Fritz Zwicky, Morphologie and Policy Analysis

Tom Ritchey
Defence Research Establishment, S-17290 Stockholm, Sweden

Fritz Zwicky pioneered the development of morphological analysis (MA) as a method for investigating the totality of relationships contained in multi-dimensional, usually non-quantifiable problem complexes. During the past two decades, MA has been extended and applied in the area of futures studies and for structuring and analysing complex policy spaces. This article outlines the fundamentals of the morphological approach and describes recent applications in policy analysis.

Keywords - methodology; morphology; morphological analysis, typologies, Zwicky, analysis and synthesis, non-quantified modelling, non-causal modelling, policy analysis, policy space

> *... within the final and true world image everything is related to everything, and nothing can be discarded a priori as being unimportant. (Fritz Zwicky: Discovery, Invention, Research through the Morphological Approach.)*

INTRODUCTION

Morphological analysis (MA) was developed by Fritz Zwicky — the Swiss-American astrophysicist and aerospace scientist — as a general method for structuring and investigating the total set of relationships contained in multi-dimensional, usually non-quantifiable, problem complexes.

Zwicky applied this method to such diverse fields as astrophysics, the development of propulsive power plants and propellants, and the legal aspects of space travel and colonisation. He founded the Society for Morphological Research and enthusiastically advanced the morphological approach for some 40 years — between the early 1930 s until his death in 1974.

More recently, morphological analysis has been extended and applied by a number of analysts and researchers in the U.S.A and Europe in the field of policy analysis and futures studies. The method is presently 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 policy analysis and futures studies. This is followed by a presentation of the fundamentals of the morphological approach along with a recent application to policy analysis. Finally, a short appreciation of Fritz Zwicky is appended.

METHODOLOGICAL BACKGROUND

Analysing complex policy fields and developing futures scenarios presents us with a number of difficult methodological problems. Firstly, many, if not all of the factors involved are non-quantifiable, since they contain strong social-political dimensions and conscious self-reference among actors. This means that traditional quantitative methods, causal modelling 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 represents even a greater blow to the idea of causal modelling and simulation.

Finally, the actual 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 process of getting from initial problem formulation 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 formal (mathematical) methods and causal modelling is a form of non-quantified modelling relying on judgmental processes and internal consistency, rather than causality. Causal modelling, when applicable, can — and should — be used as a aid to judgement. However, at a certain level of complexity (e.g. at the social, political and cognitive level), judgement must often be used, and worked with, more or less directly. The question is: How can judgmental processes be put on a sound scientific 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 problem fields can be analysed into any number of non-quantified variables and ranges of conditions. Similarly, sets of non-quantified conditions can be synthesised into well defined relationships or configurations, which represent solution spaces . In this context, there is no fundamental difference between quantified and non-quantified modelling.

Morphological analysis — extended by the technique of cross consistency assessment (CCA) — 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

In almost all of his scientific work and practical activities from 1940 onwards, Zwicky used — and openly promoted — his morphological approach . Essentially, morphological analysis is a method for identifying and investigating the total set of possible relationships or configurations contained in a given problem complex. In this sense, it is closely related to typology construction, although it is more generalised in form and conceptual range.

In his main work on the subject, *Discovery, Invention, Research through the Morphological Approach* (Zwicky, 1966), Zwicky summarises the five (iterative) steps of the process:

First step.	The problem to be solved must be very concisely formulated.
Second step.	All of the parameters that might be of importance for the solution of the given problem must be localized and analysed.
Third step.	The morphological box or multidimensional matrix, which contains all of the potential solutions of the given problem, is constructed.
Fourth step.	All the solutions contained in the morphological box are closely scrutinized and evaluated with respect to the purposes that are to be achieved.
Fifth step.	The optimally suitable solutions are ... selected and are practically applied, provided the necessary means are available. This reduction to practice requires in general a supplemental morphological study.

The approach begins by identifying and defining the parameters (or dimensions) of the problem complex to be investigated, and assigning each parameter a range of relevant values or conditions. A morphological box — also fittingly known as a Zwicky box — is constructed by setting the parameters against each other in an n-dimensional matrix (see Figure 1, below). Each cell of the n-dimensional box contains one particular value or condition from *each* of the parameters, and thus marks out a particular state or configuration of the problem complex.

For example, imagine a simple problem complex which we define as consisting of three dimensions — let us say colour , texture and size . In order to conform to Figure 1, let us further define the first two dimensions as consisting of 5 discrete values or conditions each (e.g. colour = red, green, blue, yellow, brown) and the third consisting of 3 values (size = large, medium, small) . We then have 5·5·3 (= 75) cells in the Zwicky box, each containing 3 conditions — i.e. one from each dimension (e.g. red, rough, large). The entire 3-dimensional matrix is, in Zwicky s terms, a morphological field containing all of the (formally) possible relationships involved. This is what he refers to as complete, systematic field coverage .

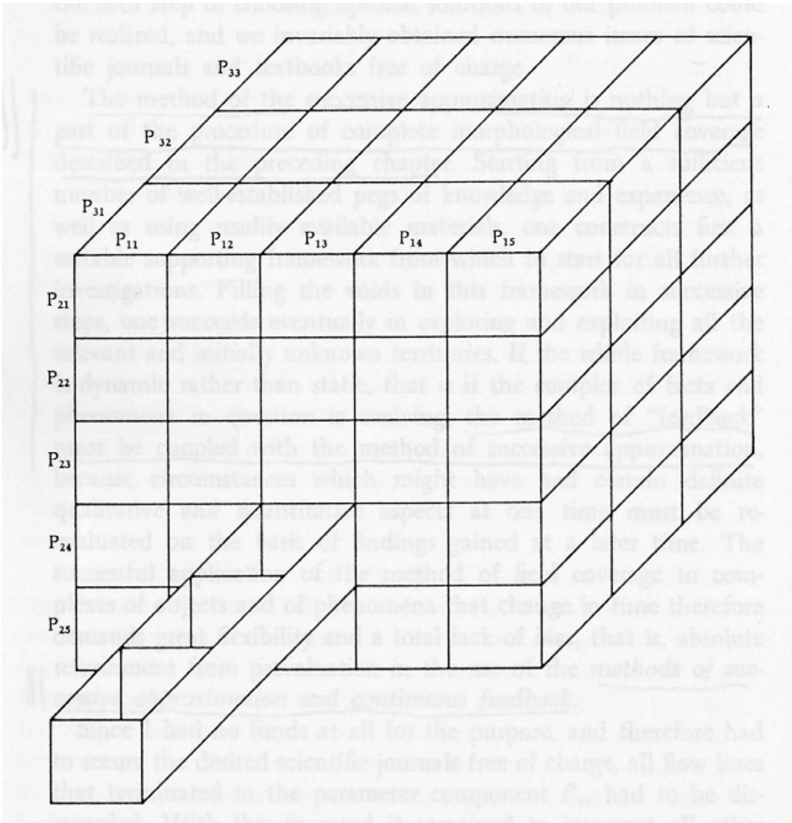

Figure 1: A 3-parameter Zwicky box containing 75 cells or configurations
(Zwicky, 1969, p. 118.)

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 what might be called a solution space. The solution space of a Zwickian morphological field consists of the subset of configurations which satisfy some criteria.

Of course, the matrixing of parameters, in order to uncover the multiplicity of relationships associated with a problem complex, is nothing new. The virtually universal use of four-fold tables and the study of typology construction as a classification technique attests to this fact (Bailey, 1994). However, Zwicky s highly systematic approach to this field (and his use of 40 dimensions and more) should not be underestimated. The method seeks both to be integrative and to explore the boundary conditions of complex problems. Used properly — and on the right types of problem complexes — the method is deceptively complex and rich.

> 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)

The morphological approach has several advantages over less structured approaches. Zwicky calls MA totality research which, in an unbiased way attempts to derive all the solutions of any given problem . It may help us to discover new relationships or configurations which may not be so evident, or which we might have overlooked by other — less structured — methods. Furthermore, it encourages the identification and investigation of boundary conditions, i.e. the limits and extremes of different contexts and problems.

It 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 (see below).

One apprehension that has been voiced against MA is that it is *too* structured — too much German *Grundligheit* — and that this risks inhibiting free, creative thinking. Zwicky would turn in his grave. For him, 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, not to obstruct it. Properly applied, morphological analysis offers an excellent balance between freedom and (necessary) constraints.

Two simple examples of morphological analysis may suffice to illustrate the principles of the method. The first of these is an example which Zwicky himself presents in his cited book. As a preparatory step in the investigation of new propulsive systems, Zwicky matrixed a list of energy forms against itself in order to examine every possible form of energy conversion.

Suppose we wanted to investigate such conversions in three steps instead of two (in this example I have shortened the list of energy forms to five.)

I = **I**nitial energy form
T = **T**ransmission form
S = Final **S**torage form

I	T	S
K (Kinetic)	K	K
E (Electrical)	**E**	E
C (Chemical)	C	**C**
T (Thermal)	T	T
N (Nuclear)	N	N

Figure 2: Energy Conversion Matrix (example)

This particular matrix involves 5^3 (=125) possible configurations, each of which can be examined from the point of view of possibility, practicability, effectiveness, applications, or whatever criteria are relevant for the problem at hand. (Note that this matrix is simply a transformation of the 3-dimensional Zwicky box in Figure 1. The marked configuration K->E->C, for instance, represents a single cell in the box.)

For example, K->E->C can represent hydroelectric generation which is then stored in a battery. C->T->K could represent an internal combustion engine (chemical energy transformed into thermal energy) leading to energy being stored in a fly-wheel. E->C->T represents a refrigerator.

Even this simple example is surprisingly complex. Zwicky examined single conversions for 10 different energy forms in a 2-dimensional matrix. Try it — and you will be surprised about how much you learn about energy.

A second example is drawn from work that the my agency — the Swedish Defence Research Establishment (FOA) — has done concerning the future of the Swedish bomb shelter program (Lindqvist & Wulff, 1994). During the Cold War period, Sweden invested large sums of money annually in the planning, building and maintenance of these shelters. With the end of the cold war, the shelter program — its form, usefulness and expense — has come under greater scrutiny. This problem, which has aspects of both policy analysis and a futures study, is eminently suited for morphological analysis.

The first problem was to identify and properly define the dimensions of the problem — that is to say, the relevant *issues* involved. These include technical, financial, political and ethical issues. One of the advantages of MA is that there are no formal constraints to mixing and comparing such different types of issues. On the contrary, if we are really to get to the bottom of the policy problem, we must treat all relevant issues *together*.

Secondly, for each issue (parameter), a spectrum of values must be defined. These values represent the possible, relevant conditions that each issue can assume. For instance, if one of the relevant issues is shelter size, then we can — with the proper expert group present or consulting from a distance — determine all possible size differentiations. In this case, in the (simplified) example below, we distinguish only between small and large . (Note that the *size* column in fact consists of a four-fold table, where we have combined two binary relationships — size and degree of crowding — into a single parameter.)

A portion of the policy space that was finally developed is presented in Figure 3, below. (It has been reduced from its original ten parameters to six.)

This segment of the shelter matrix contains 2304 possible configurations, one of which is shown in the figure. (The number of possible configurations is the product of the number of conditions under each parameter: 4x4x4x3x3x4). It is fairly easy — by hand — to identify and mark out a few dozen realistic policy configurations. Examining *all* possible configurations, however, would take a good deal more time and effort. Furthermore, the original 10-dimensional shelter matrix contained more than 100,000 possible configurations — far too many to deal with by hand.

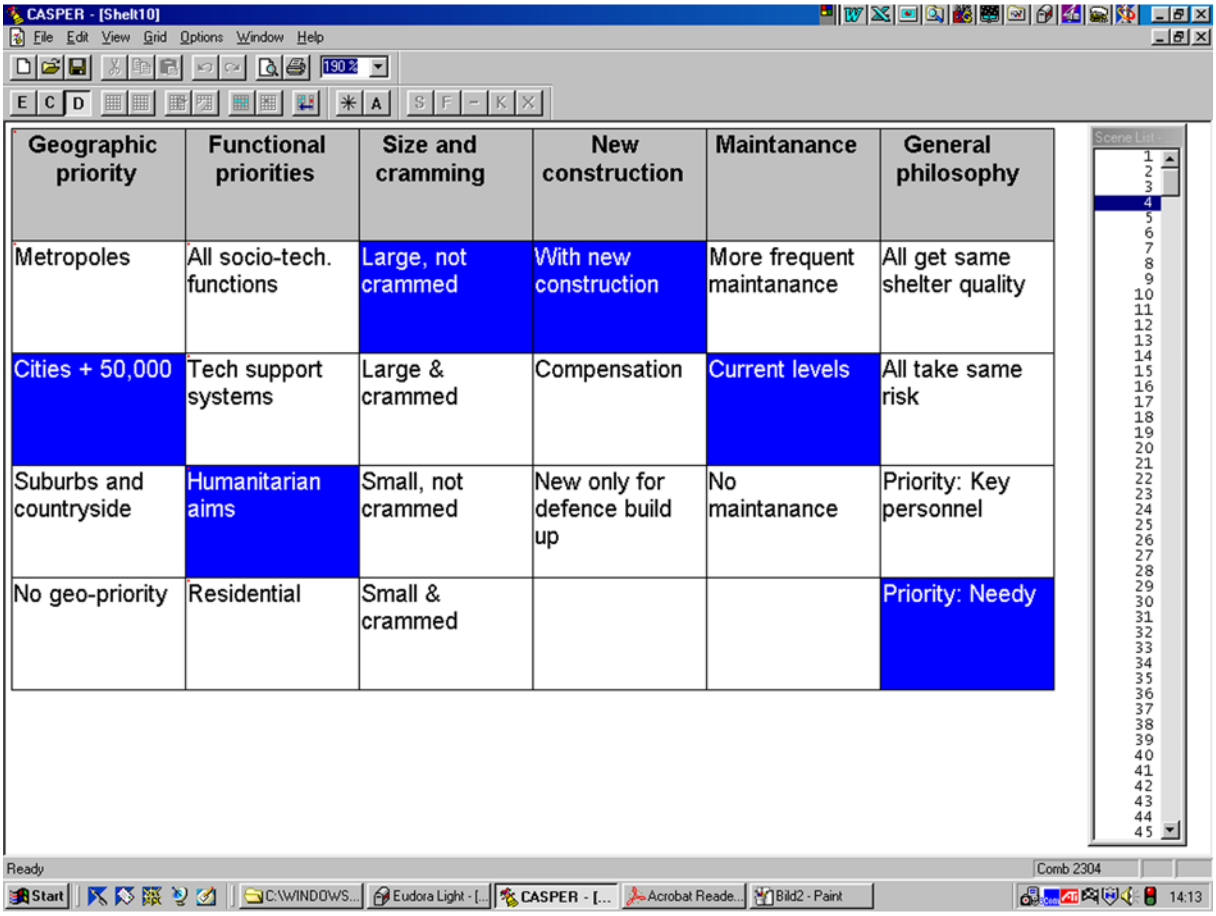

Figure 3: Segment of morphological field for the Swedish bomb shelter program showing one of 45 possible policy solutions.

ANALYSIS AND SYNTHESIS OF COMPLEX POLICY SPACES

This example brings up the problem of the practical limits of classical morphological analysis, and sets the stage for a discussion how this procedure — with computer support — has been extended into a useful group-oriented method for structuring and analysing complex policy spaces.

The main extension that has been developed for MA is a more structured and traceable procedure for reducing the total set of (formally) possible configurations in a morphological field to a smaller set of internally consistent configurations representing a solution space . The extension — specifically developed for working with futures scenarios — was developed independently by Russell Rhyne at Johnson Research Associates in California (Rhyne, 1981), and by Ute von Reibnitz working at Batelle in Switzerland (Reibnitz, 1987). Rhyne named the technique Field Anomaly Relaxation (FAR), whereas von Reibnitz refers to internal consistency analysis . For more pedagogical reasons I will call the technique cross-consistency assessment (CCA).

CCA is based upon the insight — at least as concerns complex policy spaces and scenario spaces — that there may be numerous pairs of conditions in the morphological field which are mutually inconsistent or contradictory. For instance, in the Shelter Program matrix (Figure 3), the condition All (citizens) take the same risk is incompatible with that of No geographical priority — if it is assumed that an adversary would indeed make geographical priorities by concentrating on bombing larger cities. Similarly, the shelter philosophy of All get same shelter quality is not consistent with the functional priority of concentrating on personnel responsible for Technical support systems .

Thus not all combinations of conditions are logically consistent or plausible. To the extent that a particular pair of conditions is considered to be a blatant contradiction, *then all those configurations containing this pair of conditions would also be internally inconsistent*.

In this way, configurations containing incompatible or contradictory relationships are relaxed , or weeded out of the total set of possible configurations. This is done by a process of cross-consistency assessment. A cross-impact matrix is constructed which sets each condition against every other condition, in a pair-wise manner (Figure 4). Each pair of conditions is then examined, and a judgement 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. (Rhyne uses a binary scale, indicating a relationship as either consistent or contradictory. Von Reibnitz uses a five level scale. At FOA we vary the scaling depending on the nature of the problem complex under study.)

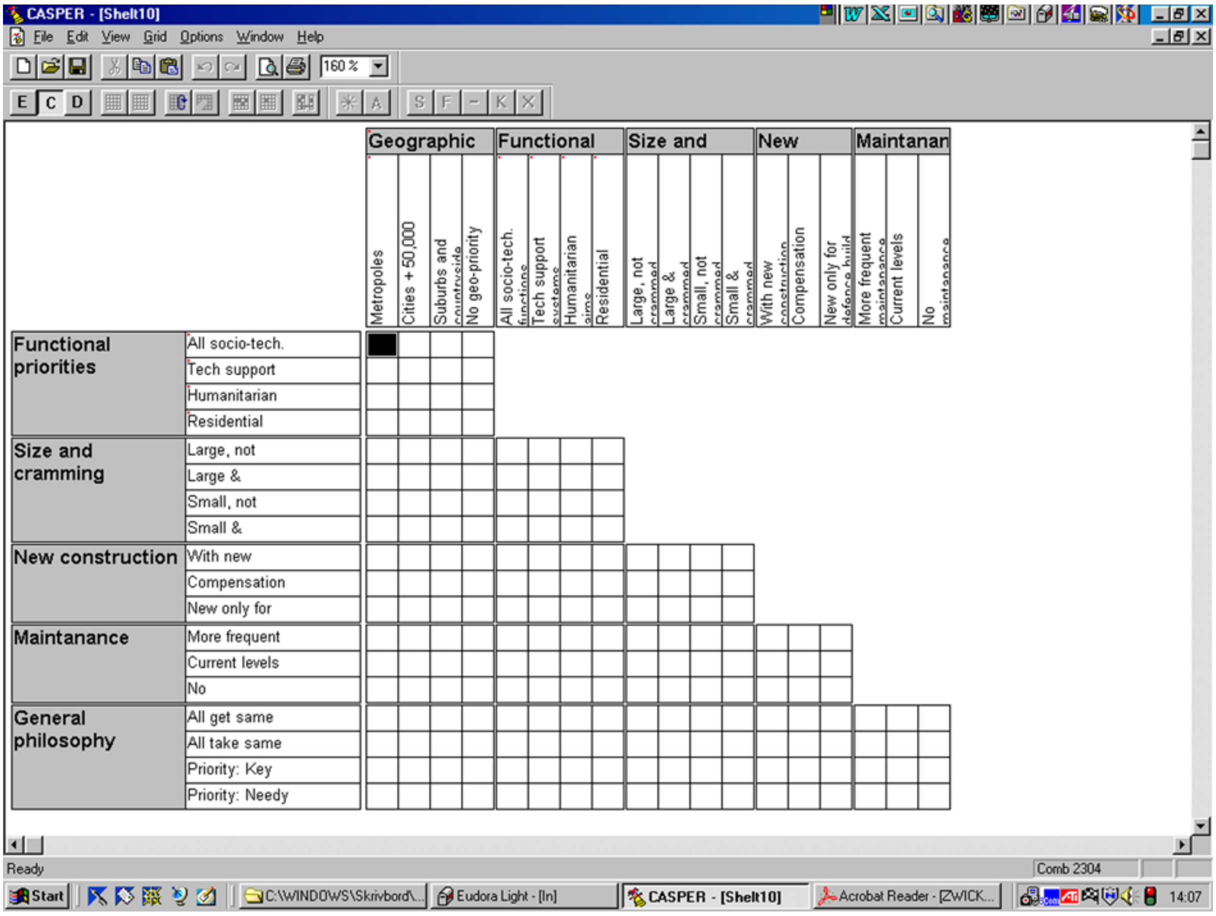

Figure 4: Cross-consistency matrix

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 only as 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 50,000 formal configurations requires no more than 450-550 pair-wise evaluations in order to create a solution space.

When one then examines all of the possible pair-wise relationships and all the possible configurations in a matrix (and for this it is handy to have a computer, which is just the thing to examine and rank 50,000 configurations), it is usually the case that 99% or more of the configurations are relaxed , i.e. they fall out of the running because they contain some sort of internal contradiction. This allows one to concentrate on a manageable number (50-500) of internally consistent configurations. These can then be ranked and examined as elements of scenarios or specific solutions in a complex policy space. (For this purpose, FOA has developed a Windows-based software package which supports the entire MA/CCA process. The program is called *CASPER*: Computer Aided Scenario and Problem Evaluation Routine.)

Both the morphological field itself, and the assessments put into the cross-consistency matrix, represent a fairly clear audit trail , which makes the judgmental processes inherent in MA relatively traceable, and — in a certain sense — even reproducible. At present we are planning trials in which identical morphological fields are presented to different groups for cross-consistency assessment. Comparing the results, and bringing the groups together to discuss diverging assessments, will not only help us to better understand the nature of the policy issues involved, but will also tell us something about the effects of group composition on the assessments.

CONCLUSIONS

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, non-quantified method for investigating problem complexes which cannot be treated by formal mathematical methods, causal modelling and simulation.

Of course, as is the case with everything else, the output of an analysis-synthesis cycle 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 sloppy parameter definitions 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 policy analysis and futures studies certainly need more of.

FRITZ ZWICKY - A SHORT APPRECIATION

Fritz Zwicky is not a household name in science today. He was not a superstar of the likes of Einstein, Hubble or Oppenheimer. Yet his influence was significant — far more so, I believe, than his lack of present-day notoriety would suggest. He was one of the broadest and most inventive scientists of his day, and combined theoretical studies with eminently practical, humanitarian activities.

Zwicky was born in Varna, Bulgeria, in 1898, the son of a Swiss merchant. At the age of 6 he was sent to his father s ancestral district in Switzerland, Glarus, for schooling. Although expected to take up a career in commerce , Fritz early bent for science apparently persuaded his father to allow him to study engineering instead.

In 1914 he moved to Z rich where he subsequently enrolled in the Federal Institute of Technology (Eidgwen ssische Technische Hochschule). There he switched to mathematics and experimental physics, wrote his examination essay for no one less than Herman Weyl, and in 1922 took his doctorate with a dissertation on ionic crystals. Three years later he moved to the California Institute of Technology in Pasadena to work with, among others, the great experimental physicists Robert Millikan.

From this point on, Zwicky more or less worked out of Pasadena, both as a faculty member of Caltech (1927-68) and research director/consultant for Aerojet Engineering Corporation (1943-61). He became Professor of Astrophysics at Caltech in 1942 and was a member of the staff of Mount Wilson and Palomar Observatories until his retirement in 1968.

Zwicky has been described as brilliant, irascible and a notorious maverick in science. He thrived on investigating and theorising about extreme phenomena or, more correctly, the boundary conditions of different problems. Primarily known for his work in astrophysics, he was overshadowed by Edwin Hubble, who made really great astronomical/cosmological discovery of the century.

However, a number of Zwicky s findings and hypotheses represented significant breakthroughs. In 1933 he applied the virial theorem to the Coma cluster of galaxies and obtained evidence of unseen mass — thus starting off the debate on what is now called dark matter . A year later, pursuing the idea that bright novae were of fundamental interest for determining the distance to far-off galaxies, he and Walter Baade coined the term supernova . These, he proposed, marked the transition from ordinary stars to neutron stars and were the origin of cosmic rays. This was an amazing (and correct) triple hypothesis and was an important step in the still on-going project to determine the size and age of the (visible) universe. (Zwicky s neutron star-hypothesis finally entered mainstream astronomy in the late 1960 s). In 1937 he proposed that galaxies could act a gravitational lenses.

Besides numerous other contributions to astrophysics — including a long-term program of cataloguing galaxies and clusters of galaxies — Zwicky was active in the aerospace industry. He was a co-founder of Aerojet Engineering and was involved in the development of jet and rocket propulsion systems (for which he obtained a number of patents attributed to the morphological approach). Just after WWII, he was appointed head of the U.S. Airforce teams that went to Germany and Japan to evaluate wartime research on jet propulsion.

On top of all this, Zwicky was engaged in a number of charitable activities, including his work to help rebuild scientific libraries destroyed during the war and participating in the Pestalozzi Foundation s program to establish war orphan villages. He was also vice president of the International Academy of Astronautics, where he promoted a program of space law .

REFERENCES

Bailey, K. (1994). *Typologies and Taxonomies - An Introduction to Classification Techniques*, Sage University Papers: Sage Publications, Thousand Oaks.

Greenstein J. & Wilson A. (1974). Remembering Zwicky. *Engineering and Science 37*:15-19.

Lindqvist S. & Wulff P. (red.) (1994). *Studieuppdrag 11: Fysisk Skydd*, Bilaga till FOA skrivelse 94-4700/S: FOA: Stockholm.

Rhyne, R. (1981). Whole-Pattern Futures Projection, Using Field Anomaly Relaxation. *Technological Forecasting and Social Change* 19, 331-360.

Ritchey, T. (1991). Analysis and Synthesis - On Scientific Method based on a Study by Bernhard Riemann. *Systems Research 8*(4):21-41.

Ritchey, T. (1997). Scenario Development and Risk Management using Morphological Field Analysis. *Proceedings of the 5th European Conference on Information Systems (Cork: Cork Publishing Company) Vol. 3*:1053-1059.

Reibnitz, Ute von (1987). Szenarien - Optionen f r die Zukunft: Mc Graw-Hill, Hamburg.

Zwicky, F. (1966). *Entdecken, Erfinden, Forschen im morphologischen Weltbild.* M nchen/Z rich: Droemersche Verlagsanstalt Th. Knaur Nachf.

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

Zwicky, F. & Wilson A. (eds.)(1967). *New Methods of Thought and Procedure: Contributions to the Symposium on Methodologies*. Berlin: Springer