A COMPUTATIONAL STRATEGY TO PLAN HOUSING SETTLEMENTS

THE CASE OF SANTA MARTA

Debora Verniz[1], José P. Duarte[2]
[1]University of Missouri
Department of Architectural Studies
vernizd@missouri.com
[2]The Pennsylvania State University
Stuckeman Center for Design Computing

SHAPE GRAMMARS
GRAMMATICAL TRANSFORMATION
INFORMAL SETTLEMENTS
HOUSING SETTLEMENTS
HOUSING QUALITY ASSESSMENT

The world is becoming more urbanized and the exponential population growth places an enormous pressure in cities. This intense urbanization gives rise to innumerous urban problems, especially when stakeholders are not able to construct sufficient buildings and infrastructure. Informal settlements emerge in this context as a self-constructed solution for housing. This research presented, proposes a computational strategy to the planning of affordable housing settlements, based on the model of favelas, and developing rules to replicate their positive characteristics while avoiding their flaws. Santa Marta favela, an iconic informal settlement in Rio de Janeiro, is the case study for this research. The research encompasses six steps: (1) data collection and modeling of the case study; (2) generating the grammar-based analytical computational model; (3) assessing the case study; (4) revising the analytical model to propose a synthetic computational model to generate favela-like settlements; and (5) validating the synthetic model. This paper focuses on steps four and five of the research by presenting the computational strategy developed to generate the synthetic grammar. This strategy contributes for the theory of shape grammars by extending the concept of grammatical transformations.

INTRODUCTION

More than half of the world's population live in urban areas (United Nations Department of Economic and Social Affairs, 2018). Many countries face challenges to meet the needs of their growing urban population and integrated policies are necessary to improve the life of both urban and rural dwellers (United Nations Department of Economic and Social Affairs, 2018). More than one billion people (or 24 percent of the world's urban population) live in informal settlements around the world (United Nations, 2020). Although informal settlements present numerous urban problems, they are one of the few solutions for the lack of housing and it has been shown that removing them is not a viable (nor civilized) solution (Skidmore, 2009).

This paper is part of a larger research that proposes a computational strategy to plan housing settlements that present the same morphologic features of informal settlements, while avoiding their flaws. The proposed strategy uses an established housing quality method to identify the physical characteristics that need improvement in an informal settlement, and uses shape grammars to change them, thereby enabling the planning of settlements with increased quality.

The research was divided in six main steps. The first step consisted in the data collection and modelling of an informal settlement selected as a case study. Physical, digital, and immersive models of Santa Marta, the selected favela, were generated using data collected from the settlement (Verniz et. al., 2016, 2018; Oprean et al., 2018, Verniz & Duarte, 2017). The second step was to generate an analytical model, a shape grammar (Stiny & Gips, 1972) that described and replicated the urban pattern identified in Santa Marta (Verniz & Duarte, 2020b). The third step was to evaluate Santa Marta, using a housing quality assessment method that included urban spaces (Pedro, 1999a, 2001, 1999b). The fourth step was to revise the analytical model (from step two) using the assessment results (from step three), generating a synthetic model, also a shape grammar. The fifth step was to validate the synthetic model. Although this paper focuses on steps four and five, we briefly introduce steps two and three to facilitate understanding.

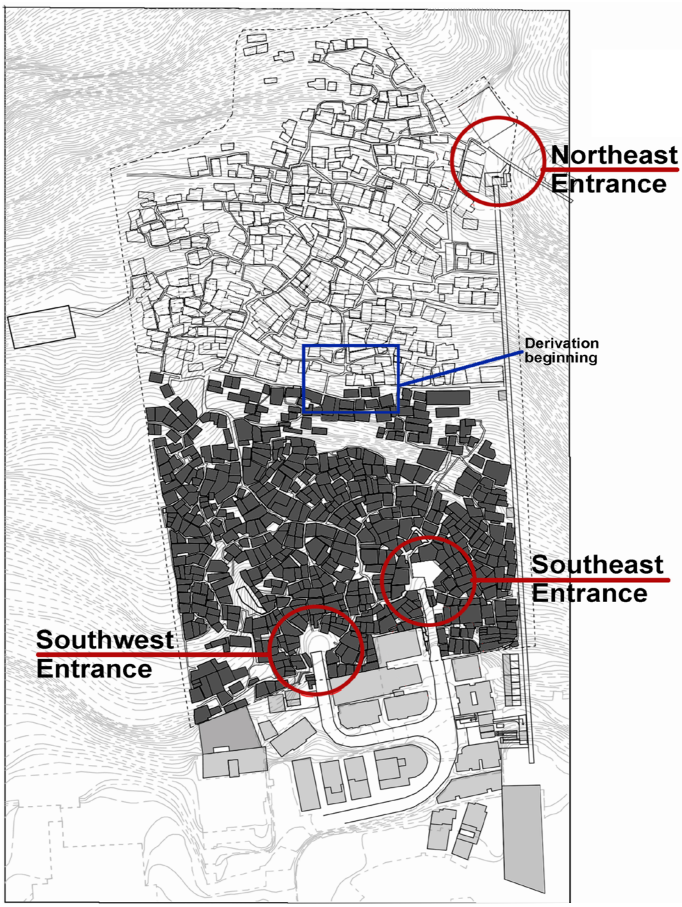
Shape grammars are algorithms that manipulate shapes to generate existent (analytic) or new (synthetic) designs, and they are especially useful for automated (computerized) processes. Shape grammars are composed by an initial shape used to start the generation process; a vocabulary of shapes that contains all the shapes manipulated in the process, including the initial shape and the final designs; and a set of rules, which determines how shapes are manipulated (Stiny & Gips, 1972). Labels (Stiny, 1980) and colors (Knight, 1989a) can also be part of the shape grammar to control the generation process, also called derivation.

This research expands on the work developed by Knight (1989b) on grammatical transformations, which are changes operated in shape grammars through the alteration, addition, or deletion of rules. Knight used grammatical transformations to describe the historic evolution one artistic style into a another. Eloy and Duarte (2011, 2012, 2015) extended Knight's theory by proposing the concept of transformation grammar. They illustrated the concept with a grammar to transform dwellings from the 1940s through the 1960s into apartments that satisfied contemporary housing needs. Following a similar approach, Guerritore and Duarte (2018) proposed a transformation grammar to convert a particular type of office buildings into collective housing buildings. In this research, it is proposed the use of a grammatical transformation to convert the Santa Marta analytical grammar into a synthetic grammar to generate new settlements that share its qualities but not its flaws.

MATERIALS AND METHODS

As mentioned above, a select case study is used to inform the development of the proposed computational strategy. Santa Marta is an informal settlement located in Rio de Janeiro, Brazil, and it can be considered a paradigmatic example of favelas that emerge in prime areas of cities, on steep terrains, close to downtown neighborhoods. The steepness of the terrain makes the area unsuitable for urban speculation. Figure 1 shows a map of Santa Marta with the three main entrances to the settlement and the steep topography, where contour lines represent a one-meter increment in height.

Fig. 1 Verniz & Duarte (2020b), Santa Marta favela's plan.



The analytical shape grammar

The analytical shape grammar, called Santa Marta Urban Grammar, is a model that encodes the formal structure of Santa Marta and can be used to describe how the informal settlement process may have generated the urban fabric following the rules used by people in the construction of their own houses. The use of parametric rules is essential to encode informal settlements with such a wide range of variation in the shape of buildings and circulation spaces. The proposed grammar is a compound parametric grammar (Verniz & Duarte, 2020b) defined in the Cartesian product of algebras for street plans and elevations, namely, $(U_{12} \times (V_{02} \times V_{12} \times V_{22}) \text{ x } (U_{12} \times (V_{02} \times V_{12 \times} V_{22}))$. Shapes in algebras U_{12} include lines that represent building footprints limits, contour lines, alleys, stairways, entrance stairs, and street elevations. Shapes in algebras V_{02} include labels (labelled points) that represent the end of pathways, the vertices of buildings, and the intersections between buildings and contour lines. Shapes in algebras V_{12} include labelled dashed line segments that represent contour lines and street axes. Shapes in algebras V_{22} include plane segments that represent buildable or built areas, stairways, entrance stairs, and elevations.

The settlement process of Santa Marta Favela was spontaneous, following the needs of its dwellers. Figure 2 shows a sequence of nine steps proposed to encode this spontaneous process. These steps reflect construction decisions made by the settlement's dwellers and are based on dependent and independent variables related with the four forces identified above. Each step addresses an aspect of the decision-making process that determines the location, orientation, and shape of buildings, which is directed to use the available resources in the most economical way. These decision aspects represent design variables and, with exception of the first step, are related with one or more rules.

The analytic model assigns labels to shapes, creating labelled points, lines, or planes, to assist in the derivation process that are deleted at the end. Three initial shapes

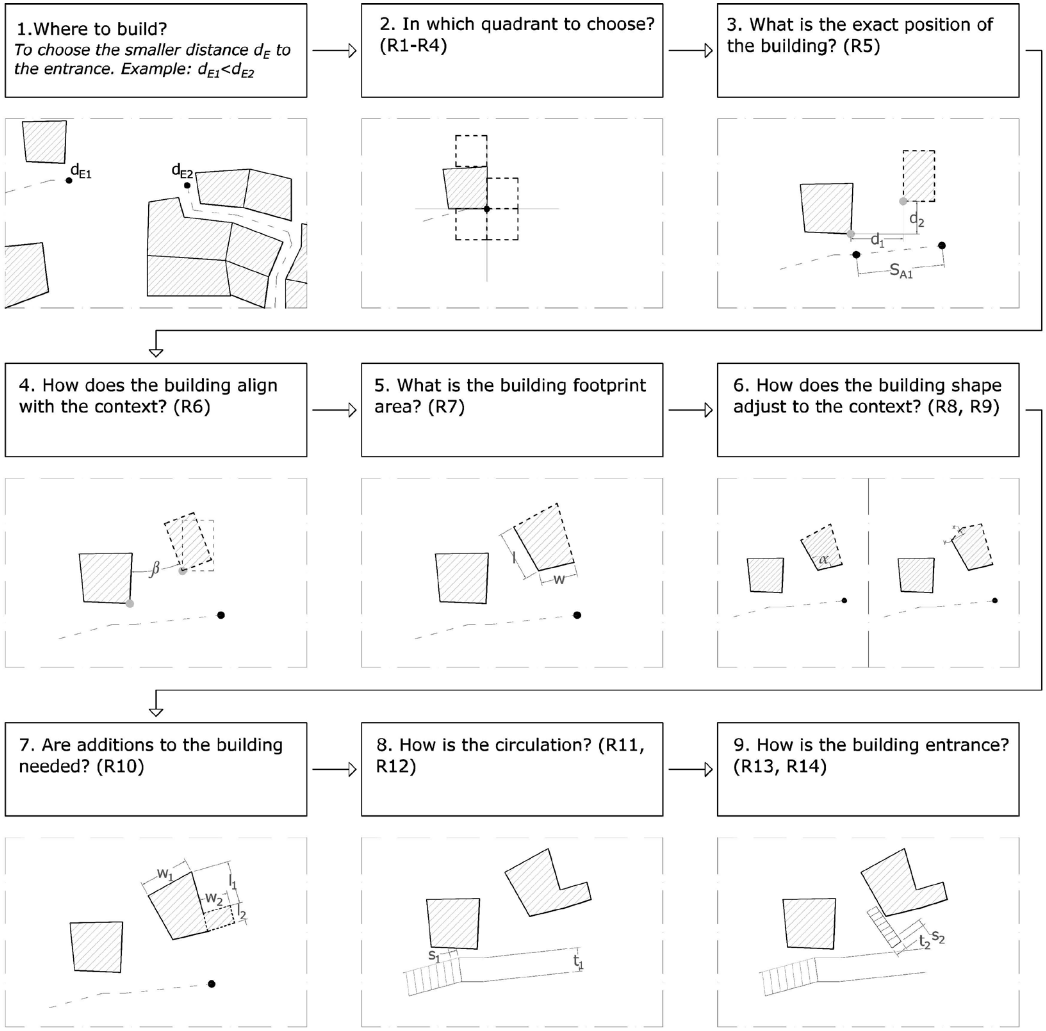
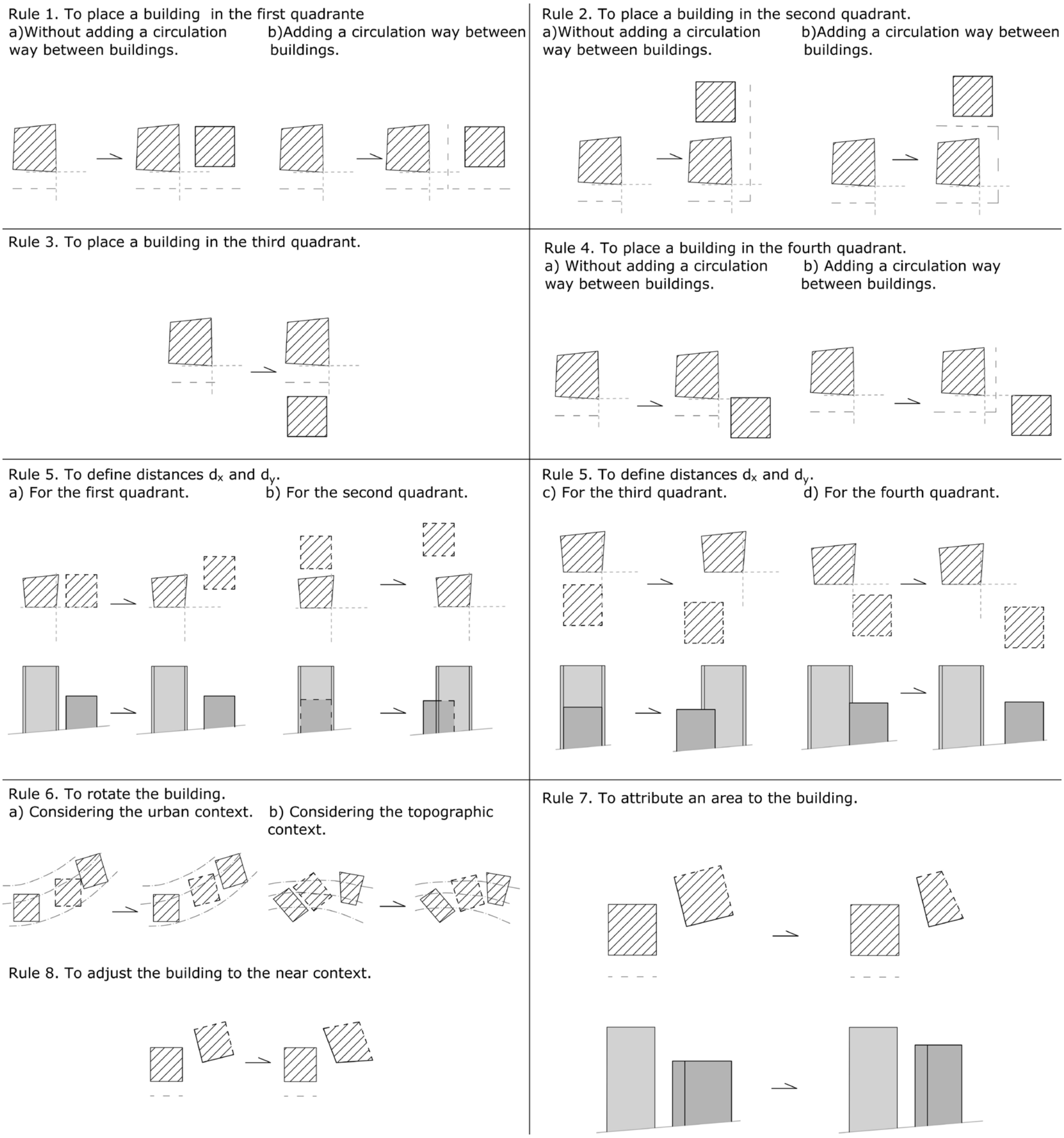


Fig. 2 Verniz & Duarte (2020b), Diagram showing how the grammar captures the rationale underlying the favela's settlement.

represent the three entrances to the settlement. Rules R1 to R10 are represented in the XY Cartesian plane and Rules R11 to R14 are represented both in the XY and XZ Cartesian planes. This shape grammar captures the bottom-up nature of the settlement process as designs are derived by sequentially adding shapes that represent buildings, which consequently defines pathways.

The rules are divided in two categories. The first is responsible for placing, aligning, and shaping buildings and it encompasses Rules 1 to 10. The second category encompasses Rules 11 to 14, and it is responsible for characterizing circulation. All detailed versions of the rules include plan and elevation views. We opted to develop



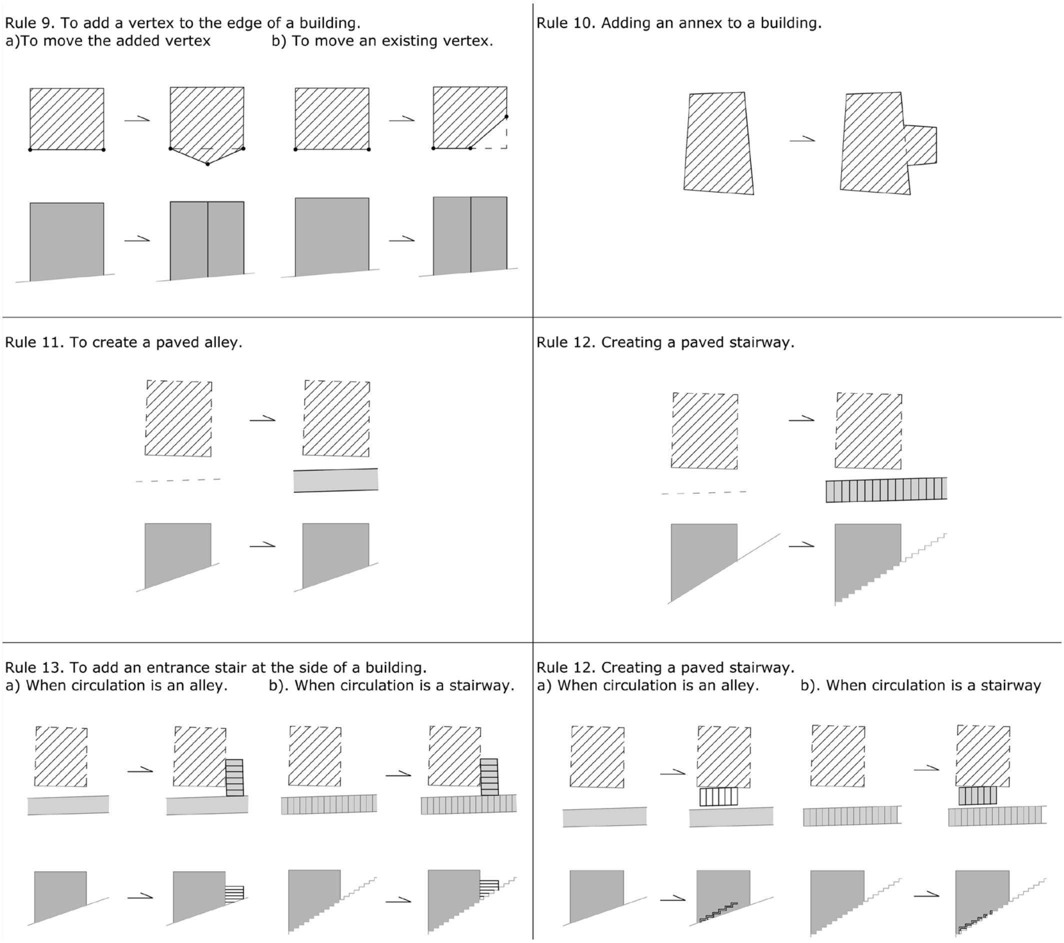


Fig. 3 Simplified rules of the analytic model.

the grammar rules using these two bidimensional planar views to facilitate their understanding. Figure 3 shows a simplified version of these rules.

Rules R1 to R4 are used to place a new building. They first create a Cartesian Plane where the X axis is aligned with the front facade of an existing building located at the end of a circulation segment, with the origin (0, 0) located at the vertex of the building closer to the end of the circulation. Then they select one of the four Cartesian quadrants to insert the new building, thereby defining the spatial relation between new and existing buildings. Rule 5 is then applied to move the new building by distances d_x and d_y on the cartesian plane. Rules R6 to R8 transform the new building, adjusting it with the immediate topographic and urban contexts. Rules R9 to R10 are applied to manipulate the building shape to further adjust it to the topographic, typological, or urban contexts. Rule R11 and Rule R12 create a paved circulation where an informal circulation has already been defined by existing buildings. Finally, Rule R13 and Rule R14 add an entrance stairway to the new building. A detailed version of the rules and the validation of the grammar are available in Verniz and Duarte (2020b).

Housing Quality Assessment of Santa Marta favela

An existing housing quality assessment method (QUARQ) was used to identify the aspects of Santa Marta that needed upgrading. This method was proposed by Pedro (1999a; 2001; 1999b) to evaluate the architectural quality of housing designs and settlements. The method operated on four scales: 'room', 'dwelling unit', 'building', and 'neighborhood'. Because this research is concerned with the urban scale, QUARQ was used to assess the quality of the settlement at the neighborhood scale. A computer implementation (that works in Microsoft Access environment) of the system was made available by Pedro (Pedro, 1999b), which greatly facilitated the application of QUARQ to Santa Marta.

The method considers three levels of quality: 'minimum', 'recommended', and 'optimum'. In the 'minimum' level (ranging from 0.51 to 1.50) it is assumed that the neighborhood satisfies the basic daily needs of residents. In the 'recommended' level (ranging from 1.51 to 2.50) the neighborhood has a better performance, allowing different uses and the eventual use of the spaces by people with disability. In the 'optimum' level (ranging from 2.51 to 3.0) the neighborhood has a performance that fully satisfies the daily needs of the residents and the permanent use of spaces by people with disability. Scores equal or lower than 0.50 are considered unsatisfactory.

According to the method, the criteria considered in the evaluation of Santa Marta at the neighborhood scale were 'articulation', 'personalization', 'pleasantness', 'safety', and 'spatial adequacy'. A detailed evaluation of Santa Marta favela can be found at Verniz (2020).

Table 1 shows Santa Marta evaluation results, where in all the main evaluation criteria reached at least the minimum score. The criteria that scored the lowest in the assessment of Santa Marta were addressed in the development of the synthetic shape grammar presented in this paper, namely, articulation, pleasantness, and spatial adequacy.

Tab. 1 Results of the evaluation of Santa Marta.

Criteria	Result	Quality Level
Articulation	1.25	Minimum
Personalization	2.87	Optimum
Pleasantness	1.20	Minimum
Safety	1.51	Recommended
Spatial Adequacy	0.94	Minimum

The QUARQ method also provides a report on which physical attributes need improvement. Regarding adequacy, results showed that the settlement lacked a proper and safe circulation network. The physical characteristics that were addressed regarding this criterion were related to the improvement of the general conditions of the circulation network, including pathways, ramps, and stairways. Regarding pleasantness, results showed that settlement lacked shaded areas and waste management, as buildings were placed giving priority to topographic features over insolation or car accessibility. The physical characteristics that were addressed in this criterion were related to the inclusion of shaded opened areas and waste management measures. Regarding spatial adequacy, the settlement lacked proper urban furniture in open areas. The physical characteristics that were addressed in this criterion included better detailing of buildings, leisure areas, and commerce.

From the report output by QUARQ, we extracted a set of ten recommendations (Verniz & Duarte, 2020a) to improve the physical characteristics negatively impacting the articulation, pleasantness, and spatial adequacy criteria. These recommendations were:

1. To protect with handrail pathways that presented potential risks for pedestrians;
2. To establish a minimum circulation width that complied with accessibility standards;
3. To establish proper dimensioning parameters for stairways;
4. To set a maximum inclination for ramps in open areas;
5. To provide more shading in open areas;
6. To provide bins in open areas and to improve the waste collection system;
7. To establish a minimum building area to accommodate at least one dwelling unit per floor;
8. To provide adequate leisure areas, properly equipped with urban furniture that is suitable for children, teenager, and adults/seniors;
9. To provide adequate areas for commerce;
10. To provide proper urban furniture, including benches, light poles, and bins in open areas.

The synthetic shape grammar

The synthetic shape grammar, called Planned Favela Urban Grammar, was inferred based on the set of recommendations listed in the previous section. These recommendations were used to guide the changes made to the analytical shape grammar. Figure 4 shows a sequence of 12 steps in the application of rules according to the transformed shape grammar. Each step is represented by a question that corresponds to an aspect of the decision-making process that determines the location, orientation, and shape of buildings in the urban fabric.

Like the analytical grammar, the synthetic grammar is a compound grammar defined in the Cartesian product of

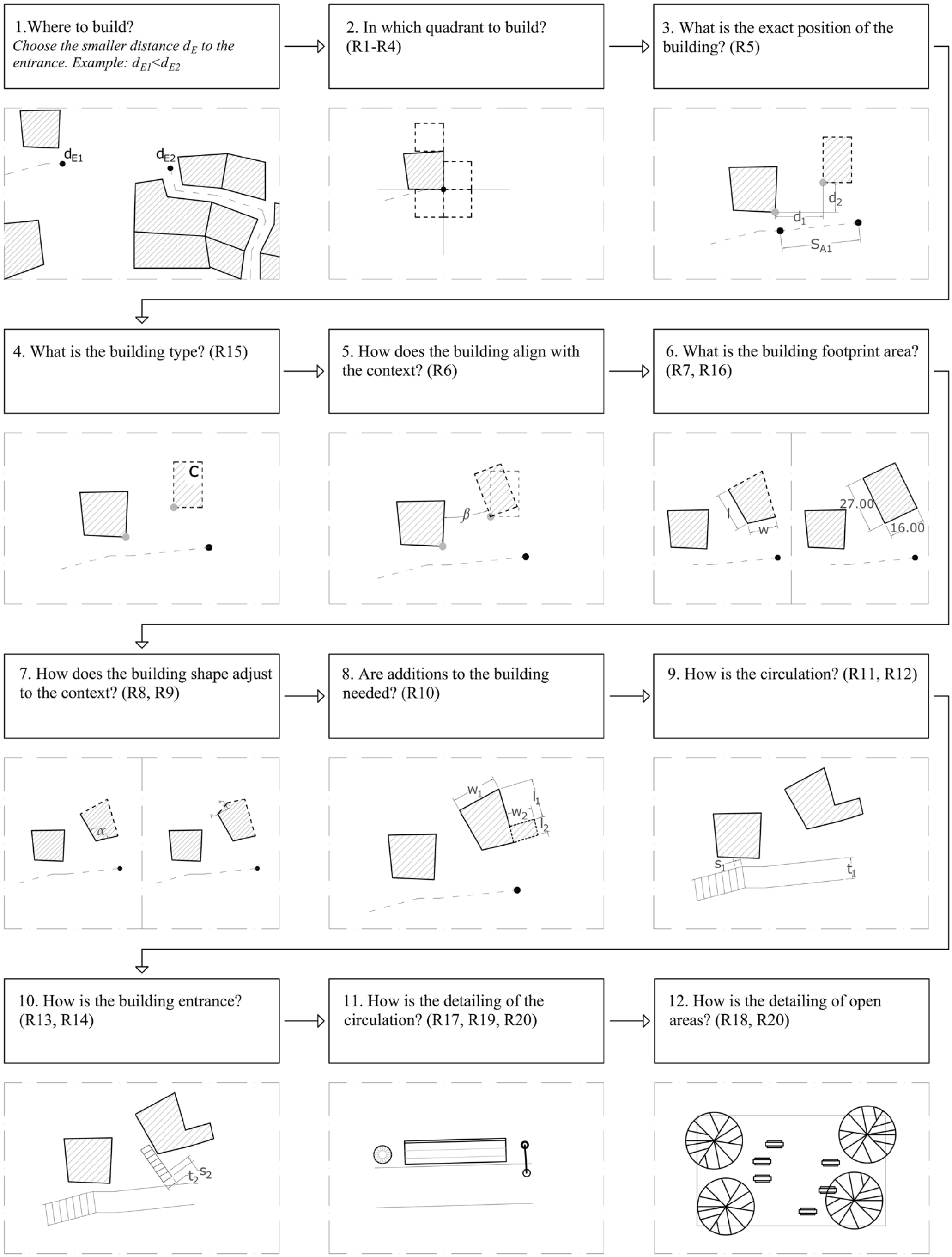

1.Where to build?
Choose the smaller distance dE to the entrance. Example: dE1<dE2
2. In which quadrant to build? (R1-R4)
3. What is the exact position of the building? (R5)
dE1
dE2
d1
d2
SA1
4. What is the building type? (R15)
5. How does the building align with the context? (R6)
6. What is the building footprint area? (R7, R16)
C
β
l
w
27.00
16.00
7. How does the building shape adjust to the context? (R8, R9)
8. Are additions to the building needed? (R10)
9. How is the circulation? (R11, R12)
α
w1
w2
l1
l2
s1
t1
10. How is the building entrance? (R13, R14)
11. How is the detailing of the circulation? (R17, R19, R20)
12. How is the detailing of open areas? (R18, R20)
t2
s2

Fig. 4 Process showing the rationale behind the application of rules. Source: the authors.

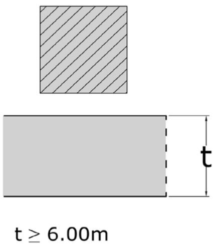


Fig. 5 Initial shape. Source: the authors.

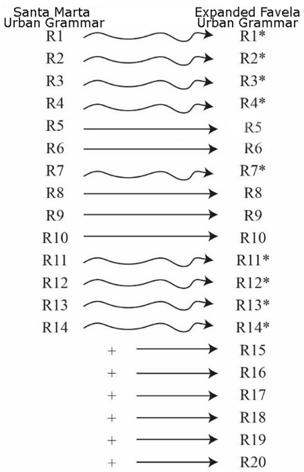


Fig. 6 Comparison between analytical model rules (on the left) and synthetic model rules (right). Source: the authors.

the algebras for both plans and street elevations: $(U_{12} \times (V_{02} \times V_{12} \times V_{22})) \times (U_{12} \times (V_{02} \times V_{12} \times V_{22}))$. Shapes in algebras U_{12} include lines to represent building footprints limits, contour lines, alleys, stairways, entrance stairs, street elevations, and handrails. Shapes in algebras V_{02} include labelled points to represent the end of pathways, the vertices of buildings, and the intersections between buildings and contour lines. Shapes in algebras V_{12} include labelled dashed line segments to distinguish contour lines and to represent street axes. Shapes in algebras V_{22} include plane segments, to represent buildable or built areas, stairways, entrance stairs, and elevations. Differences in colors (in dots, lines, and hatches) are also considered a kind of labels. These labels are used to assist in the derivation process and are deleted at the end of the derivation process.

Figure 5 shows the initial shape for the Planned Favela Urban Grammar. The initial shape is the end of an existing local street. The dimension 't' refers to the street width. In Brazil, regulations for street dimensioning are a municipal jurisdiction, so street width may vary from one county to the other.

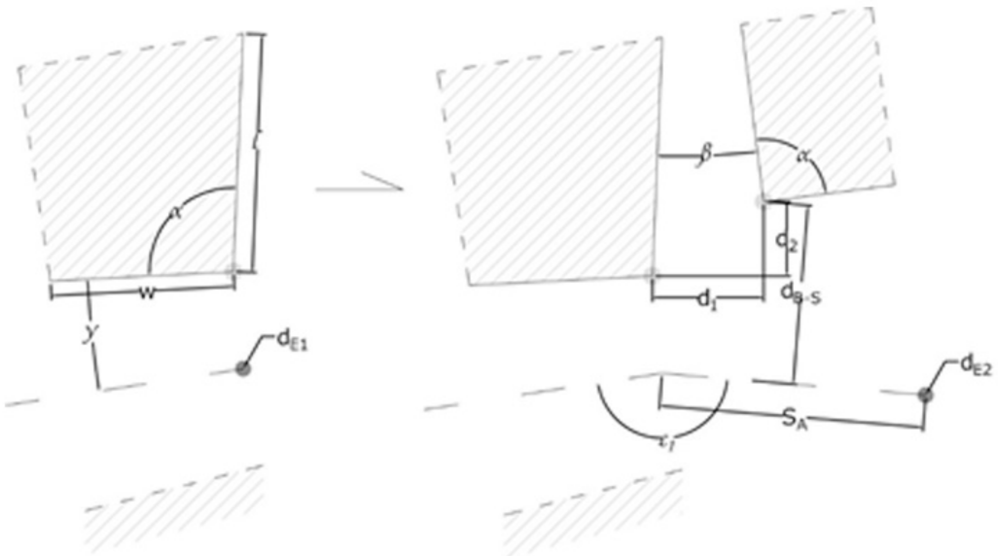
The synthetic shape grammar has a set of 20 rules. The first fourteen rules were imported from the analytical shape grammar and kept with changed or unchanged parameters. The last six rules were added to include physical features that were missing in Santa Marta and that were identified with the QUARQ method. Figure 6 shows a comparison between rules from the two grammars. Rules are named using the symbolic expression 'R_n' and rules that have the same name in both grammars are equivalent. Wavy arrows represent rules that have been changed, straight arrows represent rules that have been kept unchanged, and straight arrows with a plus sign to their left represent rules that have been added.

The rules are divided into three categories: the first category encompasses Rules R1 to R10 and Rule R15 and it is responsible for placing, dimensioning, shaping, aligning, and defining the use of buildings; the second category encompasses Rules R11 to R14, R17, and R19 and it is responsible for placing, characterizing, and detailing circulation; and the third category encompasses Rules R15, R16, R18, and R20 and it is responsible for placing and detailing open spaces.

Rules R1 to R4 place a new building. They create a Cartesian Plane where the X axis is aligned with the front facade of an existing building located at the end of a circulation section, with the origin (0, 0) located at the vertex of the building closer to the end of the circulation. Each of these rules places a new building in one of the four quadrants defined on the Cartesian Plane, thereby defining the spatial relation between new and existing buildings. Rules R6 to R8 transform the new building, adjusting it with the immediate topographic and urban contexts.

The variables associated with the first set of rules are similar to those in the analytical model and are identified in Figure 7. Angles in the figure are identified with lowercase Greek letters as follows: 'α' is the internal angle of the building; 'β' is the angle between the existing and the new buildings; 'γ' is the angle between the front limit of the building and the axis of the circulation; 'ε' is the angle

Fig. 7 Variables associated with rules R1 to R8.



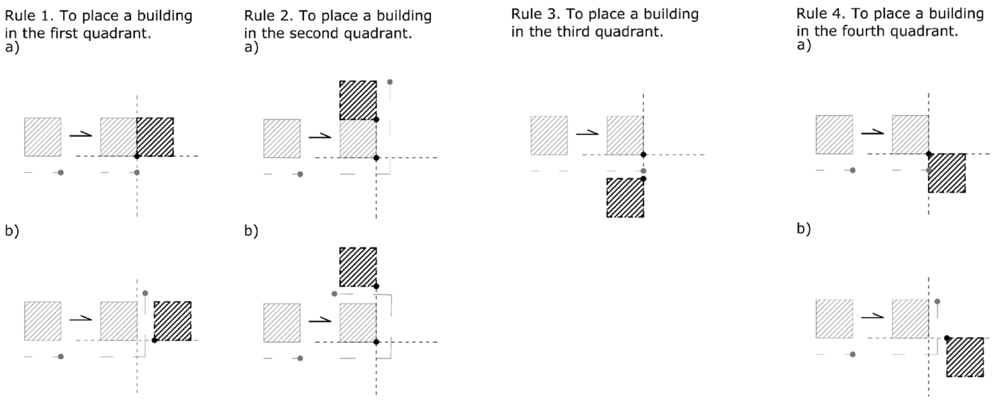


Fig. 8 Simplified rules R1 to R4: "place a new building".

between the existing and the new circulation segments. Dimensions are represented by lowercase Latin letters as follows: 'w' is the width and 'l' is the length of the building; and 'd' is the distance between buildings. Additionally, other dimensions are also represented by Latin letters (both uppercase and lowercase): 'd_{B-S}' is the perpendicular distance between the corner of the building and the circulation axis; 'd_E' is the distance between the building and the entrance to the settlement from the formal city; and 'S_A' is the length of the new circulation segment.

Rules R1 to R4 place a new building in different ways (Figure 8). The two small-dashed lines represent the X and Y axes of a Cartesian Plane with origin (0, 0) at the outer corner of an existing building located at the current limit of the settlement. The gray large-dashed line represents the axis of an existing circulation. Dark dots are labels that represent the positioning of the new building and light dots represent the end of the circulation pathway. Light-gray polygons with a diagonal hatch represent existing buildings and dark-grey polygons represent the new buildings being placed.

Rules R1 to R4 in the synthetic model are very similar to those in the analytical one. Changes were made on the parameter 'd_{B-Sn}', which indicates the distance between the corner of a new building and the circulation axis. The minimum 'd_{B-Sn}' was previously 0.25 m and this value was

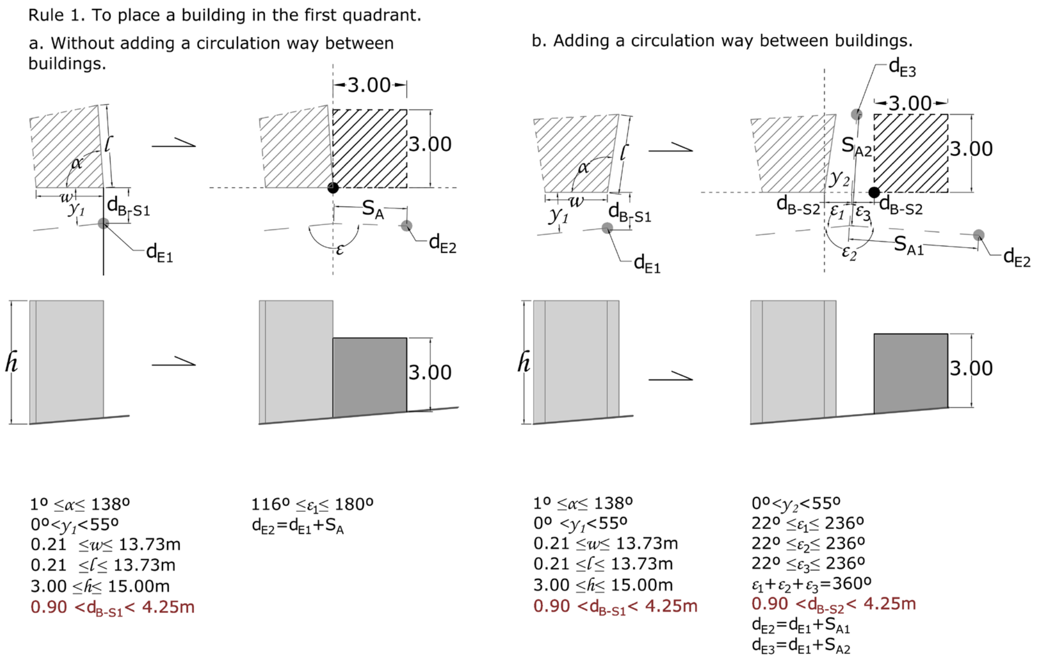


Fig. 9 Rules R1 a and b: placing a new building in the first quadrant.

inferred based on the survey of Santa Marta. The national standard NBR 9050 (Conselho de Arquitetura e Urbanismo do Brasil, 2015) states that an accessible circulation way must have a minimum width of 1.20 meters (enough to fit two wheelchairs side by side), free from any obstacle. We considered an additional 0.60 m for the placement of urban furnishing or vegetation. The final minimum value of '$d_{B\text{-}Sn}$' is 0.90 m, with a minimum width of 1.80 meters between buildings. The changed parameter is shown in red and it improves the articulation assessment criterion.

Figure 9 shows a detailed version of Rule R1 (a and b). This rule inserts a new building in the first quadrant of the Cartesian plane. Changed parameters are shown in red.

Variation a of the rule inserts a new building in the first quadrant at the side of an existing building. The left side of the rule shows an existing building represented by a 4-sided polygon, the circulation axis is represented by a dashed-grey line and the end of the circulation by a dark-grey label.

Although the existing building can take the shape of a n-sided polygon (with $4 \leq n \leq 11$) and, therefore, there should be a sub-variation of the rule for each building configuration, representation is restricted to 4-sided polygons in rules R1 to R4, as well as in all the remaining rules. On the right side of the rule, a Cartesian plane is inserted at the corner of the existing building, with the X axis aligned with the side of the building. At this point, the building doesn't have a definite configuration, being represented as a generic square, which is inserted at the origin of the cartesian system, labelled with a black dot. The circulation is then extended with a new segment whose length is equal to the width of the new building.

Variation b of the rule inserts a new building in the first quadrant at the side of an existing building but adding a circulation way between them. The representation on the left side of the rule is the same as in the first variation. On the right side of the rule, a new Cartesian system is inserted, with the new building placed along the X axis with a label at its corner (x, 0). Between the existent and the new buildings, a new circulation section is placed in a different direction. The circulation in front of the existing building is also extended as in the first variation.

Figure 10 shows detailed versions of Rules R2 (a and b). This rule inserts a new building in the second quadrant of the Cartesian plane. Changed parameters are emphasized in red.

Variation a of the rule inserts a new building in the second quadrant, at the back of an existing one and adds a new circulation segment in a new direction. The representation on the left side of the rule is the same as in Rule R1. On the right side of the rule, a new Cartesian plane is inserted, the new building is placed along the Y axis with a label at its corner (0, y), and the circulation is extended, thereby creating a new circulation segment in a new direction.

Variation b of the rule inserts a new building in the second quadrant of the Cartesian plan, in front of an existing building and adds two new circulation segments. The representation

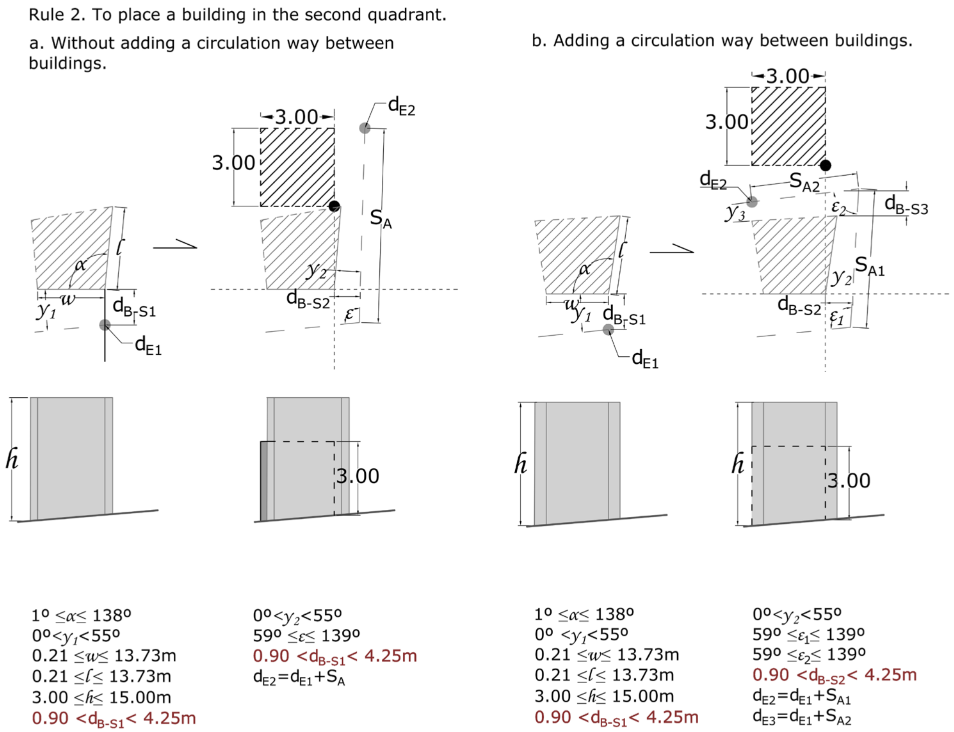


Fig. 10 Rule R2 a and b: placing a new building in the second quadrant.

on the left side of the rule is the same as in Rule R1. On the right side of the rule, a new Cartesian plane is inserted, the new building is placed at the back of the existing one, and two new circulation segments are placed around the existing building.

Figure 11 shows a detailed version of Rule R3. This rule inserts a new building in the third quadrant, in front of the existing building. The changed parameter is shown in red.

The representation on the left side of the rule is the same as in Rule R1. On the right side of the rule, a new Cartesian plane is inserted, and the new building is placed along the Y axis with a label at its corner (0, -y). Circulation is not extended in this case.

Figure 12 shows the detailed versions of Rule R4 (*a* and *b*). This rule inserts a new building in the fourth quadrant. Changed parameters are denoted in red.

Fig. 11 Rule R3: placing a new building in the third quadrant.

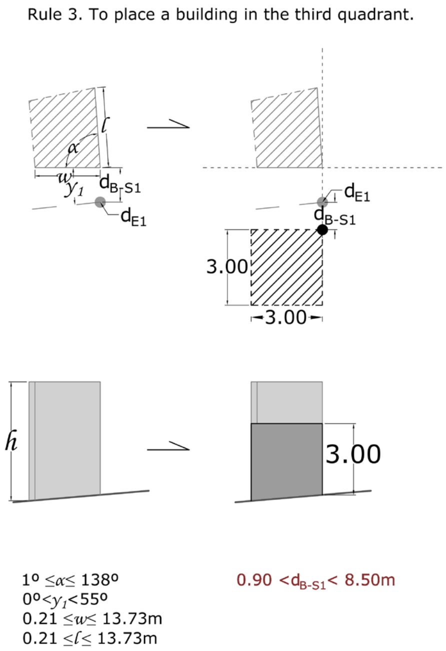
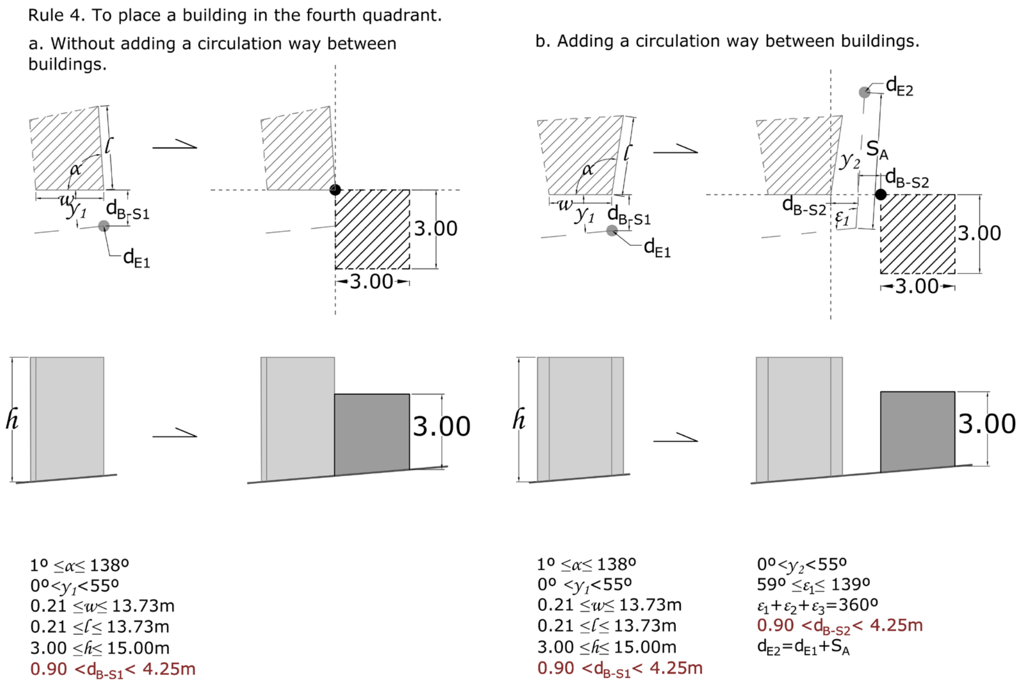


Fig. 12 Rule R4 *a* and *b*: placing a building in the fourth quadrant.



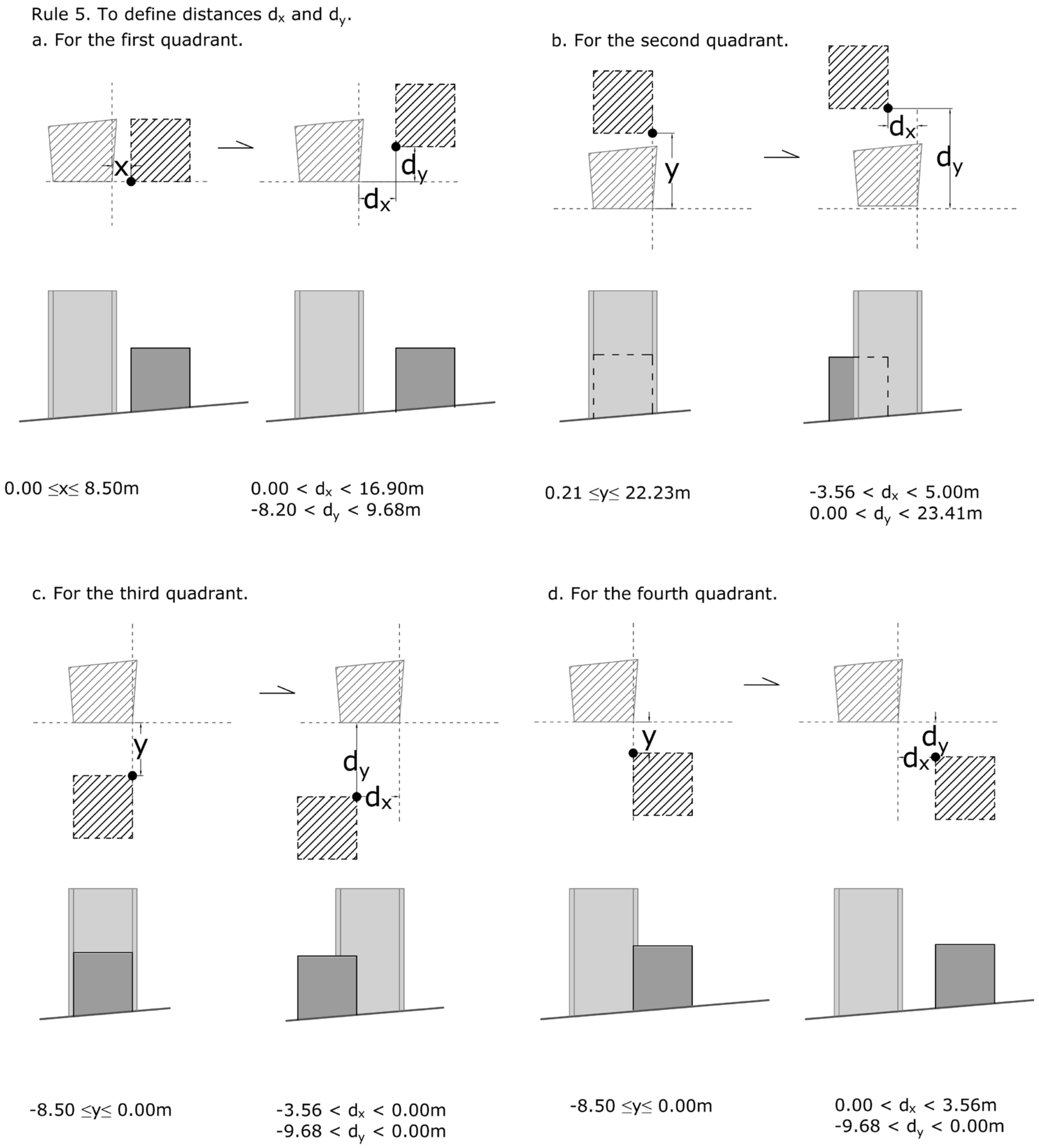


Fig. 13 Rules R5 *a* and *b*: defining the distance of the new building to the existing one.

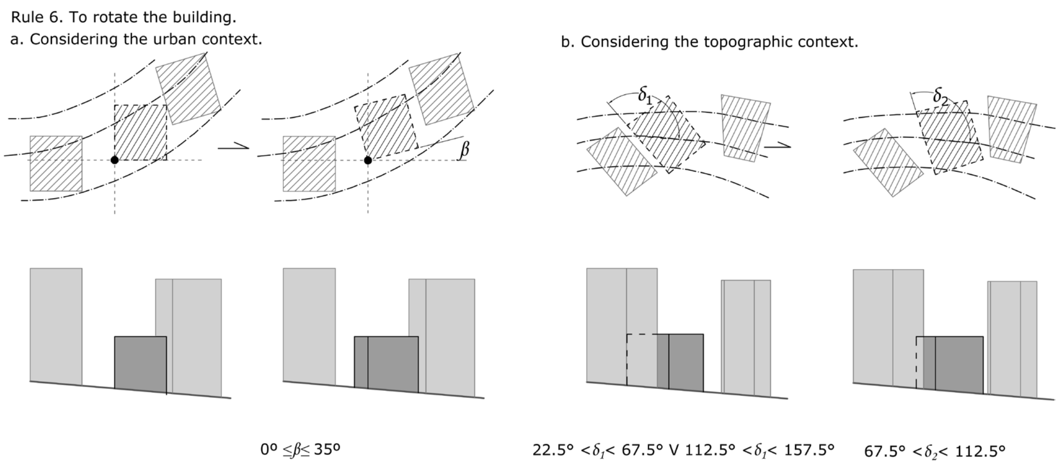
Variation a of the rule inserts a new building in the fourth quadrant in front of a circulation segment. The left side of the rule is the same as in rule R1. On the right side of the rule, a new Cartesian plane is inserted, and the new building is placed at the end of the existing circulation, creating a dead end.

Variation b of the rule inserts a new building in the fourth quadrant, in front of a circulation section, extending it. The left side of the rule is the same as in Rule R1. On the right side of the rule, a new Cartesian plane is inserted, and the new building is placed in front of the circulation, which is extended in a different direction.

Figure 13 shows the detailed versions of Rule R5 (a, b, c and d). There are no changes to Rule R5. After determining where to place the new building, the next step is to adjust its position. Variations a to d of Rule R5, one for each placement quadrant, determine the right positioning of the corner of the new building, labeled with a dark dot.

Figure 14 shows detailed versions of Rule R6 (a and b). There are no changes to Rule R6. The next step is to align the new building with the near context. Rules R6a and b rotate the building according to (a) the urban context and (b) the topography. In rule R6b, the dashed-dot line represents the medium of the contour lines that intersect the building. This medium contour line intersects the building at two different points, from which is traced a straight line that forms the angle 'δ' with the edge of the building and is used to control the alignment of the building. Please note that the contour lines shown in Figure 14 are merely exemplary

Fig. 14 Rules R6 *a* and *b*: rotating the building to adjust it to the context.



as their exact configuration in the derivation process depends on the exact context.

Figure 15 shows a detailed version of Rule R7. The changed parameter ('w*l') is denoted in red. Changes the Rule R7 are related with the minimum area of a single-family dwelling, determined by Pedro (1999a) as 32 square meters. The goal of this change was to improve spatial adequacy.

This rule defines the width 'w', length 'l', and height 'h' of the new building. Until this point, new buildings

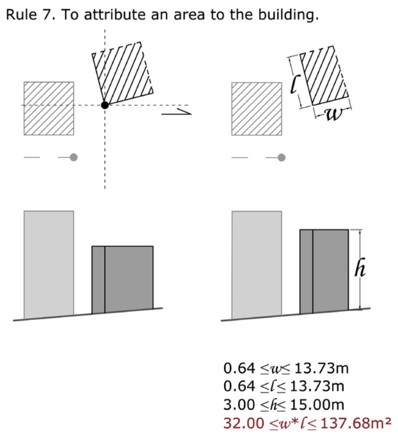


Fig. 15 Rule R7: defining the area of the building.

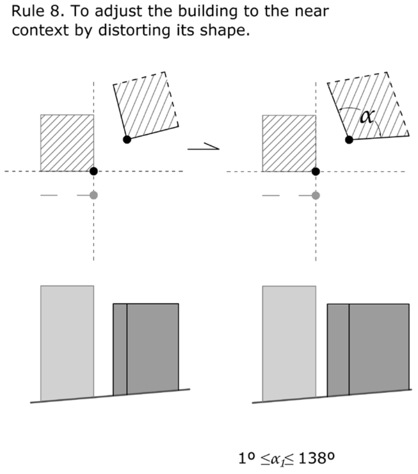


Fig. 16 Rule R7: defining the area of the building.

are represented by a dashed line because the size of its polygonal shapes have not been determined yet. The size of the building footprint can be selected from an interval that was previously defined after the analysis of Santa Marta.

Rules R8 to R10 manipulate the building shape to further adjust it to the topographic, typological or urban contexts.

Figure 16 shows a detailed version of Rule R8. There are no changes to Rule R8. When this rule is applied, the polygon that represents the building is still a rectangular shape. This rule then distorts this rectangle turning it into a quadrilateral with the same area, whose angle at the origin is 'α'. In favelas, the poligons that represent the footprint of self-constructed houses rarely present right angles, as the residents adjust their houses to the contour lines or to the urban context to maximize the footprint area.

Figure 17 shows the detailed version of Rule R9 (*a* and *b*). There are no changes to Rule R9. This rule introduces a new vertex on an edge of the building. The other edges of the building's footprint are represented with dashed-lines and the vertices with black dots. This rule can be applied to meet typological, programmatic requirements, or to further adjust the building to topographic or urban constraints, consequently increasing or decreasing its area.

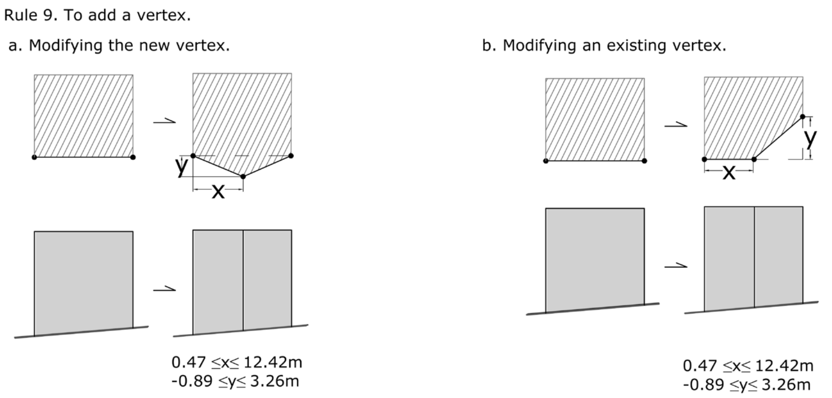


Fig. 17 Rules R9 *a* and *b*: adding a vertex on the edge of a building.

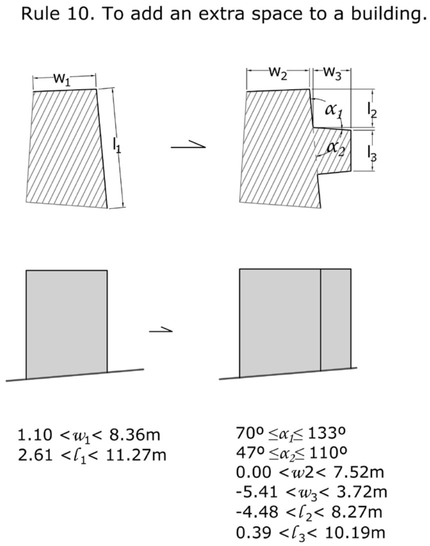


Fig. 18 Rule R10: adding an annex to a building.

Figure 18 shows the detailed version of Rule R10. There are no changes to Rule R10. This rule adds an annex to the side of a building. Variables for this rule include the width and length of the building and the annex, as well as the angles between their edges.

Rules R11, R12, R13, and R14 have changes on the following parameters: 'w', which represents the front facade of a building; 'dB-Sn', which represents the distance between the corner of a building footprint and the axis of the circulation; 't', which represents the width of the circulation pathway; 's', which represents the tread of a stairway; and 'r', which represents the rise of the stairway. All these parameters had previous limits that were based on the existing urban context of Santa Marta. The change in 'w' is a result from the addition of rule R16 that specifies a new maximum limit for the parameter, from 13.73 m to 27.00 m. The change in '$d_{B\text{-}Sn}$' was introduced with rules R1 to R4 and reflect the new minimum width for an accessible circulation and the inclusion of urban furnishing and vegetation, and it is present in Rules R11 and R12.

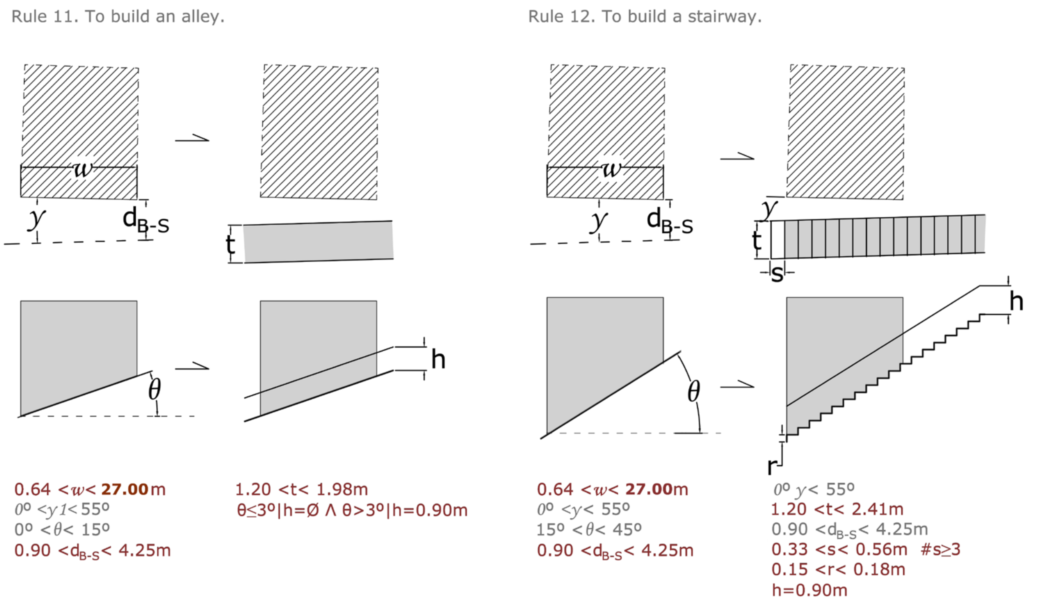


Fig. 19 Rule R11: creating a paved alley (left) and Rule R12: creating a stairway (right).

Changes in ‘s’ and ‘r’ are related with the specification of stairways that are consistent in terms of dimensions, and the requirement of a minimum of three rungs together in a stairway (Pedro 1999a). Additionally, a new parameter is introduced. With the inclusion of handrails in ramps and stairways it was necessary to include the height ‘h’ of the handrail, which is 0.90 m (Pedro 1999a). The goal of these changes was to improve the articulation and accessibility assessment criteria.

Figure 19 shows detailed versions of Rule R11 and Rule R12. Changed parameters are shown in red. Rule R11 and R1 create a paved circulation where an informal circulation has already been defined by existing buildings. Rule R11 creates a flat or an inclined alley when the inclination angle is between 0° and 3° or between 3° and 15°, respectively. Rule R12 creates a stairway when the inclination angle is bigger than 15°. Variables for these rules include the angle ‘θ’ of the slope, the width ‘w’ of the building; the angle ‘γ’ between the building facade and the circulation axis; the distance $d_{B\text{-}S}$ between the corner of the building and the circulation

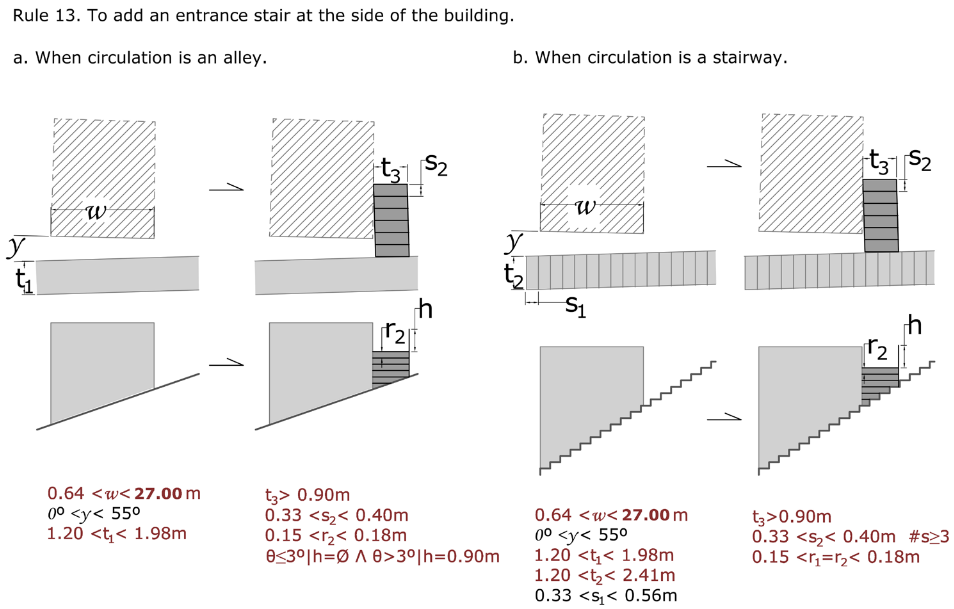


Fig. 20 Rules R13 *a* and *b*: adding an entrance stairway at the side of the building.

axis; the width ‘t’ of the circulation; and the run ‘s’; the rise ‘r’ of the stairway; and the height ‘h’ of the handrail.

Figure 20 shows the detailed version of Rule R13 (*a* and *b*). Changed parameters are denoted in red. This rule adds an entrance stairway at the side of the building. The elevation viewpoint shows how the stairway can relate to the circulation, depending on its inclination. Variables for these rules include the width ‘w’ of the building; the angle ‘γ’ between the building facade and the circulation; the width ‘t’ of the circulation; and the run ‘s’ and the rise ‘r’ of the stairs. Additionally, the parameter ‘h’ indicates the height of the handrail.

Figure 21 shows the detailed version of Rule R14 (*a* and *b*). Changed parameters are shown in red. This rule adds an entrance stairway at the front of the building. The elevation viewpoint shows how the stairway can relate to the circulation, depending on its inclination. Variables for these rules include the width ‘w’ of the building; the angle ‘γ’ between the building facade and the circulation; the width ‘t’ of the circulation;

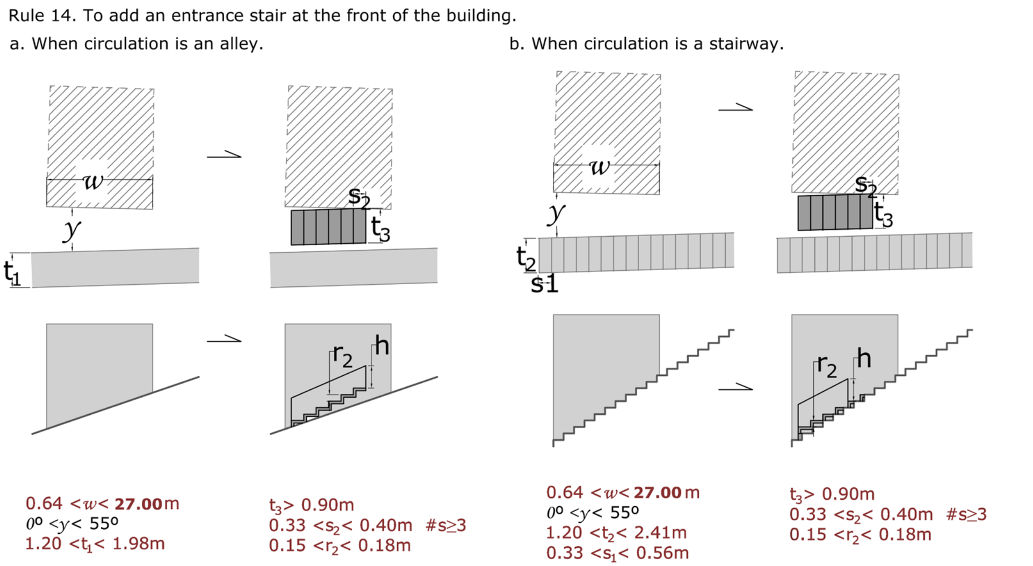


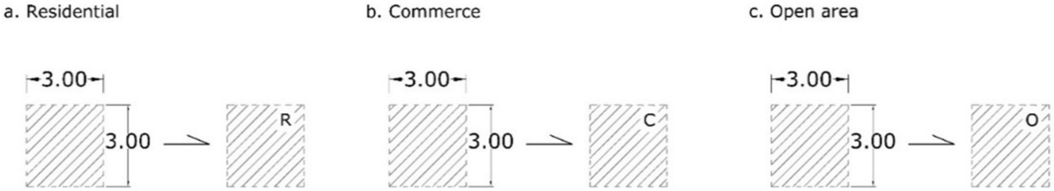
Fig. 21 Rules R14 *a* and *b*: adding an entrance stairway at the front of the building.

and the run 's' and the rise 'r' of the stairs. Additionally, the parameter 'h' indicates the height of the handrail.

Rules R15 to R20 are new rules proposed for synthetic. Figure 22 shows Rule R15. This new rule places commercial buildings in the urban fabric, during the derivation process. Label c indicates 'commerce'. This new rule allows the planned placement of commerce buildings, strategically positioned in the settlement to improve the spatial adequacy assessment criterion.

Figure 23 shows Rule R16. This new rule transforms a new building into an open area for leisure. The fixed dimensions are equivalent to a multi-sport field, but the actual detailing of the area will determine its use. On the right side of the image there are two examples of further detailing of the open area. This new rule allows the placement of open areas for leisure of

Fig. 22 Rule R15: defining the building type.



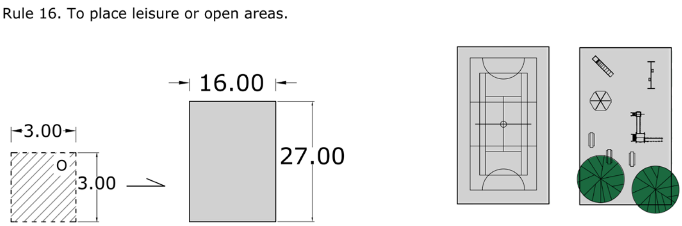


Fig. 23 Rule R16 (left): placing leisure areas on open areas. Example of leisure areas (right).

different resident age groups. This new rule is related with the improvement of the spatial adequacy assessment criterion.

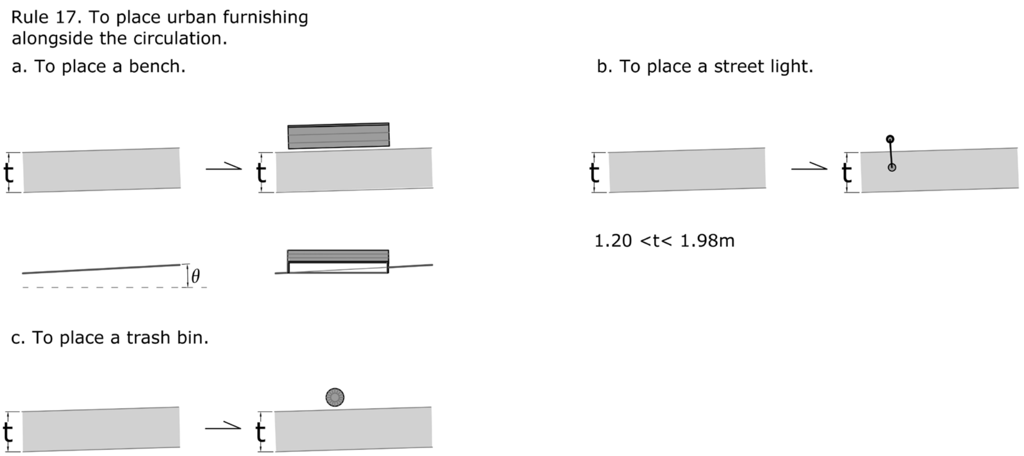
Figure 24 shows Rule R17. This new rule places urban furnishing along the circulation network. The placement of trash bins helps to improve pleasantness and the positioning of benches and streetlights help to improve spatial adequacy.

Figure 25 shows Rule R18. This new rule places urban furniture in an open area, helping to improve pleasantness and spatial adequacy.

Figure 26 shows Rule R19. This new rule places trash collectors along circulation pathways. These trash collectors are destined to receive the trash from the public bins and from residents, helping to improve pleasantness.

Figure 27 shows a detailed version of Rule R20. This new rule places a tree along the circulation (version a) or in an open area (version b), helping to improve pleasantness.

Fig. 24 Rule R17 *a* to *c*. To place urban furnishing alongside the circulation.



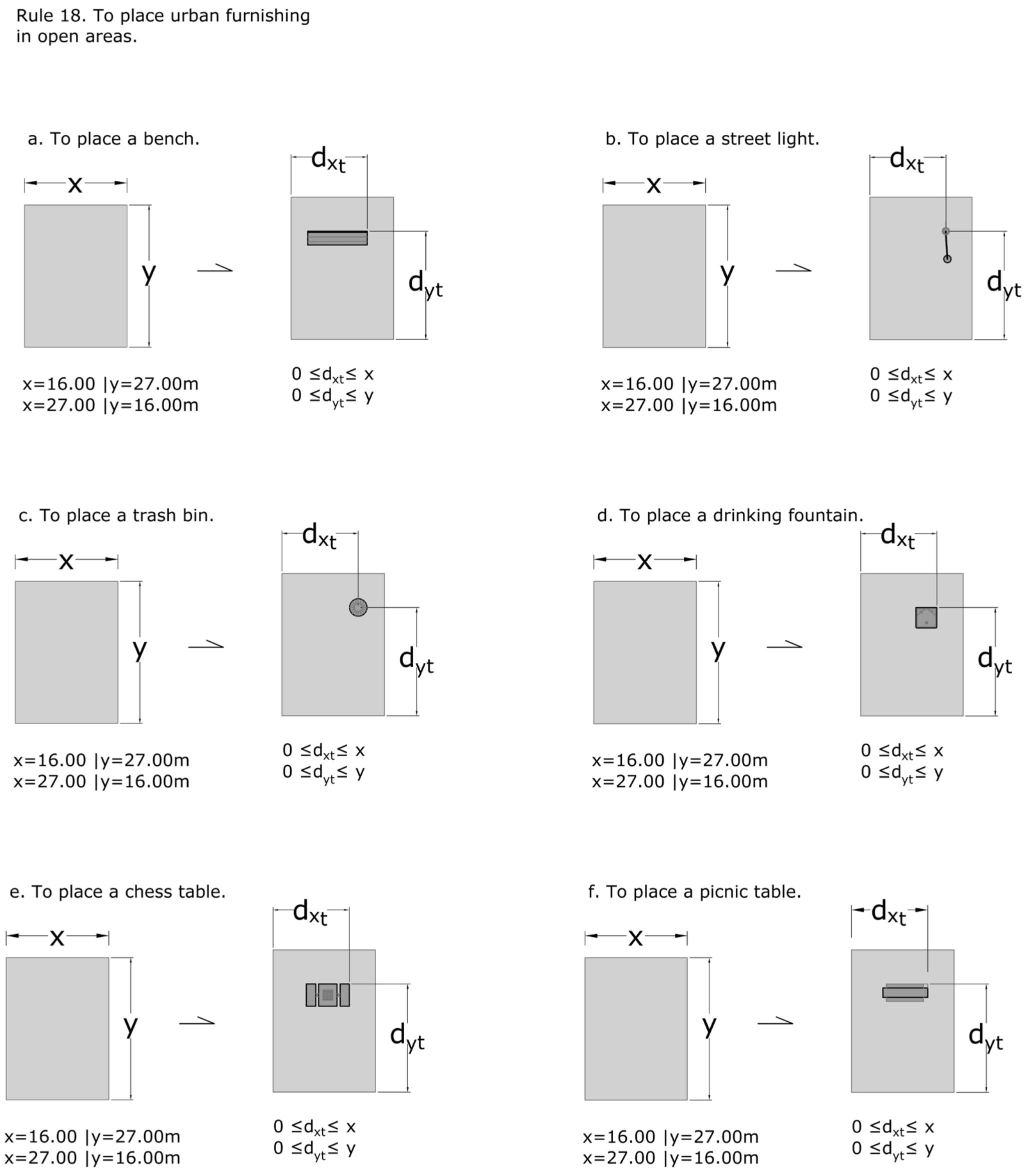


Fig. 25 Rule R18 *a* to *f*: placing urban furnishings in open areas.

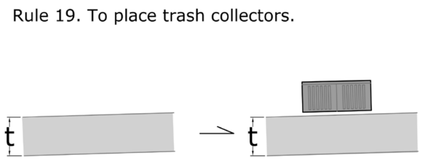


Fig. 26 Rule R19: placing trash collectors along the circulation.

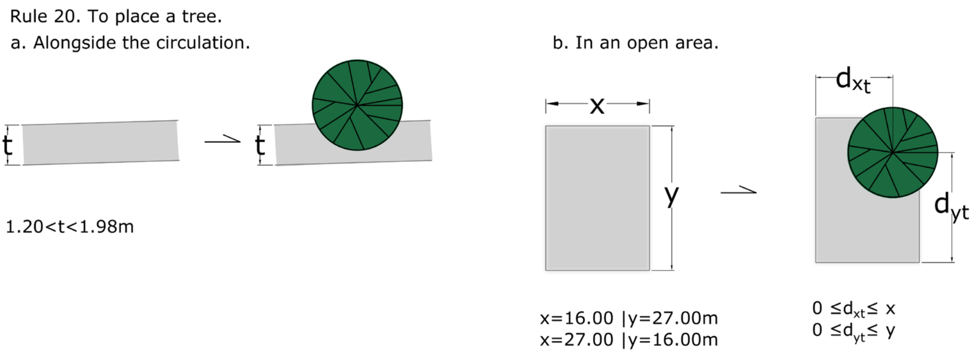
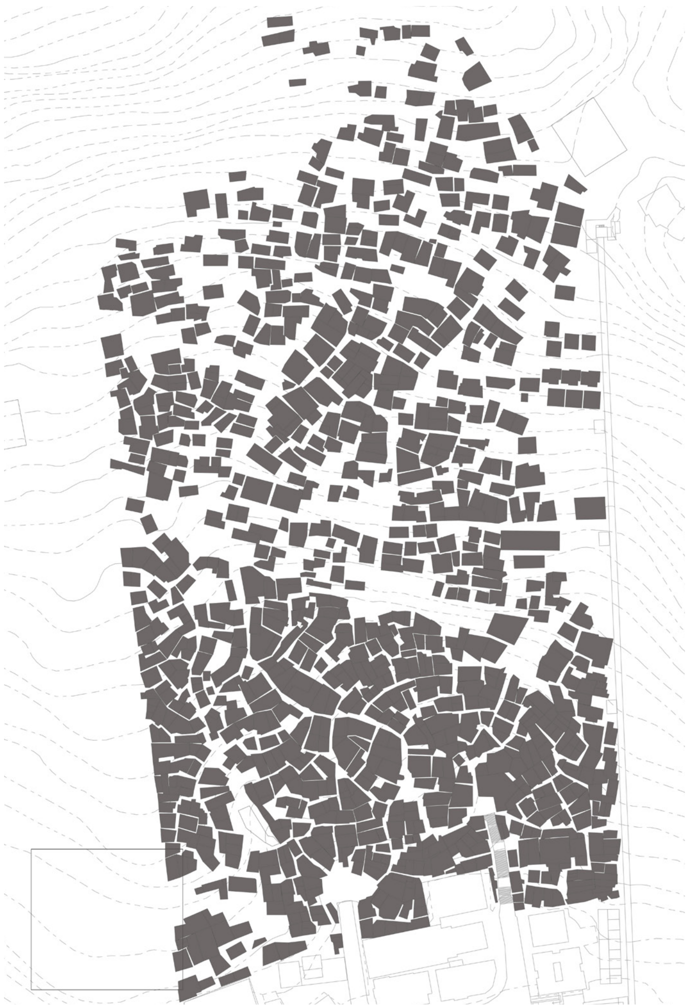
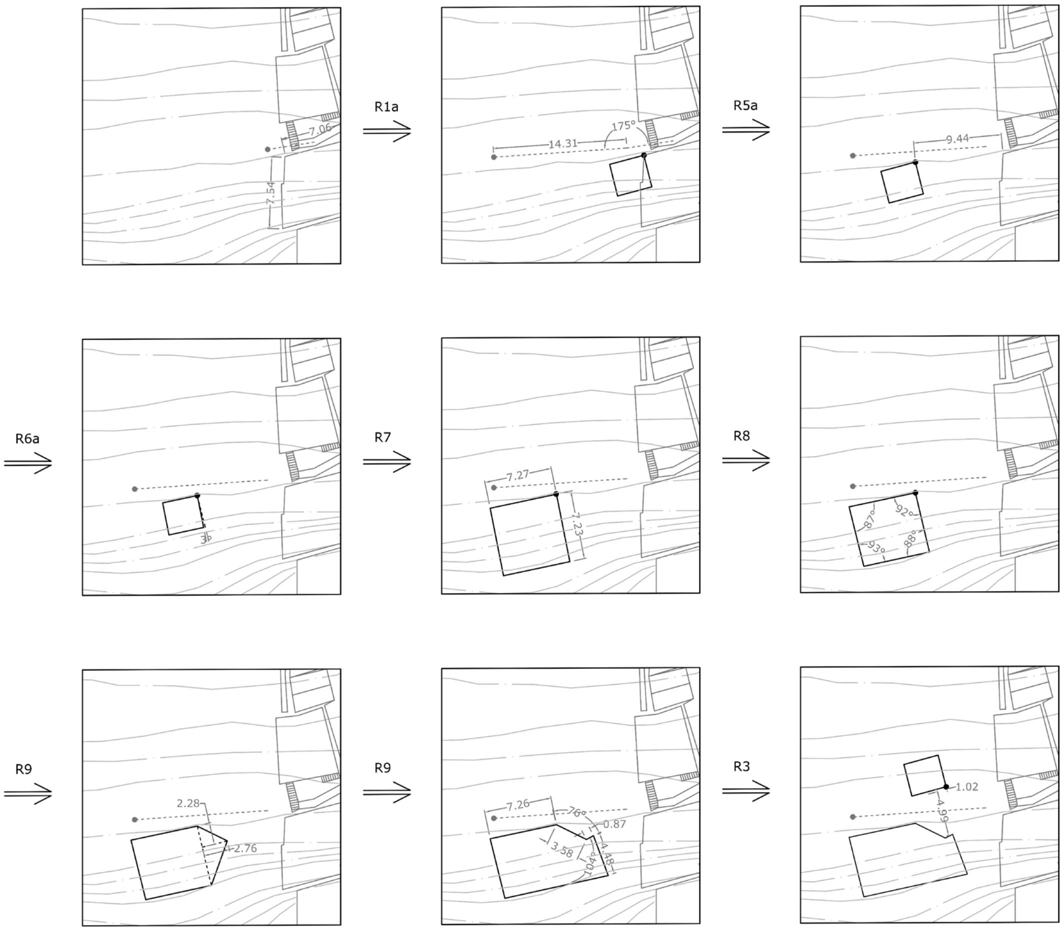


Fig. 27 Rule R20 *a* and *b*: placing a tree.

Fig. 28 Map of Santa Marta favela.



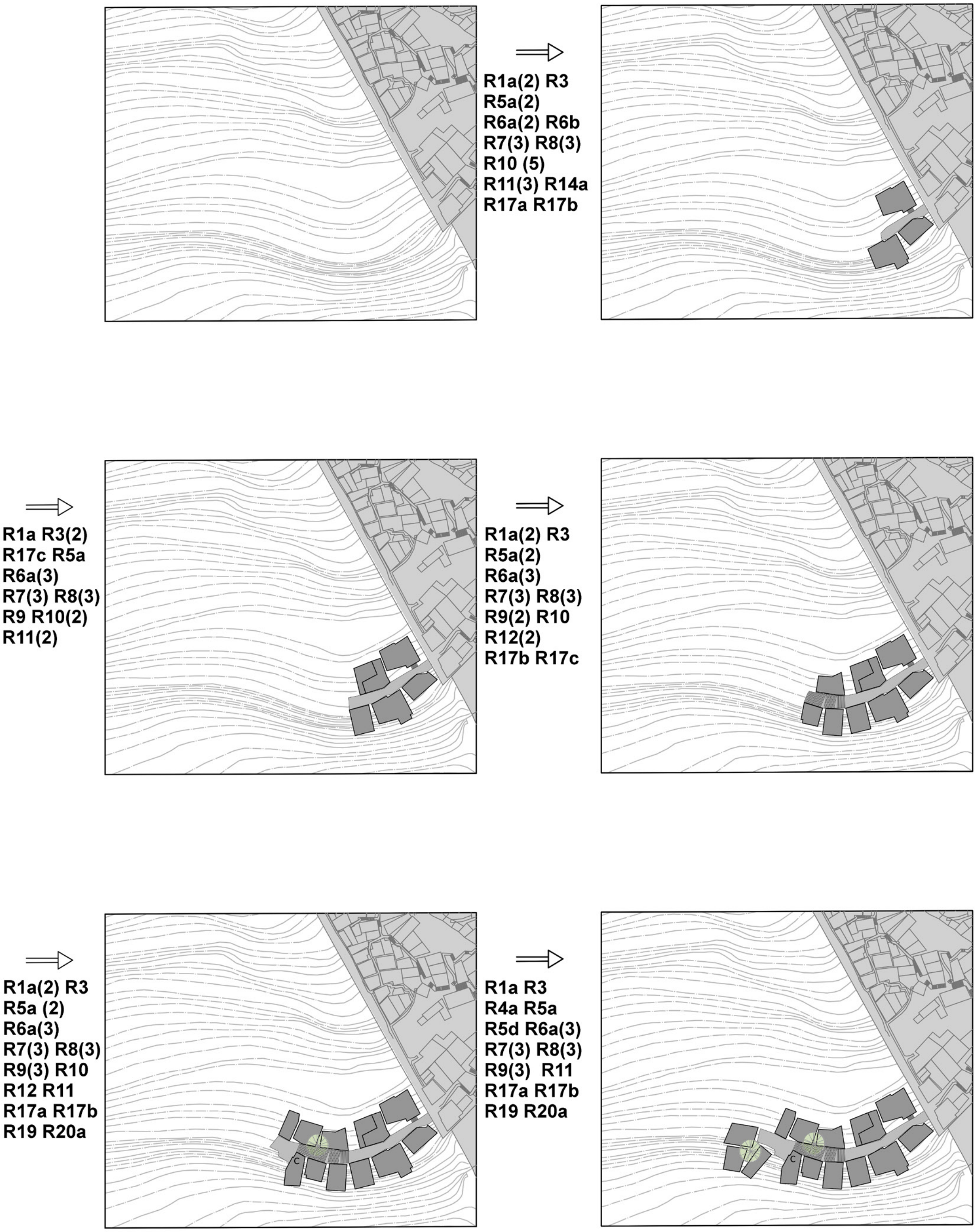


VALIDATION

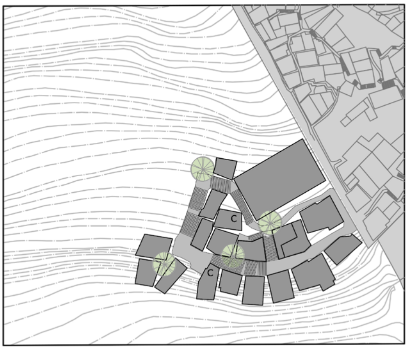
Fig. 29 The first nine steps in the derivation of the planned favela area.

Fig. 30 Simplified derivation of the planned favela area.

The synthetic model, called 'Planned Favela Urban Grammar' was proposed based on the assessment of Santa Marta favela, performed by applying the QUARQ housing quality assessment method at the neighborhood scale. The validation of this grammar encompasses generating a small neighborhood next to Santa Marta favela (a planned favela) using the grammar and assessing it with QUARQ. By comparing the results of both assessments (of Santa Marta

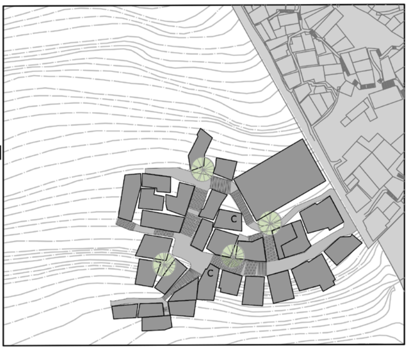

R1a(2) R3
R5a(2)
R6a(2) R6b
R7(3) R8(3)
R10 (5)
R11(3) R14a
R17a R17b
R1a R3(2)
R17c R5a
R6a(3)
R7(3) R8(3)
R9 R10(2)
R11(2)
R1a(2) R3
R5a(2)
R6a(3)
R7(3) R8(3)
R9(2) R10
R12(2)
R17b R17c
R1a(2) R3
R5a (2)
R6a(3)
R7(3) R8(3)
R9(3) R10
R12 R11
R17a R17b
R19 R20a
R1a R3
R4a R5a
R5d R6a(3)
R7(3) R8(3)
R9(3) R11
R17a R17b
R19 R20a

R1a R2b
R3 R4a
R5a R5b
R5d R6a(3)
R7(3) R8(3)
R9 R10
R11(12)
R12(6) R15
R16
R20a(2)
R17a(3)
R17b(6)
R17c(4)
R18a(3)
R18c(2)
R18d(3)
R19

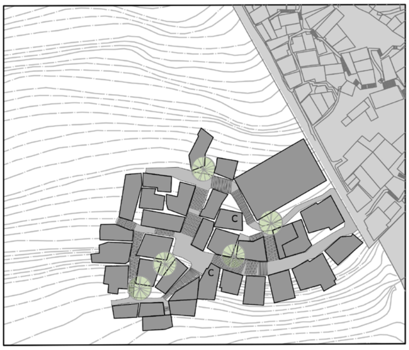


R1a(2) R1b
R2a(2) R3
R5a(3)
R5b(2) R5c
R6a(6) R7(6)
R8(6) R9(2)
R10(5)
R11(3)
R12(2)
R13a
R17a(2)
R17b(2)
R17c(2)

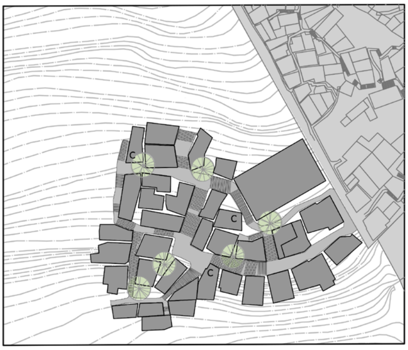
R1a R2a
R3(2) R4a
R5a R5b
R5c (2) R5d
R6a(5)
R7(5) R8(5)
R9 R11(4)
R12(2)
R17a
R17b(2)
R17c(2)



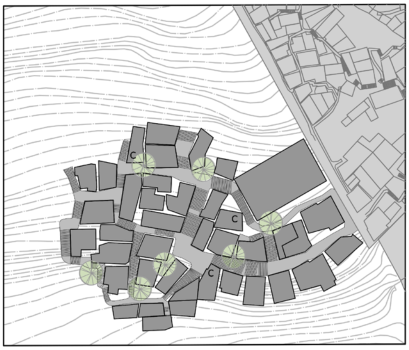
R1a(2) R3
R5a(2) R5c
R6a(3) R7(3)
R8(3) R9(2)
R10(3)
R12(2)
R17b(2)
R17c(2)
R20a



R1a R2a
R2b R5a
R5b R6a(3)
R7(3) R8(3)
R9 R11(5)
R12(5)
R17a
R17b(3)
R17c(3)
R19 R20a



R1a R2a R3
R4b R5a
R5b R5c
R5d R6a(4)
R7(4) R8(4)
R9 R10(3)
R11(5)
R12(7) R13a
R17a
R17b(7)
R17c(4) R19

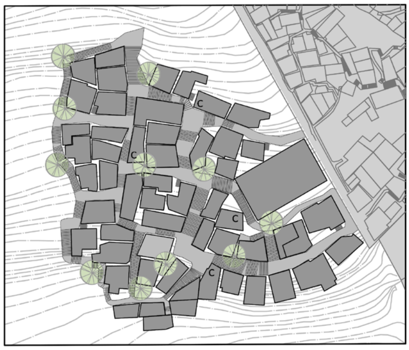


R1a(3) R2a
R5a(3) R5b
R6a(4)
R7(4) R8(4)
R9(3)
R10(2)
R11(3)
R12(3)
R17a
R17b(3)
R17c
R20(a)

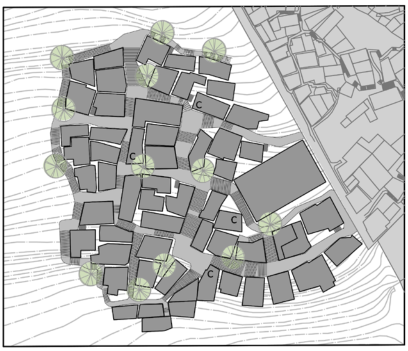
R1a(4) R3
R5a(4)
R6a(4) R7(4)
R8(4) R9(3)
R10(3)
R11(5)
R12(2)
R13a
R17a(2)
R17b(2)
R17c(2)

R1a(4)
R5a(3)
R6a(4)
R7(4)
R8(4)R10(2)
R11(2)
R12(3)
R17b(2)
R17c

R1a(2)
R2a(2) R3
R5a(2)
R5b(2) R5c
R6a(5) R7(5)
R8(5) R9
R10(2)
R11(2)
R12(2)
R17b(3)
R17c
R20a(3)



R1a(2) R1b
R5a(3)
R6a(3)
R7(3) R8(3)
R9(2) R10
R11(7)
R12(8)
R17b(2)
R20a(2)



R1a R3 R4a
R5a R5c
R5d R6b(3)
R7(3) R8(3)
R9(2) R10(2)
R11(4)
R12(3) R17b
R17c
R20a(2)

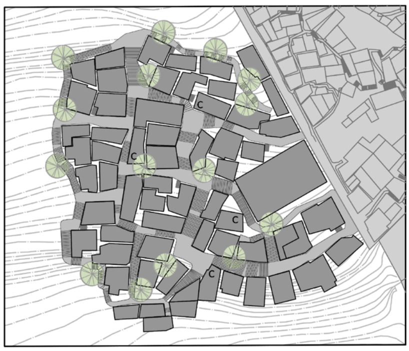


Fig. 31 *Planned favela.*

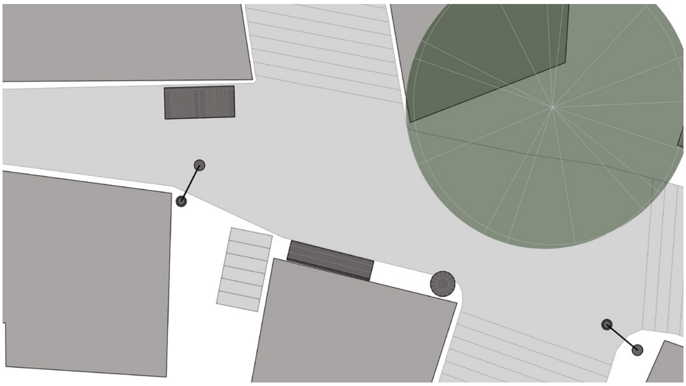


Fig. 32 Detailed image from the *Planned favela*.

favela and of the planned favela) it is possible to identify the impact of the proposed changes on the quality of the generated urban environment.

The planned favela area generated using the Planned Favela Urban Grammar was located at the side of Santa Marta. Figure 28 shows the map of Santa Marta and on the lower left side of the image, a black rectangle shows the location of the planned favela area.

A zoom in on the first set of nine steps is shown in Figure 29 as a way of illustration.

Targeted Criteria	Santa Marta		Planned favela area		Difference (%)
	Result	Quality Level	Result	Quality Level	
Articulation	1.25	Minimum +	2.13	Recommended +	+70
Pleasantness	1.20	Minimum +	2.11	Recommended+	+76
Spatial Adequacy	0.94	Minimum -	1.93	Recommended -	+105
Other Criteria	**Santa Marta**		**Planned favela area**		**Difference (%)**
	Result	**Quality Level**	**Result**	**Quality Level**	
Personalization	2.87	Optimum -	3.00	Optimum	+4
Safety	1.51	Recommended -	3.00	Optimum	+99

Tab. 2 Comparison between the housing quality assessment of Santa Marta and the *planned favela* area.

Figure 30 shows the simplified derivation of the whole planned favela area.

Figure 31 shows the final result of the derivation. The planned favela area has 62 buildings and occupies a total area of 7478 m^2. The rectangle in red corresponds to the area shown in detail in Figure 32. In the detail is visible the urban furniture placed along the circulation.

Table 2 compares the differences in the results of the assessment of Santa Marta and the planned favela area. The QUARQ housing quality assessment method is a holistic method and changes in the design of the environment influence the score in more than one criterion. Consequently, the changes proposed in the Planned Favela Urban Grammar also altered the scores of other criteria that had not been targeted for improvement, namely, safety and personalization.

DISCUSSIONS AND CONCLUSIONS

The goal of this research was to define a computational strategy to plan housing settlements that are based on the morphologic example of informal settlements but offer a better built environment, with increased housing quality. The goal was to create a methodological tool that could generate settlements that mimic the visually appealing and spatially complex spontaneous built scenario but allowed to distinguish early in the planning process commerce, residential, and open areas that included green features and urban furnishing.

This paper proposes a general computational strategy that can be applied to different urban contexts in the planning of housing settlements. Although the strategy is general, this paper focuses on a specific case, the favela of Santa Marta, an informal settlement in the southern region of Rio de Janeiro, Brazil. Shape grammars were used to decode and encode the urban attributes of Santa Marta into an analytic grammar; a housing evaluation method was used as tool to identify the physical characteristics of the settlement that needed improvement; and grammatical transformations were used to change the analytic grammar into a synthetic grammar with the capability to generate settlements that are spatially complex and yet possessed improved quality standards.

This work expands the application of grammatical transformations theorized by Knight (1989). The changes performed on Santa Marta Urban Grammar generated the Planned Favela Urban Grammar and they derived from the 10 recommendations output by the QUARQ evaluation method. Additionally, Brazilian normative policies on accessibility in urban spaces – NBR 9050 (ABNT, 2015) provided the minimum standards for dimensioning the circulation network. The assessment of a new settlement area design generated by the Planned Favela Urban Grammar confirmed the improvement in the quality standards of the designed urban environment, thereby validating the proposed computational strategy. These results are promising and they represent a step towards new planning strategies that may lead to settlements that have the spatial qualities valued in informal settlements, are still affordable as they follow similar topography-sensitive principles, and yet possess improved quality standards.

ACKNOWLEDGEMENTS

The authors would like to thank the Brazilian National Council for Science and Technological development (CNPQ), the Stuckeman Center for Design Computing (SCDC), and the Pennsylvania State University for the financial support of this research.

NOTES

1 There are several terms that can be used almost interchangeably to name informal settlements and one of the most used is *slums*. These places are multidimensional by nature and many times heavily defined by cultural constrains. We opt to use *favela* in this research due to the location of the case study. For a thorough definition of *slum* see United Nations Human Settlements Programme (2003).

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