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Morphological Analysis in Inventive Engineering

Tomasz Arciszewski

George Mason University, Successful Education LLC, United States

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ABSTRACT

The paper describes Morphological Analysis (MA) in the context of Inventive Engineering. First, a short history of MA in the area of engineering design is presented, both in the USA and Europe. Next, its seven key assumptions are introduced and explained, and a four-stage procedure for using it to generate design concepts is presented, with its various steps discussed. In addition to the generation of design concepts, five other potential applications of the approach are proposed. These include classification, comparison of design concepts, finding patent holes and building patent fences, design knowledge acquisition, and learning abstract concepts. Finally, both advantages and disadvantages of MA are discussed.

1. Introduction

From the engineering perspective, Morphological Analysis (MA) is a method for acquiring design knowledge, creating an abstract design representation space, and using this space to randomly generate potential design solutions. It is an inventive designing method, because its products may be novel design concepts, i.e. concepts that are unknown, useful, feasible, surprising, and potentially patentable. As such, it is a part of Inventive Engineering, a new engineering science focused on engineering conceptual designing leading to the development of novel design concepts (Arciszewski, 2016).

MA was proposed in late 1940s (Zwicky, 1948), but it is more important and useful today than when it was created. At that time Computer Science did not exist and its sub-domain, "Artificial Intelligence" (AI), was to emerge only some 30 years later. However, MA introduced many concepts which decades later became a part of AI. Therefore, MA can be considered as a precursor of AI. Learning MA has value not only for inventors, but also for all engineers who want to understand AI and thus to prepare themselves for using it.

Fritz Zwicky – the pioneer of modern Morphological Analysis – was a true polymath, a man of many talents and knowledge in several domains, including engineering, mathematics, and experimental physics. Most importantly, as a mathematician and a physicist he learned the art of abstract thinking and brought this thinking both to engineering designing and to engineering in general. This abstract thinking in terms of symbolic attributes, design representation spaces, or generation of solutions from a representation space, is fundamental to AI (although Zwicky's terminology, introduced in the 1940s, was obviously different from that of present-day AI or Inventive Engineering).

The objective of this paper is to provide a general description of MA in the engineering design context. A more detailed presentation of MA with extensive examples is provided in (Arciszewski, 2016).

2. History

Fritz Zwicky proposed the method of Morphological Analysis during his Halley Lecture at Oxford University, U.K., in 1948. Later (Zwicky, 1969), he published his basic book on MA, titled "Discovery, Invention, Research through the Morphological Approach". Here he presented several different areas of applications. One of the most prominent areas is that of engineering design. Indeed, during the 1960's, when the design research revolution began in Europe, MA became the subject of several engineering studies that led to practical applications. This research began in the UK (Gregory, 1962, 1966; Norris, 1963) but quickly spread throughout Europe (Holliger, 1972, 1980, Kisielnicka and Arciszewski, 1974, Arciszewski and Pancewicz, 1976, Arciszewski and Kisielnicka, 1977, Arciszewski, 1976, 1977a, 1977b, Pahl and Beitz, 1977, Koller, 1986, Odrin, 1986, Rudnicki, 1989, Ritchey, 1991, 1998, 2015, Ostergatova et al., 2011, Motte and Bjarnemo, 2013, Heller et al., 2014, Álvarez, 2014, Dragomir et al., 2015). In the U.S.A, Grant (1977, 1984) initiated research on MA in design, mostly in the context of architecture. Also in the U.S.A, Arciszewski's MA research was continued and focused on inventive structural designing, for example, (Arciszewski, 1984, 1985, 1987, 1988, 1989, 1991, Arciszewski and Ziarko, 1988a, 1988b, Arciszewski and Uduma, 1988, Haydo and Arciszewski, 1989, 1991). More recent research by other MA scholars had expanded this focus to inventive general-system-configuration designing (Jimenez and Mavris, 2010). Today, MA research is also active in Australia (Dartnall and Johnston, 2005), and in Asia (Hassan, 2012).

During the 70 years of MA's existence, several methodological

E-mail address: tarcisze@gmu.edu.

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advancements have taken place. For example:

- In Switzerland, Holliger (1980) developed "Morphological Commando", a version of MA intended for group applications.
- In Ukraine, Odrin (1986) presented MA as a system using his background in cybernetics.
- In Nigeria, in the early 80′s, Arciszewski (1987, 1988) developed a mathematical simulation model of the MA process using a non-homogenous Markov chain model. While still in Nigeria, Arciszewski used this model to develop a computer program for the automatic generation of design concepts. (Probably, it was the first robo-designer developed specifically for inventive conceptual designing). This program was used to produce a novel design concept of a complex system of wind bracings in a skeleton structure of a tall building (Arciszewski, 1985). Later, in the U.S.A., the program was improved and used to produce a design concept of a connection in a steel space roof structure (Arciszewski, 1984), which was patented in Canada and in the U.S.A. (Arciszewski, 1989, 1991).
- In the U.S.A., Weber and Condoor (1998) proposed using the Theory of Coupling (Condoor and Burger, 1998) to analyze a morphological field in order to identify, and eventually eliminate or replace, coupled attributes, which are related to the coupled functions of the system being developed (Suh, 2001).

3. Assumptions

Zwicky's MA is based on the principle of "division and integration", i.e. analysis and synthesis. In the context of engineering design, this can be described by seven basic assumptions formulated here in the language of AI and Inventive Engineering, i.e. they have been modified and expanded from Zwicky's original conceptions (Zwicky, 1948, 1969). More detailed assumptions and their discussion are presented in (Arciszewski, 2016).

1. **The domain knowledge** concerning the engineering problem to be treated is acquired and stored in what Zwicky called a "morphological box" or "morphological field", and which today is also called a "morphospace". This bounded space (see Fig. 1) represents the problem domain knowledge to be considered and is exclusively used to produce solutions.
2. **Each attribute can be analysed** (divided) into a finite number of possible conditions, states or values representing possible specific alternatives to the given attribute (the numbered items under each attribute in Fig. 1). All attributes and their respective value ranges make up solutions to the "sub-problems", and represent a body of knowledge about the possible design concepts.
3. **A design concept of an engineering system** (which may be actual or abstract) is described by a finite number of symbolic attributes and a unique combination of their values (the column heads A–E in Fig. 1). Each symbolic attribute identifies a different feature of a design concept. Ideally, such a description should be necessary and sufficient to identify all known concepts and to distinguish between them.
4. **Each sub-problem** must be considered as independent from all other sub-problems, i.e. its relationships with the other sub-problems must be temporarily suspended.
5. **The resultant morphological field** is the engineering problem's "design representation space."
6. **Any potential solution to the entire problem** (**a design concept**) is represented by a combination of attribute values, one value from each of the columns of the field.
7. **All potential solutions** to the problem are generated in an unbiased way through the random generation of combinations of symbolic values from all columns in the field, one value from a column.

Assumptions 1 through 5 are related to the process of "division" (analysis), which in this case moves from the entire problem to its sub-problems. Assumptions 6 and 7 concern the reverse process i.e. that of integrating the sub-problems into a potential solution space for the problem as a whole. Here specific values of different attributes within the entire morphological field can be combined to describe potentially new solutions.

All of these assumptions are illustrated using a simple example of the conceptual designing of a symmetric beam under transverse loading. The intent of this example is only to provide an engineering context to the introduced assumptions, and therefore only five basic attributes are used. These attributes and their values are listed below and shown in Fig. 1.

A = "**Material**" with values:
A_1 = "*Steel*", A_2 = "*Reinforced Concrete*", A_3 = "*Wood*", A_4 = "*Other*"
B = "**Section Type**" with values:
B_1 = "*Solid*", B_2 = "*Hollow*", B_3 = "*Other*"
C = "**Section Shape**" with values:
C_1 = "*Rectangular*", C_2 = "*Square*", C_3 = "*Circular*", C_4 = "*I*", C_5 = "*T*", C_6 = "*Other*"
D = "**No. of Components**" with values:
D_1 = "*1*", D_2 = "*2*", D_3 = "*3*", D_4 = "*4*", D_5 = "*> 4*"
E = "**Connectors**" with values:
E_1 = "*None*", E_2 = "*Welding*", E_3 = "*Bolts*", E_4 = "*Rivets*", E_5 = "*Adhesive*", E_6 = "*Other*"

When relevant, an additional value is added to each column, namely "*Other*", in order both to make the list exhaustive and to underline the fact that the development of a morphological field is, in practice, never

A = "Material"	B = "Section Type"	C = "Section Shape"	D = "No. of Components"	E = "Connectors"
A_1 = "*Steel*"	B_1 = "*Solid*"	C_1 = "*Rectangular*"	D_1 = "*1*"	E_1 = "*None*"
A_2= "*Reinforced Concrete*"	B_2 = "*Hollow*"	C_2 = "*Square*"	D_2 = "*2*"	E_2 = "*Welding*"
A_3 = "*Wood*"	B_3 = "*Other*"	C_3 = "*Circular*"	D_3 = "*3*"	E_3 = "*Bolts*"
A_4 = "*Other*"		C_4 = "*I*"	D_4 = "*4*"	E_4 = "*Rivets*"
		C_5 = "*T*"	D_5 = "*> 4*"	E_5 = "*Adhesive*"
		C_6 = "*Other*"		E_6 = "*Other*"

Fig. 1. A morphological field consisting of five symbolic attributes (A–E) and their respective values (listed below each attribute). The number of possible (formal) solutions is the product of the numbers of attribute values in each column, i.e. 4 × 3 × 6 × 5 × 6 = 2160.