Acta Morphologica Generalis *AMG Vol. 4 No. 1 (2015)*
© Swedish Morphological Society *ISSN 2001-2241*

Applications of General Morphological Analysis

From Engineering Design to Policy Analysis

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Abstract: Since its conception and development in the late 1940's by Fritz Zwicky at the California Institute of Technology (Caltech), the "morphological approach" – or *General Morphological Analysis* (GMA) – has been applied to many diverse areas of study, from engineering design and technological forecasting to policy analysis, organisational development and creative writing. This article outlines the numerous applications of GMA developed since the 1950's and gives examples from some 80 published articles. Early examples of Zwicky's work are also described and an overview of modern, computer-aided GMA is presented.

Keywords: General morphological analysis, non-quantified modelling, engineering design, scenario development, policy analysis, product design, design theory, technological forecasting, Fritz Zwicky.

1. Introduction and background

The term "morphology" (from the Greek μορφή, morphé = form) is used in a number of scientific disciplines to refer to the study of the *structural relationships* between different parts or aspects of the object of study. For example, in biology, morphology is the study of the form and structure of organisms and their specific structural features; in linguistics, it is the branch of grammar that studies the structure of forms of words, mainly through the use of the morpheme construct; geomorphology is the study of landforms and the processes that shape them; urban morphology is the study of the form of human settlements and the process of their formation.

In this context, "morphological analysis" refers to the analysis of structural relationships within the particular scientific discipline where this term is used. However, in the 1940s and 50s, Fritz Zwicky, the Caltech astrophysicist, *generalised* the "morphological approach" as a method for structuring and analysing *any type* of multi-dimensional, essentially non-quantified problem complex.

> "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, 1969, p. 34)

Zwicky applied *general morphology* to a number of different fields of enquiry including astronomy, engineering design (especially jet and rocket propulsion systems), social policy, legal systems and ethical issues – in fact any complex social-technical problem that requires "… an integrated view which relates ... technical, political, psychological and ethical factors. … All of these factors add up to a complex task which is beyond the power of ordinary scientific, technical and managerial experts." (Zwicky, 1960).

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This breadth of application is not surprising, given that General Morphological Analysis (GMA) is essentially a *general method for non-quantified modelling*. However, to date there is no overview of the literature in GMA, and no classification of the diverse areas of study to which it has been applied. For this purpose, we have attempted to categorise the *main areas* in which GMA has been applied to date. We have settled on the following:

- Engineering and product design
- General design theory and architecture
- Futures studies and scenario development
- Technology foresight/technological forecasting (broken out of Futures Studies)
- Management science, policy analysis and organisational design
- Security, safety and defence studies
- Creativity, innovation and knowledge management
- Modelling theory, OR methods and GMA itself

Some comments are in order here. Firstly, this classification was not developed according to any deeper theoretical considerations. It is mainly based on two decades of working with GMA in different contexts. Its aim is to provide an intuitive overview of how and for what purpose GMA has been/can be applied, rather than attempting to formulate a strict taxonomy. As can be seen, these categories are hardly water-tight: they are not all on the "same level" so to speak, and there is a good deal of overlap between them. For this reason, many of the articles presented here could well fit into more than one of the categories (although we have chosen not to do this).

There are also a good many examples of studies employing GMA which are not captured in any of these categories (unless we allow for the category of "general design theory" to cover all stray dogs). During the past 20 years, numerous enquiries have been made, and in some cases studies carried out, concerning the most varied of structural forms, e.g. morphologies of psychotherapeutic procedures; of techniques in the plastic arts; of story-line development for screenplays; of facilitation techniques and methods of group counselling.

Finally – and perhaps needless to say – this is a survey aimed at presenting *relevant examples* of the varied applications of GMA, not an attempt to give an *exhaustive presentation* of the literature. We have undoubtedly missed some relevant works, and we apologise if we have overlooked any important contributions. In this context, it should also be kept in mind that the concept of "morphological analysis" (or the "morphological approach") as a method for creative thinking and problem structuring is *mentioned* in hundreds – if not thousands – of articles from the 1960's forward. We do not include such articles, but only those whose focus is actually on applying GMA.

A personal note from co-author Tom Ritchey: I apologise for the fact that so many of my own contributions are included here. Initially, I chose to limit the number of "Ritchey articles" to one per category – in hopes of avoiding being branded a self-aggrandising twit. However, some of my colleagues pointed out that many of the articles that I had decided not to include treated important methodological issues concerning modern GMA, and that I would be a bigger twit if I left them out. They also said that I should have the guts to "take the flack" if need be. So be it.

For those readers who are not previously acquainted with GMA, a brief theoretical and methodological overview is provided in **Section 11**. If you are new to this area, things will make more sense if you read this first.

2. Zwicky's early work with GMA

Fritz Zwicky's original work with general morphology was in the fields of astrophysics and engineering design. The three examples presented here represent some of the earliest work done with GMA. They are presented purely for historical reasons, to show how Zwicky conceived of the "morphological approach" relatively early on.

Two of the examples are taken from Zwicky's visionary work in astrophysics: *Morphological Astronomy* from 1948 (also expanded and published in book form in 1957). Here Zwicky proposes the application of morphological methods in order to "gain an overall perspective of what still can be done, of what is possible with available means and manpower and what might come if these means were radically expanded beyond those presently realized".

Example 1: Designing a new type of telescope

Zwicky uses this first example mainly as an exercise to show how the morphological approach works. After initially formulating the problem to be studied (which sometimes is a formidable, *iterative* task in itself), one begins by identifying and designating all of the possible *quantitative and non-quantitative parameters that are relevant to the problem*. In this case, it would consist of all possible attributes of telescopes and their performance characteristics. For instance, one significant parameter would be the ratio **r** of the energy entering the telescope aperture to the energy absorbed in the recording instrument. This ratio might be:

$$A_1\text{: } r > 1; \quad A_2\text{: } r \cong 1; \quad A_3\text{: } r < 1$$

A second parameter could list all the recording devices available (i.e. photographic plates, ionization chambers, photocells, etc.). A third parameter could describe "the type of interaction of the light with the optical parts of the telescope", e.g. reflection, diffraction, refraction, etc.

Thus an array of parameters, represented by their respective (discrete) values ranges, is given in the matrix in Figure 1. This is the original form that Zwicky gave to a *morphological field* that came to be called an n-dimensional *Zwicky Box*.

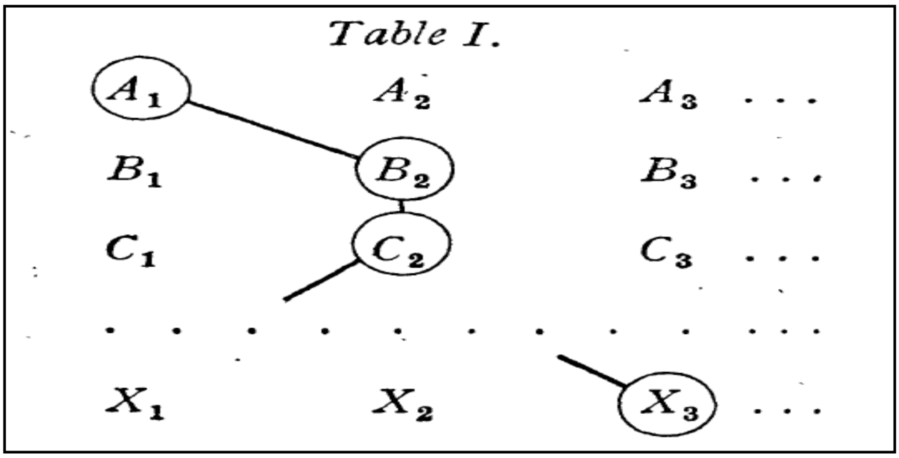


Fig. 1: Zwicky's original representation of the morphological field for an X-dimensional problem, with one "solution" displayed (circles). (From Morphological Astronomy, 1948).

If the number of elements in each parameter is respectively n_A, n_B, n_C, ... n_X, then the total number N of types of possible telescopes is $N = n_A \bullet n_B, \bullet n_C ... \bullet n_X$. In Fig. 1, one of these possible combinations of parameters is displayed in ($A_1 + B_2 + C_2 + \ldots + X_3$).

One then carries out a *performance analysis of the telescopes arising from each of all the possible combinations arrived at.* This process represents two strangely superimposed (and what might seem to be mentally contradictory) tasks: on the one hand, of identifying combinations of attributes which are seen to be logically impossible or empirically implausible – and discarding them; and on the other hand, of keeping one's mind open for the discovery of strange and novel combinations that we may not hitherto have imagined. (This exhaustive method of examining each possible "configuration" can be done if the model is small enough. Already 6 parameters, each containing 4 attributes, will result in 4096 possible combinations.)

Example 2: The general problem of astronomy

Zwicky then goes on to outline the more ambitions challenge of showing how the morphological method might be applied to "the general problem of astronomy", which would include the following areas:

(a) Observation of celestial phenomena
(b) Experimentation with celestial phenomena
(c) Theoretical integration
(d) Use of the knowledge gained in construction
(e) Dissemination of the knowledge and its bearing on all activities of Man.

Note that these areas, in turn, can each be studied as (initially) separate small morphological models. He thus breaks down the "Observation of celestial phenomena" into the following parameters:

(α) The instruments to be used for observation
(β) The location of these instruments
(γ) The alternative of manned and unmanned instruments
(δ) The objects of observation (divided into (δ_1) the contents of the universe and their quantitative and qualitative nature, and (δ_2) the physical laws governing the interactions of the celestial bodies and the general fields

Although Zwicky does not go on to formulate a full morphological field for these parameters, it could look something like Figure 2, rendered in contemporary GMA field-format.

The instruments to be used for observation	**The location of instruments**	**The alternative of manned and unmanned instruments**	**The objects of observation**
Telescopes for different wave-lengths: E.g. gamma ray to radio telescopes	Earth-bound observatories	Manned re-entry recovery	The contents of the universe and their quantitative and qualitative nature
Photo-electric telescope (e.g. CCD)	High flying aircraft	Unmanned re-entry recovery	The physical laws governing the interactions of the celestial bodies and the general fields
Neutrino detectors	Balloons	Telemetrics back to earth	
Gravitational wave detectors	Non-orbiting rockets		
Dark matter detectors	Earth-orbiting satellites		
	Moon-based		
	Interplanetary		
	Interstellar		

Figure 2. Hypothetical morphological field for Zwicky's outline for "Observation of celestial phenomena". Note that the parameter "The objects of observation" could be turned into two separate parameters, each broken down into a number of sub-categories.

Example 3: A Morphology of Propulsive Power

The third example is taken from one of Zwicky's most well known works in the area of engineering design: "Morphology of Propulsive Power" (Zwicky, 1962). Here he categorised and exemplified 576 theoretically possible modes of propulsion systems using six parameters (Figure 3).

Character of chemical reactions	Mechanical character of propulsion system	Method of thrust augmentation	Physical state of propellants	Operating mode of propulsive power plant	Reactivity or Reaction Speed of the Propellants
Self-contained - carries all chemicals necessary for activation and operation.	No motion	No thrust augmentation.	Gaseous state.	Continuous operation.	Propellants are self-igniting.
If air-propelled, carries only fuel and uses atmospheric oxygen.	Translatory motion.	Internal thrust augmentation.	Liquid state.	Intermittent (pulsating) operation.	Artificial ignition is necessary.
If propelled through or over water, uses water as propellant reacting with an on-board water-reactive chemical.	Rotary motion.	External thrust augmentation.	Solid state.		
If propelled through or over the earth may use earth as propellant reacting with an on-board earth-reactive chemical.	Oscillatory motion.				

Figure 3. Zwicky's propulsive power morphology from 1962, containing six dimensions (parameters) and 576 (4x4x3x3x2x2) formal configurations – one displayed.

While *Morphological Astronomy* and *Morphology of Propulsive Power* remain among his most well known works, Zwicky made scores of morphological studies from the late 1940's until his retirement in 1969. Many of these still languish, unpublished, in the Zwicky Archives in his home town of Glarus in Switzerland. However, we can get an idea of the diversity of his work in some of his other published studies. These include "Morphology of Justice in the Space Age"; "Morphology of Multi-Language Teaching"; and "Morphology of Codes of Conduct in Law and the Administration of Justice". All of Zwicky's publications are listed on the site of the Fritz Zwicky Stiftung, at: www.zwicky-stiftung.ch. There is also a recent English language biography published by the Stiftung:

- Ströckli, A. & Müller, R. (2011) *Fritz Zwicky: An Extraordinary Astrophysicist*, Cambridge Scientific Publishers.

A review of this biography is available online:

- Book Review: "Fritz Zwicky: An Extraordinary Astrophysicist" by Tom Ritchey. *Acta Morphologica Generalis*, 1(3), 2012. [http://www.amg.swemorph.com/pdf/amg-1-3-2012.pdf]

There are also two available summaries of Zwicky's life and work:

- *Remembering Zwicky* by Jesse Greenstein and Albert Wilson. *Engineering and Science* 37:15-19, 1974. [http://calteches.library.caltech.edu/3021/1/zwicky.pdf]

- *Idea Man* by Stephan M. Maurer. *Beamline*, 2002. [http://www.slac.stanford.edu/pubs/beamline/31/1/31-1-maurer.pdf]

3. Applications in Engineering and Product Design

GMA is an ideal fit for engineering design, given the large number of diverse variables generally involved in engineering problems. Indeed, engineering design was one of the main applications for GMA from its beginnings (see K.W. Norris, below). With far more advanced IT techniques now available, the application of GMA to engineering and product design is becoming more widespread. Here are examples of some of the many articles available.

3.1 The morphological approach to engineering design (1963)

Norris, K. W. (1963) “The morphological approach to engineering design”, in J. C. Jones and D. G. Thornley (eds), *Conference on Design Methods*, New York: Macmillan.

This is the classic, often cited forerunner in applied morphological analysis (other than Zwicky’s own work). It describes how “the morphological approach” was applied by a pioneering engineering firm – the Norris Brothers in Sussex, England – in a historical milestone in engineering design: the development of the Bluebird hydroplane and cars, which set eight world speed records. Ken Norris outlines his interpretation of the morphological approach to engineering design, giving various examples to showcase its strengths and potential weaknesses. Norris proposes establishing standard terms for the design process in general and the morphological approach in particular in order to aid education and discussion. He also proposes investigating the possibility of using computers to “separate and collate solutions… so that the elimination procedure becomes more automatic and less dependent upon the engineer’s intuition”. A more detailed presentation of the Norris brothers’ work with GMA is given in the article:

Álvarez, A. (2014) “The Norris Brothers Ltd. morphological approach to engineering design – an early example of applied morphological analysis”. *Acta Morph Gen*, 3(2). [Available at: http://www.amg.swemorph.com/pdf/amg-3-2-2014.pdf]

3.2 Long-range process design (1968)

Bridgewater, A. (1968) "Long Range Process Design and Morphological Analysis", *The Chemical Engineer*, April 1968.

Bridgewater, a great proponent of GMA, advanced it in a number of areas, including *Technological Forecasting* (see /u). This is one of the earliest applications after Norris’ initial article.

3.3 Morphology in systems engineering (1969)

Hall, Arthur D. (1969) "Three-Dimensional Morphology of Systems Engineering", *IEEE Transactions on Systems Science and Cybernetics*, 5(2).

From the abstract: “This valuable approach is essentially a search technique for piling up alternatives in a design problem. In this paper the technique will be used to present a new and simple model of the field of systems engineering that may be useful in surprising ways”.

3.4 Analysis of the design space of input devices (1991)

Card, S., Mackinlay, J. & Robertson, G. (1991) “A Morphological Analysis of the Design Space of Input Devices”, *ACM Transactions on Information Systems*, 9(2). Xerox Palo Alto Research Center.

In 1991, three researchers at the Xerox Palo Alto Research Centre published a paper on a way to systematise input devices for communication between humans and computers by means of morphological analysis. In particular, they used a morphological matrix to show why a "mouse" is a more effective input device than a "head-mouse", and where in the design space there is likely to be a more effective device than the "mouse".

3.5 Morphological analysis for product design (2000)

Belaziz, M., Bouras, A. & Brun, J-M (2000) "Morphological analysis for product design", *Computer-aided Design* - CAD , 32(5-6).

This article describes how morphological analysis can be applied in Computer-Aided Design (CAD). It contributes highly in product optimisation while decreasing design cost and time. For analysis applications, the adaptation of the product geometry is required and consists of producing an idealised model from a "solid" product. This tool is based on a morphological analysis of the solid model followed by a two-phase process: simplification and idealisation.

3.6 Morphological analysis for innovative mechanical design (2005)

Dartnall, J. & Johnston, S. (2005) "Morphological Analysis (MA) leading to Innovative Mechanical Design", *International Conference on Engineering Design,* Iced 05, Melbourne.

Morphological Analysis is applied to a conceptual design where the designer is attempting to exhaustively search a defined design space in order to select the most appropriate (innovative) design solution. The essence of the methodology is that the designer should be looking for new opportunities and for contradictions, and be prepared to modify a previously defined exhaustive morphological procedure as new information surfaces. In the case study presented here, the initial search was to find all the ways to assemble the basic elements of down-hole water lifting piston pump.

3.7 Integrated Design and Manufacturing (2005)

Gogu, G. (2005) "Evolutionary Morphology", in Bramley, A, Brissaud, D., Coutellier, D. & McMahon , C. (2005) *Advances in Integrated Design and Manufacturing in Mechanical Engineering*, Springer.

From the abstract: "The paper presents a new structured approach to inventive engineering design, called evolutionary morphology (EM), as proposed by the author of this article. In the first part of the paper we present the main paradigms and the formalization of this new method integrating morphological and evolutionary approaches. EM and evolutionary algorithms are in fact complementary methods. The main EM paradigms are inspired by the synthetic theory of evolution developed by modern biology."

3.8 Application to the design of a robotic laparoscope (2009)

Villegas Medina, G., Pham, M. & , Marquis-Favre, W. (2009) "A Modified Zwicky's Morphological Analysis: Application to the design of a robotic laparoscope", Proceedings of the International Federation for Medical and Biological Engineering (IFMBE), (22).

From the abstract: "This paper deals with a Modified Zwicky's Morphological Analysis procedure whose the main goal is to reduce the analysis time by introducing a weight and preference coefficients with respect to sets of criteria. The proposed method is applied to the design of a laparoscopic flexible system. A discussion of the results is presented in order to show the implications of the procedure but also to highlight the possible improvements."

3.9 The development of morphological analysis in Systems Engineering (2010)

Jimenez, H. & Mavris, D. (2010) "An Evolution of Morphological Analysis Applications in Systems Engineering", Proceeding of the 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Orlando, Florida.

Morphological analysis is described as a simple yet powerful technique that has been incorporated in many different forms within systems engineering and design applications. Its relevance in systems engineering lies in the way that it supports the practical implementation of system decomposition and synthesis, recognized as fundamental systems engineering concepts. Recent advances in its implementation are discussed, leveraging on new mathematical formulations and software development. This had addressed some of the earlier shortcomings and reveals an evolution of this technique across multiple systems engineering applications.

3.10 Design of modular systems (2012)

Levin, M. S. (2012) "Morphological methods for design of modular systems (a survey)", *arXiv:1201.1712v1.*

From the abstract: "This article is a technical survey of morphological approaches to the design of modular systems using a number of different mathematical/combinational methods and techniques. Several MA-based system design approaches are described, where is deemed useful to extend MA based approaches in engineering, computer science, and management, e.g. the use of morphological methods in allocation (layout, positioning) problems and using morphological methods in combinatorial evolution and forecasting of modular systems."

3.11 Design of production systems (2012)

Ostertagová, E., Kovác, J., Ostertag, O. & Malega, P. (2012) "Application of Morphological Analysis in the Design of Production Systems", *Procedia Engineering,* 48.

This paper describes morphological analysis applied to production process design. In this analysis, the basic functions of a production system are defined, and lists of all possible variations are created (building elements or subsystems). Then all the possible combinations of the building elements are generated. The next step is the identification of applicable variants in practice ("acceptable solutions"). This is described as an iterative process which ultimately leads to a final reduction whereby the final variants are selected according to decision analysis as well as on the basis of certain limiting factors.

4. Applications in (General) Design Theory and Architecture

In contrast to Engineering and Product design, (general or conceptual) Design Theory and Methodology today encompasses an essentially unbounded domain. Already in the early 1990s, Richard Buchanan could write:

> *"Despite efforts to discover the foundations of design thinking in the fine arts, the natural sciences, or most recently, the social sciences, design eludes reduction and remains a surprisingly flexible activity. No single definition of design, or branches of professionalized practice such as industrial or graphic design, adequately covers the diversity of ideas and methods gathered together under the label. Indeed, the variety of research reported in conference papers, journal articles, and books suggests that design continues to expand in its meanings and connections, revealing unexpected dimensions in practice as well as understanding." (Buchanan, R. "Wicked Problems in Design Thinking", Design Issues: Vol. 8, Number 2, 1992, p5.)*

4.1 Conceptual design using a synergistically compatible morphological matrix (1989)

Weber, R.G. & Condor, S.S. (1989) "Conceptual design using a synergistically compatible morphological matrix", *FIE '98 Proceedings of the 28th Annual Frontiers in Education*, 1.

From the abstract: "The morphological matrix is a key methodology that can improve the effectiveness of the concept generation phase of the design process. However, as discussed in the paper, there are difficulties identifying independent design functions and determining the synergistic compatibility of combining solution alternatives. In order to address these difficulties, the authors extend the morphological matrix methodology by including the theory of coupling. A case study is presented to illustrate the overall methodology and its impact."

4.2 Generating design solutions (1997)

Evbuomwan, N. (1997) "Generation of Design Solutions using Morphological Analysis", *International Conference on Engineering Design*, Iced 97, Tampere.

From the abstract: "The generation of conceptual designs is a principal activity within the design process, which places a high demand on the designer to use engineering science, practical knowledge, production methods, commercial and marketing considerations in making a viable design decision. In general, designers tend to rapidly choose a single design solution, which is then continuously refined until a good solution is found. The adoption of this approach limits the propensity for developing innovative and creative designs, due to the lack of exploring the design solution space. The ability to create a variety of products satisfying a wide range of customers is imperative, if manufacturing companies are to remain competitive. Hence the need for a systematic approach to the generation of innovative design concepts. This paper aims to demonstrate the application of the Morphological Analysis technique for the generation of conceptual design solutions within the Design Function Deployment design system."

4.3 Computer-supported methodology for the conceptual planning process (2000)

Bezerra, C. & Owen C. L. (2000) "Evolutionary Structured Planning. A Computer-Supported Methodology for the Conceptual Planning Process", in J.S. Gero (ed.) (2000). *Artificial Intelligence in Design'00*, Kluwer Academic Publishers, Dordrecht.

This paper describes a computer-supported method for complex decision-making in design, with origins in Morphological Analysis and Structured Planning (a computer-supported design planning process). The authors argue that complex design decisions require not only the use of information from the artifactual world (objective, quantitative data), but also from the world of culture (subjective, qualitative data). This paper describes Evolutionary Structured Planning, a computer-supported extension to a method that supports synthesis of objective and subjective information in the design planning process. The method introduces Genetic Algorithms as means for dealing with compound solution concepts in large combinatorial solution spaces. The method is described as being extremely flexible and capable of being applied to virtually any design problem at the conceptual level.

4.4 Methodology for architectural design (2001)

Proposka, A. (2001) "Application of Morphological Analysis Methodology in Architectural Design", *Acta Polytechnica*, 41(1).

This article discusses how the theory of system and design methodology can be applied to a more precise description, analysis and improvement of the methods of the real architectural design process. Starting from the early work of Lull's *art of combinatorics*, it describes how morphological analysis can be applied as a method for architectural design. From the architect's point of view it is worth studying the rules and peculiarities of this method as it has been applied in engineering design.

4.5 Design concept emergence in design meetings (2009)

Zeiler, W. & Savanovic, P. (2009) "Morphological analysis of design concepts emergence in design meetings", *Proceedings of Iced 09, the 17th International Conference on Engineering Design*, Vol. 6.

This paper explores the possibility of applying morphological analysis to design sessions. The basis for this approach is the methodology of Integral DOesign. A distinguishing feature of this model is the use of morphological charts for design activities in each stage of the process. The morphological charts created by each designer can be combined into a morphological overview that can be used to reconstruct the emergence of design concepts in an architectural and an engineering meeting. Besides being capable of presenting the development of design concepts, morphological charts proved to be effective in reducing the time needed to analyse a rich set of data. This complexity reduction offers the possibility of doing research on more (complex) design meetings more effectively, which is beneficial for generalization of findings.

4.6 An Ontological Basis for Design Methods (2009)

Kannengiesser, U. (2009) "An Ontological Basis for Design Methods", in *Undisciplined! Design Research Society Conference 2008*, Sheffield Hallam University, Sheffield, July 2008.

This paper describes a function-behaviour-structure (FBS) ontology to represent design methods as process artefacts. This view encompasses five fundamental approaches to methods: black-box, procedural, artefact-centric, formal and managerial approaches, all of which describe method structure but emphasize different aspects of it. Capturing these differences is meant to address common terminological confusions relating to methods. The paper also provides an overview of the use of the fundamental method approaches for different purposes in designing, in which GMA is presented as an artefact-centric approach.

4.7 Morphological analysis applied to Western apparel (2010)

Chen, J. and Lai, Ch. (2010) "The theory of morphological analysis applied to western apparel—a case study of Renaissance era", *International Journal of Computer Science and Network Security*, 10(4)

From the abstract: “This paper is aimed at using morphological analysis to augment seeking clothing design solutions. A case of western apparel in Renaissance era is applied to illustrate how to use this powerful fast-developing design computer tool. In using morphological analysis, we first divide western apparel into several independent design attributes, such as headdress, neckline, sleeves, farthingale, cobsters for female and ruff, doublet, zimarre, sleeves, cannions, duckbill shoes for male. Secondly, we find all possible design solutions for each design attribute. Finally, we can establish morphological matrix charts, which can be transformed as inputs for computer searches or computer-supported design decision-making and enlarge clothing design idea areas. In conclusion, morphological analysis is a potential computer tool used to aid apparel designers to obtain innovative ideas.”

4.8 Application to curriculum design in training and instruction (2010)

Ritchey, T. (2010) "Specifying Training and Instruction Requirements using Morphological Analysis", *Proceedings of ICELW 2010* (International conference on e-learning in the workplace), Columbia University, New York.

From the abstract: “Training and instruction (T&I) is increasingly based on advanced learning tools such as e-learning, simulators and virtual environments. In order to utilise these tools in an effective way, a first set of global requirements for T&I programs should be specified in order to identify appropriate needs and effective instructional methods. General Morphological Analysis (GMA) is a non-quantified modelling method for structuring and analyzing the total set of relationships in complex social, organizational and educational problem fields. GMA has been employed to develop a generic inference model for specifying T&I needs at an early stage, and identifying the relationships between needs and means. This article presents and application to the development of T&I programs, and an example of a generic model for identifying alternative T&I requirements for a specific case.”

4.9 Application to a sustainable school design (2011)

Zeiler,W. (2011) “Morphological Analysis of a Sustainable School Design”, *International Conference on Engineering Design*, ICED 11, 2011, Technical University of Denmark.

From the abstract: “Principals experiment with different ways to stimulate Integral D0esign teams, in which designers from different disciplines start designing together almost from the same moment in the design process. The design competition session for the conceptual design of a sustainable school was put on video and analyzed by applying morphological analysis. This analysis is based on a functional transcript of the process and the transforming of that in to a morphological overview. That overview represents the interpretation of the design brief by the design team as well as the solutions known within the design team related to them. … Some results of the analysis are presented especially focusing on the difference between architects and engineers in the design process.”

4.10 Triz, Morphological Analysis and Brainstorming (2013)

Kannengiesser, U., Williams, C. & Gero, J.S. (2013) "What Do the Concept Generation Techniques of Triz, Morphological Analysis and Brainstorming have in Common?", *International Conference on Engineering Design*, ICED 13, Seoul.

From the abstract: One of the goals of design research is to identify regularities across different design processes. This paper presents experimental evidence that there exist commonalities between three separate concept generation techniques: TRIZ, Morphological Analysis, and Brainstorming. This evidence is based on protocol studies involving mechanical engineering students that use the three techniques for performing different design tasks.

5. Applications in Futures Studies and Scenario Development

Using GMA for scenario development and futures projections was one of the early spinoffs from Zwicky's work. This is because of the many non-quantified social, political and ideological variables that need to be taken into account, and the inherent uncertainties involved. The very first uses of computer-aided GMA at the Swedish Defence Research Agency in the early 1990's were in the area of futures projections and scenario development, and eventually for the development of versatile scenario modelling frameworks which can be periodically updated. However, scenario development utilising GMA started already in the 1960s.

5.1 Scenarios for non-national nuclear threats (1967)

Taylor T. (1967) "Preliminary survey on non-national nuclear threats", *Stanford Research Institute Technical Note SSC-TN-5205-83*.

This is a classic early utilisation of GMA for futures projections which was ahead of its time, both methodologically and from the point of view of security analysis. It is included here (instead of under Security and Defence Analysis) because of its innovative nature concerning foresight studies. Theodore Taylor (1925-2004) was a theoretical physicist and prominent nuclear weapons designer who later in life became a nuclear disarmament advocate. He knew first hand of Zwicky's work and began employing the morphological approach while working at the Stanford Research Institute. This paper was not noticed at the time of its release in 1968, but Taylor later went on record with his warnings in a series of interviews publicised in *The New Yorker*. This was later described in the book by McPhee, J. (1973) *The Curve of Binding Energy*, Ballantine.

5.2 "Whole-Pattern" futures projection (1981)

Rhyne, R. (1981) "Whole-Pattern Futures Projection, Using Field Anomaly Relaxation", *Technological Forecasting and Social Change*, 19(4).

This is one of the earliest detailed descriptions of how to use GMA for scenario development. Working in association with the Stanford Research Institute in the late 1960's, Russell Rhyne picked up on Taylor's earlier work and began to apply a somewhat restricted form of morphological analysis as a general scenario development technique. Rhyne re-packaged it under the somewhat esoteric name of 'field anomaly relaxation' – FAR, a term borrowed from mechanical engineering. His unilateral renaming of an already established method and his *sometimes* claims in later life that he had invented morphological analysis "independently" of Zwicky (which is contradicted in his earlier works as well as in conversations with other researchers in the 1990s), was not appreciated by all.

However, Rhyne's great contribution to GMA was that he almost singlehandedly – and with little institutional support – continued to develop and disseminate general morphology in the 1980s and early 1990s. He established both the present day format for the Morphological Field, and the process of assessing the *total* Cross-Consistency matrix for internal consistency. He wrote several articles for *Futures* and *Technological Forecasting and Social Change* outlining morphological methods, as well as a thoughtful and candid book on the trials and tribulations of doing GMA by hand (which often lead to mistakes in generating the solution space). (See Rhyne, 1995, below.)

5.3 Comparing relevance trees and morphological analysis (1994)

The Futures Group International (1994) "Relevance tree and morphological analysis", *Futures Research Methods,* V. 2.0, AC/UNU Millennium Project, 1994.

The paper describes the possibility of the application to futures studies of the combination of morphological analysis and relevance trees – an analytic technique that subdivides a broad topic into increasingly smaller subtopics. The output is a pictorial representation with a hierarchical structure that shows how a given topic can be subdivided into increasingly finer levels of detail. It describes the method proposed, its strengths and weaknesses – which the authors argue can be solved by used of computer software –, and a number of projects in which the combined method was applied. Coincidentally, the first dedicated computer-software for general morphological analysis was developed one year later (1995) at the Swedish Defence Research Agency.

5.4 Scenarios for alternative Indonesian sea-sovereignty systems (1995).

Rhyne, R. (1995) *Evaluating Alternative Indonesian Sea-Sovereignty Systems,* Informs: Institute for Operations Research and the Management Sciences.

This book reports a study carried out in 1979. *From the abstract*: "This sea-control project was the first major study of any kind by the operational analysis establishment and at the time, no other team of analysts, outside the US, had undertaken a study of such tremendous scope. It dealt explicitly with the subjective aspects of a politico-military mission that required several innovations. The study made use of little-known methods of futures projection [e.g. GMA] to compose patterned contexts as backdrops for intra-analytical judgments; it used psychometric scaling to get value weightings on the importance of partial accomplishments of component missions; it developed an apparently sound method for designating the plausible threat. Above all, it wove these component techniques together within a coherent plan of work."

5.5 Scenarios for south-east Asia and the south-west Pacific (1995)

Coyle, R. & McGlone, G. (1995), "Projecting scenarios for South-east Asia and the South-west Pacific", *Futures*, 27(1).

The late R.G. (Geoff) Coyle essentially took over FAR after Russell Rhyne, although he readily acknowledged that FAR was Zwicky's morphological analysis with a new name. Coyle has also written several articles for *Futures* promoting FAR/GMA, as well as the book "Practical Strategy" (Prentice Hall, 2004) in which morphological methods and Zwicky are afforded a chapter. *From the abstract*: "The article describes further work to validate and assess a method of futures projection. The full methodology is shown in the context of a projection of plausible future trends for South-east Asia and the South-west Pacific. A number of scenarios are developed and it is shown that the future for that region may be fraught with considerable problems. Finally, the methodology is assessed and suggestions for future work are made."

5.6 Scenario planning as a Strategic Management Tool (2001)

Godet, M. (2001) *Creating Futures: Scenario Planning as a Strategic Management Tool*, Paris: Economica.

Michel Godet is *the* scenario and futures studies guru of France. In this handbook for professionals, managers, planners, and entrepreneurs he puts forward a set of futures-thinking techniques – from workshops to scenario-building software – that enhance the collective process. Although GMA is only one of the many techniques he promotes in this book, no survey of work with general morphology would be complete without him. He has kept morphological methods alive in France, when many other countries (e.g. the U.K. and Germany) more or less forgot them.

5.7 Scenario Development Using Computerized Morphological Analysis (2002)

Eriksson, T. & Ritchey, T. (2002) "Scenario Development Using Computerized Morphological Analysis", *Proceeding of the Winchester International OR Conference*, Oxford, 2002.

From the abstract: "Morphological analysis (MA) is a non-quantified modelling method for structuring and analysing technical, organisational and social problem complexes. It is well suited for developing scenarios, and the method is highly appropriate for complex cases where expertise from several areas is required. It is also useful for developing and relating operational and tactical scenarios to force requirements. Using MA for problem solving or scenario generation typically involves workshop sessions supported by a computer tool. An example of how MA is used for the development of a set of scenarios is given. These scenarios were developed for the Swedish Armed Forces' long-term planning and describe a number of long-term strategic situations, including peace support operations."

5.8 Methods in future research and scenario analysis (2008)

Kosow, H. & Gaßner, R. (2008) "Methods of Future and Scenario Analysis. Overview, Assessment, and Selection Criteria". *Studies / Deutsches Institut für Entwicklungspolitik*.

This book provides an overview and evaluation of methods of futures research and scenario analysis methods, focusing on the way in which these methods might be applied to research and policy advising in the development policy arena. It describes the application of GMA to futures and scenario analysis, based on the selection and evaluation of the consistency of combinations of key factors within a workshop involving various stakeholders. The authors argue that GMA is particularly useful for futures and scenario analysis in that different dimensions of a scenario field (demography, the economic sector, techniques etc.) can be first distinguished from one another and then studied as a whole. It is a creative technique for comprehensive study of a scenario field and its possible future developments and systematic identification of relationships and structures. Simultaneously, definitions, evaluations and decisions can be well documented and visualized, which results in increased transparency.

5.9 The Millennium Project: Futures Research Methodology (2009)

Glenn, J. & Gordon, T. (eds.) (2009). *The Millennium Project: Futures Research Methodology,* Version 3.0, Chapter 17: "Morphological Analysis", The Millennium Project (at: http://www.millennium-project.org/millennium/FRM-V3.html).

The Millennium Project's *Futures Research Methodology Version 3.0* is the largest, most comprehensive internationally peer-reviewed collection of articles on methods and tools to explore future possibilities ever assembled in one resource. The series begins with an introductory chapter to futures research and concludes with a synthesis of methods and a discussion about the future of futures research methods. Each of the following 37 chapters covers one specific method. Morphological analysis, as a method for generating and examining alternative futures is presented in chapter 17.

5.10 Morphological prospection: three lineages of morphological methods (2009)

Voros J. (2009) “Morphological prospection: Profiling the shapes of things to come”, *Foresight*, 11(6).

From the abstract: “The purpose of this paper is two-fold. First, to describe in detail a particular sub-class of powerful prospective methods based on the method of ‘morphological analysis’. And second, to extend their use to create a basis for strengthening strategic analysis and policy development. [It] Examines the history and use of morphological methods in foresight work, briefly describes three main ‘lineages’ currently in use, and proposes some extensions to models of practice. … Recent research in cognitive psychology suggests that requiring a detailed and systematic examination of future possibilities before a decision is made leads to more effective assessments of futures. Morphological methods, by design and construction, are perfectly suited to this, and so can form an exceptionally strong basis for thinking systematically about the future.”

5.11 Modelling alternative futures with GMA (2011)

Ritchey, T. (2011) “Modelling Alternative Futures with General Morphological Analysis”, *World Future Review*, Spring 2011.

This article outlines the fundamentals of the morphological approach and describes its use in a number of case studies in scenario development and futures projections done for Swedish government authorities and NGOs. The four future projection models presented are 1) Scenarios and strategies for an extended producer responsibility system, 2) Future human actions affecting long-term nuclear waste storage, 3) Nuclear sabotage threat scenarios and 4) Climate change conflict scenarios.

5.12 Scenarios for the introduction of electric vehicles in urban traffic

Correia da Silva, L. (2011) “Morphological Analysis of the Introduction of Electric Vehicles in São Paulo’s Urban Traffic”, *Future Studies Research Journal*, São Paulo, 3(1).

From the abstract: “This study aims to contribute with the construction of future scenarios in 2020 concerning the introduction of electric vehicles in São Paulo´s urban traffic, an integral part of the CNPq/FINEP research project which is being undertaken at the University of São Paulo (USP/FEA). The Morphological Analysis method was adopted given the fact that it facilitates the structuring of the managerial and technological complexities of the proposed problem, with views to identifying the variables and their critical relations for the prospection of scenarios.”

6. Applications in Technological Forecasting / Technology Foresight

A number of often cited, early works from the late 1960's describe how GMA began to be applied as a method for technology foresight. It seems to have started out with Erich Jantsch's book in 1967, and took off two years later. Today, modern GMA is firmly established as one of the basic methods employed in technology foresight studies.

6.1 Technological forecasting in perspective (1967)

Jantsch, E. (1967) *Technological forecasting in perspective,* OECD, Paris.

Written by one of the early proponents of complexity theory and a leader in the social systems design movement in Europe, Jantsch's book contains one of the first descriptions of the morphological approach as a technology foresight technique. Jantsch started out in astrophysics and thus had early knowledge of Zwicky's work.

6.2 Morphological Analysis for Technological Forecasting (1969)

Ayres, R. (1969) "Morphological Analysis" (Chapter 5) in *Technological Forecasting and Long Range Planning,* New York: McGraw-Hill.

6.3 Morphological Methods - Principles and Practice (1969)

Bridgewater, A. (1969) "Morphological Methods - Principles and Practice", in Arnfield, R. (ed.) (1969) *Technological Forecasting*, University of Strathclyde. Edinburgh University Press.

6.4 Morphological Methods: Antecedents and Associates (1969)

Gregory, S. (1969) "Morphological Methods: Antecedents and Associates", *Technological Forecasting, Some Techniques,* Proceedings of a Symposium at Aston University, Birmingham.

6.5 Some Theoretical Principles in Morphological Analysis (1969)

Watts, R. (1969) "Some Theoretical Principles in Morphological Analysis", *Technological Forecasting, Some Techniques,* Proceedings of a Symposium at Aston University, Birmingham.

These articles (6.2 – 6.5), especially Ayres and Bridgewater, are often cited as early examples of this application. GMA was a new technique that many wanted to try. But 1969 was still early days: Zwicky's major book on the subject was first published in English that year. The modern morphological field format had not yet been established, nor the idea of assessing the total cross-consistency field. Many of the so-called *morphological fields* presented were in fact typologies, a concept-structuring format that had been in use by social scientists for almost a century.

6.6 New approaches to technological forecasting (1970)

O'Neal, C. (1970) "New approaches to technological forecasting— Morphological analysis: An integrative approach", *Business Horizons*, 13(6).

The author states that most of the techniques for technological forecasting in the late 1960's could be classified as either normative or exploratory, but that the two types must be meshed for a complete forecast. Morphological analysis facilitates this two-way meshing. The author describes the three steps involved in such an analysis, which is an integrative approach that forces examination of all possibilities. In a simplified example, the technique is demonstrated by developing a function-technology matrix for color television set circuitry. The results include a forecast and a scenario for the 1980's.

6.7 Applications to a company TF investigation (1976)

Wissema, J. (1976) "Morphological analysis: Its Application to a Company TF Investigation", *Futures*, 8(2).

From the abstract: "Of all the techniques used in technological forecasting, morphological analysis is probably the one least used by TF practitioners and least known to the public. Delphi investigations, trend analysis, scenarios, and most recently dynamic models are widely employed, but the use of morphological analysis is rarely reported, though it is mentioned in every textbook on technological forecasting. The reason may be that morphological analysis is a technique to structure a problem rather than solve it."

6.8 Technology Futures Analysis (TFA) methods (2004)

Technology Futures Analysis Methods Working Group (2004) "Technology futures analysis: Toward integration of the field and new methods", *Technological Forecasting and Social Change*, 71(3).

This collectively authored paper seeks to lay a framework from which to advance the processes to conduct and the methods used in *technology futures analysis* (TFA). The paper provides a compilation and overview of TFA methods – including GMA, which is described as a "soft" (qualitative) method belonging to the "Descriptive and matrices" family, which is both normative and exploratory.

6.9 Identifying new technology opportunities (2005)

Yoon, B. & Park, Y. (2005) "A systematic approach for identifying technology opportunities: Keyword-based morphology analysis", *Technological Forecasting and Social Change*, 72(2).

From the abstract: "Morphology analysis (MA), a representative qualitative technique in technology forecasting (TF), has been utilized to identify technology opportunities. However, conventional MA is subject to limitations in that there is no scientific or systematic way in establishing the morphology of technology, and it is difficult to prioritize the alternatives. As a remedy, we propose a keyword-based MA that is supported by a systematic procedure and quantitative data for concluding the morphology of technology. To this end, a technology dictionary is developed by factor analysis for keywords that are extracted from patent documents through text mining. Then, the morphology of patents is identified based on the technology dictionary. By listing the occupied configurations of collected patents, the unoccupied territory of configurations are suggested as technology opportunities. Moreover, the priority of alternatives is concluded, and similar and substitutive technologies can be analyzed for the purpose of extending morphology structure."

6.10 Patent text mining and patent technology (2012)

Feng, X & Fuhai, L. (2012) "Patent text mining and informetric-based patent technology morphological analysis: an empirical study", *Technology Analysis & Strategic Management*, 24(5).

Patent technology morphological analysis utilises the advantages of both patent information analysis and morphological analysis to provide more detailed information on current and future patent technology. The authors argue that current patent technology morphological analysis methods are largely reliant on manual expertise in the construction of morphological boxes with few approaches to the evaluation of future morphological configurations. This paper describes a patent text mining and informetric-based patent technology morphological analysis technique.

6.11 Analysis of technologies using multidimensional scaling (2012)

Zheng,W., Kankaanranta, J. & Suominen, A. (2012) "Morphological analysis of technologies using multidimensional scaling", *Journal of Business Chemistry*, 9(3).

Morphological Analysis is used as a framework for applying expert opinion, bibliometrics, text mining and multidimensional scaling to problem structuring. The authors describe the method used and its application to a case of portable fuel cell technology. They argue that the results demonstrate the practicality of using Morphological Analysis in structuring complex problems and offer an example of its application in assessing the status of a technology.

7. Applications in Management science, Policy analysis and Organisational design

Although GMA started off as problem structuring method in engineering design and as a technique for developing scenarios, it eventually became clear that it was excellent method for structuring policy spaces and strategy alternatives, and for organisational planning. All of these are natural complements to developing scenario spaces and have been used extensively for government authorities and NGOs. Applications in business management and the commercial sector have not developed as quickly as within the public sector for reasons concerning institutional goals and time horizons. We believe, however, that GMA has significant applications within the corporate sector.

7.1 Analysis for health care systems planning (1975)

Turley, R., Richardson, W. and Hansen, J. (1975) "Morphological analysis for health care systems planning", *Socio-Economic Planning Sciences*, 9(2).

From the abstract: "Health care planners are continually challenged by the difficulty of ordering and understanding of the complexities of health care delivery systems. Methods are needed which can aid in extending thought processes into multi-dimensional solution space and rationalizing the thinking of various health care interests. This paper describes a useful approach to designing and evaluating health care systems utilizing a case study of a large metropolitan community. The major dimensions of the system which were of concern were 1) Patient, 2) Type of care needed, 3) Organisation base for services, 4) Ownership and 5) Provider reimbursement."

7.2 Creativity in the management field (1991)

Proctor, R. (1991) "The Importance of Creativity in the Management Field". *British Journal of Management*, 2(4).

From the abstract: "Creative problem-solving is an important dimension to managerial activity. Rapidly changing business environments produce problems which managers have not previously encountered. Tried and trusted methods of approaching new problems can meet with failure. The need for creative problem-solving methods which overcome such difficulties is of paramount importance. There are a number of established creative problem-solving aids, such as brainstorming, lateral thinking, etc. and a new set of aids which are computer-assisted. This paper outlines newer developments."

7.3 GMA as a policy analysis tool (1998)

Ritchey, T. (1998) "Fritz Zwicky, 'Morphologie' and Policy Analysis", *Proceedings of the 16th EURO Conference on Operational Analysis*, Brussels.

This was one of the first articles describing computer-aided GMA using the MA/Casper (later the MA/Carma) software system. It presented the Swedish bomb shelter program as an example of a policy issue to be treated. The article was adapted in 2002 as "General Morphological Analysis: A general method for non-quantified modeling" (available for download at: http://www.swemorph.com/pdf/gma.pdf). Thus was born the present-day acronym GMA, to distinguish Zwicky's *general* morphology from the many other *specific* "morphological analyses" used in different scientific disciplines.

7.4 Strategies for Economic Development for Indigenous People in Australia (2004)

Duczynski, G. (2004) "Systems Approaches to Economic Development for Indigenous People: A Case Study of the Noongar Aboriginals of Australia", *Futures* 36(8).

"This paper illustrates a case study in the application of systems approaches to securing economic development for a specific group of indigenous people in Australia. The case study combines Field Anomaly Relaxation (FAR) with Effects-Based Operations (EBO) planning to realise more purposeful actions and endeavours in pursuit of economic development. The approach is a hybrid of Checkland's Soft Systems Methodology (SSM), Rhyne's FAR and an advancement of the EBO process emerging from within national security domains."

7.5 Strategies for an Extended Producer Responsibility (EPR) system (2004)

Stenström, M. & Ritchey, T. (2004) "Scenario and Strategy Laboratories for an Extended Producer Responsibility System", Report to the Swedish Ministry of the Environment, *Swedish Morphological Society,* (available at: www.swemorph.com/pdf/epr9.pdf).

This paper presents a study done for the Swedish Ministry of the Environment to evaluate an Extended Producer Responsibility (EPR) system in Sweden. The purpose of the study was to formulate a range of contextual environmental scenarios and, by identifying the most important parameters of an EPR system, develop alternative EPR strategies, which can be tested within the context of these scenarios. The study employed computer-aided GMA in order to develop scenario and strategy laboratories which can be used as interactive ("if-then") inference models.

7.6 Morphological approach in management decision-making (2006)

Sharif, A. & Irani, Z. (2006) "Applying a fuzzy-morphological approach to complexity within management decision-making", *Management Decision*, 44(7).

From the abstract: "Noting the scarcity of complexity techniques applied to modelling social systems, this paper attempts to formulate a conceptual model of decision-making behaviour within the information systems evaluation (ISE) task, against the backdrop of complexity theory. Complexity theory places an emphasis on addressing how dynamic non-linear systems can be represented and modelled utilising computational tools and techniques to draw out inherent system dynamics. In doing so, the use of fuzzy cognitive mapping (FCM) and morphological analysis (MA) (hence a fuzzy-morphological approach), is applied to empirical case study data, to elucidate the inherent behavioural and systems issues involved in ISE decision making within a British manufacturing organisation."

7.7 Modeling financial decision making (2007)

Petrusel, R. & Mocean, L. (2007) "Modeling decisional situations using morphological analysis". *Informatica Economica*, 4 (44).

From the abstract: "This paper presents models for financial decision-making in small and medium enterprises, applying morphological analysis. This technique is used for model scale reduction, not by reducing the number of variables involved but rather by reducing the number of possible combinations between variables. As an example, it provides a morphological table for the problem "a decision regarding the cashing method is required when a new invoice is issued in Romania".

7.8 Knowledge transfer in organizations (2009)

Kumar, J.A. & Ganesh, L.S. (2009) "Research on knowledge transfer in organizations: a morphology", *Journal of Knowledge Management*, 13(4).

From the abstract: "The purpose of this paper is to present and describe a morphology of the research literature on knowledge transfer in organizations. A comprehensive framework characterizing the knowledge transfer literature in terms of dimensions and options was developed by an extensive scanning of the pertinent literature. Eight dimensions were found suitable to characterize the knowledge transfer research literature. Corresponding to each dimension, two to six options were found. The morphology demonstrates the extensiveness and variety of knowledge transfer research. To academics, the morphology can serve as a map of the knowledge transfer territory. … To the best of the authors' knowledge, a morphological approach has not been attempted so far to characterize KM research literature. The approach used can be applied to other areas of management as well, for similar purposes."

7.9 ICT applications in government service delivery (2010)

Plauché, M., de Waal, A., Grover, A S. & Gumede, T. (2010) "Morphological Analysis: A Method for Selecting ICT Applications in South African Government Service Delivery", *Information Technologies & International Development*, 6(1).

From the abstract: "Successful ICT projects depend on complex, interrelated sociological and technical factors for which there are no standard theoretical framework for prediction or analysis. Morphological analysis is a problem-solving method for defining, linking, and evaluating problem spaces that are inherently non-quantitative. In this article, we show how our research team created a telephony impact model using morphological analysis to strategically select a national ICT telephony project for South Africa from several possibilities, based on non-quantitative, socio-technical criteria. The telephony impact model provides a rigorous framework to the diagnostic and planning phases of our action research that is a vast improvement over "best practices" guidelines. We believe that this approach takes a first step toward predictive models and theories for ICT deployment."

7.10 Knowledge Management Maturity Models (2010)

Kuriakose, K.K, Raj, B., Satya Murty, S.A.V., Swaminathan, P. (2010) "Knowledge Management Maturity Models – A Morphological Analysis", *Journal of Knowledge Management Practice*, 11(3).

From the abstract: "A Knowledge Management Maturity Model is a structured approach for implementing Knowledge Management. Many practitioners and researchers have developed Knowledge Management Maturity Models, which have different forms, structure and characteristics. Despite the availability of many models, a comprehensive framework that can represent different perspectives and provide a holistic picture of Knowledge Management Maturity Model is not found in literature. This paper attempts to fill this gap by developing a morphological framework of Knowledge Management Maturity Model through literature survey and analysis."

7.11 Business model creation using case-based reasoning (2011)

Lee, J. & Hong, Y. (2011) "A Morphological Approach to Business Model Creation using Case-Based Reasoning", *Proceedings of the International Conference on Engineering Design*, ICED 11, Technical University of Denmark.

From the abstract: "This study aims to provide a structured methodology for a business model creation. Based on a morphological analysis of business model, we propose the methodological chart named as business model creation template with which one can generate a variety of business model alternatives. The template consists of a set of predefined building blocks which describes the strategic patterns and/or constituent elements of a business model. Those building blocks have been collected and verified through comprehensive analysis of real-world business model cases and relevant literature. Furthermore, we develop case-based reasoning system for supporting a new business model creation. The system aims to provide the business model planner of intuitive cases in creating a new business model."

7.12 Market innovation in business markets (2012).

Storbacka, K. & Nenonen, S. (2012) "Competitive Arena Mapping: Market Innovation using Morphological Analysis in Business Markets", *Journal of Business-to-Business Marketing*, 19(3).

From the abstract: "The authors illustrate the use of morphological analysis for competitive arena mapping in a market definition and innovation context... The article builds a bridge between the market definition literature in strategic management and the industrial market segmentation literature, by introducing a novel method for increasing the granularity of market definition, using morphological analysis. Furthermore, the paper responds to the lack of research addressing strategic segmentation processes by developing a six-step market definition process."

7.13 Developing new business models (2013)

Im, K & Cho, H (2013) "A systematic approach for developing a new business model using morphological analysis and integrated fuzzy approach", *Expert Systems with Applications*, 40(11).

From the abstract: "This study proposes a systematic approach to new business model development (NBMD) that helps business practitioners to develop, evaluate and select the best business model to meet the business objectives. The proposed approach comprises two stages: identification of business model alternatives and business model evaluation and selection. Morphological analysis (MA) has been employed for the derivation and aggregation of business model alternatives, and decision-making approach that integrates fuzzy extent analytic hierarchy process (FAHP) and fuzzy technique for order of preference by similarity to ideal solution (TOPSIS) methods is used as an evaluation and selection tool."

7.14 Business model prototyping (2014)

Seidenstricker, S., Scheuerle, S. & Linder, C. (2014). "Business Model Prototyping – Using the Morphological Analysis to Develop New Business Models", *Procedia - Social and Behavioral Sciences*, Volume 148.

From the abstract: "Practice has shown that new businesses have managed to change the structure of market sectors and to open positions of power by business model innovation. Often, the origin was new technological possibilities, innovative products, changes in the supply chain management, optimized cost structures or unique resources. Regarding strategic marketing and innovation management, it now is interesting how such potentials can be unlocked and implemented in business model innovations. … Thus, the subject of this paper shall be the development of such a method systematically generating business model ideas based on morphological thinking."

8. Applications in Security, Safety and Defence studies

This category cuts across many of the categories presented above. However, for various reasons, defence and security analysis is one of the areas that adopted GMA at a relatively early stage. This was especially the case in Sweden, where modern computer-aided techniques were originally developed at the National Defence Research Agency. By the very nature of such studies, however, many of them are not publically available. Here are some examples of those that are available.

8.1 Evaluating preparedness for HAZMAT accidents (2002)

Ritchey, T., Stenström, M. & Eriksson, H. (2002) "Using Morphological Analysis to Evaluate Preparedness for Accidents Involving Hazardous Materials", *Proceeding of the 4th International Conference for Local Authorities*, Shanghai, 2002.

From the introduction: "Accidents involving hazardous materials, e.g. dangerous chemical substances, are relatively rare in Scandinavia. However, the fact that such accidents are rare makes it difficult for rescue services to gain sufficient experience and routine, as is the case with fire fighting or traffic accidents. One way to increase preparedness is through theoretical evaluations and with the help of scenarios, in order to identify potential deficiencies and to see where improvements can best be made. For this purpose, the Swedish National Rescue Services Agency commissioned a study to develop a computer-based instrument for evaluating Swedish Rescue Services' preparedness for accidents involving hazardous materials, and also for terrorist actions involving the intentional release of chemical agents. An expert group consisting of nine experienced fire marshals and fire engineers from different parts of Sweden, together with the authors, developed the prototype model during 1999 and 2000."

8.2 Nuclear Facilities and Sabotage (2003)

Ritchey, T. (2003) "Nuclear Facilities and Sabotage: Using Morphological Analysis as a Scenario and Strategy Development Laboratory", *Proceedings of the 44th Annual Meeting of the Institute of Nuclear Materials Management*, Phoenix, Arizona.

This article outlines the fundamentals of the morphological approach and describes recent applications in modelling threat scenarios and revised preparedness planning for nuclear facilities in Sweden.

8.3 Modelling Society's Capacity to Manage Extraordinary Events (2004)

Lövkvist-Andersen, A., Ritchey, T., Olsson, R, & Stenström, M. (2004) "Modelling Society's Capacity to Manage Extraordinary Events: A Generic Design Basis (GDB) Model", *Presentation at the SRA (Society for Risk Analysis) Conference*, Paris, 2004. (Available at: http://www.swemorph.com/pdf/sra.pdf)

This paper reports the development of a Generic Design Basis (GDB) model as a *strategic decision support framework* for treating the uncertainties involved in the emergence of extreme societal events. The starting point is the identification, structuring and analysis of undesirable *consequences* for society (i.e. effects), rather than any fix set of causes. These consequences are defined *inter alia* on the basis of *political values and norms*, which take the form of a national security strategy. The aim is to identify and set priorities between different measures which will increase Sweden's capacity to manage extreme events which represent serious threats to society.

8.4 Effects-Based Operations (2006)

Duczynski, G. (2006) “Effects–Based Operations between Australia and the United States”, *Security Challenges*, 2(1).

From the abstract: “Whether we are concerned with issues of national security, continuing problems in Iraq, the overcrowding of public hospitals or the graffiti problem at the local school, it is likely that the area of interest is exhibiting systemic behaviours. The systemic behaviours form the interactions between factors that shift the prevailing conditions (the same conditions outlined earlier in our examination of definitions for end–state). The method is based on Fritz Zwicky’s morphological analysis…”

8.5 Multi-hazard disaster reduction strategies (2006)

Ritchey, T. (2006) "Modeling Multi-Hazard Disaster Reduction Strategies with Computer-Aided Morphological Analysis", *Proceedings of the 3rd International ISCRAM Conference*, Newark, USA.

From the abstract: “Disaster Risk Management (DRM) is a multi-dimensional problem complex requiring knowledge and experience from a wide range of disciplines. It also requires a methodology which can collate and organize this knowledge in an effective, transparent manner. Towards this end, seven specialists from the social, natural and engineering sciences collaborated in a facilitated workshop in order to develop a prototype multi-hazard disaster reduction model. The model, developed with computer-aided morphological analysis (MA), makes it possible to identify and compare risk reduction strategies, and preparedness and mitigation measures, for different types of hazards.”

8.6 A framework for Proactive Risk Management (2009)

Jimenez, H., Stults, I. & Mavris, D. (2009) ”A Morphological Approach for Proactive Risk Management in Civil Aviation Security”. *Proceeding of the 47th AIAA Aerospace Sciences Meeting*, American Institute of Aeronautics and Astronautics, Orlando.

From the Abstract: “In this study, morphological analysis is used to develop a framework for proactively assessing the risk of a terrorist attack on the air transportation system. Morphological analysis, a first order method pioneered by Fritz Zwicky, is employed to exhaustively create possible attack scenarios. Morphological analysis is then used to assess the likelihood of each scenario. Given a consequence estimation method, the risk for each of these scenarios can be determined. A method for developing profiles of various terror organizations is outlined and, given this information, a more specific assessment of high-risk scenarios can be made.”

8.7 A model for peace support operations (2009)

Leenen, L. Modise, M., le Roux, H. (2009) “A model for peace support operations: an overview of the ICT and interoperability requirements”, *Proceedings of the 4th International Conference on Information Warfare and Security*, Cape Town, South Africa.

From the abstract: “This paper is part of a long term research project conducted by the Council for Scientific and Industrial Research (CSIR) in South Africa. The objective of the project is to construct a model for the planning and execution of Peace Support Operations (PSOs). In this paper, the authors describe the development methodology for a PSO planning model and they investigate the required interoperability information and communication technologies (ICT) requirements for PSOs.” Morphological analysis is used to develop the first phase of the model.

9. Applications in Creativity, Innovation and Knowledge Management

Morphological analysis is featured, or at least mentioned, in most books and articles concerned with methods and techniques for innovation and creative problem solving. In this sense, there are literally thousands of articles to choose from. Here, however, we list only articles that specifically focus in on GMA in this context.

9.1 Morphological Creativity (1952)

Allen, M.S. (1952) *Morphological Creativity*. Englewood Cliffs: Prentice Hall.

Allen's book from 1952 is the earliest general promotion of GMA by someone other than Zwicky. Unfortunately, both it and the later 1962 edition (which includes the silly sub-title "The Miracle of Your Hidden Brainpower"), are more in the popular science hype-tradition than scientific texts. It is doubtful that they did the "morphological approach" any good. They are only mentioned for the record.

9.2 Morphological Analysis: A Method for Creativity (1973)

Gerardin, L: (1973) "Morphological Analysis: A Method for Creativity", in Bright, J. & Shoeman, E. (eds.) (1973) *A Guide to Practical Technological Forecasting,* New Jersey: Prentice-Hall.

Lucien Gérardin was Research Director for Look-Out Studies at Thomson-CSF in Paris. We could find no documentation available on this article, but cite it for the record.

9.3 Creativity in technological forecasting (1976)

Jones, H. (1976) "Morphology and creativity in technological forecasting", *R&D Management*, 6(3).

This article could also just as well have been placed under *technological forecasting*, but Jones puts special emphasis on creativity. *From the abstract*: "Although the morphological approach to the exploration of technological possibilities was first described by Zwicky in 1962 in relation to jet engine systems ... it has received less attention as a tool for creativity than it deserves. Jantsch in his classical review of technological forecasting attempted to establish interest in the methodology, referring to it as 'a systematic investigation of all the possible solutions to a given problem, without any prejudice, using matrix representations in as many dimensions as there are basic parameters'".

9.4 Designing for Creativity (1980)

Rickards, T. (1980) "Designing for Creativity: A State of the Art Review", *Design Studies,* 11(5).

From the abstract: "This review concerns itself with the so-called structured aids to creative behaviour. The published literature is outlined and shown to be extensive but fragmentary, diffuse and inconclusive. Four major families of techniques are discussed: brainstorming, synectics, morphological analysis and lateral thinking. Some less well known techniques are also considered briefly, and the problem of classification considered."

9.5 Morphological Gap-Analysis (2013)

Ritchey, T. (2013) "Morphological Gap-Analysis: Using GMA to find the Δ", *Acta Morphologica Generalis,* 2(2).

From the abstract: "Gap-analysis is the process of structuring and comparing two different situations or states in order to determine the difference or "gap" that exists between them. Once the "gap" is understood – and possibly also the "distance" between the states measured or otherwise assessed – it may then be possible to identify the steps or processes required to *bridge* the gap. General Morphological Analysis (GMA) is a non-quantified modelling method that employs a process and a spatial format that makes gap-analyses intrinsic. This article will summarise GMA and give examples of how it can be used as a computer based gap-analysis support method. ... The examples include a knowledge management tool for identifying the gaps between *knowledge bases* and *knowledge requirements*."

9.6 Creativity approach to Business Model Innovation (BMI) (2014)

Seidenstricker, S. & Linder C. (2014) "A morphological analysis-based creativity approach to identify and develop ideas for BMI", *International Journal of Entrepreneurship and Innovation Management,* 18(5-6).

From the abstract: "Practice has shown that new businesses have succeeded in changing the structure of market sectors and opening positions of power through business model innovation. Regarding entrepreneurship and innovation management, it has become of interest to learn how such potentials can be unlocked and implemented using business model innovations. Here, the development of ideas plays an important role as it usually the first stage of each innovation and utilisation process. While this phase of development is assigned great significance, methodological support regarding existing procedures and process models have not, however, been given. Thus, the subject of this paper is the development of a method of systematically generating business model ideas based on morphological thinking. This includes guaranteeing consistency of the ideas developed as well as structured selection. The method was applied within a high-tech company."

9.7 Managing co-creation design (2015)

Frow,P., Nenonen, S., Payne, A. & Storbacka, K (2015) "Managing Co-creation Design: A Strategic Approach to Innovation", *British Journal of Management,* DOI: 10.1111/1467-8551.12087

From the abstract: "Co-creation offers firms and their network of actors significant opportunities for innovation, as each actor offers access to new resources through a process of resource integration. However, despite the significant advantages that co-creation can offer, there is surprisingly little research providing a strategic approach for identifying the most advantageous co-creation opportunities, especially when many possible options are available. Recently, scholars have called for research that develops tools and processes related to co-creation. This study addresses these priorities, making two contributions. ... A co-creation design framework is developed, which incorporates multiple design dimensions and categories that can reveal new co-creation opportunities. Second, the research extends the application of a design approach, specifically within the context of co-creative activities. ... A *morphological approach* is used to explore how a lead firm can identify attractive co-creation opportunities. An innovation solution in one organization provides an illustration of how the co-creation design framework can be applied."

10. Applications in modelling theory, OR methods and GMA itself

Besides Zwicky's early promotion of the "morphological approach", the technical side of GMA has been addressed in the areas of operational research and modelling theory in general. Most of the authors in this context have backgrounds in some form of "decision science", e.g. operational analysis, management science, risk analysis, etc.

10.1 Morphological techniques in Operational analysis (1975)

Müller-Merbach, H. (1976) "The Use of Morphological Techniques for OR-Approaches to Problems", *Operations Research 75*. North-Holland Publishing Company.

This is one of the earliest appeals for the use of GMA in Operational Research programs. Müller-Merbach, professor of Business Administration and Operational Research at the Technical University in Darmstadt, pointed out that general morphology is especially suitable for operational research, not the least because of the growing need for operational analysts to be part of the problem structuring and formulation process, and not simply a 'receiver' of predefined problems.

10.2 The mathematics of morphological analysis (1987)

Arciszewski, T. (1987) "Mathematical modelling of morphological analysis", *Mathematical Modelling*, 8.

Tomasz Arciszewski at George Mason University in Virginia, U.S.A. has been a long-time promoter of GMA in the engineering field. *From the abstract*: "A mathematical model of morphological analysis is given. A search of a morphological table is simulated by a non-homogeneous Markov chain. This model was used in the developed computer program, which has been successfully applied in structural engineering for the generation of a number of innovative, patentable solutions."

10.3 Problem structuring with GMA (2006)

Ritchey, T. (2006) "Problem structuring using computer-aided morphological analysis", *Journal of the Operational Research Society*, 57.

From the abstract: "This article gives a historical and theoretical background to GMA as a problem structuring method, compares it with a number of other 'soft-OR' methods, and presents a recent application in structuring a complex policy issue." (A pre-copyedit version of the article is available at: http://www.swemorph.com/pdf/psm-gma.pdf)

10.4 Combining morphological analysis and Bayesian networks (2007)

de Waal, A. & Ritchey, T. (2007) "Combining morphological analysis and Bayesian networks for strategic decision support", *ORiON*, 23(2).

From the abstract: "Morphological analysis (MA) and Bayesian networks (BN) are two closely related modelling methods, each of which has its advantages and disadvantages for strategic decision support modelling. MA is a method for defining, linking and evaluating problem spaces. BNs are graphical models which consist of a qualitative and quantitative part. The qualitative part is a cause-and-effect, or causal graph. The quantitative part depicts the strength of the causal relationships between variables. Combining MA and BN, as two phases in a modelling process, allows us to gain the benefits of both of these methods. Short summaries of MA and BN are provided, followed by discussions how these two computer aided methods may be combined to better facilitate modelling procedures. A simple example is presented, concerning a recent application in the field of environmental decision support."

10.5 A morphology of modelling methods (2012)

Ritchey, T. (2012) "Outline for a Morphology of Modelling Methods: Contribution to a General Theory of Modelling", *Acta Morphologica Generalis*, 1(1).

From the abstract: "The purpose of this article is to classify and compare – in essence to *model* – a number of different types of modelling methods employed within Operations Research and the Management Sciences (OR/MS). The classification of these methods is based on a selected number of generally recognised modelling properties. On the basis of this meta-model, requirements for the successful application of different modelling methods – for the study of given systems or objects of scientific enquiry – can be examined. The method employed for this meta-modelling task is General Morphological Analysis (GMA). The problem of a General Theory of Modelling (GTM) is also discussed." (Available at: http://www.amg.swemorph.com/pdf/amg-1-1-2012.pdf)

10.6 Dynamic Morphological Exploration (2013)

Williams, P. & Bowden, F. (2013) "Dynamic Morphological Exploration", *Proceeding of the 22nd National Conference of the Australian Society for Operations Research*, Adelaide, Australia.

In this paper, a "Dynamic Morphological Exploration" is proposed as an extension of General Morphological Analysis. The driving principle behind this method is to create an exhaustive tree mapping of optimal search paths, based on all possible outcomes of previous state space tests. The analyst is then able to refer to the Dynamic Morphological Exploration Tree during an experiment or analytical campaign to objectively decide the next set of parameters to be tested. With sufficient forethought, the Tree will guide the analyst away from repetition and dead-ends.

10.7 Morphological models about decision support modelling (2104)

Ritchey, T. (2014) "Four Models about Decision Support Modelling", *Acta Morphologica Generalis*, 3(1).

From the abstract: "Models and modelling methods play an essential role in Operational Research and Management Science (OR/MS). This article presents four models which concern how OR/MS employs different modelling methods for different modelling tasks, under different constraints, and for different forms of uncertainty. Two of these "meta-models" concern how OR/MS modelling has been employed in decision support for the Swedish Defence Research Agency: one of them from a more academic or theoretical perspective, the other more from the perspective of the practitioner. The third model concentrates on how different modelling techniques are constrained by varying stakeholder positions. The final model is introspective and classifies a variety of modelling methods on the basis of a number of formal modelling properties. All of these meta-models were developed using the non-quantified modelling method General Morphological Analysis (GMA)."
(Available at: http://www.amg.swemorph.com/pdf/amg-3-1-2014.pdf)

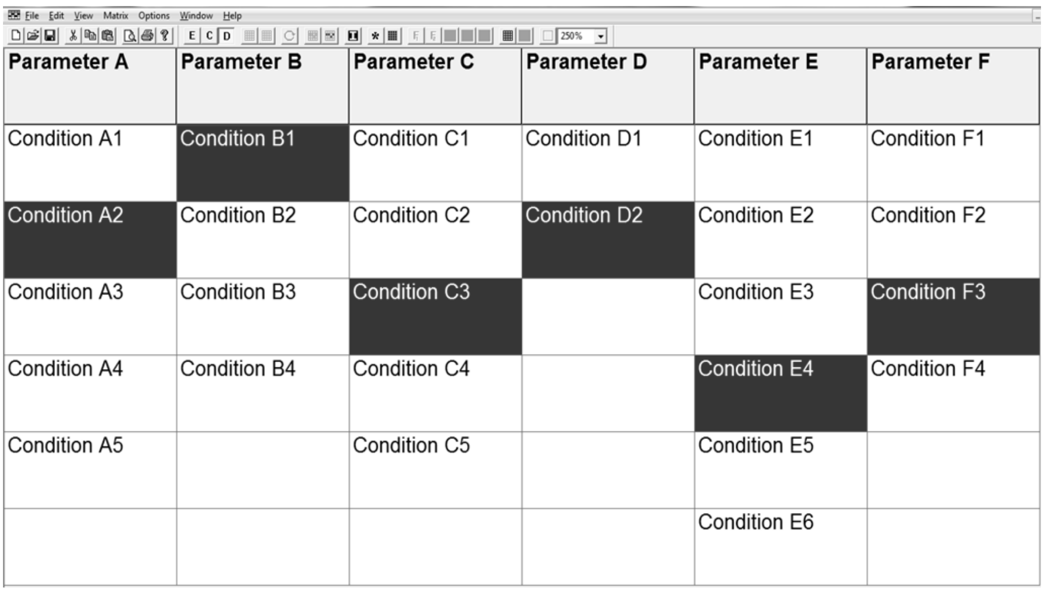
11. Overview of General Morphological Analysis

Essentially, GMA is a method for identifying and investigating the total set of possible relationships 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.

The method begins by identifying and defining the most important *parameters* of the problem complex to be investigated, and assigning each parameter 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. (Note that we are using the term *parameter* not in its formal mathematical sense, but in its more general, systems science meaning: i.e. one of a number of factors that define a system and determine its behaviour, and which can be varied in an experiment, including a *Gedankenexperiment*).

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 black 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.

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 possible configurations which satisfy some criteria. The primary criterion is that of *internal consistency*.



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 4,800 possible (formal) configurations.

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 7-parameter field with 6 conditions under each parameter contains almost 280,000 possible configurations.
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 "reduction" is achieved by a process of *cross-consistency assessment* (CCA). All of the parameter values in the morphological field are compared with one another 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 to direction or causality, but only to mutual consistency. Using this technique, a typical morphological field can be reduced by to 90% or even 99%, depending on the problem structure.

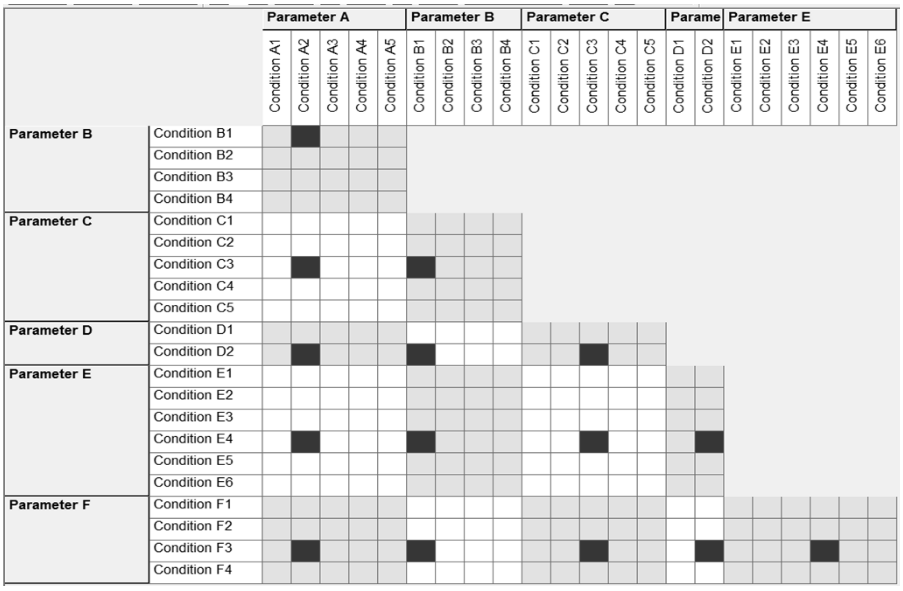


Figure 2: The cross-consistency matrix for the morphological field in Figure 1. The dark cells represent the 15 pair-wise relationships in the configuration given in Figure 1.

There are three principal types of inconsistencies involved in the cross-consistency assessment: purely *logical* contradictions (i.e. "contradictions in terms"); *empirical* constraints (i.e. relationships judged to be highly improbable or implausible on practical, empirical grounds), and *normative* constraints (although these must be used with great care, and clearly designated as such).

This technique of using pair-wise consistency assessments, in order to weed out internally inconsistent configurations, is made possible by the combinatorial relationships inherent in morphological models, or in any discrete configuration space. While the number of configurations in such a space grows "factorially" 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 is, that a morphological field involving as many as 100,000 formal configurations can require no more than few hundred pair-wise assessments in order to create a solution space.

When this solution (or outcome) space is synthesized, the resultant morphological field function as 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 different 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.

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