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Strategic Decision Support using Computerised Morphological Analysis

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Abstract

Morphological analysis (MA), pioneered by Fritz Zwicky at the California Institute of Technology in the 1930s and 40s, was developed as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes. During the past ten years, MA has been extended, computerized and applied in developing futures scenarios, structuring and analyzing complex policy spaces, and modeling strategy alternatives. This article outlines the fundamentals of the morphological approach and describes recent applications in developing threat scenarios and strategy models.

1. INTRODUCTION

Morphological analysis (MA) was developed by Fritz Zwicky – the Swiss-American astrophysicist and aerospace scientist based at the California Institute of Technology (CalTech) – as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes [Zwicky 1969, Zwicky & Wilson, 1967].

Zwicky applied this method to such diverse tasks as the classification of astrophysical objects, the development of jet and rocket propulsion systems and the legal aspects of space travel [Greenstein and Wilson, 1974]. More recently, morphological analysis has been extended and applied by a number of researchers in the U.S.A and Europe in the field of futures studies, policy analysis and strategy modeling [Coyle *et.al.*, 1994; Rhyne 1995; Ritchey 1997, 2003; Stenström & Ritchey 1999; Eriksson & Ritchey 2000]. The method is currently experiencing somewhat of a renaissance, not the least because of the development of small, fast computers and flexible graphic interfaces.

This paper will begin with a discussion of some of the methodological problems confronting complex, non-quantified modeling as applied to scenario development and strategy analysis. This is followed by a presentation of the fundamentals of the morphological approach along with reference to three recent applications: the development of a threat scenario laboratory for the Swedish Nuclear Power Inspectorate; the development of an instrument for evaluating preparedness for terrorist actions involving chemical releases for the Swedish Rescue Services; and a tactical scenario laboratory for evaluating requirements for future ground target systems, for the Army Tactical Command.

2. METHODOLOGICAL BACKGROUND

Developing threat scenarios and modeling complex socio-technical and organization 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. This means that traditional quantitative methods, mathematical modeling and simulation are relatively useless.

Secondly, the uncertainties inherent in such problem complexes are in principle non-reducible, and often cannot be fully described or delineated. This includes both antagonistic uncertainty (conscious, willful actions among actors) and so-called non-specified uncertainty (e.g. uncertainties concerning what types of scientific and technological discoveries will be made in the future). This represents even a greater blow to the idea of causal modeling and simulation.

Finally, the creative process involved in such studies is often difficult to “trace” – i.e. we seldom have an adequate “audit trail” describing the iterative process from problem formulation, through alternative generation to specific solutions or conclusions. Without some form of traceability, we have little possibility of scientific control over results, let alone reproducibility.

An alternative to mathematical modeling is a form of non-quantified modeling relying on “judgmental processes” and internal consistency, rather than causality. Causal modeling, when applicable, can – and should – be used as an aid to judgment. However, at a certain level of complexity (e.g. at the social, political and cognitive level), judgment must often be used, and worked with, more or less directly. The question is: How can judgmental processes be put on a sound methodological basis?

Historically, scientific knowledge develops through cycles of analysis and synthesis: every synthesis is built upon the results of a preceding analysis, and every analysis requires a subsequent synthesis in order to verify and correct its results [Ritchey, 1991]. However, analysis and synthesis – as basic scientific methods – say nothing about a problem having to be quantifiable.

Complex social-political systems and policy fields can be analyzed into any number of non-quantified variables and ranges of conditions. Similarly, sets of non-quantified conditions can be synthesized into well-defined relationships or configurations, which represent “solution spaces”. In this context, there is no fundamental difference between quantified and non-quantified modeling.

Morphological analysis – extended by the technique of internal “cross consistency assessment” (CCA, see below) – is a method for rigorously structuring and investigating the internal properties of inherently non-quantifiable problem complexes, which contain any number of disparate parameters. It encourages the investigation of boundary conditions and it virtually compels practitioners to examine numbers of contrasting configurations and policy solutions.

Finally, although judgmental processes will never be traceable in the way, for example, a mathematician formally derives a proof, MA goes a long way in providing as good an audit trail as one can hope for.

3. THE MORPHOLOGICAL APPROACH

Essentially, morphological analysis is a method for identifying and investigating the total set of possible relationships contained in any given, multi-dimensional problem complex that can be parameterized.

The method begins by identifying and defining the most important parameters (dimensions) of the problem complex to be investigated, and assigning each parameter a range of relevant “values” or conditions. This is done in natural language. A morphological field – also fittingly known as a “Zwicky box” – is constructed by setting the parameters against each other in an n-dimensional configuration space (see Figure 1, below). Each configuration contains one particular “value” or condition from *each* of the parameters, and thus marks out a particular state or (formal) solution within the problem complex.

If a morphological field is small enough, one can 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 so, we mark out in the field a relevant “solution space”. The “solution space” of a Zwickyian morphological field consists of the subset of configurations, which satisfy some criteria -- usually the criteria of internal consistency.

However, a typical morphological field can contain between 50,000 and 5,000,000 formal configurations, far too many to inspect by hand. 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 all mutually contradictory conditions.

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 causality, but only to internal consistency.

There are two 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 to be highly improbable or implausible on empirical grounds). (Normative constraints can also be applied, although these must be used with great care.)

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

When this solution space (or outcome space) is synthesized, the resultant morphological field becomes a flexible model, in which anything can be "input" and anything "output". Thus, with computer support,

the field can be turned into a laboratory with which one can designate one or more variables as inputs, in order to examine outputs or solution alternatives (see Figure 3, below).

The morphological approach has several advantages over less structured approaches. It 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 parameters become immediately (and embarrassingly) evident when they are cross-referenced and assessed for internal consistency. The method does, however, require strong, experienced facilitation.

Aggressor's group size	Purpose/ goal	Level of knowledge concerning: W=weapons S=systems	Method	Equipment	Part of facility targeted	Consequences
One person No insider	Map/survey	W: high S: high	Reconnaissance	Hand tools	Perimeter	No radiological consequences
One person Insider	Influence opinions	W: high S: low	Illegal trespassing	Information technology (IT)	Protected areas	Loss of fissionable material
Group (< 7 pers.) No insider	Steal fissionable material	W: low S: high	Unauthorized access to computer systems	Handheld fire arms	Surveillance systems	Loss of secret information
Group (< 7 pers.) Insider	Disturb operations	W: low S: low	Threat to disturb the facility	HPM	Nuclear material storage	Limited emission
Group (7-20 pers.) No insider	Stop operations		Blackmail against employee	Explosives	Vital facility areas	Large emission
Group 7-20 pers. Insider	Take control of the facility		Infiltration	Car bomb	Reactor safety systems	Massive emissions
Group (> 20 pers.) No insider	Destroy and cause emissions		Sabotage from within	Short-range missile		
Group (> 20 pers.) Insider	Maximum destruction		Sabotage from outside	B-weapons		
			Massive armed attack a	Chemicals & C-weapons		
				Radiological substances		
				Aircraft		
				Middle/Long-range missiles		
				Nuclear weapons/ EMP		

Figure 1: One of the morphological models used to generate “terrorist threat scenarios” for the Swedish Nuclear Power Inspectorate.

	Aggressor's group size	Purpose/ goal										Level of knowledge												
		No insider	Insider	No insider	Insider	No insider	Insider	No insider	Insider	No insider	Insider	Map/survey	Influence opinions	Steal fissionable material	Disturb operations	Stop operations	Control of the facility	Cause emissions	Maximum destruction	W: high	W: low	S: high	S: low	
Purpose/ goal	Map/survey	M	-	F	-	M	-	F	-															
	Influence opinions	M	-	F	-	M	-	F	-															
	Steal fissionable material	X	K	-	K	-	K	-	K															
	Disturb operations	-	-	-	-	-	-	-	-															
	Stop operations	K	-	-	-	-	-	-	-															
	Take control of the facility	X	K	-	M	M	M	M	M															
	Destroy and cause emissions	X	-	-	M	M	M	M	M															
	Maximum destruction	X	X	K	-	-	F	F	F															
Level of knowledge concerning: W=weapons S=systems	W: high	K	-	-	-	-	M	-	M	-	-	K	-	-	-	-	-	-	-					
	W: high	-	M	-	M	-	X	-	X	F	-	-	M	M	-	-	-	-	-					
	W: low	K	-	-	-	-	-	-	-	-	M	K	M	M	M	-	-	K						
	W: low	F	K	K	X	K	X	K	X	F	F	-	-	K	X	X	X							
Method	Reconnaissance	-	-	-	-	-	-	-	-	S	-	-	-	-	-	-	-	-	-	M	-	M		
	Illegal trespassing	-	X	-	-	-	-	-	-	F	F	-	-	-	K	X	X	-	-	-	-	-	-	
	Unauthorized access to computer	-	M	-	M	-	M	-	F	F	F	X	F	-	X	X	X	-	-	-	-	-	X	
	Threat to disturb the facility	-	-	-	-	-	-	-	-	-	M	K	F	-	X	X	X	-	-	-	-	-	-	
	Blackmail against employee	-	-	-	M	-	M	-	M	F	M	F	-	F	F	-	-	-	-	-	-	-	-	
	Infiltration	-	X	-	-	-	-	-	-	F	-	-	-	-	F	-	-	-	-	M	-	M		
	Sabotage from within	-	K	F	-	F	-	F	-	X	M	X	F	F	K	-	-	F	F	-	F	-	M	
	Sabotage from outside	K	F	-	F	-	F	-	F	X	X	X	-	F	-	F	F	F	-	F	X			
Massive armed attack	X	X	M	M	-	-	-	-	X	X	X	-	F	-	F	F	F	F	F	X	X			

Figure 2: Portion of the assessed Cross Consistency Matrix for the Nuclear Threat Scenario study.

4. COMPUTER AIDED MORPHOLOGY

The Swedish Defense Research Agency (FOI) has utilized morphological analysis in some 40 projects during the past 10 years. For this purpose, we have developed software to support the entire analysis-synthesis cycle, which MA involves -- the so-called MA/Casper system.

MA-projects typically involve developing computerized laboratories for generating scenarios and modeling complex systems involving a wide range of disparate, non-quantified variables. Such laboratories have been developed as instruments for *inter alia*: generating threat scenarios and strategy alternatives for the Swedish Armed Forces; identifying alternative long-term social evolutionary trends for the Swedish Nuclear Waste Management Agency; evaluating the Swedish bomb shelter program and studying the structure of organized crime. (More information on MA-projects is available at: www.foi.se/ma).

Figure 1, above, is one of the morphological models developed for the Swedish Nuclear Power Inspectorate in order to generate threat scenarios. The field contains over one million possible formal “configurations”, which were reduced (by internal consistency assessment) to 2154 specific or “designated” scenarios. The highlighted scenario is one of 24, which have the designated input of “One person/insider” and “Stop operations”.

We have found MA especially suitable in pitting strategy models against scenarios. In such cases, we develop two complementary morphological fields: one for generating different possible scenarios based on factors that cannot be directly controlled (an "external world" field); and one for modeling strategy or system variables, which can -- more or less -- be, controlled (an "internal world" field). The fields are then linked by cross-consistency assessments in order to establish which strategies would be most effective and flexible for different ranges of scenarios.

Two examples of this technique are given below. Figure 3 represents part of an instrument currently being delivered to Sweden's Emergency Rescue Services. It will be used to assess preparedness for both chemical accidents and (in the case shown here) terrorist actions involving the release of chemical agents.

RESOURCE FIELD -----><----- SCENARIO RESPONSE FIELD

PLANNING/PLANS	EDUCATION AND TRAINING	PERSONNEL AVAILABLE	EQUIPMENT AVAILABLE	COMMAND LEVEL	EVACUATION and CORDONING of buildings	Indication of sources and identification of substance group	Information to public (Command center)	HELP and SUPPORT for seriously injured	DEGASIFICATION efforts
Object oriented planning and inter-agency coordinated exercises for C-agents	Advanced training and recurrent general exercises with chemical agents	20 or more	Specialized equipment for specific case of C-agent	Level 4	Beginning of effective evacuation within 15 minutes	Indicate source and identify substance within 15 minutes	Alarm and information within 5 minutes	Help up to 20 people with degasification within 15 minutes	Complete degasification and redressing procedure begun within 30 minutes
Special planning program for C-agents	Basic training with recurrent general exercises with chemical agents	13 - 19	Base equipment for C-agents	Level 3	Beginning of effective evacuation within 30 minutes	Indicate source and identify substance group within 15 minutes	Alarm and information within 30 minutes	Help up to 5 people with degasification within 15 minutes	Complete degasification and redressing procedure begun within 60 minutes
Routine with checklist for C-agents (for command personnel)	Basic training with recurrent general exercises for chemical accidents	8 - 12	Less than base equipment for C-agents	Level 2	No effective evacuation start within 30 minutes	Indicate source and identify substance within 30 minutes	No measures taken within 30 minutes	Help removes injured within 15 minutes	Re-dressing begun within 30 minutes
General standard routine for chemical accidents		5-7		Level 1		Indicate source and identify substance group within 30 minutes		No measures taken within 15 minutes	Organized airing and observation after evacuation
						No measures taken within 30 minutes			No measures taken within 60 minutes

Figure 3: Linked morphological fields for accessing preparedness for terrorist actions involving the release of chemical agents.

The morphological model is made up of a 5-parameter **Preparedness Resource** field on the left, linked to a 5-parameter, scenario-defined **Response** field on the right. The scenario in question concerns a sarin release in a department store. The dark grey configuration in the Resource field is the designated “input”, and the black configuration in the Response field the generated “output”. The light grey field shows what improvements in response would be generated by improvements in resources – in this case, better “Planning” and “Training”

Figure 4 (below) is a so-called overlay model, which pits tactical scenarios against a range of ground target systems. From the left, tactical scenarios are expressed as **demands placed on the systems**. From the right, current and planned ground target systems are expressed in terms of their **properties**. Thus, demands and properties are expressed in the same terms, “overlaid” and assessed for internal consistency.

The marked configuration shows a designated scenario (scenario 3) as "input", and the designated demands and system configurations as "output".

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

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

Figure 4: Two superimposed fields: tactical scenarios (demands) vs. system configurations (properties).

5. CONCLUSIONS

Morphological analysis, extended by the technique of “cross-consistency assessment”, is based on the fundamental scientific method of analysis – synthesis cycles. For this reason, it can be trusted as a useful, conceptual modeling method for investigating non-quantified problem complexes, which cannot be treated by formal mathematical methods, causal modeling and simulation.

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. This type of garbage detection is something that strategy analysis and futures studies certainly need more of.

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