A Spatial Grammar Model for Designing Mass Customized High-rise Housing Blocks

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Emergence as a product of natural processes is a typical feature for traditional and vernacular housing settlements created by different users with their various needs. However, this feature disappears in housing production approaches for uniform and standard users due to mass production concerns. The main reason is that user needs cannot be fully transferred to design strategies due to excessive standardization. One of the main factors in this is the need for design tools and methods that effectively evaluate preferences with complex relationships. Shape grammars and spatial grammars, one of the generative design approaches, exhibit original emergence examples with their rich diversity and adaptability to different approaches. Hence, it can be seen as an alternative for solving such problems. This article presents a parametric spatial grammar model that can design high-rise housing blocks with a customized dwelling for each family. The compositions of these houses are grounded on specific spatial relationships defined by parametric rule sets. In the article, the generative design process was developed in two stages. The first stage includes the formal, syntactical, and functional relations of the spaces in a floor plan, their representation according to the rules, and generating alternative solutions. The second stage consists of the representation of the façade rules and the parametric grammar that generates the façades. In the developed spatial grammar model, user preferences are transferred to the computer through the designed interface. Dimensional properties of housing blocks are defined by a grid system, which is determined according to user preferences and used as a starting base for spatial grammar. Plan layouts are generated on this defined grid and by sequential application of rules. In conclusion, the adaptability of spatial grammar and the rich alternatives designers can use and develop are emphasized.

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Keywords: Emergence, Spatial Grammar, Mass Customization, Housing Design, Generative Design.

Özelleştirilmiş Kitlesel Çok Katlı Konut Blokları Tasarımı için Mekânsal Gramer Modeli

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Doğal süreçlerin bir ürünü olan belirme, farklı kullanıcıların farklı ihtiyaçlarla bir araya gelerek oluşturduğu geleneksel ve yöresel konut yerleşmeleri için tipik bir özelliktir. Ancak seri üretim kaygılarına bağlı, tek düze ve ortalama kullanıcılar için konut üretim yaklaşımlarında bu özellik kaybolmaktadır. Buradaki temel neden, aşırı standartlaşmaya bağlı olarak kullanıcı ihtiyaçlarının tasarım yaklaşımlarına tam anlamıyla aktarılamamasıdır. Bunda da ana etkenlerden biri, karmaşık ilişkiler içeren tercihlerin etkili bir şekilde değerlendirildiği tasarım araçları ve yöntemlerine duyulan ihtiyaçtır. Üretken tasarım yaklaşımlarından biçim gramerleri ve bir türevi olan mekânsal gramerler zengin çeşitliliği ile özgün belirme örnekleri sergiler ve farklı yaklaşımlara uyarlanabilir niteliktedir. Dolayısıyla, bu tür problemlerin çözümü için bir alternatif olarak görülebilir. Bu makale, her aile için özelleştirilmiş konutlara sahip çok katlı konut blokları tasarımında kullanılabilecek parametrik bir mekânsal gramer modeli sunar. Bu evlerin kompozisyonları, parametrik kural setleri ile tanımlanan belirli mekânsal ilişkilere dayalıdır. Makalede üretken tasarım süreci iki aşamada geliştirilmiştir. Birinci aşama bir kat planındaki mekanların biçimsel, sözdizimsel ve işlevsel ilişkilerinin kurallarla temsillerini ve alternatif çözümler üretmeyi içerir. İkinci aşama, cephe kurallarının temsili ve cepheleri oluşturan parametrik grameri içerir. Geliştirilen mekânsal gramer modelinde, kullanıcı tercihleri tasarlanan arayüz aracılığıyla bilgisayara aktarılmaktadır. Konut bloklarının boyutsal özellikleri, kullanıcı tercihlerine göre belirlenen ve mekânsal gramer için başlangıç altlığı olarak kullanılan gridal bir sistem ile tanımlanır. Plan düzenleri tanımlanan bu ızgara üzerinde ve kuralların ardışık uygulanmasıyla türetilir. Sonuç bölümünde, mekânsal gramerin uyarlanabilir olma özelliğine ve tasarımcıların kullanabileceği ve geliştirebileceği zengin alternatiflere vurgu yapılmaktadır.

Anahtar Kelimeler: Belirme, Mekânsal Gramer, Kitlesel Özelleştirme, Konut Tasarımı, Üretken Tasarım.

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1. INTRODUCTION

Architectural design development processes generally begin with a design brief used to drive a design process that starts with initial design concepts, usually in the form of hand-drawn sketches, and ends with a design definition (McKay et al., 2012). There are a few computational tools in the early design phases to support designers' ways of thinking and enhancing design creativity, for example, by offering non-obvious design alternatives that the designer did not initially recognize. This paper proposes a generative grammar for designing plan layouts and façades of high-rise housing blocks within a computational design synthesis approach.

Many researchers have studied the generative grammars in design by shape grammar theory, which can develop architectural design languages (Stiny, 1980a; Stiny & March, 1981; Stiny & Mitchell, 1978). Many studies are concerned with rule-based configurations, which consist of encoding syntactical knowledge of architectural designs. Some of these grammars have been derived from a given corpus of designs during the first three decades. Palladian villa plans (Stiny & Mitchell, 1978), Bungalows of Buffalo (Downing & Flemming, 1981), the prairie houses of Frank Lloyd Wright (Koning & Eizenberg, 1981), the architecture of Guiseppe Terragni (Flemming, 1981), Queen Anne houses (1987), traditional Turkish houses (Çağdaş, 1996), Malagueira houses (Duarte, 2005), and façades of historical Brazilian town (Godoi & Celani, 2008) exemplify these shape grammar applications. The common point in all these studies is regenerating the solutions belonging to various designs in a generative approach. These languages emerged as vernacular architecture, neoclassical architecture, and the individual designs of some well-known architects. These approaches are an analytic type of shape grammar formalism. The researchers created most of these grammars on paper, and only a minority was computationally implemented like that Duarte (2005), Grasl (2012), Granadeiro et al. (2013), and Strobbe et al. (2016).

After these studies, some researchers have studied to present new design languages as another approach in shape grammar formalism. It is original grammar based on generalized rules intended to create instances of original designs. These types of grammar have not been prevalent as analytical grammar. There are a few kinds of research on this subject (Hoisl & Shea, 2011).

In the literature, there are also different generative design approaches that have benefited from the techniques like genetic algorithms and agent-based systems that generate plan schemes for housing apartments and other housing units (Carta et al., 2020; Gungor et al., 2011; Guo & Li, 2017). However, this paper presents a parametric spatial grammar for high-rise housing blocks with mass-customized dwellings for every floor. The plan layouts of these houses are based on certain spatial relations, which provide the basis for a parametric spatial grammar. The rules represent the formal compositional aspects of this housing grammar. In the context of this paper, it is essential to note that spatial grammar is primarily used for generating geometric forms of housing layouts and façades and is a tool for generating alternative mass-customized plan layouts for occupants. Generative novel designs are not a concern of this paper, and it aims to contribute to real design scenario applications using the proposed parametric design tool to generate design alternatives. The model presented in this paper also has a user-friendly interface that helps users make decisions about their spatial organization of dwelling. The interactivity of a computational design model is an essential subject for mass-customized design products.

Nowadays, in our country, urban transformation is an important subject. As the current old building stocks have been demolished in the construction industry, new high-rise housing blocks have been built increasingly. But the householders are not satisfied with the plan layouts of these new housing designs. For this reason, designing mass-customized housing is a vital role for architects. Unfortunately, the new housing blocks for low-income groups are similar to plan layouts and façade characteristics in every city. Also, regional and socio-cultural differences have been considered. The architectural language presented in this paper grounds on housing layouts that satisfy user requirements in Turkey.

2. PARAMETRIC SPATIAL GRAMMAR

Shape grammars are proved to have all the generation and analysis capabilities of traditional production systems while representing knowledge about a product's functionality and form (Agarwal & Cagan, 2000). It is possible to model various generation processes on shape transformations and manipulations. Shape grammars are applications in which shapes are represented as design descriptions and transformed according to a rule-based formalism (Stiny, 1980a).

Emergence appears to be a result of the holistic behaviour of complex system architectures. Besides, it is more than the sum of the parts. It has characteristic features like complexity, non-linearity, unpredictability, and self-organization (Knight, 2003). In computational systems, there is a certain degree of emergence behaviour. So, emergence is a fundamental feature in shape grammar as a type of these systems. Emergence is generally in the form of identification and evaluation of the emergent shapes by computation. In addition, the emergent shapes are not pre-defined; they exist in the results of the rule applications.

A conceptually more straightforward form of shape grammars is that of set grammars and spatial grammars. These are grammars that manipulate compositions made up of elements. Stiny (1980b, 1982) made the distinction between set and shape grammar. Set grammars have certain implementational advantages. They are more adaptable to representation for computer programming and conform more readily to the production system formalism. They also reflect how the designer's world is often perceived: composed of hierarchically describable things. Complex descriptions of objects can be manipulated more readily than under a shape grammar (Coyne, 1989, p. 103).

Spatial grammar can be an active partner through the computational synthesis of designs, supporting the human designer. They can help routine design tasks by generating alternative arrangements and, even more interesting, developing spatially novel solutions beyond what a designer might think. They provide a rule-based, generative shape design method but have yet to find general application within CAD systems. Most spatial grammars are hard-coded; i.e., a practitioner cannot change their vocabulary and rules without re-programming (Hoisl, 2012).

In this paper, the term 'spatial' is preferred instead of shape grammars because the definition of spatial grammar is appropriate to the representation of the spaces and the façade elements like set grammar. The contribution of spatial grammar to the design process of the mass-customized housing would be to compose the vertical and horizontal relations of the spaces. Rectangular units (cells) represent these spaces in the computational model. The rules present the neighborhood relations.

3. SPATIAL GRAMMAR FOR DESIGNING MASS CUSTOMIZED HIGH-RISE HOUSING BLOCKS

The proposed model for designing mass-customized housing buildings where different users share a common culture and form a whole by different needs together have a top-down and a bottom-up process that operates as two and three-dimensional. It is possible to examine the model in two sections.

3.1 Generation of Floor Plan Layouts

There is a two-pronged approach that enforces a specific set of rules in the grammar configuration. The first approach includes preparing a rectangular schema or a grid as an initial step and re-organizing the composition generation in the following steps. The other method involves a generation process that starts by locating a particular space and continues with adding the different rooms/spaces to the plan composition. In these approaches, spatial relations are represented by hierarchical and multiple rule sets, similar to Palladian, Bungalow, Japanese tearooms, and Queen Anne grammars.

In this paper, the generation of the plans for mass-customized houses occurs in the second approach. The generation process progresses on an imaginary grid mechanism. In the defined rule sets, square or rectangular shapes in the grid placement represent the vocabulary elements to determine the topological configurations of the spaces. As the vocabulary elements of this parametric spatial grammar are represented as blocks, this grammar can be considered a set grammar. The vocabulary elements of the grammar (i.e., the façade elements) operate as modules in the block grammar.

As Stiny states, "Spatial relations for a given vocabulary sometimes allow its shapes to interpenetrate in designs. Interpenetration like spatial ambiguity can be a valuable technique in design. Architects and designers often conceive of designs in terms of interpenetrating masses or volumes. In those cases, however, where interpenetration is felt to be undesirable, it can be prohibited by labeling the shape rules used to construct designs" (Stiny, 1980b), p.440). Stiny (1980b) developed a labeling scheme for preventing interpenetration in designs constructed by shape rules. This scheme is helpful in labeling shape rules based on spatial relations that can specify by sets of shapes defined in a discrete, cubical grid. Similarly, in this grammar, there is a grid layout to represent the blocks and their spatial relations to prevent spatial ambiguity and control interpenetration of the blocks and, consequently, the spaces or the façade elements. The functions of the spaces label the spatial blocks.

When considering today's multistorey housing designs based on mass production, it is not difficult to observe that the floor plan organizations usually include similar combinations of one or more of four or five different typical dwelling layouts. These layouts are in the form of one living room and the other room/s (one room+ a living room, two rooms+ a living room, three rooms+ a living room, four rooms+ a living room) with other service spaces (WC-bathroom, entrance hall, kitchen, etc.). Their numbers can also vary on a floor plan according to building size. They have the same plan scheme limiting the users' choices on each floor. However, the proposed model encourages variety and flexibility because it is a parametric computational model that produces alternatives using the "generate and test" method. This model evaluates different user preferences for each floor as digital data and offers new formation possibilities with innovative features. In the model, each spatial unit affects the generation of others according to this digital data, and they come together to form different dwellings. Thus, variations naturally emerge by themselves.

A floor plan area defines the boundaries of a generation space. There are basic requirements and specific relationships with the other rooms for the design of each room in a dwelling. By this knowledge, the model manages the positions of the rooms in the workspace. All of them happen with determining locations of rooms, allocating functions, and generating and defining new spaces in the proposed model. Also, there is a central or linear vertical stable circulation area as a building public space. This vertical public space is in the center, and the other rooms/dwellings place throughout the housing block.

Moreover, there is a structural system that allows for spatial flexibility and variety in this model. As Christopher Alexander (1997) pointed out before, using rectangular spaces is widespread, and these spaces provide ease of use and flexibility (Guo & Li, 2017). Accordingly, the model is based on a rectangular grid layout, and the structural design is in a grid system of n x n dimensions. The grid planes define a potential generation field for each unit of dwellings by its division into smaller units (n/2 x n/2 meters). Model regulates each dwelling plan on these grids by the knowledge of dwelling typologies which are pe-defined in its database (**Figure 1**).

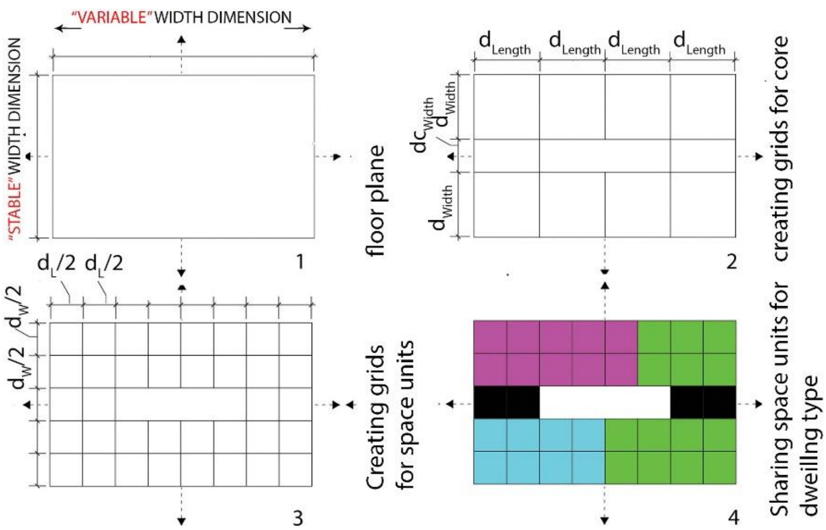

Figure 1: Grid divisions of floor plan layouts.

The design of floor plan schemas for housing blocks occurs in certain stages, such as determining types of a dwelling like Type A (one bedroom), Type B (two bedrooms), and Type C (three bedrooms) according to user preferences, generating their variations, and evaluating their results. The model envisages that each dwelling type will have a living room and bedrooms. At first, the model compares user preferences and the knowledge of the pre-defined dwelling type to determine the patterns of the dwellings that will occur in the chosen floor plan schema. It makes a share of the total floor area among types of residences described in the selected floor in the context of user preferences. It evaluates the sizes of each type of dwelling by considering the constraints of minimum and maximum area, which are specific for the defined dwelling types. It eliminates the residences which stay under the minimum values and shares their areas among the other kinds of dwellings according to preferences. Also, if the maximum area value is exceeded, it reviews each of the chosen dwelling types regarding their space capacity to build more than one dwelling. Thus, it balances users' demands and spatial requirements.

Then interior space designs initiate after the decision of production states and numbers of the chosen dwelling types. In the generation of the plans, the operation process starts with the placements of the spatial units on the shared floor plan areas according to the rules of spatial relationships. These units comprise the entrance hall of the building, entrance hall of the house (G), bathroom (W), kitchen (K), living room (L), bedrooms (B), and terraces (T).

The rule sets for plan layouts are as follows:

- After placement of entrance hall units, voids are controlled at the right and left of each "entrance hall" unit according to their relations with the main circulation area. A kitchen or bathroom cell settles into the void unit (R_{221}, R_{222} R_{231}, and R_{232}). Also, for some dwellings, placement of living room cells is done (R_{223} and R_{224}).
- If there are spatial units on both sides of an "entrance hall" unit and this "entrance hall" is a member of Type A (one room and one living room) dwelling, then a living room exists in front of this unit (R_{211} and R_{212}). In such cases, at the end of the process, a two-cell dwellings type may occur and is called a "Type D" dwelling with a mixed-function room.
- After controlling right and left neighborhoods of the entrance halls, in front of these cells and the other generated ones, a kitchen ($R_{233,}$ R_{234}) or a living room ($R_{211,}$ R_{212}) unit for large dwellings (Type B and C) and a bedroom ($R_{225,}$ R_{226}) for a small dwelling (Type A) place.
- A kitchen may be near the entrance hall ($R_{221,}$ R_{222}). Then a living room exists in the front or at the right or left of that unit ($R_{321,}$ R_{322}).
- The living room consists of more than one cell in large housing units. So, after placing a living room near a "kitchen" unit, if there is a void cell near the existing one, a new "living room" unit exists on the void cell ($R_{431,}$ R_{432}).

- A living room can locate next to an entrance hall. Then, a new "living room" or a "terrace" cell exists in front of this unit (R_{433}, R_{434} $R_{227,}$ and $R_{228)}$
- According to its position, at right and left or in front of a "WC-bathroom" cell, bedroom cells place ($R_{531,}$ $R_{532,}$ R_{533}, and R_{534}).
- In large dwellings (like Type C), a new "WC-bathroom" unit is put in at the right or left of the existing "WC-bathroom" according to its position ($R_{551,}$ R_{552}).
- If there is a void around the existing "bedroom" unit, a new one locates in there ($R_{633,}$ R_{634}).
- Similarly, if the existing bedroom unit in a dwelling is directly adjacent to the housing block's main circulation area, a bedroom or terrace unit is located in front of that unit ($R_{631,}$ R_{632} $R_{635,}$ and R_{636}).

All the rule sets are on the scheme in **Figure 2**. The scheme demonstrates which spatial unit each basic spatial unit triggers to exist in each dwelling type after its generation.

Spatial units represented by cells generate dwelling types in a floor plan according to a specific set of neighborhood relations rules in the bottom-up process. The generation of dwelling types starts when each entrance unit locates on the floor plan simultaneously. These generated units also represent a dwelling. The other spatial units affected by the created entrance or different spatial units also join in the defined house plans (units) during the generation. In the model, each space cell has specific rules based on its topologic architectural relations with the others separately (**Figure 3**).

After the generation of spatial units, the model controls the fitness of the created dwelling samples. The essential criteria of this evaluation phase are the value of the minimum area specific to each dwelling type. Suppose the dwelling size doesn't meet the criteria necessary for the corresponding dwelling type and cannot define any other housing types. In that case, the model deletes the generation of this dwelling unit and removes the created room units from the workspace. It re-evaluates spaces left empty to generate the other selected types of dwellings. The operations such as evaluating remaining empty areas, generating new units in these areas, or changing the functions of existing units contribute to variation and unique emergence despite the initial choice conditions. The model generates different dwelling types (Type A, Type B, and Type C) in a floor plan (**Figure 4** and **Figure 5**).

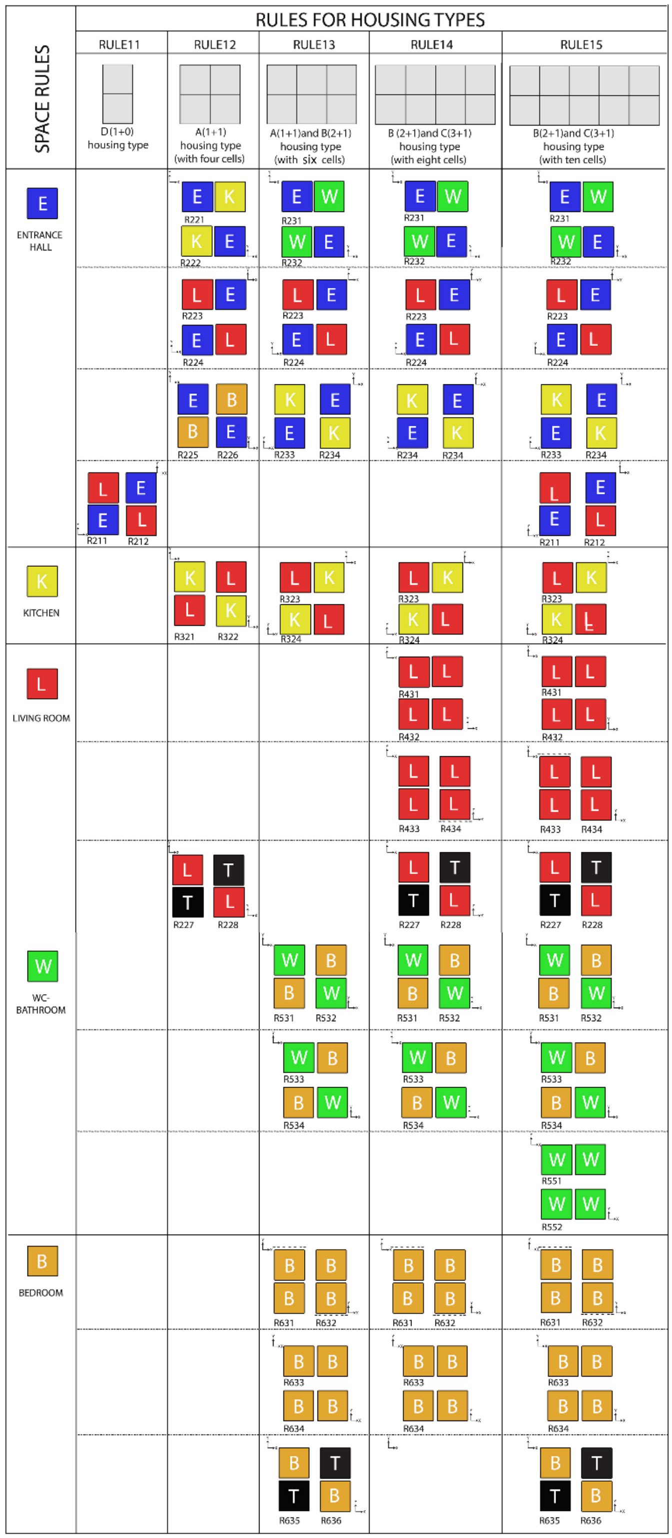

Figure 2: The rule sets for plan layouts.

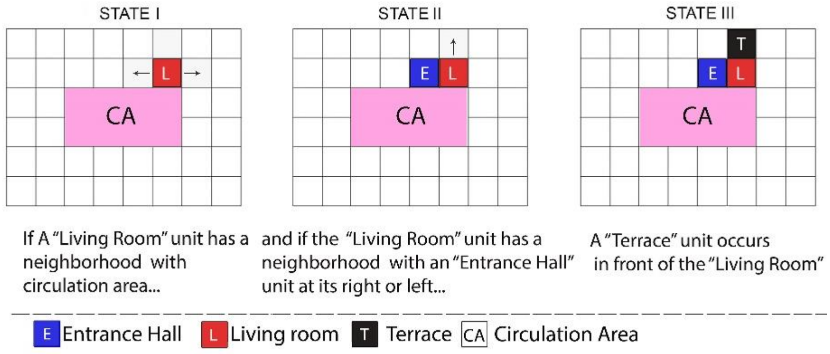

Figure 3: The initial shape of the spatial grammar and first stages of the generation process.

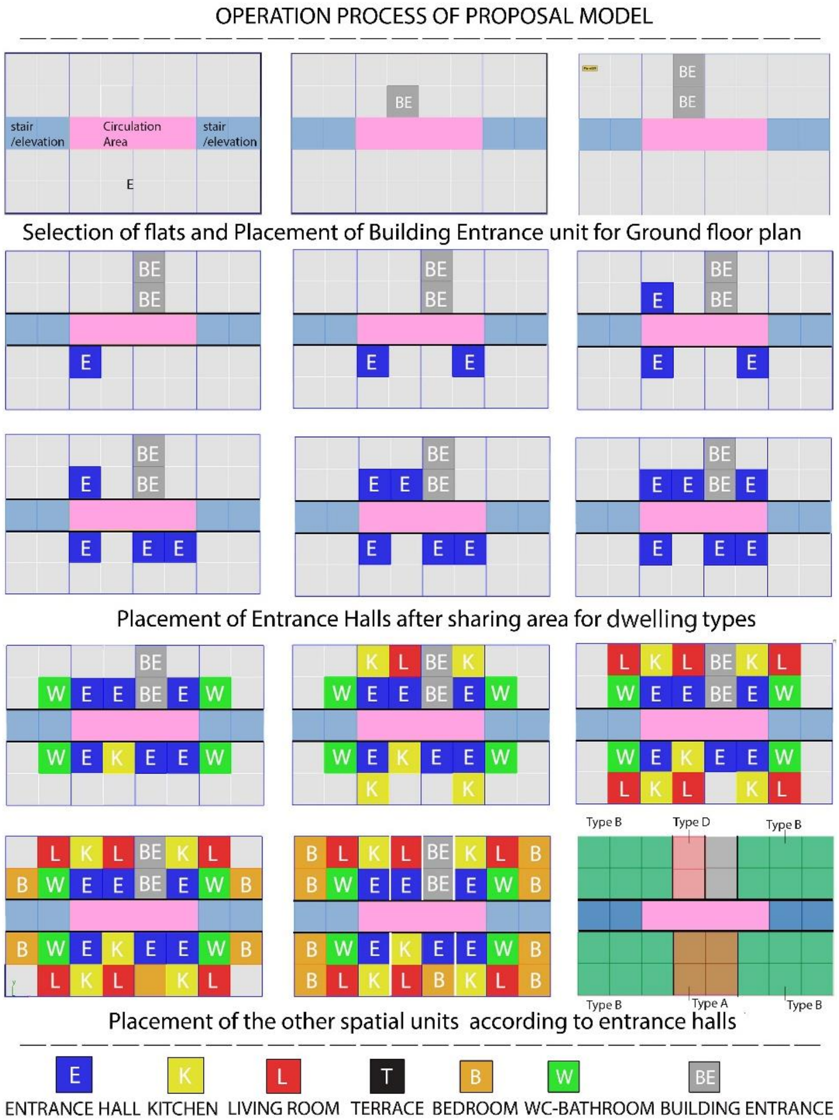

Figure 4: Generating the process of alternative solutions for a floor plan has a linear circulation core.

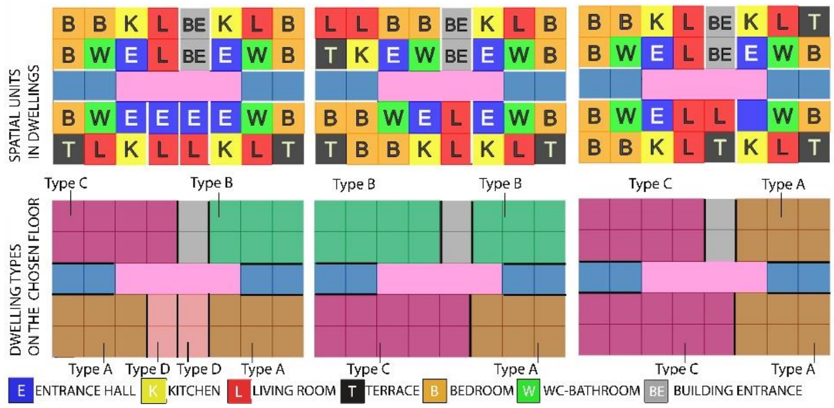

Figure 5: Solution alternatives for one floor (ground floor plan) of a selected building according to different user preferences.

As the sample of the generation process shows, there are characteristics of emergence by the harmonization process and its results between user preferences and functional architectural requirements in the model. Although the apartment examples created with the rules may seem standard solutions, they evolve into different typologies depending on the process. Floor plans with other solutions fill the skeletal structure and support the holistic structure feature naturally.

3.2 Generation of Building Façades

There are additional developed rules for façade configurations of the building blocks to address possible aesthetic problems. According to the floor plans, these rules follow the relationships of the spaces on the façade vertically and horizontally. The states of cantilevers and setbacks are determined in the façade design of the building envelope by interior spaces directly connected to the exterior façade. In other words, the states of spatial units of a building block affect the generation of cantilevers and setbacks in the model. The model groups the spatial units according to façade direction and their locations. The grouped units on each façade determine the formation of cantilevers or setbacks together under the vertical and horizontal neighbouring relationships (**Figure 6a**). In this context, there has been a set of façade rules for locating façade cantilevers. Among them, the most important one is the rule to manage cantilevers' generation in the frame of the formal dynamism and their relationships of every spatial unit on floors (F1 rule). The rule contains various sub-parameters according to the conditions.

Some of the other rules are as follows (**Figure 6b**):

- If a living room has only one unit in a dwelling type, a cantilever exists in front of this space (F2 rule). However, a cantilever on a façade is allowed for only one unit in a living room with more than one unit in large dwellings (F3 rule).
- If two living room units in different dwellings are adjacent, they can have cantilevers (F4 rule).
- If there is a cantilever at one side of a living room in the floor plan corner, a new cantilever exists on the other side (F5 rule).
- In some dwellings, if two "Bedroom" units are adjacent and one of them is neighbor with the central circulation area, Then A room that consists of these two units is considered a significant volume. Therefore, the space can't have a cantilever, but its volume can create a setback (F6 rule).
- A "kitchen" unit on the façade can have a semi-open cantilever or create a setback like "Bedroom" units (F7 rule).

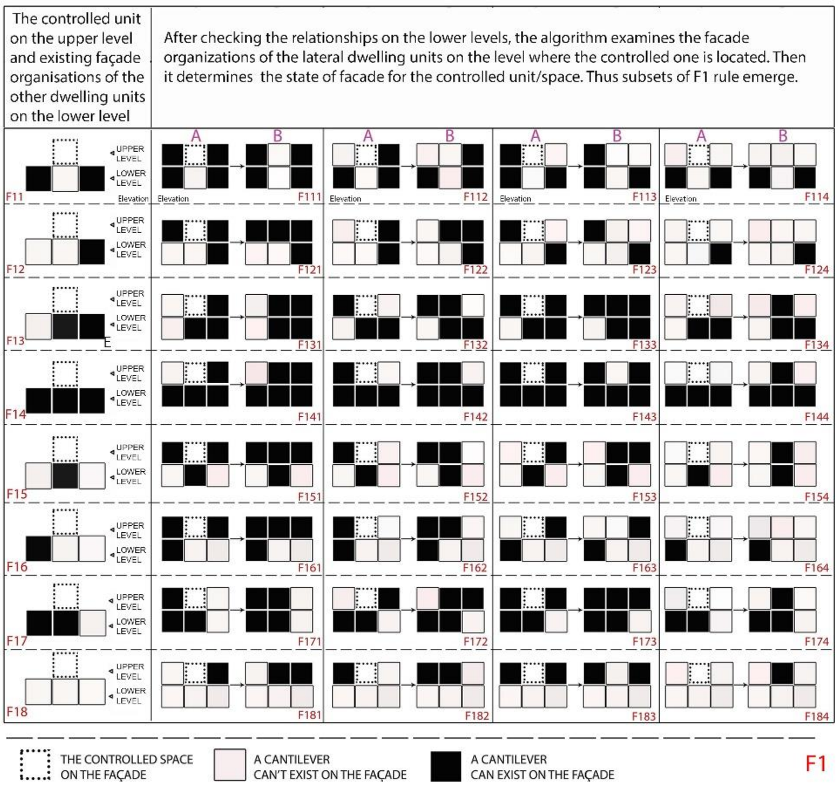

Figure 6a: F1 rule and its subset matrix. In this rule, according to each chosen spatial unit and the other ones around it, a cantilever emerges or not.

Apart from these rules, in the implementation phases, the model generates alternatives by its feature of randomness for obtaining more variations. Furthermore, the model makes generations simultaneously realized on all façades. In **Figure 7**, some of the façade alternatives of the mass-customized housing blocks are generated by this model.

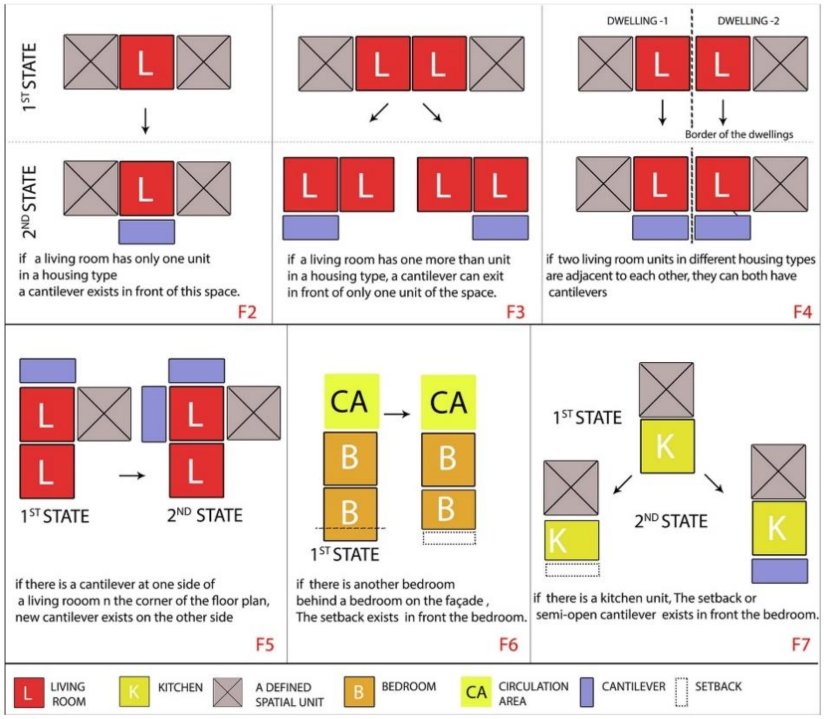

Figure 6b: According to spatial conditions in the plans, whether the chosen units have a cantilever or a setback is determined.

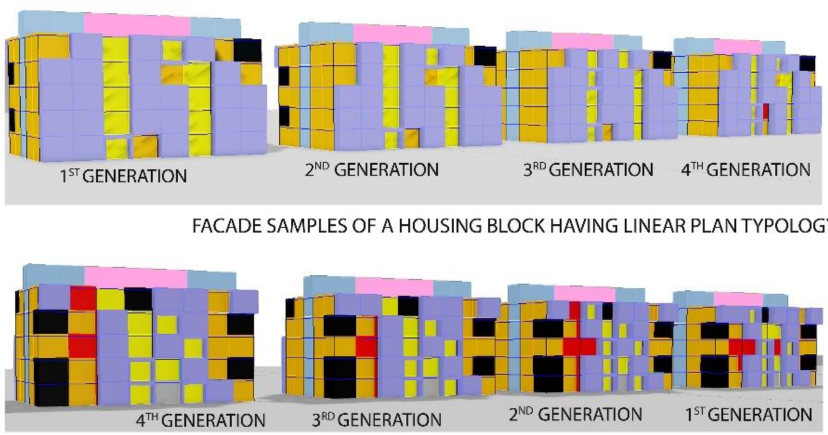

Figure 7: Façade solutions for housing blocks

Façade applications have shown that it increases dimensional diversity in all floor plans and allows users to use different open spaces. In addition, it has led to the organic formation in the third dimension. Instead of a pre-defined understanding of form based on the dominance of designers' aesthetics, it exhibits a holistic formation that combines aesthetic rules and functionality with self-organization and a bottom-up process. There is more objective comprehension in the process. As in the plan alternatives, with the different probabilities obtained by the randomness criterion in each generation, the decision-making option for façade designs is left to the designers. In other words, the model generates adaptive alternatives by these rule sets based on basic architectural requirements and some aesthetic considerations. Still, it doesn't include a fitness ranking criterion among the generated choices. Therefore, in the proposed process, the designer seems to be a leading decision-maker in developing and choosing these schemes.

3.3 User Interface of the proposed model

The presence of a user-friendly interface is essential for fast data flow in the model. It should be simple, understandable, and offer a high level of interaction possibilities. Unlike the visual programming applications, which have been in common recently, this study developed the model structure by the scripts (maxscript) of 3D modeling software. However, the model has an extensible feature where the user (expert) can add, revise or develop rules. The designed interface has provided these rules to operate on one of the blocks generated in a site plan (Figure 8 and Figure 9). Thus, the model generates the floor solutions step by step, and different solutions emerge when the model runs each time. The interface includes two basic sub-menus. At the same time, one of them is concerned with the definitions of building mass layouts. The other menu consists of the applications of floor plans and façade (data entry of user preferences and generation adjustments).

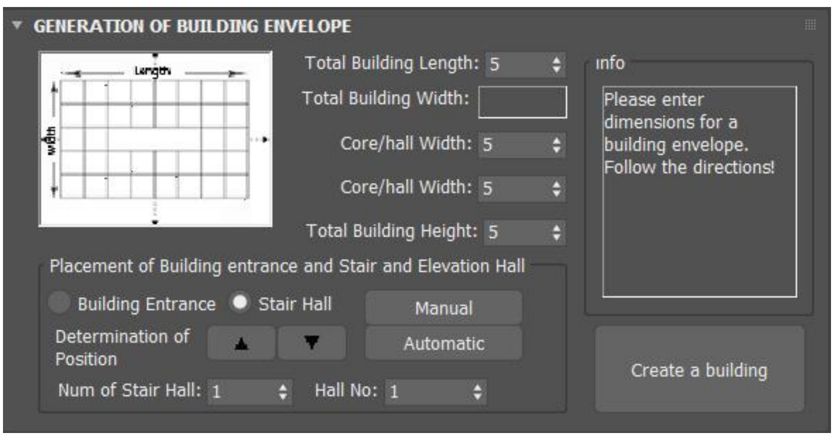

Figure 8: The interface for generating building envelopes.

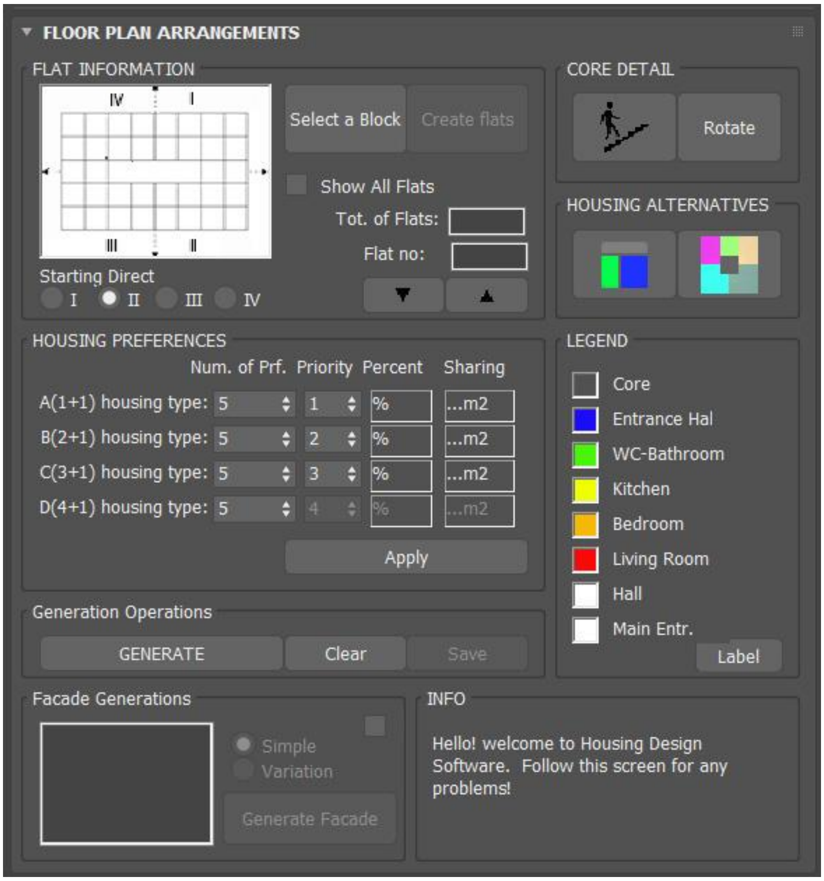

Figure 9: The interface for generation of floor plan layouts.

4. CONCLUSION

Shape or spatial grammars have been successfully applied in different domains to describe languages of shapes and generate alternative designs. This paper presents a 2D grammar model approach based on a set of parameterized spaces and façade elements. Although the model generates two-dimensional alternative plan layouts for every floor of a housing block, it also generates their façades. It includes the interactive and visual development of two-dimensional spatial grammar rules as well as their automatic application. The rule development phase consists of creating and positioning geometric objects in 2D space within a CAD environment.

The model has been developed by scripts of 3ds Max software and is a proposal of a parametric computational approach that provides flexibility and variety for designers and practitioners and generates alternatives by "generate and test." This model is an example of an emergent process that presents innovative features by turning user preferences into digital data as a design parameter. Each spatial unit initiates the generation of others according to this parameter, and they define different dwellings together. Thus, variety and generativity emerge naturally. The implementation of the parametric spatial grammar model presents to architects and users an effective tool for the future design market. The applicability of this proposed model has been evaluated with various scenarios. Such models are examples of decision-support tools for architectural designs and present an alternative approach by using techniques that lead to variety instead of monotonous and repetitive solutions in mass-produced housing designs which ignore or subordinate users' preferences. Significantly, the model has produced outcomes that quickly offer different alternatives for the generated blocks' floor plans and façade solutions.

Grammar rules represent the spatial relations, and generation algorithms proceed in a bottom-up approach. In this parametric spatial grammar, which presents a generative process, additive rule sets represent the spatial relations in the plan layouts. The syntactic and formal knowledge about grammar and spatial relations between the spaces, given in set grammar rules, can be defined parametrically. It is possible to generate rooms with different dimensions by changing constraints and parameters. The rule sets of the parametric spatial grammar have been for two-dimensional plan layouts. Although, the same model generates the façade alternatives of these plans.

The other results can be listed as follows:

- The model suitable for design problems offers designers opportunities for variety. In other words, the model expands solution space for them in different design phases.
- Shapes of the building blocks are central or linear forms; their floors are rectangular. Selection of the rules and arrangements of the relationships among spaces have become in the frame of this configuration. However, these rules and relationships are as generalizable as possible. For future studies, they can be adaptable to the plan schemes in different forms by enriching their contents by regulations and adding new rules specific to these forms. Ultimately it is likely to get positive results by new suggestions.

- By the model, a designer can obtain many alternative and developable solutions, which seem challenging and time-consuming with traditional methods, in-floor plans, and façades. These solutions are evolvable schemes with designers' approaches and interventions, users' demands, and the context. Thus, as the number of generated alternatives increases with designers' intuition and initiative, designers' efficiency and dominance in the process are preserved.
- As stated before, the proposed model doesn't have a fitness function for thoroughly evaluating the generated alternatives. The ability of the model to guide the designer can be improved by multiple simultaneous choices and a scoring method among them by using the increased fitness function criteria values.
- The proposed model is based on the primary spatial configurations according to users' needs in the form of a residential block with a developable and flexible grid layout. In the model, technical service spaces place around the core with rules. However, these primary spatial schemes can be further developed and detailed by new interior rules, technical constraints, and minimal interventions for the following stages.
- The importance of interactive processes with feedbacks for architects has drawn attention during the generation of alternatives in computational design.

The main contribution of this model is not only based on a specific architectural language but also to provides a flexible platform supporting designers/users with visual, interactive definition and application of their spatial relations and façade compositions in a familiar CAD environment without programming.

References

Agarwal, M., & Cagan,J. (2000). On the use of shape grammars as expert systems for geometry-based engineering design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, *14*(5). https://doi.org/10.1017/S089006040014507X

Alexander, C. (1997). *A Pattern Language: Towns, Buildings and Construction*. Oxford University Press.

Çağdaş, G. (1996). A shape grammar: The language of traditional Turkish houses. *Environment and Planning B: Planning and Design*, *23*(4), 443–464. https://doi.org/10.1068/b230443

Carta, S., Loe, S. S., Turchi, T., & Simon, J. (2020). Self-organising floor plans in care homes. *Sustainability (Switzerland)*, *12*(11), 4393. https://doi.org/10.3390/su12114393

Coyne, R. (1989). *Logic Models of Design*. Pitman.

Downing, F., & Flemming, U. (1981). The bungalows of Buffalo. *Environment and Planning B: Planning and Design*, *8*(3). https://doi.org/10.1068/b080269

Duarte, J. P. (2005). Towards the mass customization of housing: The grammar Siza's houses at Malagueira. *Environment and Planning B: Planning and Design*, *32*(3). https://doi.org/10.1068/b31124

Flemming, U. (1981). The secret of the Casa Giuliani Frigerio. *Environment and Planning B: Planning and Design*, *8*(1). https://doi.org/10.1068/b080087

Godoi, G. De, & Celani, G. (2008, December 1-5). *A study about façades from historical brazilian town using shape grammar*, Sigradi 2008: the 12th Iberoamerican Congress of Digital Graphics, La Habana, Cuba.

Granadeiro, V., Duarte, J. P., Correia, J. R., & Leal, V. M. S. (2013). Building envelope shape design in early stages of the design process: Integrating architectural design systems and energy simulation. *Automation in Construction*, *32,* 169-209. https://doi.org/10.1016/j.autcon.2012.12.003

Grasl, T. (2012). Transformational Palladians. *Environment and Planning B: Planning and Design*, *39*(1). https://doi.org/10.1068/b37059

Gungor, O., Cagdas, G., & Balaban, O. (2011). A mass customization oriented housing design model based on Genetic Algorithm. *Respection Fragile Places, 29th ECAADe Conference Proceedings*, 325–331.

Guo, Z., & Li, B. (2017). Evolutionary approach for spatial architecture layout design enhanced by an agent-based topology finding system. *Frontiers of Architectural Research*, *6*(1), 53–62. https://doi.org/10.1016/j.foar.2016.11.003

Hoisl, F., R. (2012). *Visual, Interactive 3D spatial grammars in CAD for computational design synthesis*. Technische Universität München.

Hoisl, F., & Shea, K. (2011). Interactive, visual 3D spatial grammars. In S. Gero, J. (Ed.), *Design Computing and Cognition '10* (pp. 643–662). Springer. https://doi.org/10.1007/978-94-007-0510-4_34

Knight, T. (2003). Computing with emergence. *Environment and Planning B: Planning and Design*, *30*(1), 125–155. https://doi.org/10.1068/b12914

Koning, H., & Eizenberg, J. (1981). The Language of the Prairie: Frank Lloyd Wright's Prairie Houses. *Environment and Planning B: Planning and Design*, *8*(3). *https://doi.org/10.1068/b080295*

McKay, A., Chase, S., Shea, K., & Chau, H. H. (2012). Spatial grammar implementation: From theory to useable software. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, *26*(2), p143–159. https://doi.org/10.1017/S0890060412000042

Stiny, G. (1980a). Introduction to shape and shape grammars. *Environment and Planning B: Planning and Design*, *7*, 343–351. https://doi.org/10.1068/b070343

Stiny, G. (1980b). Kindergarten grammars: designing with Froebel's building gifts. *Environment and Planning B: Planning and Design*, *7*(4), 409–462. https://doi.org/10.1068/b070409

Stiny, G. (1982). Shapes are individuals. *Environment and Planning B: Planning and Design*, *9*(3), 359–367. https://doi.org/10.1068/b090359

Stiny, G., & March, L. (1981). Design machines. *Environment and Planning B*, *8*, 245–255.

Stiny, G., & Mitchell, W. J. (1978). The Palladian grammar. *Environment and Planning B: Planning and Design*, *5*(1), 5–18. https://doi.org/10.1068/b050005

Strobbe, T., Eloy, S., Pauwels, P., Verstraeten, R., De Meyer, R., & Van Campenhout, J. (2016). A graph-theoretic implementation of the Rabo-de-Bacalhau transformation grammar. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, *30*(2). https://doi.org/10.1017/S089006041600003