A grammar-based system for building envelope design to maximize PV performance

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Abstract

This article explores the application of photovoltaic technology on the outer envelope (roof and facade) of buildings, thereby decentralizing and diversifying places where energy is produced. The article builds on previous work concerned with the development of a methodology for designing the shape of the outer envelope of the buildings that optimizes the amount of electricity they generate. Accordingly, it is developed a computational design system that works by applying a shape grammar, which enables the automatic generation of shapes. Based on the geographic location of the building and its initial shape as defined by the architect, the computer system suggests shapes for the envelope that optimize solar exposure and, therefore, their capacity to generate electricity. In brief, the shape grammar works as follows: to an initial shape drawn by the architect, shape transformation rules are applied recursively to optimize the solar exposure of the envelope. It is described how the initial shape can be defined, as well as a set of transformation rules, and then illustrated how the grammar works through a series of examples. The goal is to implement the grammar in software that supports architects in the early stages of design of the envelope shape of buildings.

Keywords: Buildings Envelopes Design, Solar Exposure, Computational Design System, Shape Grammars, Optimization, Software.

1. Introduction

The present article addresses the theme of energy generation on the outer envelope of buildings, including roof and facades, by converting sun rays through photovoltaic technology. Traditionally, supplying energy to cities requires large devices outside cities to capture the energy from a natural source and a complex infrastructure network to transport the captured energy to the city, where it is needed. Both the factories and the infrastructure have a significant presence in the landscape and imply other negative environmental impacts. This article builds on previous research [1] that seeks an alternative approach, in which the goal is to produce energy within the city. The idea is to increase or optimize the amount of electric energy generated in the outer envelope of buildings and the research is focused on how to design the shape of the outer envelope of buildings for that purpose. In that sense, we are proceeding to the development of a design methodology resorting to a Shape Grammar. This grammar has the ability to transform the shapes designed by architects in the conceptual phase of architectural projects in more efficient shapes from the point of view of electricity generation in the outer envelope of buildings. Once the grammar is implemented into a computer program, it can serve as a design tool to assist architects during the initial phase of the design process.

The shapes suggested by the grammar-based tool constitute a reference for the designer seeking to find an appropriate shape for the outer envelope of buildings. The designer may then interact with the computer program in the course of the design process, changing the suggested shapes according to other criteria considered relevant, including objective goals such as structural performance, or subjective ones like aesthetics. The article describes the development of the shape grammar, namely the grammar features, how the initial shape can be defined, the transformation rules that can be applied, and illustrates how the grammar works through an example of application. The solutions generated by applying the grammar are analysed according to their potential for generating electricity, and the results are discussed. The article concludes by outlining future research planned for the development of the shape grammar.

2. Shape Grammar

It is intended that the developed shape grammar can be applied to any type of building, as well as to any shape. However, to simplify the problem, it was decided at this stage to consider only the buildings for collective housing, with parallelepiped shapes. In a next stage, the intention is to expand the capacity of the grammar for more types of buildings as well as for more complex shapes. The grammar developed to date can be designated as “Grammar for Outer Envelopes of Parallelepiped Buildings” and is characterized by being a compound grammar (Set Grammar), composed by parametric parallel grammars, as shown in Scheme 1.

			STAGES				
			A Set the Initial Shape (I)	B Set the orientation of the building envelope	C Set the building envelope shape	D Set the energy generation areas	E Set the openings of the building envelope
GRAMMARS	Set Grammar	W: $<U_{33}\ V_{03}>$	X	X	X	X	X
	Lot Grammar	L: $<U_{33}\ V_{03}>$	X				
	Building Envelope Grammar	E: $<U_{33}\ V_{03}>$	X	X	X	X	X
	Surfaces Grammar	S: $<U_{33}\ V_{03}>$			X	X	X
	Photovoltaic Elements Grammar	F: $<U_{33}\ V_{03}>$			X	X	X
	Labels Grammar	M: $<U_{33}\ V_{03}>$		X	X	X	X

Scheme 1: Functional scheme of the Set Grammar

The grammar has five stages:

- Stage A: Set the Initial Shape (I);
- Stage B: Set the orientation of the building envelope;
- Stage C: Set the building envelope shape;
- Stage D: Set the energy generation areas;
- Stage E: Set the openings of the building envelope.

And is composed by the following parametric parallel grammars:

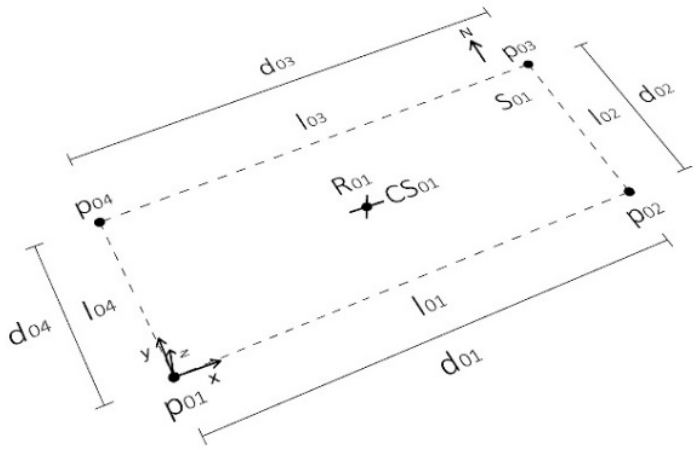
- General Grammar W: $<U_{33}\ V_{03}>$;
- Lot Grammar L: $<U_{33}\ V_{03}>$;
- Building Envelope Grammar E: $<U_{33}\ V_{03}>$;
- Surfaces Grammar S: $<U_{33}\ V_{03}>$;
- Photovoltaic Elements Grammar F: $<U_{33}\ V_{03}>$;
- Labels Grammar M: $<U_{13}\ V_{03}>$.

The General Grammar contains the elements of all the others grammars, showing the overall result of the grammars. The Lot Grammar contains elements relating to the lot for where the building is designed, the Building Envelope Grammar the elements relating to the outer envelope, the Surfaces Grammar that ones that refer to the surfaces of the building envelope considered individually, the Photovoltaic Elements Grammar contains the information related with the photovoltaic elements and the Labels Grammar integrates auxiliary elements, which guide the implementation of the grammar rules and allow the transition between the different grammars. The way a shape grammar works can be consulted on previous work [1], as well as in articles related with shape grammars [2]. Next, are presented some main transformation rules of the grammar developed to date.

STAGES AND RULES OF THE SHAPE GRAMMAR FOR OUTER ENVELOPES OF PARALLELEPIPED BUILDINGS

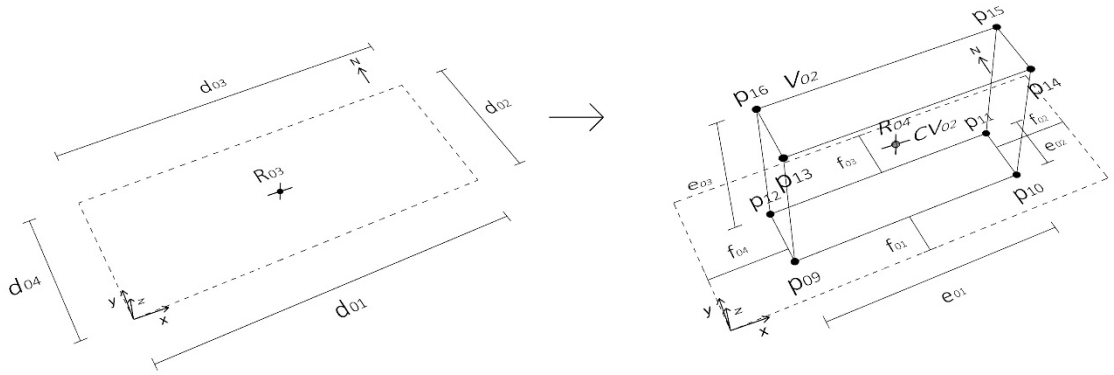
STAGE A – SET THE INITIAL SHAPE OF THE LOT AND OF THE BUILDING ENVELOPE

Set Grammar W: $< U_{33}\ V_{03} >$
Initial Shape – Architect sets (draws, models or inserts) the shape of the Lot



Control Conditions:
Dimensions:
in the case study, d01 = d03 = 110m ∧ d02 = d04 = 45m

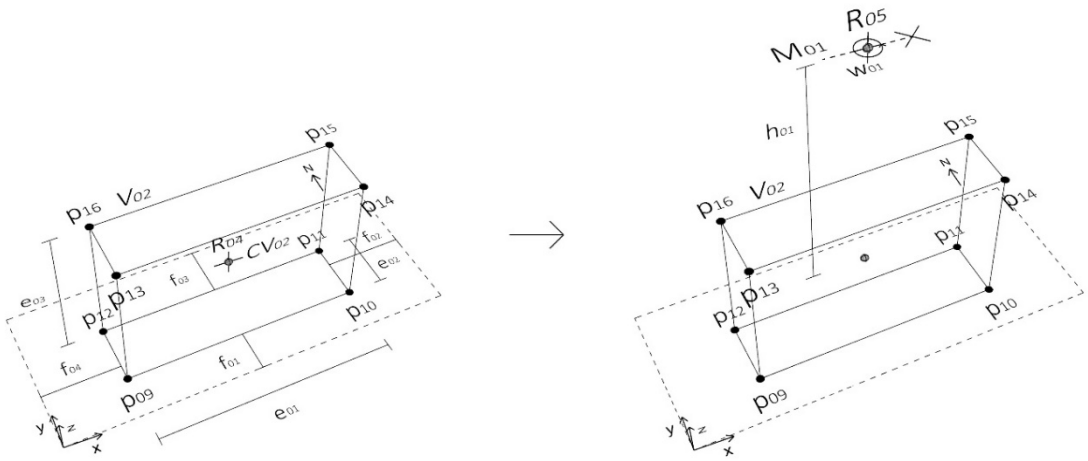
Set Grammar W: < U_{33} V_{03} >
Rule 3 – Architect draws/models the initial shape of the building envelope in the Lot



Control Conditions:
V_{02} C V_{01}
V_{01}: Buildable volume of the Lot
V_{02}: Volume of the building envelope
Dimensions:
in the case study, 22m ≤ e01 ≤ 110m, 17m ≤ e02 ≤ 45m, 14m ≤ e03 ≤ 70m
and 0m ≤ f01 ∧ f03 ≤ 28m, 0m ≤ f02 ∧ f04 ≤ 88m

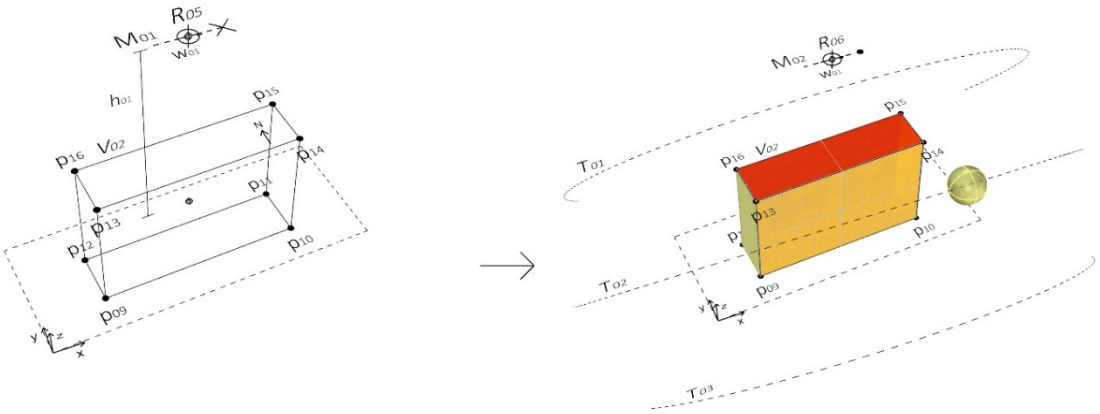
STAGE B – SET THE ORIENTATION OF THE BUILDING ENVELOPE

Set Grammar W: < U33 V03 >
Rule 4 – Insert rotation label (M_i)



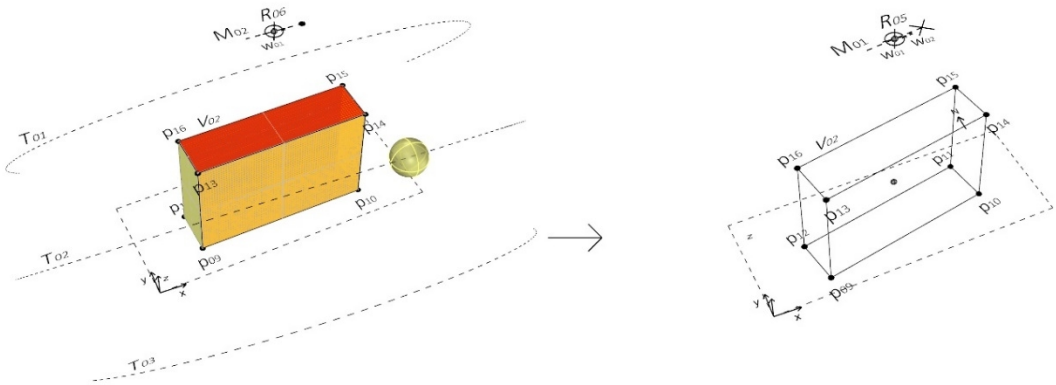
Control Conditions:
V_{02} C V_{01}
V_{01}: Buildable volume of the Lot
V_{02}: Volume of the building envelope
Dimensions:
h_{01} = 100m

Set Grammar W: < U33 V03 >
Rule 5 – Insert paths of the sun (T_i) and evaluate incident radiation



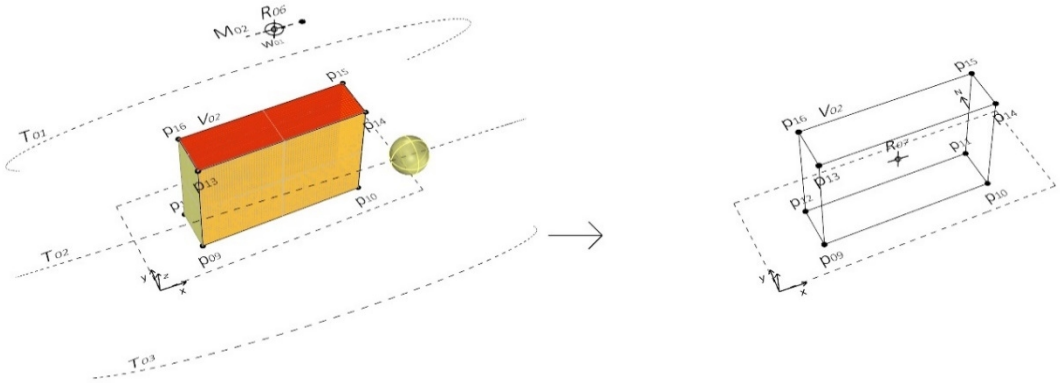
Control Conditions:
V_{02} C V_{01}
V_{01}: Buildable volume of the Lot
V_{02}: Volume of the building envelope

Set Grammar W: < U33 V03 >
Rule 6 – Rotation of the building envelope



Control Conditions:
V02 C V01
V01: Buildable volume of the Lot
V02: Volume of the building envelope

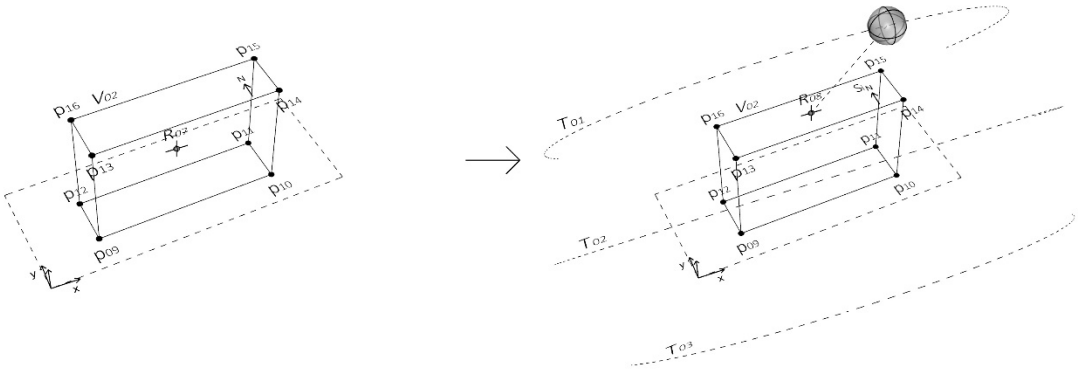
Set Grammar W: < U33 V03 >
Rule 7 – Elimination of the rotation label and choice of the best orientation



Control Conditions:
V02 C V01
V01: Buildable volume of the Lot
V02: Volume of the building envelope

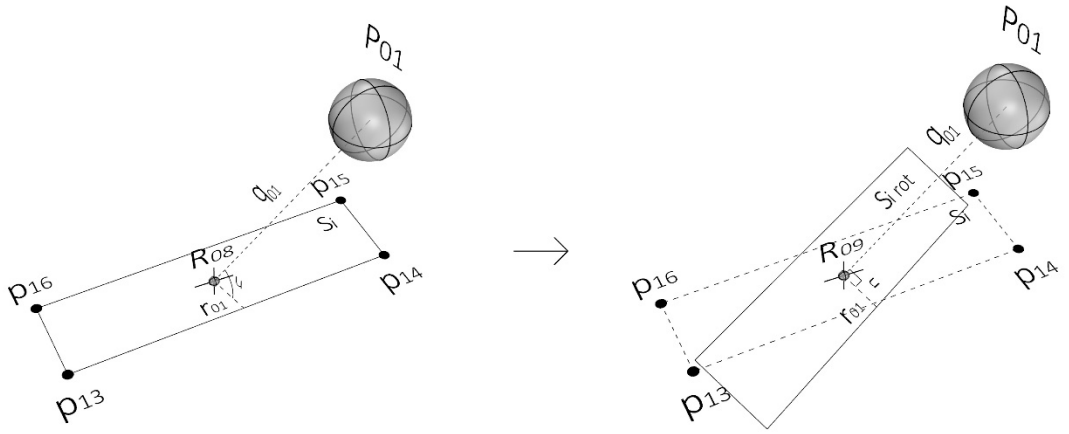
STAGE C – SET THE SHAPE OF THE BUILDING ENVELOPE

Set Grammar W: < U33 V03 >
Rule 8 – Select surface with more incident radiation



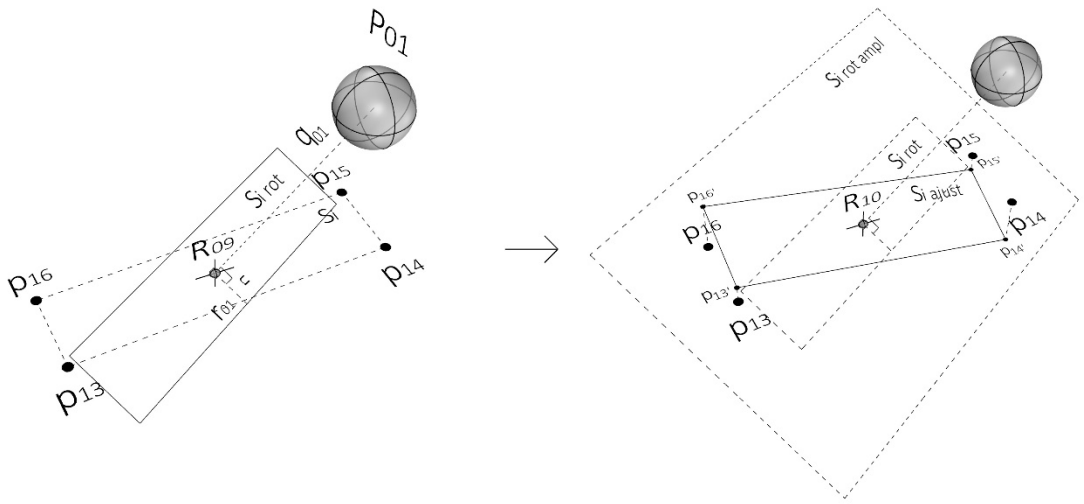
Control Conditions:
V02 C V01
V01: Buildable volume of the Lot
V02: Volume of the building envelope

Surfaces Grammar W: < U33 V03 >
Rule 9 – Make the surface perpendicular to the closest position of the sun



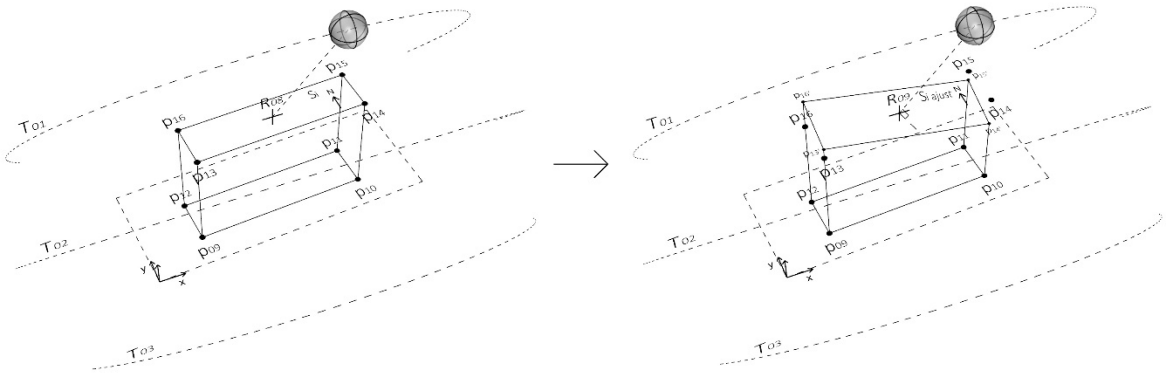
Control Conditions:
Si → Si rot
Dimensões:
0° ≤ ui ≤ 180° → ui = 90°

Surfaces Grammar W: < U33 V03 >
Rule 10 – Adjusting the shape of the surface to the location of the volume of the building envelope



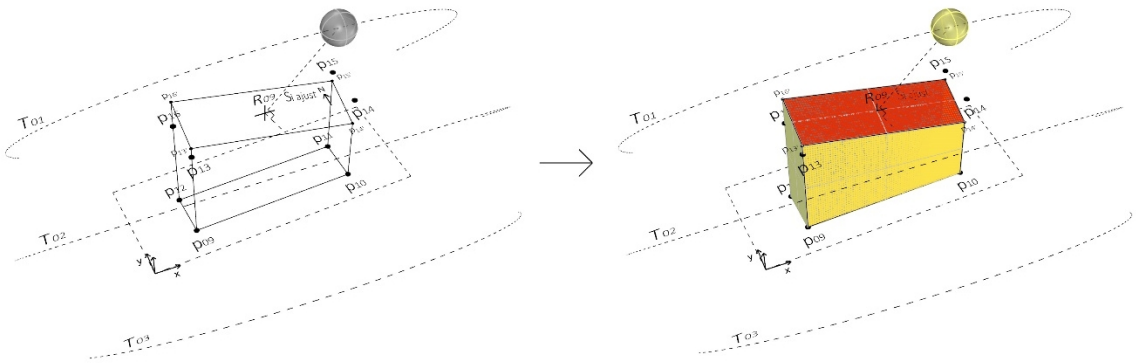
Control Conditions:
Si rot → Si rot ampl → Si ajust
Si rot ampl: surface Si rot, scaled
pi': projection of the points pi in the surface Si rot ampl
Si ajust: surface Si rot, adjusted

Set Grammar W: < U33 V03 >
Rule 11 – Rotate and adjust surface in the volume of the building envelope



Control Conditions:
$S_i \rightarrow S_i$ ajust

Set Grammar W: < U33 V03 >
Rule 12 – Evaluate incident radiation in the building envelope



Surfaces Grammar W: < U33 V03 >
Rule 17 – Division of one surface in two equal surfaces

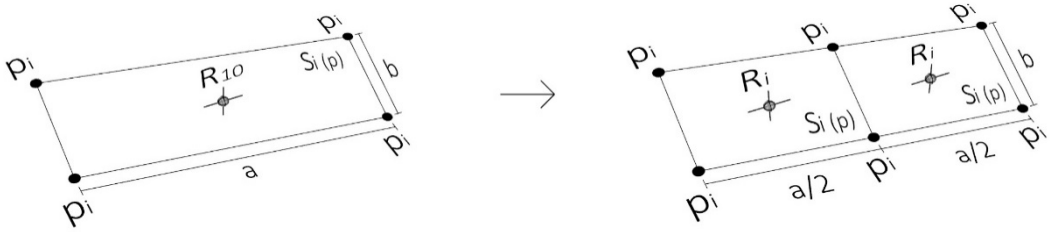


Table 1: Stages and rules of the shape grammar

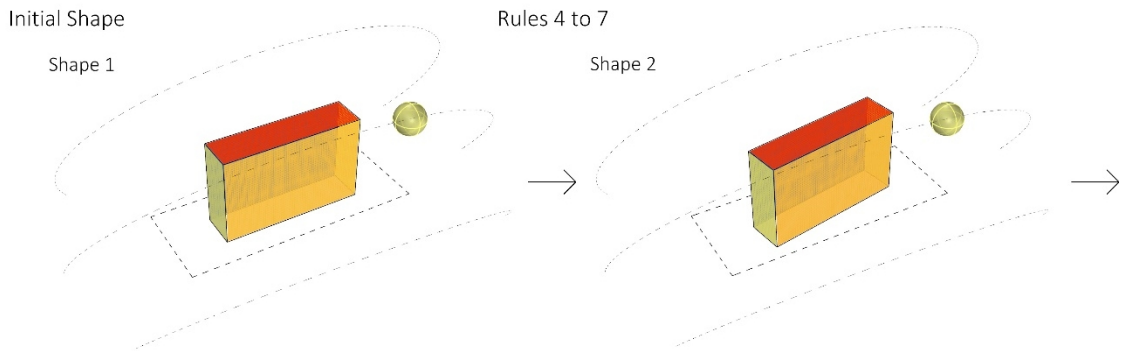
According with Table 1, in Stage A (Set the Initial Shape of the Lot and of the Building Envelope), the Initial Shape is the shape of the lot, defined by the architect. In Rule 3, the architect draws, models or inserts in the lot the initial shape of the building envelope. There are other complementary rules at this stage, but these are the main ones. After that, Stage B (Set the Orientation of the Building Envelope) begins with Rule 4, that inserts a rotation label (M_i) over the building envelope, to guide its rotation inside the limits of the lot. Rule 5 inserts the solar path, throughout the day and year, according to the geographic location of the envelope, and evaluates the incident solar radiation on it. Rule 6 rotates the building envelope, by initial definition, from ten to ten degrees. It is possible to change this value, if desired. It is ensured that are only considered the rotations of the envelope within the lot, through the control condition V_{02} C V_{01}, where V_{02} is the Volume of the building envelope and V_{01} is the Buildable volume of the lot. Rule 7 eliminates the rotation label, ending the rotation series, and selects the building envelope orientation with the higher value of incident radiation.

The next Stage, the C (Set the Shape of the Building Envelope), begins with Rule 8, that selects the surface of the envelope with higher value of incident radiation, that has not been yet transformed by rules. Rule 9 rotates in three dimensions the surface, making it perpendicular, from its centroid, with the nearest sun position. This increases the efficiency of the absorption of the sun rays, because their absorption by a surface is optimized when the incident angle on the surface is of ninety degrees. Rule 10 adjusts the transformed surface, so that it stays over the volume defined by the remaining surfaces of the envelope. Rule 11 is a rule of the general grammar that shows the result of rules 9 and 10, that are from the surfaces grammar, in the building envelope. Rule 12 evaluates the incident radiation in the envelope, after the application of a rotation and adjustment rule to a surface. Rule 17 divides one surface into two equal surfaces.

3. Example of grammar implementation and evaluation of results

Through the implementation of the grammar, it is possible to generate various shapes for the building envelope, which are more efficient than the initial shape for the absorption of solar rays and therefore for the generation of electricity. In Figure 1 is shown the application of a possible sequence of rules, with the assessment of the incident radiation, made by the software DIVA in Rhinoceros. To the initial shape are applied Rules 4 to 7, corresponding to the rotation of the envelope and to the choice of the best orientation. Rules 8 to 12 are then applied, rotating and adjusting the surface with higher incident radiation, to increase its efficiency. Next, a sequence of Rules 8 to 12 and 17 are applied to the same surface, dividing it in four parts and rotating that parts according to positions of the sun, further increasing the efficiency of the envelope. The same sequence of Rules 8 to 12 and 17 are also applied to the surface with the second highest value of incident solar radiation.

Results are shown in Table 2. It is possible to see that the value of incident radiation per square meter in the building envelope increases as the rules are applied, since the 843,95 KWh/m^2 of the initial shape to the 935,79 KWh/m^2 of the last shape. The total value of incident radiation also increases, from the 6 690 833 KWh of the initial shape to the 7 442 270 KWh of the last shape. There is an exception, in the transformation of the shape 3 to the shape 4, where the value decreases from 7 045 478 KWh to 6 930 777 KWh, but this is due to the fact that the surface area of the envelope also decreases. With the application of a rule that changes the scale of the envelope, the total value will increase.



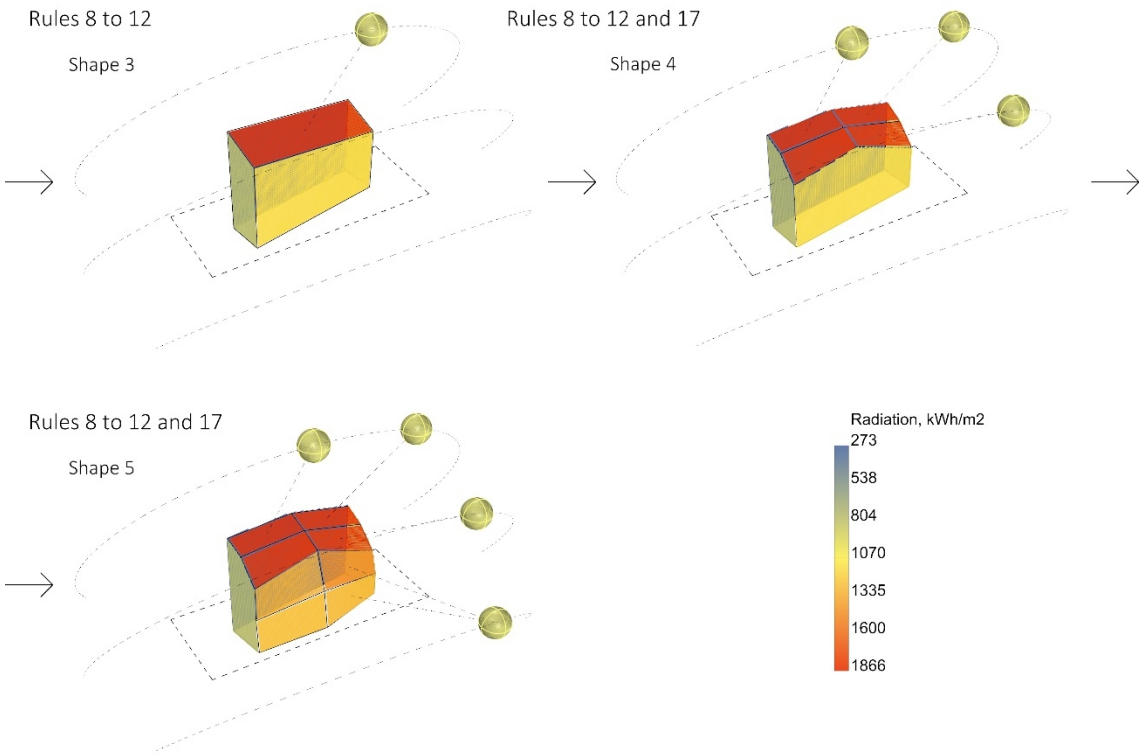


Figure 1: Application of a sequence of rules

	Shape 1	Shape 2	Shape 3	Shape 4	Shape 5
Incident radiation per m^2 (KWh/m^2)	843,95	852,05	872,72	883,46	935,78
Total value of incident radiation (KWh)	6 690 833	6 755 067	7 045 478	6 930 777	7 442 270

Table 2: Values of incident radiation in the shapes of the building envelope

4. Conclusions and future research

The results achieved in the grammar implementation prove that the developed shape grammar for outer envelopes of parallelepiped buildings is efficient as a tool for achieve higher values of incident radiation in the conceptual design of the building envelope. It has the capacity of maximize the performance of the photovoltaic elements placed in the envelope surfaces, leading to higher values of electricity generation. Future research will develop the shape grammar, its structure and rules, and will implement it in a software to be used by architects in the conceptual design of buildings.

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