pair can coexist, i.e. represent a consistent relationship. Note that there is no reference to direction or causality, but only to *mutual consistency*. Using this technique, a typical morphological field can be reduced by to 90% or even 99%, depending on the problem structure. Further reduction of the number of scenarios can be achieved through the application of advanced algorithms (Field Anomaly Relaxation – FAR, fuzzy logic, Bayesian tree model etc.), which may be observed as extensions of the classic GMA method.

For the purpose of application of the GMA method in disaster management, first the relevant disaster management domains and their components are identified (Table 1)[[2]](#footnote-2).

On the basis of the Table 1, the general GMA matrix is created (Table 2). The matrix contains 6 domains and 15 parameters, each of which may have values from 1 to 7.

Depending on the type of accident and other systemic parameters, it is possible to identify possible scenarios for disaster management using GMA and cross-impact matrix. That way, the initial number of all combinations, which may amount to several or several hundred million, can be reduced to less than one hundred realistic scenarios. This can be done by using professional software such as Carma[[3]](#footnote-3) developed by Swedish Morphological Society or other specifically designed software, but even with widely available applications such as Excel etc.

Furthermore, with the goal of analyzing disaster management process, the simulation could be run iteratively, in time segments, with inputs to system dynamics (SD) model modified as the inferences from the MA scenario being used as a continuously changing inputs fed into the SD simulation.

# SYSTEM DYNAMICS SIMULATION IN DISASTER MANAGEMENT

System Dynamics is an academic discipline and a tool useful in the analysis of social, economic, ecological and other systems. It starts from the basic presumption that a system’s structure defines its behavior. SD links the behavior of a system to its underlying structure. The SD simulation approach relies on understanding complex interrelationships existing between different elements within a system, by developing a model that can simulate and quantify the behavior of the system. SD facilitates feedback analysis via a simulation model of the effects of alternative system structures and control policies on system behavior. SD simulation may help us understand how structural changes in one part of a system might affect the behavior of the system as a whole. In addition it shows combined predictive (determining the behavior of a system under particular input conditions) and learning (discovery of unexpected system behavior under particular input conditions functionality), and enables active involvement of stakeholders in the modeling process. (Simonović 2011:116-117)

The basic elements of the SD model are stocks, flows and variables. Stocks are accumulations that characterize the state of the system and generate the information upon which decisions and actions are based. Stocks are altered by inflows and outflows. The other important elements are feedbacks and delays. Whilst feedback relationships need not be particularly explained, delays are a critical source of dynamics in nearly all systems. According to Simonović (2011), they are omnipresent in management of disasters, as it takes time to measure and report extreme precipitation or flood flow. Simonović distinguishes material recovery delays – capturing the physical flow of material, and information delays – gradual adjustment of perceptions or beliefs. Stocks create delays by accumulating the difference between the inflow to a process and its outflow. (Simonović, 2011)

On the basis of the Table 1 (Disaster management domains), a conceptual SD model was created whose diagram is represented on the Figure 1. This is a causal loop system dynamic diagram based on stocks and flows. The model was built using [Vensim](http://vensim.com/) modelling software tool.[[4]](#footnote-4) The following *flows* are represented at the diagram *POPULATION/OBJECTS, EXPOSED, UNSECURED, DAMAGED and RECOVERED*. These *flows* represent certain states of the population or facilities in different phases of the disaster actuation and its management. Moreover, on the SD diagram the following main control variables can be noticed: *exposed control, threat, decision making and accident intensity*. These variables have the decisive managing role on the states within the system during the accident. Finally, on the SD diagram are also present the following input variables : *ACCIDENT(1), SECURITY ASSESSMENT(2), PREPAREDNESS(3), SUPPORT(4), ORGANIZATION(5) and ACCIDENT MANAGEMENT(6).* These variables are identified on the basis of scenarios generated through GMA matrix (Table 2.) and define the initial states and controls within the system. Depending on the chosen scenario and characteristics of the accident/disaster, on the basis of such designed SD diagram and obtained states, the simulation can assist in decision making about the choice of an optimal strategy.



**Figure 1. SD disaster management model**

Stocks (*POPULATION/OBJECTS, EXPOSED, UNSECURED, DAMAGED and RECOVERED*) represent a temporal integral from the corresponding *rate*. For instance:

All *variables* (*vi* ) are expressed in the following equation form:

in which *fa(t)* are non-linear functions or coefficients, which can be time dependant, and *ca* represent weighting factors.

# COMBINED GMA AND SD DISASTER RISK REDUCTION MODEL

Conceptual approach of combined GMA and SD methods in disaster management is represented in Figure 2. On the basis of the type of an accident an initial GMA matrix is defined according to the Table 2. The data obtained from the initial scenario are then introduced in the SD model (Figure 1) as variables 1 to 6. Then the simulation in the SD model is initiated. In the SD model response the flows *EXPOSED, UNSECURED, DAMAGED, RECOVERED* and the key variable *threat* are observed as significant indicators. Their estimated values, obtained from the stable state of the model or after a certain time segment of simulation, are then incorporated into the expanded GMA matrix (Table 3).

SD

GMA

*ACCIDENT*

**Figure 2. Concept of combined GMA and SD methodology in disaster management**

On the basis of Table 3 new values for variables 2 to 6 are defined that are incorporated in the SD model, and then the new cicle of simulation is initiated. Such iterative procedure enables the observation of system in a longer time period, as well as definition of optimal disaster management strategies.

Depending on the type and components of the assessed system, for the implementation of this methodology the qualitative values of the variables 1 to 6 need to be translated into quantitative, numerical values. (Simonović and Sajjad, 2005) This can be done in the manner represented in the Equation (2), in which the choice of a function *fa(t)*, as well as weighting factors *ca* is performed on the basis of the knowledge of the system operation and calibration through experimental testing of the model. For the sake of the efficient *sensitivity* testing, ideally *fa(t)* and *ca* would be normalized within the 0 to 1 range.

The relationship in Equation (2) describes the relative importance (weight) of each variable used in SD model. For instance, the input variable ***ACCIDENT\_MANAGEMENT(6)****,* on the basis of Table 2 may be defined in the following manner:

***ACCIDENT\_MANAGEMENT(6)*** = (EXPOSED\_monitoring) \* c1 + (ACCIDENT\_monitoring) \* c2 +

 + (RESPONSE\_delay) \* c3 + (INFORMATION\_delay) \* c4 + (RECOVERING\_period) \* c5 +

 + (DECISION\_making) \* c6

Likewise, the other input variables from 1 to 5 may be defined by equations and have more components (see Table 2).

A control variable ***decision\_making***, based on the Figure 1, may be defined as:

***decision\_making*** = (EXPOSED) \* c10 + (UNSECURED) \* c11 + (DAMAGED) \* c12 +

 + (RECOVERED) \* c13 +[SECURITY\_ASSESSMENT(2)] \* c14 +[ACCIDENT\_MANAGEMENT(6)] \* c15 ++ (accident\_intensity) \* c16 + + (monitoring) \* c17 +(threat) \* c18

Similarly, the function ***rate*** in the SD model may be defined in the following manner:

***exposed\_rate* = (**POPULATION\_OBJECTS) \* c20 +(exposed\_control) \* c21 +(threat) \* c22

In the same way all other components in the SD model in Figure 1 may be defined.

Quantification of weights is done through the model calibration procedure. Data may be collected from the Emergency Management Organizations provided details on the management process (length, timing, number of people/objects etc) and compared with the outcome of the model simulations. The weights are adjusted during testing of the model using the standard calibration procedure. Namely, the closest ones to the observed historic data are selected and used in the model for further simulations.

**CONCLUSION**

In XXI century most people live in urban settlements that are becoming more complex, interconnected and with interdependent infrastructure. When a disaster strikes in such environment, due to large number of elements (stakeholders, population, facilities, objects, environment, businesses, symbolism etc.), interconnections and interdependencies, its management represents undoubtedly a wicked problem. As wicked problems are intrinsically connected with the notion of uncertainty, there is a need for development a series of future possibilities, i.e. scenarios. In addition, those scenarios should be viewed as dynamic events and analyzed as such. For that sake we believe that the combination of General Morphological Analysis (as a scenario generating method) and System Dynamics (a holistic assessment of scenario dynamics) may be beneficial.

The main purpose of the model is to allow for the different policy options available to emergency managers to be evaluated before an emergency situation occurs. The limitation of this paper is that the proposed methodology is presented only at the conceptual level. The next step is creation of concrete, real-life, scenarios and SD simulations by teams of experts, depending on analyzed system and the type of a disaster.

The different policy choices related to the emergency warning dissemination in particular can be investigated using the model. The utility of the model may be confirmed through a set of experiments designed for testing the efficiency of management procedures. Methodology used for testing is sufficiently general to be applied to different types of disasters, as well as conceptually oriented towards the type of an accident.

The simulation could be run iteratively, in time segments, with inputs to SD model modified as the inferences from the MA scenario being used as a continuously changing inputs fed into the SD simulation. The results obtained from the SD model simulation may then be used as input in a new GMA matrix for defining of new disaster management scenarios. Thus, the behaviour of the analyzed system in a longer time frame may be observed, which can finally result with the identification of the optimal disaster management strategy.

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Carma software: <http://www.swemorph.com/macarma.html>

Vensim software: <http://vensim.com>

**APPENDIX 1 – TABLES**



**TABLE 3. Extended GMA matrix**

**TABLE 2. Disaster management – GMA matrix**

**TABLE 1. Disaster**

**management domains**

**and their components**

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2. The tables are given in Appendix 1. [↑](#footnote-ref-2)
3. <http://www.swemorph.com/macarma.html> [↑](#footnote-ref-3)
4. <http://vensim.com> [↑](#footnote-ref-4)