Non-Quantified Modeling with Computer-Aided Morphological Analysis

Tom Ritchey

Swedish Defense Research Agency
SE-172 90 Stockholm, Sweden
ritchey@foi.se

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 strategy modeling.

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 1966, 1969).

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. 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 (Rhyne 1981, 1995; Coyle et.al. 1994, 1995; Jenkins 1997; 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 systems modeling as applied to futures studies and strategy analysis. This is followed by a presentation of the fundamentals of the morphological approach along with two recent applications: the development of an instrument for evaluating preparedness for accidents or terrorist actions involving chemical releases; and a tactical scenario laboratory for evaluating requirements for future artillery systems for the Army Tactical Command.

Methodological background

Developing futures 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 organizational 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 (for instance, 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 by which conclusions are drawn 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 and causal 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 proceeding 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 may never be fully 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.

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. morphological analysis.

The method thus begins by identifying and defining the most important dimensions (or parameters) 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 “Zwick 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.

For example, suppose that we wished to review and re-conceptualize the Swedish national bomb shelter program since the end of the cold war (a task we actually did for the Swedish Rescue Services Board in the middle of the 1990's). This is a complex policy issue, which contains a number of disparate dimensions or variables: financial, technical, political, geographical, ethical, etc. As an example, consider the following dimensions:

1. What size of cities should we concentrate on?
2. Who should we be sheltering?
3. How big (or small) and how many people should we pack into such shelters?
4. Under what circumstances should we take up new construction?
5. What level of maintenance?
6. What is the point (philosophy) of the shelter program?

With these 6 dimensions, a morphological field like the one shown in Figure 1 could be created.

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 Zwickian morphological field consists of the subset of configurations, which satisfy some criteria -- usually the criteria of internal consistency.

However, a typical morphological field may contain between 50 and 500 thousand 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.
Figure 1: Segment of a morphological field used in the Swedish bomb shelter study. This field contains 4x4x4x3x3x4 (=2304) possible “configurations” -- one of which is highlighted.

This is achieved by a process of cross-consistency assessment: all of the parameter values in the morphological field are compared with one another, pairwise, in the manner of a cross-impact matrix (see Figure 2, following page). 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 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 be highly improbable or implausible on empirical grounds). Normative constraints can also be applied, although these must be used sparingly, and one must be very careful not to allow prejudice to rule such judgments.

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 dimensionally 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 in proportion to the triangular number series -- a quadratic polynomial. 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 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 Figures 3 and 4, below).

The morphological approach has several advantages over less structured approaches. Zwicky called MA “totality research” which, in an “unbiased way attempts to derive all the solutions of any given problem”. It seeks to be integrative and to help discover new relationships or configurations, which might be overlooked in other – less structured – methods. Importantly, it encourages the identification and investigation of boundary conditions, i.e. the limits and extremes of different parameters within the problem space. For Zwicky, the whole point of morphological analysis and systematic “complete field
coverage” is to push consciousness to the limits of the conceivable and to facilitate discovery (Zwicky & Wilson, 1967).

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.

Computer Aided Morphological Analysis

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 risk and alternative preparedness measures for terrorist actions involving chemical and biological agents.

We have found MA especially suitable in pitting strategy models against scenarios. Thus in such studies, we develop two complementary morphological fields: one for generating different possible scenarios based on factors which 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).
These two fields can then be linked by cross-consistency assessments in order to establish which strategies would be most effective and flexible for different ranges of scenarios.

Figure 3 is an overlay model, which pits tactical scenarios against a range of artillery systems. From the left, tactical scenarios are expressed as demands placed on artillery systems. From the right, the properties of current and planed artillery systems are expressed.

The marked configuration shows a designated scenario (scenario 3) and its situational demands as "input"; with systems and system-properties as "output".

---

<table>
<thead>
<tr>
<th>Tactical scenarios</th>
<th>Purpose</th>
<th>Effect/penetration</th>
<th>Effect/precision</th>
<th>Guidance system: final phase</th>
<th>Attack attitude</th>
<th>Time to effect after decision to employ</th>
<th>Special weapon system demands/properties</th>
<th>System configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Destroy</td>
<td>Bunker buster</td>
<td>Great accuracy</td>
<td>Visual</td>
<td>Vertical</td>
<td>Within 10 sec.</td>
<td>Recognition/identification capacity</td>
<td>System 1</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Pin down, hinder, stop</td>
<td>Kinetic energy + RSV (Hard)</td>
<td>Great accuracy Limited side effects</td>
<td>IR</td>
<td>Horizontal</td>
<td>Within 1 minute</td>
<td>Command self-destruction (Abort mission)</td>
<td>System 2</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Disrupt</td>
<td>30 mm (medium)</td>
<td>Good accuracy</td>
<td>Radar</td>
<td>Within 10 minutes</td>
<td>Updateable target co-ordinates</td>
<td>System 3</td>
<td></td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Warn</td>
<td>Small-bore + fragmentation (soft)</td>
<td>Area effect -- 200x300 m</td>
<td>Acoustic</td>
<td>Within 30 minutes</td>
<td>Sensor guided warhead</td>
<td>System 4</td>
<td></td>
</tr>
<tr>
<td>Scenario 5</td>
<td></td>
<td></td>
<td>Co-ordinate guided</td>
<td>Within 1 hour</td>
<td>Pre-programmed target co-ords.</td>
<td>System 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 6</td>
<td></td>
<td></td>
<td>Basic capacity</td>
<td>Within 5 hours</td>
<td>System 6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 7</td>
<td></td>
<td></td>
<td></td>
<td>Within 24 hours</td>
<td>System 7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>More than 24 hours</td>
<td>System 8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Two superimposed fields: tactical scenarios vs. system properties.
Figure 4: Preparedness assessment for accident involving toxic condensed gas (e.g. ammonia).

Figure 4 (above) is an instrument currently being delivered to Sweden's Emergency Rescue Services. It will be used to assess preparedness for chemical accidents and, in its next application, terrorist actions involving the release of chemical agents.

The model is composed of two linked fields: a 6-parameter resource field on the left, and a 3-parameter scenario-specific response field on the right. The response field can be changed in order to express different accident scenarios and chemical releases. A rescue service "clicks" in its current level of resources (red field) and is presented with an expert-judged response preparedness level (dark blue). The light blue field shows what would be required in the form of improved resources in order to increase response levels. In this case, the resource field is treated as "input", and the response field as "output". The model can also be employed the other way around: a response level can be the designated as input, in order to see what level of preparedness resources would be required.

Morphological analysis, extended by the technique of "cross-consistency assessment", 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 cannot be treated by formal mathematical methods, causal modeling and simulation.

As is the case with all methodologies, 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.

Conclusions
References


