EVOLUTION AND FUTURE TRENDS IN GENERATIVE PRODUCT DESIGN

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Abstract

Generative design (GD) constitutes a different way of breaking creative blockings by letting the computer generate alternatives. The designer can explore a much wider range of possible product designs in a comparatively lower time. This is a relatively new discipline in industrial design, which is more widely spread in architecture design, where the algorithmic nature of the generated geometry fits perfectly into the modern building aesthetics. This paper intends to gather comprehensively the many contributions to this field to establish a wide vision of its role and identify its possible applications in other less explored areas such as product design. The studies found in the bibliography are analysed to observe the evolution of generative design and its future trend. Moreover, it is important to know the advantages and challenges that may arise from the application of the different tools that the generative design provides in order to identify their optimal applications.

Keywords: Product design, Generative design, Shape grammars.

1. INTRODUCTION

Conceptual design stage is commonly known as being mainly creative. Many authors have studied the processes that lead to successfully creative product concepts, as well as the obstacles that hamper the designer tasks at this stage. A typical research field focuses on the relationship between sketching (as product shape depiction) and creativity (Do, Gross, Neiman, & Zimring, 2000; Goel, 1995; Goldschmidt, 1991; Obrenovic, 2009; Schon & Wiggins, 1992; Suwa & Tversky, 1997; van Sommers, 1984).

In this design exploration process, GD has gradually had a more relevant place, mainly because it does not have preconceived ideas about objects, as is the case in the traditional creation process, where it begins with a model based on the knowledge of the designer. Instead, GD begins with design parameters that are gradually refined to create the optimal model.

According to (Krish, 2011) the research in what is now known as generative design was pioneered by Frazer in the early 1970's. At the beginning of its development the academic researchers focused mainly on design theory, without the advancement of implementation methodologies; consequently, formal methods for generative design were not immediate.

The term generative design is defined in many ways in the literature, some definitions oriented to each segment of research interests, but in general the definitions by Sivam Krish portray the essential objective of generative design.

"Generative Design is the transformation of computational energy into creative exploration energy empowering human designers to explore greater number of design possibilities within modifiable constrains" - Sivam Krish, 2013.

This work intends to summarize the efforts carried out in the development of the different implementations of generative design along these last thirty years and classifying each of these works in a field in which it is possible to identify trends throughout this time. As will be shown, researchers have carried out the most intensive efforts in three particular fields: shape grammars, optimization and genetic algorithms.

Our literature research has been conducted using ScienceDirect, Scopus, Mendeley, ProQuest, SAGE Journals, SpringerLink and Google Scholar databases. In this research we found several methodologies whose objective is to generate designs through the application of a GD methodology individually or by coupling with some other techniques.

2. THE MANY FLAVORS OF GENERATIVE DESIGN

2.1 Shape Grammars

Shape Grammars (SG) can be defined as a method to represent geometry in a generative form by applying a geometric logic of the object (Krish, 2011). Thus, by applying a set of rules that are based on inherent characteristics of the object and that begin with an initial shape to transform (McCormack, Cagan, & Vogel, 2004) This field, as will be appreciated later, is the most adopted in the different research.

Shape Grammars deserve a special mention, as they are the most notable algorithms used in generative design. The work of Stiny and Gips (George Stiny & Gips, 1972) set the basis for this generative formalism. This research deals with the generation of paintings and sculptures, although the authors remark the possibility of algorithmically produce other type of objects such as music pieces, chemical compounds, or language sentences. An interesting consideration about aesthetics is also noted. Later, Stiny introduced parametric shape grammars for the generation of Hepplewhite-style chair-back designs (George Stiny, 1980).

A recent and comprehensive description of different SG approaches can be found in (Garcia, 2017). More specifically related to product design is the work of (McKay, Ang, Chau, & Pennington, 2006), whose comparative table is taken as a basis of our research. This research presents a proposal combining genetic algorithms and SG using a Coca Cola bottle as an example. Some particular reviews such as "Evaluation of a 3D Shape Grammar Implementation" by (Chau, Chen, McKay, & de Pennington, 2004) provide information on the implementations of the SG between 1975 and 2005.

Since those initial publications, many applications of this formal approach emerged. Initially, the natural growing fields for SG were arts and architecture (Khemlani, 1995; Liebich, 1994). The journal "Environment and Planning B: Planning and Design" constitutes a flagship in the publication of shape grammar papers, most of them falling on the architectural side. The extraction of a grammar style for further replication is a common topic (Buelinckx, 1993; Chiou & Krishnamurti, 1995; Downing & Flemming, 1981; U Flemming, 1981; Ulrich Flemming, 1987; Herbert, Sanders, & Mills, 1994; Koning & Eizenberg, 1981; G Stiny & Mitchell, 1978; Yan, 1992).

In (Çağdaş, 1996) a whole description of the English row houses grammar is given. (Seebohm & Wallace, 1998) present a three-dimensional interpretation of Stiny of shape grammars. Different approaches to structural design can be found as well in (Shea, Aish, & Gourtovaia, 2005; Shea & Cagan, 1999), in these studies we can also appreciate the application of SG with shape annealing and simulated annealing. (Smyth & Edmonds, 2000) analyse the use of SG in the conceptual stage of architectural design and propose four areas for SG development.

This abundance of style research gives an idea of the impact of the shape grammar concept in the field of architectural design. In the literature it is also possible to find more current research in this field (José P. Duarte, 2005), Siza´s houses at Malagueira; here also introduce the use of Description Grammar (DG) to process the data provided by the user and the site. Related to the GD in the work of (Stouffs, 2018) the SG and DG are used as a guide for the generative process. In addition, this work presents abundant applications of DG existing in the literature.

Others works in architectural design and the use of shape grammar are the Chinese Bracket System of (Wu, 2005), the connection with semantic in (Liu, Xu, Pan, & Pan, 2006) Semantic modelling for ancient architecture of digital heritage, the customization of apartment's plans in (Veloso, Celani, & Scheeren, 2018).

in the field of urban design, the research of (Mandić & Tepavčević, 2015) presents various approaches to shape grammar application. Furthermore, in a recent research, (Ozdemir & Ozdemir, 2018) produces, with shape grammar using two of multi-criteria decision-making (MCDM) techniques, variations of store plan alternatives.

It is notable that the SG grew mainly in the architecture field; however, its application also arose in other fields such as mechanical and industrial design. One of the first works found in the literature related to product design, is *The generation of Hepplewhite-style chair-back designs* (Knight, 1980), which uses the work of G. Stiny (George Stiny, 1977) as reference for the development of a parametric shape grammar.

Some other works can be found on mechanical design (Flasiński, 1995) or manufacturing processes (Brown, McMahon, & Sims Williams, 1996), here with the use of SG and semantic. The work of (M Agarwal & Cagan, 1998) is the first using SG for product design. They consider the product functionality and generate alternative formal structures. Interestingly, they recognize the limitations that such an approach imposes to the creative process in terms of radical design changes.

Continuing with the use of SG in product development, (S.-W. Hsiao & Chen, 1997) also combine SG with a semantic approach to define significant shape structures for an office chair, which are then modified by means of several regulation rules. Later, a work by (S.-W. Hsiao & Wang, 1998) used a similar approach to produce car designs, but in this time adding fuzzy set technique. Both examples used a 3D CAD system connected to the semantic database. The use of computers to develop SG solutions was relatively low back then. In (Gips, 1999), Gips summarize a state of the art of the software implementations of SG.

In 2002, the work of (S.-W. S. W. Hsiao & Huang, 2002), uses again the example of office chairs to build an emotional design expert system based on neural networks. It can predict the emotional evaluation of different chair alternatives, generated by means of a simplified shape grammar procedure. Similarly, in the research of (Garcia & Menezes Leitão, 2018) presents a multipurpose chair grammar through the implementation of SG, especially set grammars.

Shape grammars can be simplified using set grammars, this statement can be found in the work of (Granadeiro, Pina, Duarte, Correia, & Leal, 2013). “Set grammars are a simpler form of shape grammars, more constrained, in which sub-shape recognition, shape emergence and iterative rule application are not freely used”.

SG are subsequently applied during the following years, for different products in works worth mentioning, such as the research of (McCormack et al., 2004). This is an interesting study in which SG are used to capture Buick brand identity and generate alternatives following it. This research as well as the work of (Chen & McKay, 2004) reviews the brand identity. Chen & McKay examine the personal care bottles to analyze their basic design principles and codify them within a parametric shape grammar.

We can find an extensive brand identity research in the study of (Chau, 2002) in which, through grammatical approach intends to preserve brand identity, and also presents some cases of study such as Dove grammar. Also in (Pugliese & Cagan, 2002) the brand capture is discussed in aim to model a motorcycle Harley-Davidson brand throw a motorcycle shape grammar.

In 2006 the study of (Orsborn, Cagan, Pawlicki, & Smith, 2006) uses of SG to quantify the differences between vehicle classes, it allows the creation of new forms of vehicles with a cross-over trend. Beside, Manish presented a study of coffee machines design related to its costs (Manish; Agarwal, Cagan, & Constantine, 1999) By these days, works linking automatic generation and automatic fabrication of objects begin appearing (J.P. Duarte & Simondetti, 1997; Sass, 2008; Yufei Wang & Duarte, 2001).

Later, mass customization of ceramic tableware was introduced in (Castro E Costa & Duarte, 2013), this was the first effort to set up a system of mass customization by a system based on SG that automatically produce elements of tableware. Duarte denotes that the first step to get in the implementation of a mass customization system is the development of the design system.

Another research for mass customization is found in (Barros, Duarte, & Chaparro, 2011, 2015) where is presented a model for mass customization for the furniture industry, specifically in development and implementation of a grammar-based design system for Thonet chairs. In this case, the use of other GD techniques such as shape annealing, and parametric modeling are mentioned.

In some others studies such as (S. W. Kielarova, Pradujphongphet, & Bohez, 2014; Somlak Wannarumon Kielarova, Pradujphongphet, & Bohez, 2015), grammars and evolutionary strategy were applied to the development of specific products such as jewelry, with the aim of supporting designers to explore different and innovative shapes.

In the work of (Ruiz-Montiel et al., 2013) a SWOT analysis of the SG is presented. In this analysis, the strengths and weaknesses of the SG are identified; Furthermore, the areas of opportunity and threat factors. Within their strengths, its versatility is mentioned since SG can produce any shape, also provide an intuitive method for shape definition. SG are considered compact as they can generate complex designs and unexpected shapes with few rules, allowing automation to produce many design alternatives. On the other hand, its weaknesses can be defined as the difficulty to create and control the SG when it comes to achieving the design objectives, and its execution demands considerable computational resources. The feasible opportunities are the increase of design capabilities by computers, along with their more accentuated inclusion in design. Finally, Ruiz-Montiel identifies the reluctance of designers to use SG as a threat.

In (Scott C Chase, 2002) an interactive generative system is envisioned. Interestingly, the author discusses about the possibility of automatic grammar generation, an issue that we consider of the utmost importance to achieve an efficient generative design system. The use of direct graphical features instead of text coded grammar rules, this issue is also considered in (S C Chase, 2005).

Several works by these years use a combination of shape grammars and evolutionary algorithms (EA): Coca Cola brand designs (McKay et al., 2006); ethnic Zhuang embroidery (Cui & Tang, 2013); a review of the Frank Lloyd Wright's prairie houses (Granadeiro et al., 2013), (Turrin, Von Buelow, & Stouffs, 2011) addresses the performance-oriented design process, with a specific focus on architectural design.

In a series of works, (Lee, Herawan, & Noraziah, 2012) (Lee & Tang, 2009) pioneers the combination of SG and EA for product design. The evolutionary grammar is a kind of "parametric design-generative algorithm" approach. The combination of these two elements is usually referred as "Grammatical Evolution", a particular discipline using grammars as descriptive systems and EA as variation generators.

As can be seen in the development of this work, the SG evolved from a somewhat rudimentary application in its beginnings, to being combined with other techniques of GD and reaching its application through the advantages of the computer. Beginning in recent years, with his practice with other more advanced techniques such as evolutionary algorithms.

2.2. Optimization

Topology optimization is the process of defining the optimal distribution of material and connectivity within a design domain (Deaton & Grandhi, 2014). Within this search process, procedures that are well suited to generative design methodologies are integrated. In these cases, the search for solutions is usually carried out with the combination of other generative design techniques, mainly with algorithms that allow achieving the best solution. Some works to denote the different applications of generative design methodologies related to this group, are mentioned below.

The combination of L-system (a generative method), genetic algorithms and topology optimization converge giving a solution to a problem, that consists of maximizing the fundamental natural frequency of an aluminum panel with integral reinforcement, is presented in the research of (Ikonen & Sóbester, 2018).

In the work of (Yedong Wang et al., 2018) is proposed a generative design method for lattice structure (initialization, analysis, and optimization, IAO). IAO consisting of 3 stages, the first in the automatic generation of the structure with hollow struts, then the finite element analysis is used to determine the stress and deformation factors; finally a rapid optimization method is presented to optimize the distribution of materials on the internal structure.

For their part, (Tutum, Chockchowwat, Vouga, & Miikkulainen, 2018) use a generative design algorithm such as variational autoencoders and efficient global optimization to generate and optimize the designs of a car-launcher mechanism to subsequently generate the prototype of the best solutions by fused deposition modeling (3D Printing).

Talking about optimization, not only is it about the topology optimization, but we can also talk about the optimization of the parameters of the design of an element, as well as its validation. In other words, methods to navigate in the design space and search for solutions with better suitable solution. In the work of (Shieh, Li, & Yang, 2018) this issue can be exemplified, its authors use Multi-objective evolutionary algorithm (MOEA) and Kansei engineering system to obtain optimal alternatives for the design of products. In addition, this research presents a case study, the design of a vase.

In the research of (Khan & Gunpinar, 2018) addresses the optimization by improving the solutions provided with the application of Teaching-Learning-Based Optimization (TLBO). In their study Khan and Gunpinar use different products like yacht hull, wine glass and wheel rim to exemplify their study.

A state of the art of generative design and topology optimization is presented in (Tyflopoulos, Flem, Steinert, & Olsen, 2018); in addition, an interesting comparison of the different topology optimization approaches is given. In this research suggest the use of a topology optimization algorithm to calculate the optimal adaptation limits of the structure, this with respect to the external design parameters in the design of a ski binding.

This classification of optimization approaches is very close to the next group of generative design methodologies, due to the wide application of Evolutionary Computation (EC) in structural engineering, specifically in structural optimization problems.

2.3. Genetic Algorithms

The Genetic Algorithms (GA) are an optimization technique that emulates the process of natural selection. An initial population of individuals is defined as strings, individuals are then selected and their strings combined to create new individuals in a random process that takes into account their fitness to a given objective function (Ruiz-Montiel et al., 2013).

GA have been used separately or combined with SG or Neural Networks (NN) to produce generative design systems. Some early works can be found in the 90's (Apineda, 1993; Gero, 1996; Hybs & Gero, 1992; Pollalis, 1994). One of the first applications of GA in the literature is GENE_ARCH, a generative design system based on GA which is used to develop sustainable and eco efficient architectural solutions (Caldas, 2008).

As can be appreciated, like the SG, the application of GD using GA and related methodologies have also been applied to architecture, but in more recent studies; As is the case of (Medjdoub & Bi, 2018), Medjoboud uses constraint-based programming with the objective of to determine the route of duct for ceiling mounted fan coil systems in buildings.(Miao et al., 2018) developed a Computational Urban Design Prototyping (CUDP), a method for rapid urban design prototyping. In (Sun & Taplin, 2018) use GA through the algorithm Computational Urban Layout Design to generate residential plans. Beside of this, Cellular Automata is used as a generative tool to explore alternative forms in buildings and urban spaces.

Artificial intelligence is also having an impact on generative design, as can be seen in the work of (Heusler & Kadija, 2018) where the creation of advanced design of complex facades is sought. In the research of (Pantazis & Gerber, 2018) the design and evaluation of facades design is generated through Multi Agent System, which is considered an example of distributed artificial intelligence. Besides this, (Francalanza, Fenech, & Cutajar, 2018) design the link modules between the joints of an articulated robot using evolutionary and artificial intelligence.

An extensive state of the art of EC reviews can be found in (Kicinger, Arciszewski, & De Jong, 2005). It also presents a chronological classification of applications of EC in structural engineering. Moreover, a recent review of improvement of generative models in machine learning and the use of learning techniques in design is given in (Bidgoli & Veloso, 2018). An interesting description of contributions and applications of GA in design is presented in (Renner & Ekárt, 2003), mentioning several works and research about these applications.

The research of (Neill et al., 2010) shows a powerful combination between SG and Grammatical Evolution (GE) with a new evolutionary design tool, that conceptual designs of shelters could be generated. Moreover, in the work of (Strug, Grabska, & Ślusarczyk, 2014) propose a combination of genetic algorithms and hypergraph representations, using a table design as example. The genetic operators are represented by hierarchical hypergraphs.

In (Cluzel, Yannou, & Dihlmann, 2012) use evolutive design to interactively sketch car silhouettes and stimulate designer creativity. Their authors use Fourier harmonics to describe car silhouettes and a GA to derive alternatives. In addition, here is a comparison of SG and GA, it is pointed out that SG as coding method has a better completeness compared to other methods, also better robustness, and consistency, but a low extensibility and adaptability to genetic algorithms.

In the year 2016, (Ji, 2016) presents an algorithm of "T"-shape joint patterns. It focuses on the production of geometric shapes for the design of Chinese lattice with irregular shapes and independent structure. This, made by programming with the software Grasshopper and VB script component.

As in the SG, the development of products related to jewelry is present, as is the case of the work of (S. W. Kielarova et al., 2014), here is proposed an interactive-generative design system based on a hybrid of SG and evolutionary strategy. In (Somlak Wannarumon Kielarova et al., 2015), using EA increases significantly the solutions of earring designs. More recently in (Sansri & Kielarova, 2018) the EA for multi-objective optimization "Strength Pareto Evolutionary Algorithm" (SPEA-II) is used to reach two objectives as shape and weight ratio in a case of study into the jewelry design. Sansri and Kielarova also address the case of a perfume bottle design through a generative design system for shape optimization by an interactive-genetic algorithm integrated with multi-objective genetic algorithm (Somlak Wannarumon Kielarova & Sansri, 2016).

The unexpected emergence can be produced in different ways, in the research of Krish the design parameters are varied in a random manner within predefined limits in order to generate various solution options to subsequently filter these solutions through various restrictions to ensure their viability. (Krish, 2011). In the work of (Strug et al., 2014) it is admitted that the use of evolutionary design provides the benefit of introduce new, unexpected solutions. Gero recognizes the need to allow introducing or changing the values of the design parameters to favor the emergence of novel and unexpected solutions. In his work (Gero, 1996) several models of emergence processes are presented, which are based on notions of additive and substitutive variables.

In the research of (Albers, Rovira, Aguayo, & Maier, 2008) illustrate how the early activities in genetic algorithms helped to produce the first computer shapes that simulate a creative performance. In more recent research (Gunpinar & Gunpinar, 2018) also use genetic algorithms for shape variations for CAD products with the intention of suggesting innovative forms of products to designers and consumers.

3. RESULTS

3.1 Actual Trends and Areas of Interest

As stated in (Chau et al., 2004) since the introduction of (George Stiny & Gips, 1972) are at least 20 shape grammars in the literature. Shape grammars at the beginning were used to analyze painting and arts, to later study some fields in architecture. Between the years 1995 and 2005, it began to be used in engineering, thus giving the inclusion of shape grammars in the product development. In (McKay et al., 2006) is a summary and analysis of research related to shape grammar work and product designs.

Other generative design techniques have proved to be a viable approach to generate innovative designs. In the last 15 years different research can be found in the literature (Fig. 1), mainly in fields such as architecture and product development. Since the mid-1990s, the commonly generative design techniques have been notably discontinued in fields such as decorative arts, sculpture, and painting.

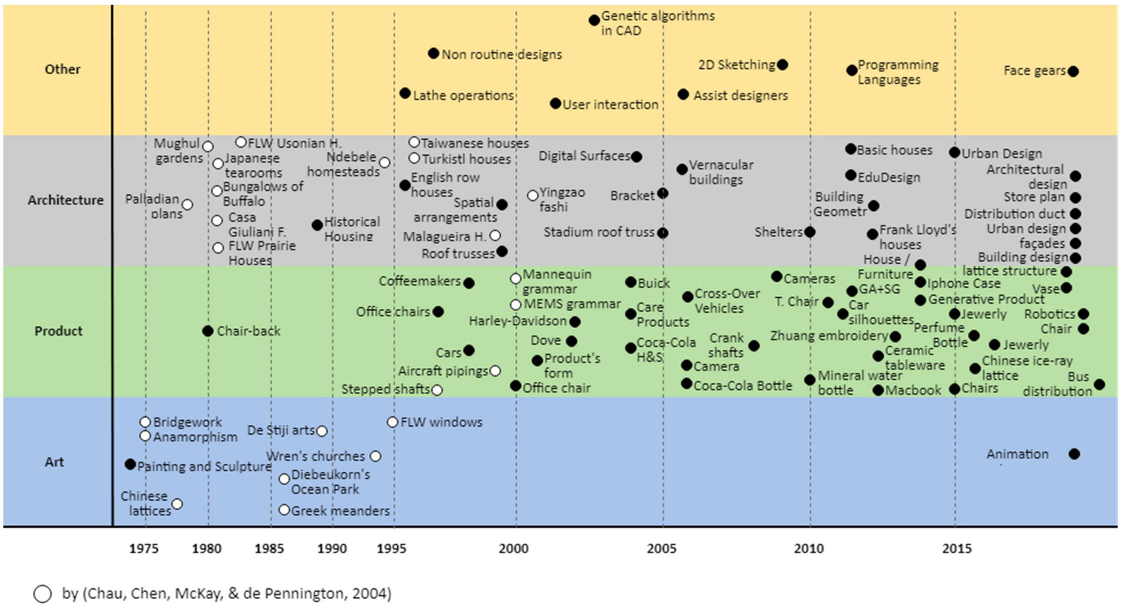

Figure 1. Applications of Generative Design.

The use of shape grammars in architecture dates from the late 80's, with the work of (Ulrich Flemming, 1987). The application of shape grammars in this field and other generative design techniques was considerably upward from this date. The use of generative design focused on product development, was visibly increased at the beginning of the 2000's and shows a higher tendency than in architecture, doubling the studies in this field in the period of years 2011-2015 and continuing the difference in the 2016-2021 period, as is shown in Fig. 2.

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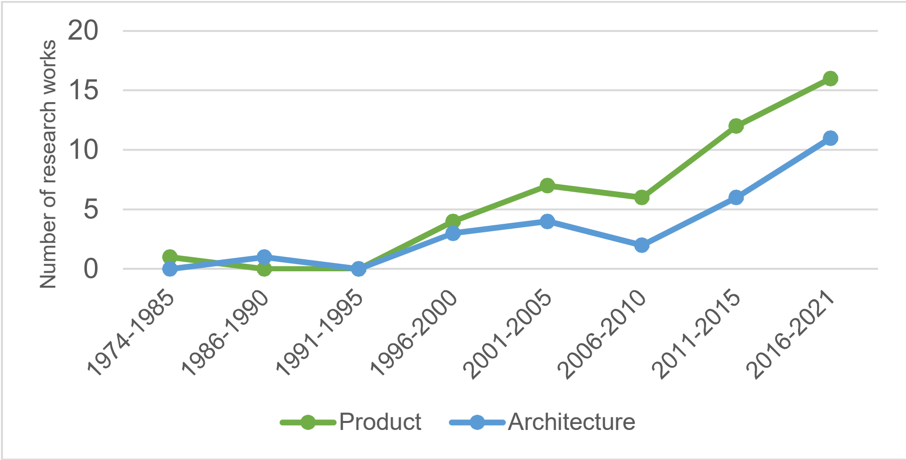

Figure 2. Presence of GD by field.

4. CONCLUSIONS

A review of the main works found in the literature related to the GD were exposed, mainly in three techniques, shape grammars, optimization, and genetic algorithms. Its main applications and the evolution manifested over the past years. In addition, the different advantages and disadvantages of some generative design techniques were denoted. The main trends of generative design were analysed, as well as the evolution of shape grammars and evolutionary algorithms. On the other hand, the combinative presence of GD techniques, and the technological tools that have been used were evidenced.

The challenges in the current scenario were also highlighted, such as the cumbersome process for extracting the grammar, parameterisation, the usability, and ease of exploration in the different GD techniques, issues in which evidently it is necessary to continue investigating. Finally, a compendium of applications related to generative design in the product field was presented, in order to document the growth of GD in this field in recent years, where the trend of using generative design for products design is visibly on the rise.

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