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Developing Scenario Laboratories with Computer-Aided Morphological Analysis

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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.

Parameter A	Parameter B	Parameter C	Parameter D	Parameter E	Parameter F
Condition A1	Condition B1	Condition C1	Condition D1	Condition E1	Condition F1
Condition A2	Condition B2	Condition C2	Condition D2	Condition E2	Condition F2
Condition A3	Condition B3	Condition C3		Condition E3	Condition F3
Condition A4	Condition B4	Condition C4		Condition E4	Condition F4
Condition A5		Condition C5		Condition E5	
				Condition E6	

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.

		Parameter A					Parameter B				Parameter C					Param		Parameter E					
		Condition A1	Condition A2	Condition A3	Condition A4	Condition A5	Condition B1	Condition B2	Condition B3	Condition B4	Condition C1	Condition C2	Condition C3	Condition C4	Condition C5	Condition D1	Condition D2	Condition E1	Condition E2	Condition E3	Condition E4	Condition E5	Condition E6
Parameter B	Condition B1																						
	Condition B2																						
	Condition B3																						
	Condition B4																						
Parameter C	Condition C1																						
	Condition C2																						
	Condition C3																						
	Condition C4																						
	Condition C5																						
Parameter D	Condition D1																						
	Condition D2																						
Parameter E	Condition E1																						
	Condition E2																						
	Condition E3																						
	Condition E4																						
	Condition E5																						
	Condition E6																						
Parameter F	Condition F1																						
	Condition F2																						
	Condition F3																						
	Condition F4																						

Figure 2: The cross-consistency matrix for morphological field in Figure 1.

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.

DEMANDS ON SYSTEMS -----> <----- SYSTEM PROPERTIES

Tactical situations	Purpose	Effect/ penetration:	Effect/ precision:	Guidance system: final phase	Attack attitude:	Time to effect after decision to employ	Special weapon system demands/ properties	System
S 1	Destroy	Bunker buster	Great accuracy Little or no side effect	Visual	Vertical	Within 10 s	Recognition/ identification capacity	System 1
S 2	Pin down, stop	Kinetic energy + RSV (Hard)	Great accuracy Limited side effect	IR	Horizontal	Within 1 minute	Command self-destruction (Abort mission)	System 2
S 3	Disrupt	30 mm (medium)	Good accuracy Some side effects	Radar		Within 10 minute	Updateable target co-ords.	System 3
S 4	Warn	Small-bore + fragmentation (soft)	Area effect 200x300	Acustic		Within 30 minute	Sensor guided warhead	System 4
S 5			Area effect 500x400	Co-ordinate based		Within 1 hour	Pre-programmed target co-ords.	System 5
S 6						Within 5 hours	Basic capacity	System 6
S 7						Within 24 hours		System 7
						More than 24 hours		System 8
								System 9
								System 10
								System 11

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

DEMANDS ON SYSTEMS -----> <----- SYSTEM PROPERTIES

Tactical situations	Purpose	Effect/ penetration:	Effect/ precision:	Guidance system: final phase	Attack attitude:	Time to effect after decision to employ	Special weapon system demands/ properties	System
S 1	Destroy	Bunker buster	Great accuracy Little or no side effect	Visual	Vertical	Within 10 s	Recognition/ identification capacity	System 1
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S 3	Disrupt	30 mm (medium)	Good accuracy Some side effects	Radar		Within 10 minute	Updateable target co-ords.	System 3
S 4	Warn	Small-bore + fragmentation (soft)	Area effect 200x300	Acustic		Within 30 minute	Sensor guided warhead	System 4
S 5			Area effect 500x400	Co-ordinate based		Within 1 hour	Pre-programmed target co-ords.	System 5
S 6						Within 5 hours	Basic capacity	System 6
S 7						Within 24 hours		System 7
						More than 24 hours		System 8
								System 9
								System 10
								System 11

Figure 4. System configurations (inputs: grey) determine tactical situations (outputs: blue)

THE DEVELOPMENT OF AN AIRBORNE CAPABILITY: PROBLEM FORMULATION

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

“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.

Task and milieu for Airborne Unit as whole	Task and milieu for Airborne Ground Combat Unit (AGCU)	Airborne Ground Combat Unit (Combat system)	Number of combat helicopters (75% availability)	Unit's effective range	Command and control	Degree of collective training with ...	Personnel and preparedness time	External support: time and degree of precision	External support: range
Engage mechanized brigade in open terrain	Retard armored tank units in open and covered and partially covered terrain	Light infantry	2 companies (16 helicopters)	Up to 100 km	Single overall organizational C&C	High	Full time employed 48 hours	Precision within minutes	100 km
Engage II units in open and partially covered terrain	Engage advanced units in urban milieu	Combat system 2005-2010	1 company (8 helicopters)	Up tp 150 km	No overall organizational C&C	Medium	Conscripts 10 days	Precision with a few hours	150 km
Take and hold terrain in urban and partially covered milieu	Take bridgehead in partially covered urban terrain	Combat system 2015-2020	None	Up to 200 km		Low	Contract 30 days	Saturation strike within minutes	200 km
Engage advanced units in urban terrain	Relief/rescue operation			> 200 km				Saturation strike within hours	> 200 km
Rescue and evacuate	Surface surveillance Target designation								
Supervise and support mission in open and partially open terrain									

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.

Scenario	Root causes	Proximate causes	Intervening factors	Trigger events (examples)	Scope	Principal national/regional stakeholders	International stakeholders
Authoritarian minority rule	Governance	Predominance of minority appointments	Growing political intolerance at local level	Attacks against Peace Monitors	Local Hot spots	National government	UN
Separatism	Territory	Presence of weapons	Frequent attacks against minorities	Assassination of key figure	Regional in country	Political parties	EU & other reg. org
Human rights violations	Natural resources	Poverty	Unassisted resettlement of IDPs and refugees	Kidnapping or imprisonment of key figure	National	Traditional power elite	INGOs
Corrupt elections	Economic distribution & infrastructure	Economic decline	Increasing local tension over land	Mass demonstrations/ uprisings	Regional	Mil & police	IGOs (e.g. SIDA)
	Environmental security	Impunity	Violent army and police cleansing operations	Coup	International	Religious leaders	International Financial Institutions
	Occupational power	Refuges & IDPs	Political persecution	Terrorist action		Judicial actors	Multi/international businesses
	Previous war	Gender issues	Marginalization & deprivation	Mass refugee movement		Intellectual elite and educational system	
	Corruption	Corruption	Censorship			Criminal groups & warlords	
		Ethnic, religious, cultural (drivers)	Impunity & extra judicial processes			National orgs, NGO and unions	
		Security / human security				Media and opinion makers	
						Identity groups	
						Social movement groups	

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.

Scenario	Global mean temp change (C) Sea level rise (cm)	Area influenced (examples)	Consequences for area influenced	Main sectors influenced	Possible societal consequences for affected area	Conflicts that can befall influenced areas
Extreme case (A1F1)	Mean temp increase: 6-8 C Sea level rise: 70-80 cm	Baltic Sea area	Heavy drought	Agriculture	Structural changes in international competition	Civil war, internal conflicts
High temp renewable energy (B1)	Mean temp increase: 5-6 C Sea level rise: 50-60 cm	Middle Europe	Desert spreading	Forestry	Increased regional divergence	Regional war/conflicts over land and water areas
Mild rise, renewable energy (B2)	Mean temp increase: 3-4 C Sea level rise: 20-40 cm	Southern Europe	Flooding	Energy production	Mass immigration ("climate refugees")	Economic resource conflicts (incl. fresh water)
Kyoto +	Mean temp increase: 1-2 C Sea level rise: 10-20 cm	North Africa/Sahel	Greatly increased precipitation	Transport	Mass emmigration ("climate refugees")	Closed borders
		Tropical Africa	Decreased water supplies	Living environment (housing)	Brain drain	War lordism
		Southeast China	Increased heat waves	Fishery	Increased spread of contagions (infection)	Increased international terrorism
		Northeast China	Warmer and shorter winters	Industrial production	Increased poverty	Nothing
		Arctic region		Tourism	Extreme protectionism	
		Russia		Water supplies	Financial crises	
		USA		Infrastructure	"Failed state"	
				Nothing		

Figure 6: C*limate change conflict* scenario model with worst case scenario selected for Baltic Sea area

Scenario	Global mean temp change (C) Sea level rise (cm)	Area influenced (examples)	Consequences for area influenced	Main sectors influenced	Possible societal consequences for affected area	Conflicts that can befall influenced areas
Extreme case (A1F1)	Mean temp increase: 6-8 C Sea level rise: 70-80 cm	Baltic Sea area	Heavy drought	Agriculture	Structural changes in international competition	Civil war, internal conflicts
High temp renewable energy (B1)	Mean temp increase: 5-6 C Sea level rise: 50-60 cm	Middle Europe	Desert spreading	Forestry	Increased regional divergence	Regional war/conflicts over land and water areas
Mild rise, renewable energy (B2)	Mean temp increase: 3-4 C Sea level rise: 20-40 cm	Southern Europe	Flooding	Energy production	Mass immigration ("climate refugees")	Economic resource conflicts (incl. fresh water)
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		Tropical Africa	Decreased water supplies	Living environment (housing)	Brain drain	War lordism
		Southeast China	Increased heat waves	Fishery	Increased spread of contagions (infection)	Increased international terrorism
		Northeast China	Warmer and shorter winters	Industrial production	Increased poverty	Nothing
		Arctic region		Tourism	Extreme protectionism	
		Russia		Water supplies	Financial crises	
		USA		Infrastructure	"Failed state"	
				Nothing		

Figure 7: C*limate change conflict* scenario model with worst case scenario selected for 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.

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