Developing Scenario Laboratories with Computer-Aided Morphological Analysis

Presented at the
14th International Command and Control Research and Technology Symposium
Washington DC – June 15-17, 2009

Track 6: Modeling and Simulation

Tom Ritchey

Swedish Morphological Society
Lyckselevägen 35
SE-16267 Vällingby, Sweden
Contact: ritchey@swemorph.com
Abstract

General morphological analysis (GMA) is a method for structuring and analyzing the total set of relationships contained in multi-dimensional, non-quantifiable problem complexes, and for synthesizing solution spaces. During the past 15 years, GMA has been extended, computerized and applied by the Swedish Defence Research Agency (FOI) for scenario development, long-term strategy management and organizational structuring. It is especially useful for rapid prototyping as concerns tactical and operational scenarios and force structuring. This article outlines the fundamentals of the morphological approach and describes its use in a number of case studies in scenario development done for the Swedish Armed Forces and other defense agencies between 1997 and 2007.

1. INTRODUCTION AND METHODOLOGICAL BACKGROUND

The development of scenarios is a common task within military analysis. Scenarios are designed – inter alia – in order to test the capabilities of different force structures and to define the capability requirements for different tactical and operational situations. However, developing complex operational and tactical scenarios presents us with a number of difficult methodological problems.

Firstly, many of the factors involved are non-quantifiable, since they contain complex organizational and environmental factors. Secondly, the uncertainties inherent in scenario modeling are in principle non-reducible and involve conscious self-reference among actors. Finally, the very process by which scenarios are developed is often difficult to trace – i.e. we seldom have an adequate “audit trail” describing how relevant parameters are identified and how these parameters are related to each another. Without some form of traceability we have little possibility of scientific control over results. How, then, can the task of developing complex operational and tactical scenarios be put on a sound methodological basis?

With this question in mind, a research program was initiated at FOI (the Swedish Defence Research Agency) in the early 1990's that was aimed at developing a methodological framework for creating models of systems and processes, which cannot be meaningfully quantified. We began by attempting to develop an extended form of what is called typology analysis (Baily, 1969). Initially, we thought we were doing something new. However, we subsequently learned that extended typology analysis was invented as early as the 1940’s by Professor Fritz Zwicky at the California Institute of Technology in Pasadena. He called it the morphological approach.

The term morphology derives from antique Greek (morphe) which means shape or form. The general definition of morphology is "the study of form or pattern", i.e. the shape and arrangement of parts of an object, and how these conform to create a whole or Gestalt. The "objects" in question can be physical (e.g. an organism or an ecology), social/organizational (e.g. a corporation or a defense structure), or mental (e.g. linguistic forms or any system of ideas).

The first to use the term morphology as an explicitly defined scientific method would seem to be J.W. von Goethe (1749-1832), especially in his "comparative morphology" in botany. Today, morphology is associated with a number of scientific disciplines where formal structure, and not necessarily quantity, is a central issue, e.g. linguistics, geology and zoology.
Zwicky proposed a *generalized form of morphology*, which today goes under the name of General Morphological Analysis (GMA)

“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, 1966, p. 34)

Zwicky developed GMA as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes (Zwicky 1966, 1969). He applied the method to such diverse fields as the classification of astrophysical objects, the development of jet and rocket propulsion systems, and the legal aspects of space travel and colonization. He founded the Society for Morphological Research and championed the "morphological approach" from the 1940's until his death in 1974.

More recently, morphological analysis has been applied by a number of researchers in the USA and Europe in the fields of policy analysis and futures studies (e.g. Rhyne 1981, 1995; Coyle 1995, 1996). In 1995, advanced computer support for GMA was developed at FOI (Ritchey, 2003a). This has made it possible to create non-quantified inference models, which significantly extends GMA's functionality and areas of application (Ritchey 1997, 1998, 2002, 2003b, 2004, 2005a, 2005b, 2006a, 2006b). Since then, some 80 projects have been carried out using computer aided GMA, for structuring complex policy and planning issues, developing scenario and strategy laboratories, and analyzing organizational and stakeholder structures.

This article will begin with a historical and theoretical background to GMA, followed by a number of examples of scenario laboratories developed for the Swedish Armed Forces between 1997 and 2007.

2. GENERAL MORPHOLOGICAL ANALYSIS

Essentially, GMA is a method for identifying and investigating the total set of possible relationships or “configurations” 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 (Ritchey, 1991).

The method begins by identifying and defining the most important dimensions (or *parameters*) of the problem complex to be investigated, and assigning each dimension a range of relevant *values* or *conditions*. This is done mainly in natural language, although abstract labels and scales 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 (Figure 1). A particular *configuration* (the darkened cells in the matrix) within this space contains one "value" from each of the parameters, and thus marks out a particular state of, or possible formal solution to, the problem complex.
Figure 1: A 6-parameter morphological field. The darkened cells define one of 4800 possible (formal) configurations.

The point is, to examine all of the configurations in the field, in order to establish which of them are possible, viable, practical, interesting, etc., and which are not. In doing this, we mark out in the field a relevant solution space. The solution space of a Zwickian morphological field consists of the subset of all the configurations which satisfy some criteria. The primary criterion is that of internal consistency.

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 6-parameter field with 6 conditions under each parameter contains more than 46,000 possible configurations. Even this is a relatively small field compared to the ones we have been applying.

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.

This is achieved by a process of cross-consistency assessment. All of the parameter values in the morphological field are compared with one another, pair-wise, in the manner of a cross-impact matrix (Figure 2). 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 here to direction or causality, but only to mutual consistency. Using this technique, a typical morphological field can be reduced by up to 90 or even 99%, depending on the problem structure.
There are two principal types of inconsistencies involved here: purely *logical* contradictions (i.e. those based on the nature of the concepts involved); and *empirical* constraints (i.e. relationships judged be highly improbable or implausible on empirical grounds). *Normative* constraints can also be applied, although these must be used with great care, and clearly designated as such.

This technique of using pair-wise consistency assessments between conditions, in order to weed out internally inconsistent configurations, is made possible by a principle of dimensionally inherent in morphological fields, or any discrete configuration space. While the number of configurations in such a space grows exponentially with each new parameter, the number of pair-wise relationships between parameter conditions grows only in proportion to the triangular number series – a quadratic polynomial. Naturally, there are also practical limits reached with quadratic growth. The point, however, is that a morphological field involving as many as 100,000 formal configurations can require no more than few hundred pair-wise evaluations in order to create a solution space.

When this solution (or outcome) space is synthesized, the resultant morphological field becomes an *inference model*, in which any parameter (or multiple parameters) can be selected as "input", and any others as "output". Thus, with dedicated computer support, the field can be turned into a laboratory with which one can designate initial conditions and examine alternative solutions.

GMA seeks to be integrative and to help discover new relationships or configurations. Importantly, it encourages the identification and investigation of boundary conditions, i.e. the limits and extremes of different parameters within the problem space. The method also has definite advantages for scientific communication and – notably – for group work. As a process,
the method demands that parameters, conditions and the issues underlying these be clearly defined. Poorly defined concepts become immediately evident when they are cross-referenced and assessed for internal consistency. Like most methods dealing with complex social and organizational systems, GMA requires strong, experienced facilitation, an engaged group of subject specialists and a good deal of patience.

3. SCENARIO LABORATORIES: FOUR EXAMPLES

Since 1996, FOI has carried out more than 40 projects involving morphological modeling for Swedish Defence authorities – principally with the Swedish Armed Forces, the Ministry of Defence and the Defence Material Procurement Agency. Most of the modeling done for the Swedish Armed Forces falls into two main categories: scenario models (including mission formulation, operational environment and political constraints) and force structure models (including force composition and weapons systems). This paper concentrates mainly on scenario models. However, scenario models are seldom developed for their own sake: most of the models for the Swedish Armed Forces were developed in order to help specify and/or test the capabilities of different force structures for different tactical and operational environments.

Please note that some of the models presented here have been altered slightly or generalized in order to be classified as unrestricted. The details of their cross consistency assessments are, however, still restricted.

The four scenario models presented here are:

- Tactical scenarios for future ground target systems
- The development an airborne capability: problem formulation
- Scenarios for a conflict etiology
- Climate change conflict scenarios

TACTICAL SCENARIOS FOR FUTURE GROUND TARGET SYSTEMS

This was a study carried out for the Swedish Armed Forces in order to determine what types of weapons systems would be most appropriate under different tactical situations. The study resulted in a number of inference models, one of them presented below. Figures 3 and 4 show a so-called overlay model, which in this case pits tactical scenarios against a range of ground target systems. From the standpoint of the left-hand side of the field (Tactical situations), the five central parameters (Effect/penetration ... to ... Time to effect...) express demands placed on weapons systems. From the right hand side (System) these parameters express weapons systems’ properties. Thus, demands and properties are expressed in the same terms, “overlaid” and assessed for internal consistency. After this is done, defining the demands involved in any new tactical situation automatically selects relevant weapons systems.

The configuration in Figure 3 shows a designated tactical situation (S3) as "input”, and the resulting demands and system configurations as "output”. Figure 4 works from the other side, designating two systems as “input”, and the resulting tactical situations as “output.”
**THE DEVELOPMENT OF AN AIRBORNE CAPABILITY: PROBLEM FORMULATION**

This was a study carried out for the Swedish Army Command with the following focus statement:

---

**Figure 3.** Two superimposed fields: tactical situation (input: grey) determines system configurations (output: black).

---

**Figure 4.** System configurations (inputs: grey) determine tactical situations (outputs: blue)
“Analyze the concept airborne capability and investigate to what degree such a capability can enhance operational and tactical levels of armed forces’ operations. Describe an airborne unit consisting of a ground combat unit, a transport helicopter unit and a combat helicopter unit as one organized unit or, alternatively, as separately organized units. Investigate both the potentials and possible limitations involved in different alternatives -- and recommend one.”

In order to formulate the problem complex, we created a preliminary morphological field describing what we believed an airborne unit should consist of, and what kind of tasks and environments this unit should be able to manage. As a starting point, we worked with the question of what types of missions the airborne unit should undertake and in what environments (column 1 in Figure 5, below). This resulted in several tactical scenarios (expressed in columns 1 & 2), which we then utilized as references in order to generate alternative forms and organizations for the airborne unit.

This morphological field helped us to understand where the major difficulties in the development of an airborne unit lay, where we lacked requisite knowledge and, importantly, what other systems of variables are dependent upon, and in their turn influence, how the airborne unit should be configured.

<table>
<thead>
<tr>
<th>Task and milieu for Airborne Unit as whole</th>
<th>Task and milieu for Airborne Ground Combat Unit (AGCU)</th>
<th>Airborne Ground Combat Unit (Combat system)</th>
<th>Number of combat helicopters (77% availability)</th>
<th>Unit's effective range</th>
<th>Command and control</th>
<th>Degree of collective training with ...</th>
<th>Personnel and preparedness time</th>
<th>External support: time and degree of precision</th>
<th>External support: range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engage mechanized brigade in open terrain</td>
<td>Relate armored tank units in open and covered and partially covered terrain</td>
<td>Light infantry</td>
<td>2 companies (16 helicopters)</td>
<td>Up to 100 km</td>
<td>Single overall organizational C2/C</td>
<td>High</td>
<td>Full time employed 48 hours</td>
<td>Precision within minutes</td>
<td>100 km</td>
</tr>
<tr>
<td>Engage II units in open and partially covered terrain</td>
<td>Engage advanced units in urban milieu</td>
<td>Combat system 2006-2010</td>
<td>1 company (8 helicopters)</td>
<td>Up to 150 km</td>
<td>No overall organizational C2/C</td>
<td>Medium</td>
<td>Conscripts 10 days</td>
<td>Precision with a few hours</td>
<td>150 km</td>
</tr>
<tr>
<td>Take and hold terrain in urban and partially covered milieu</td>
<td>Take bridgehead in partially covered urban terrain</td>
<td>Combat system 2016-2020</td>
<td>None</td>
<td>Up to 200 km</td>
<td>Low</td>
<td>Contract 30 days</td>
<td>Saturation strikes within minutes</td>
<td>200 km</td>
<td></td>
</tr>
<tr>
<td>Engage advanced units in urban terrain</td>
<td>Relate/Rescue operation</td>
<td></td>
<td></td>
<td>&gt;200 km</td>
<td></td>
<td></td>
<td>Saturation strikes within hours</td>
<td>&gt;200 km</td>
<td></td>
</tr>
<tr>
<td>Rescue and evacuate</td>
<td>Surface surveillance Target designation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supervise and support mission in open and partially open terrain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.** Morphological field for Airborne Unit, with option space defined for the designated task: Rescue and evacuate.

**SCENARIOS FOR A CONFLICT ETIOLOGY**

The Folke Bernadotte Academy, a Stockholm-based government agency for international conflict and crisis management, sponsored the development of a conflict etiology model in order to generate examples of conflict causes for local, national and regional conflicts. Of special
importance was the relationship between root (structural) causes, proximate causes, intervening factors and triggering events. The model in Figure 8 is a prototype and demonstrator developed as “proof-of-principle”. Four test scenarios were developed, one shown here. The work is ongoing.

**Figure 8**: Prototype conflict etiology model with four scenario examples, one selected (grey cell).

**CLIMATE-CHANGE CONFLICT SCENARIOS**

The climate change conflict scenario model was developed for an EU financed project called Climate Tools, presently being carried out by the Swedish Defence Research Agency (FOI). The study was directed at hypothesizing how different climate change scenarios, involving both temperature and sea level increases, might affect different areas of the world, and in which ways. The inputs for the model are a scenario involving a given temperature and sea level increase and a specific area influenced. The outputs concern possible physical consequences, what main sectors of society would be most affected, subsequent societal consequences and possible types of conflict that could arise out of this.

In Figures 6 and 7, a worst-case scenario was selected involving a mean global temperature rise of 6-8 degrees and a sea level rise of 70-80 centimeters. The time perspective was 50-100 years. Note that in this model, the Baltic area manages fairly well as compared e.g. to southern Europe.
4. CONCLUSIONS
General Morphological Analysis is based on the fundamental scientific method of alternating between analysis and synthesis. For this reason, it can be trusted as a useful, conceptual modeling method for investigating problem complexes which are not meaningfully quantifiable and which cannot be treated by formal mathematical methods and causal modeling.

Morphological Analysis, with dedicated computer support

- systematically deals with multi-dimensional problems with non-quantified dimensions,
- provides for a well-structured discussion concerning such complex problems,
- is well suited for working with groups of experts that represent different areas of competence,
- produces an “audit trail” and documentation,
- is well suited for developing scenario and strategy laboratories.

As is the case with all modeling methods, the output of a morphological analysis is no better than the quality of its input. However, even here the morphological approach has some advantages. It expressly provides for a good deal of in-built “garbage detection”, since poorly defined parameters and incomplete ranges of conditions are immediately revealed when one begins the task of cross-consistency assessment. These assessments simply cannot be made until the morphological field is well defined and the working group is in agreement about what these definitions mean.

5. REFERENCES AND FURTHER READING


Zwicky, F. (1969) *Discovery, Invention, Research - Through the Morphological Approach,*
Toronto: The Macmillan Company.