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Spatial Reasoning as a Syntactic Method for Programming Socio-Spatial Parametric Grammar for Vertical Residential Buildings

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Abstract:

Integrating social constraints in computational models remains a challenge due to the difficulties in representing them algorithmically. Different methods, such as shape grammar and space syntax, consider the morphology of the overall form and its components. This research aims to find a mechanism for combining both methods for exploring spatial-formal features that affect the social life in vernacular houses in the Middle East and North Africa region. A developed model of ‘spatial reasoning’ analysis, embedded in Rhino/Grasshopper, offers an alternative method for extracting topological relations, understanding the social logic of spaces, and exploring the residents’ behaviour by evaluating privacy, social interaction, and accessibility. The results of an analysis for vernacular houses and neighbourhoods were transformed into codes and parameters to be used for designing new vertical developments inspired from local traditions. The constructed grammar was used for developing a computational tool that generates alternatives which successfully achieved the principles of social sustainability.

Keywords: Social sustainability; qualitative representation; parametric grammars; spatial reasoning; generative systems; residential buildings.

1. Introduction

In the field of architecture, computational models are widely used for processing the design in its various stages - including analysis, simulation, and generation - efficiently and accurately. Parametric design is an interactive computational based approach, which is used for understanding the logic and the language embedded in the design process algorithmically and mathematically (Woodbury 2010; Terzidis 2006). In the parametric model, the geometric properties of objects and correlations between each other are clearly defined as rules and relationships (Oxman and Gu 2015). When this model is implemented, designers can revise parameters and rules to modify their designs at any stage. Accordingly, this flexibility in the design allows the emergence of unexpected solutions (Jabi 2013; Fernandes 2013).

Currently, the focus of computational models is primarily limited to formal/geometrical aspects. However, non-geometrical components, such as functional, environmental, and psychological requirements; topological relations; and social/cultural constraints are also important, as they offer a comprehensive understanding of the design problem and harmonize the output with its context and the needs of its users. However, encoding such qualitative criteria and integrating them in the computational process remains a challenge due to the intractability and difficulty of algorithmic representation (Yüksel 2014).

This research builds on the benefits of the parametric design approach to find a mechanism for measuring and coding the non-geometrical aspects of designs and integrating these qualities with geometrical parameters. This process of ‘humanizing’ the computational models allows a holistic understanding of the design problem, keeps the process more flexible, and generates contextual and potentially sustainable solutions. The design of residential developments is addressed as a case. The Middle East and North Africa (MENA) region is selected for the application of the model, as

most of the current projects ignore the specifics of the place and the society (Wood 2013). One approach for generating new designs is to draw inspiration from local traditions and historical cases, as these precedents could have formal, semantic, syntactic, or systematic features related to the problem at hand (Eilouti 2009). Previous studies show that the vernacular model of houses in the study area represents a socially cohesive and healthy environment and reflects the cultural values of the society (Al-Jokhadar and Jabi 2016; Al-Masri 2010).

The next section presents an overview of ways to understand local culture and the different factors that affect social-cultural sustainability in residential buildings. ‘Spatial reasoning’ and ‘syntactic analyses’ were adopted as rigorous methods for measuring such qualitative properties within a computational process. These two approaches of spatial exploration allow designers to extract topological relationships between spaces. Different associated tools were defined, evaluated and discussed. Based on these evaluations, an analytical computational model was developed using Rhino/Grasshopper to address the social reality in relation to formal and geometrical qualities. Information gained from the analytical process was used to identify vocabularies, typologies, specifications and topological relationships. This database, combined with the requirements of vertical residential buildings, allowed for the construction of a specific parametric grammar. Validation and reflections are discussed in the last section.

2. Measuring Non-Geometric Qualities of Design

Social and cultural qualities of residential buildings could be explained through spatial configurations. Based on the extensive literature review regarding social sustainability and behavioural studies (Al-Kodmany 2018; Modi 2014; Oldfield 2012; Schwarz and Krabbendam 2013; Lang 1987; Taylor 1985; Rapaport 1969; Maslow 1943), the authors

identified 13 social indicators that need to be addressed in the design of residential buildings. These indicators include: population density and crowding; the hierarchy of spaces; the relationship between living spaces and social interaction; human comfort; accessibility; visual privacy; acoustic privacy; olfactory privacy; spirituality; security and safety; views of the outdoors; availability of services; and hygiene. Each indicator is linked with the spatial design of buildings through different units of representations, such as numbers, diagrams, or textual descriptions, in order to facilitate the design process and ensure the translation of these social qualities into design parameters. Table (1) illustrates the different measurements for each indicator at the scale of residential units.

Table 1. Spatial features and modes of representation for defining and measuring aspects of social sustainability in residential buildings.

Social indicators and spatial features	Modes of representation
- Social Indicator (1): Population Density and Crowding	
- Number of rooms for the apartment based on the size of the household structure (single, couple, couple with children).	Number
- Area of apartment based on the size of the household structure.	Number (m ²)
- Number of apartments/houses in the building/cluster.	Number
- Area of common spaces in the building/neighbourhood.	Number (m ²)
- Width of alleys and transitional spaces between houses.	Number (m)
- Social Indicator (2): Hierarchy of Spaces	
- Arrangement of spaces from public to private zones and from formal to less formal spaces (in neighbourhoods/buildings and inside the house).	Diagrams
- Relationships between spaces according to connectivity, integration, depth, and control values.	Diagrams & Numbers (syntactic values)
- Social Indicator (3): Social Interaction and Area of Living Spaces	
- Area of common and gathering spaces in buildings and neighbourhoods.	Number (m ²)
- Area of living spaces inside the house.	Number (m ²)
- Social Indicator (4): Human Comfort	
- Percentages of covered, semi-open (shaded), and open spaces relative to the total area of the house/building/neighbourhood.	Number (%)
- Architectural treatments, such as shading devices, louvers, screens, water features, wind towers, or greenery.	Diagrams
- Area of glazed facades.	Number (m ²)
- Thickness of walls.	Number (cm)
- Construction materials.	Textual descriptions
- Geometric shapes of spaces.	Diagrams

- Proportion of spaces.	Number (x:y)
- Orientation of spaces.	Diagrams
- Height of spaces (inside the house) and height of adjacent buildings/houses (urban scale).	Number (m)
- Social Indicator (5): Accessibility	
- Width of transitional areas and circulation elements.	Number (m)
- Area of transitional spaces and circulation elements in comparison to the area of the building/neighbourhood/house.	Number (m ²)
- Spatial arrangement of transitional areas and circulation elements in buildings/neighbourhoods/houses.	Diagrams
- Special treatments for alleys and transitional spaces (such as ramps, handrails, differences in levels).	Diagrams
- Arrangement of functions and facilities in vertical buildings, or multi-floor houses.	Diagrams
- Differences in levels should be considered especially for the elderly and children.	Diagrams
- Number of entrances for the building, neighbourhood, or large-size residential units.	Number
- Social Indicator (6): Visual Privacy	
- Distribution of openings (doors and windows).	Diagrams
- Special treatments, such as screens, partitions or greenery in front of private spaces.	Diagrams
- Location of spaces that are dominantly used by females.	Diagrams
- Social Indicator (7): Acoustical Privacy	
- Spatial arrangement of quiet zones and living activities inside the house.	Diagrams
- Treatments for walls, floors, and windows (materials and thicknesses).	Textual descriptions, Number (cm)
- Height of spaces.	Number (m)
- Social Indicator (8): Olfactory Privacy	
- Location and orientation of kitchen and sanitary facilities.	Diagrams
- Orientation of open spaces.	Diagrams
- Availability of trees and flowers.	Diagrams
- Social Indicator (9): Spirituality	
- Meanings associated with orientation of spaces.	Textual descriptions
- Special treatments for sleeping areas, dining rooms, or bathrooms.	Diagrams
- Availability of fountains, trees and green areas.	Diagrams
- Social Indicator (10): Security and Safety	
- Availability of fences on balconies and terraces.	Diagrams
- Availability of secure gates for houses and buildings.	Diagrams
- Treatments for open spaces and commons areas that are connected with the outside context.	Diagrams
- Social Indicator (11): Views of the outdoor	
- Area of open spaces, terraces, balconies, and glazed facades that are connected directly with the outside context.	Diagrams
- Social Indicator (12): Availability of Services	
- Percentages of storage spaces relative to the total area of the house.	Number (%)
- Availability of entrances that are connected with services (kitchen and storage areas).	Diagrams
- Availability of commercial activities and services in neighbourhoods or buildings.	Diagrams

- Social Indicator (13): Hygiene	
- Size of windows, which allow the penetration of natural light and air inside houses and common spaces in buildings/neighbourhoods.	Number (m)
- Special treatments, such as the separation of clean areas from services, entrances, and open spaces, generated by using gates, sunken areas, or thresholds.	Diagrams
- Arrangement of alleys in neighbourhoods and open spaces in buildings/houses to block excessive air movement that carries sand and dust.	Diagrams

3. Spatial Reasoning as a Method for Exploring Home Cultures

Jerome Bruner, in his studies about the psychology of knowing, defined ‘reasoning’ as ‘going beyond the information given’ (Bruner 1973). In the field of architecture, spatial reasoning is a logical process of analysis that enables designers’ understanding of the layout complexity and the exploration of features that have social or experiential significance (Abshirini and Koch 2013). For instance, tracing the visual fields from a certain location in a building allows a clear evaluation of spatial elements that affect the privacy of its occupants.

To understand this complexity, different approaches have been adopted. First, typological and formal-geometric analyses for 48 traditional houses and neighbourhoods distributed in MENA region were conducted to draw inspirations from local traditions. The study area includes 17 countries, which could be divided into three zones: (1) The Middle East: Jordan, Palestine, Lebanon, Syria, Iraq, and Turkey; (2) The Gulf Area: Saudi Arabia, Bahrain, Kuwait, Oman, United Arab Emirates, and Yemen; and (3) North Africa: Egypt, Algeria, Tunisia, Morocco, and Libya. Most of these countries share the same social and cultural values, local traditions, living patterns, lifestyle, and the hot-arid climate.

Typological analysis involves categorizing components of designs that have shared characteristics according to predefined criteria (Eilouti 2009). The roots of this approach builds on the work of Christopher Alexander, ‘A Pattern Language’, in 1977.

A 'pattern', which could vary in its scale from a city to a building or a detail, addresses a problem and then recognizes solutions and design practices that are balanced within the defined context in an attempt to reconstruct the knowledge about what makes architecture beautiful (Alexander 1977). Using this type of investigation, the main vocabularies of houses are examined, and topological relationships between these elements are defined. The results of such explorations show that these precedents have distinctive formal, semantic, syntactic, and systematic features related to the problem at hand. Accordingly, information extracted from these cases are categorized into classes and prototypes and organized in abstracted diagrams. Each one is associated with descriptions and spatial parameters to construct a discursive grammar (Duarte 2005).

A second approach, based on 'space syntax theory' developed by Hillier and Hanson, was adopted to explore social relations implicit in the architectural setting. Based on their book, 'The Social Logic of Space', this process requires understanding of physical topologies between design elements, taking into account all other spaces in the system (Hillier and Hanson 1984). These relations are represented visually, through 'justified node-and-connection' graphs that show the hierarchy of the overall layout; and mathematically, such as connectivity, integration, and control values, to quantify syntactic analyses (Hillier, Hanson, and Graham 1987). The results extracted from these tests are useful for interpreting the overall configuration and the social life in the building (e.g., high integration values indicate that spaces are busy, more accessible, and less private). In contrast, low values can mean that these functions are more segregated and more controlled in movement. However, studies focusing on how the space syntax approach might be used for generating or inspiring new designs remain limited (Lee, Ostwald, and Gu 2013). Another limitation facing space syntax methods is that the justified graph does not generate descriptions for the formal reality of the design

(Osman and Suliman 1995). Furthermore, functions located on different levels/floors need to be identified from other nodes in the system.

Three computational tools were used for carrying out syntactic analyses (Figure 1):

- (1) *Agraph*: a 'node-and-connection model' that produces syntactic calculations and justified graphs (Figure 2), such as depth and integration of spaces.
- (2) *Syntax2D*: a tool to execute *isovist* analysis that addresses the visual fields of a person at one location of the environment and along a movement path (Figure 3).
- (3) *DepthmapX*: a 'visibility graph analysis (VGA)' tool, which is based on the reflection of light to understand the spatial configuration of the environment. VGA includes five types of tests: (a) connectivity analysis, which creates visibility connections between all spaces; (b) visual integration, which specifies the degree of privilege of one point over its immediate neighbours; (c) through-vision analysis, which looks at how visual fields varies within an environment; (d) depth analysis, which shows changes of direction that would take to get from the selected location to any other locations; and (e) agent analysis, which indicates patterns of movement, and the frequent use of spaces released from one point (Figure 4).

In addition to the abovementioned methods, the authors developed a model of syntactic analysis that adds new aspects to the justified graph of Hiller and Hanson as a representation of formal and social realities (Figure 5). These issues are:

- (1) Patterns of movement and distances between the centre of the courtyard and the centre of each space, which can be used to analyse the accessibility and security inside houses;

- (2) The actual geometry of each space rather than symbolic nodes;
- (3) Hierarchy of spaces (public, semi-public, semi-private, private, and intimate);
- (4) Orientation (West, East, North, South, North-East, North-West, South-East, and South-West);
- (5) Type of enclosure (covered, open, semi-open);
- (6) Shared surfaces between adjacent spaces;
- (7) Entry point(s) between spaces;
- (8) Geometric proportions for each space;
- (9) Percentage of space area from the overall area of the house;
- (10) Area of the space in relation to the area of the courtyard; and
- (11) The dominant users for each space (male, female, or both).

Approach	Phenomenological Approach					Syntactical Approach					Formal Analysis Approach		
Methods	A. Identification of Current Social/Spatial Problems and Needs					B. Syntactical Analysis (Integration, Depth, and Control Values)		C. Syntactical Analysis (Integration, Depth, and Connectivity Values, based on Visibility Graph Analysis (VGA))		D. Agent Analysis and Patterns of Movement	E. Isovist Analysis		F. Geometric Analysis
Tools	Field Survey (Questionnaire)					AGraph Software (Mathematical Calculations and Justified Graphs)		DepthmapX Software		DepthmapX Software	Syntax2D Software		Typological/Spatial Analysis
Indicators of Social Sustainability	1. Population Density	2. Hierarchy of Spaces	3. Social Interaction	4. Human Comfort	5. Accessibility	6. Visual Privacy	7. Acoustical Privacy	8. Olfactory Privacy	9. Spirituality	10. Security and Safety	11. Viewing the Outside	12. Availability of Services	13. Hygiene
Methods	A	B C F	A B C F	A F	A B D F	A B C E F	A F	A F	A F	A F	C E F	A F	A F

Figure 1. Methods and tools for analysing social sustainability in residential buildings.

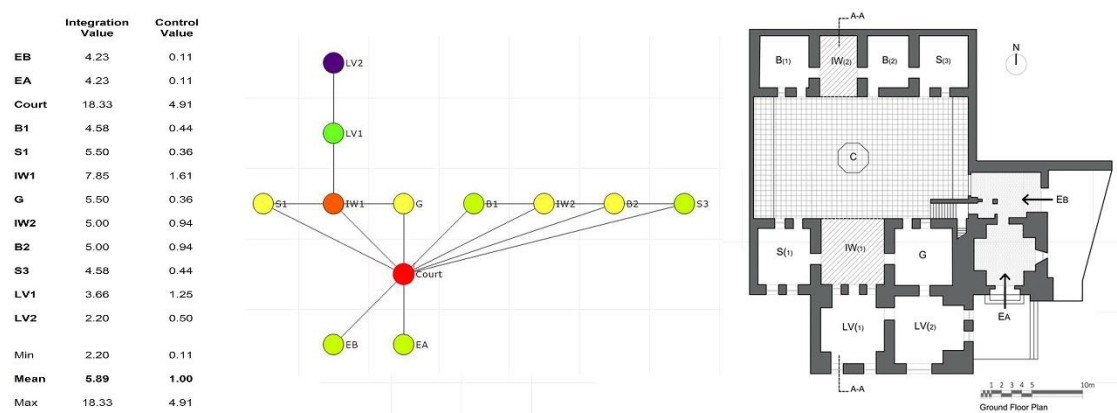


Figure 2. A justified graph showing the integration value for each space, which was produced by authors using *AGraph* software.



Figure 3. Samples of *isovist* analysis for three traditional courtyard houses located in Syria, which was produced by authors using *Syntax2D* software.

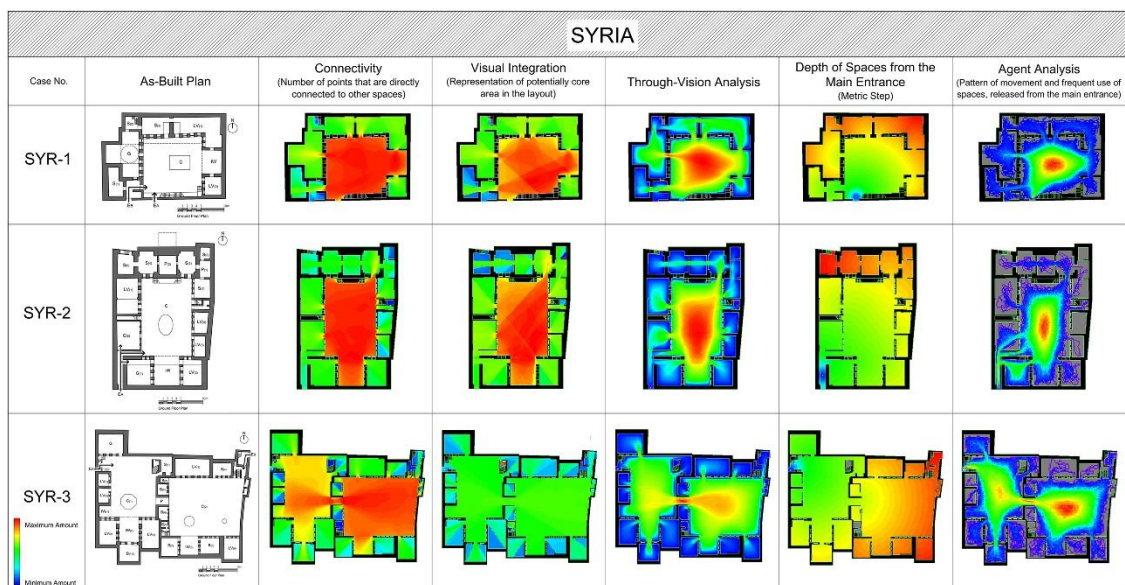


Figure 4. Samples of ‘visibility graph analysis’ for three traditional courtyard houses located in Syria, which was produced by authors using *DepthmapX* software.

4.1. Model Workflow and the User Interface

The model depends on generating the layout of historical cases according to a ‘space partitioning’ mechanism (Knecht and König 2010). It commences by splitting a region into sub-spaces (cells). This geometric representational technique, using non-manifold topology (NMT), defines topological relations between adjacent spaces without any void (Jabi 2016). The first step requires users to draw the overall layout boundary for the building (as a polyline), internal partitions representing shared surfaces between spaces (as lines), and doors (as rectangles). However, thicknesses of walls are ignored. Once these features are obtained from a ‘selection’ component, the partitioning process is executed accordingly using NMT. A unique legend number is assigned automatically to each cell. This process could be applied to any layout that is composed of regular or irregular geometries (Figures 6 and 7).

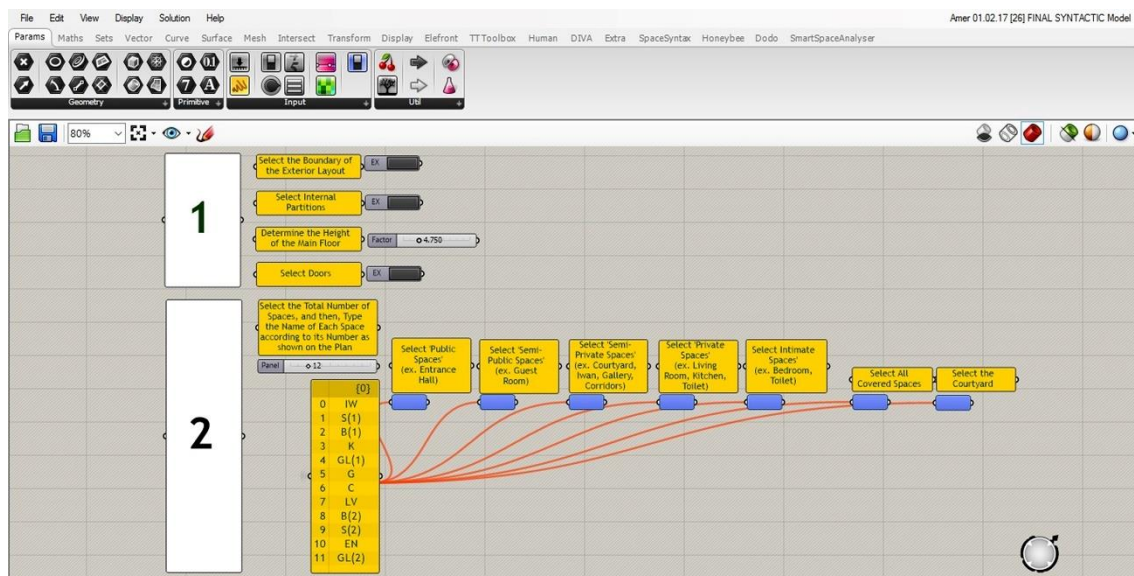


Figure 6. A screenshot for the interface in Grasshopper showing the required inputs from the user.

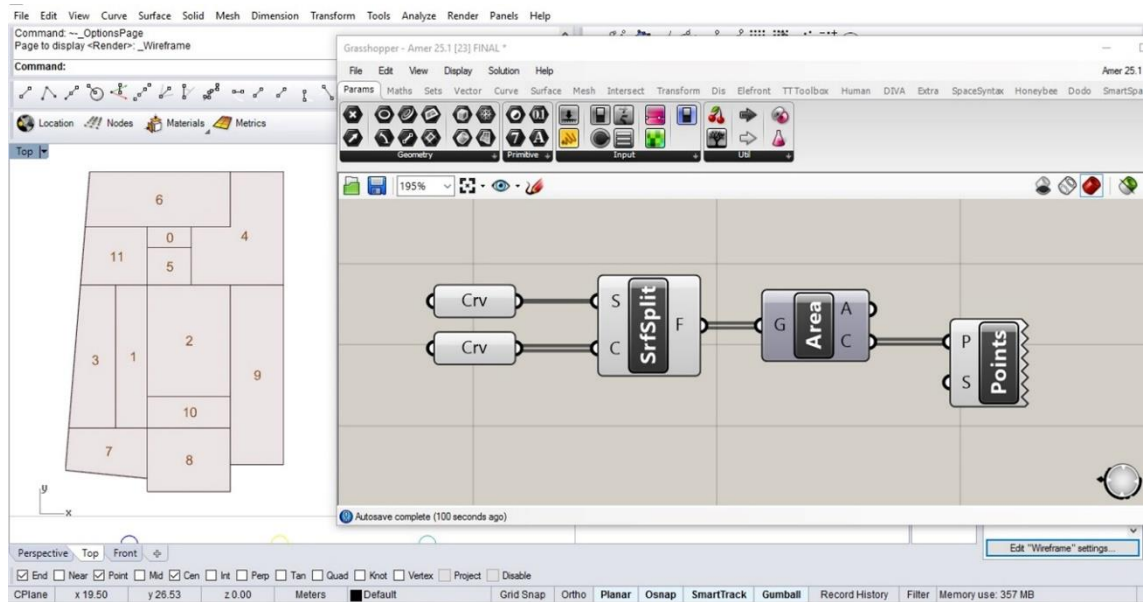


Figure 7. A screenshot for the interface in Grasshopper showing functions to carry out the partitioning process using non-manifold topology (NMT).

The second step involves typing a function label for each cell, and then selecting spaces from lists according to two criteria: hierarchy of spaces (public, semi-public, semi-private, private, or intimate zone); and type of enclosure (open or covered area). A tag component is implemented for each cell. The model is then able to compute different values, which are delivered in the form of an Excel spreadsheet (Figure 8), in addition to generating different visual diagrams (Figure 9).

spaces. Based on these records and specifications, designers can generate contextual design solutions that are related to social and cultural needs. Shape grammars, as a rule-based system of formal generation, is used. However, creativity, flexibility, and adaptability are also important issues that need to be addressed in the design process. Therefore, a parametric design approach is incorporated in the construction of this grammar.

In comparison to traditional computer modelling, two main characteristics are associated with parametric design. First, designs are defined through variables, parameters, rules and logical relationships between objects. Second, designers can revise parameters and rules, at any stage, to modify their designs and generate a number of alternatives (Oxman and Gu 2015; Jabi 2013). In this way, designers can generate new solutions that belong to a language defined by the grammar through changing values of parameters within certain limits. For this study, the following parameters were defined:

- Area of each space in comparison to the total area of the house/cluster,
- Geometric properties of each space (length and width),
- Location of each space, obtained through defining the Cartesian coordinates of the space,
- Functions that are adjacent to the space,
- Patterns of openings,
- Orientation.

5.1. The Language of Vernacular Houses and Neighbourhoods in MENA Region

Traditional dwellings in the study area are inward-looking with living spaces organized around a central open space (a courtyard). This dominant element is widely used to

maintain a shaded area in summer and to receive solar radiation in winter. Moreover, it acts as a circulation zone and a recreational living space, which provides security, privacy, and comfort for the family (Moossavi 2014). Courtyard houses and clusters are distinguished with a hierarchical system of movement that offers privacy for the family. Spaces are categorized into five main zones: (a) 'public' spaces, such as entrances; (b) 'semi-public' zone, which is located adjacent to the main entry hall and includes reception rooms for male and female guests; (c) 'semi-private' spaces, such as courtyards, galleries, and *iwans*, which are sheltered spaces located in front of the courtyard that act as transitional areas between indoor and outdoor spaces; (d) 'private' spaces that include mixed-function rooms, domestic living areas, kitchens, storage spaces, services and toilets; (e) 'intimate' spaces, such as bedrooms and bathrooms, which could be located on the ground and/or first floor. Spatial calculations show that the percent of public and semi-public spaces relative to the total area of the house is only 13-15%. The average areas of private, semi-private and intimate zones represent 32%, 38%, and 16% respectively.

Different spaces inside the house are considered as active architectural elements that facilitate social gathering between family members. Traditional houses offer approximately half area of the house for social interaction between family members, and more than third area of the house with a variety of seasonal semi-private and private spaces. These living spaces include closed areas, such as living rooms, which represent 12% of the total area of the house; semi-open spaces, such as *iwans*, which represent 7% of the total area; and open spaces, such as courtyards, terraces, and balconies, which represent 16% of the total area. Moreover, the amount of living spaces in comparison to the area of guest rooms is a major aspect that accommodates daily living activities and, at the same time, encourages interaction between the family members. The spatial

analysis of the different cases shows that guest rooms accommodate nearly 7-8% of the total area of the house, which represents only a quarter of living rooms' area.

Based on that analysis, two sets of grammars were constructed. The first set deals with generating neighbourhoods, and the second set allows the construction of vernacular houses (Figure 10).

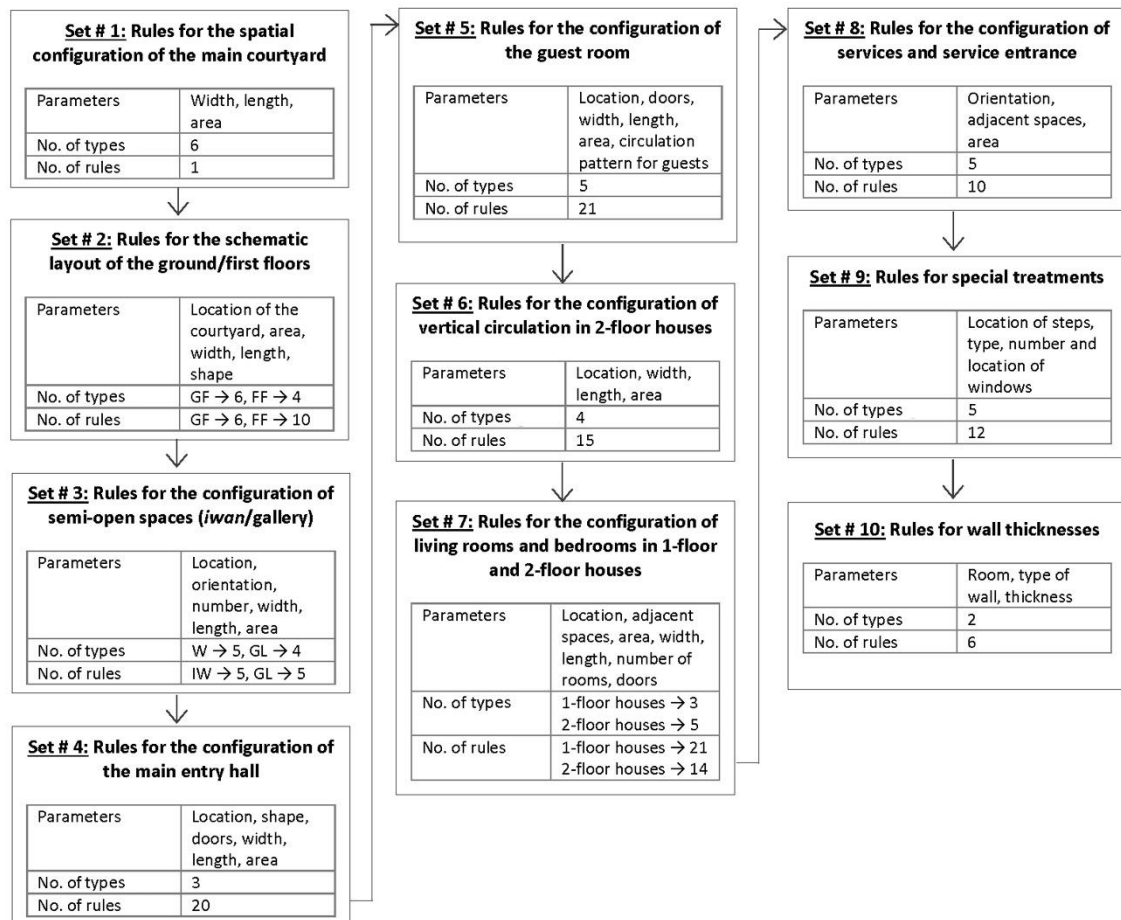


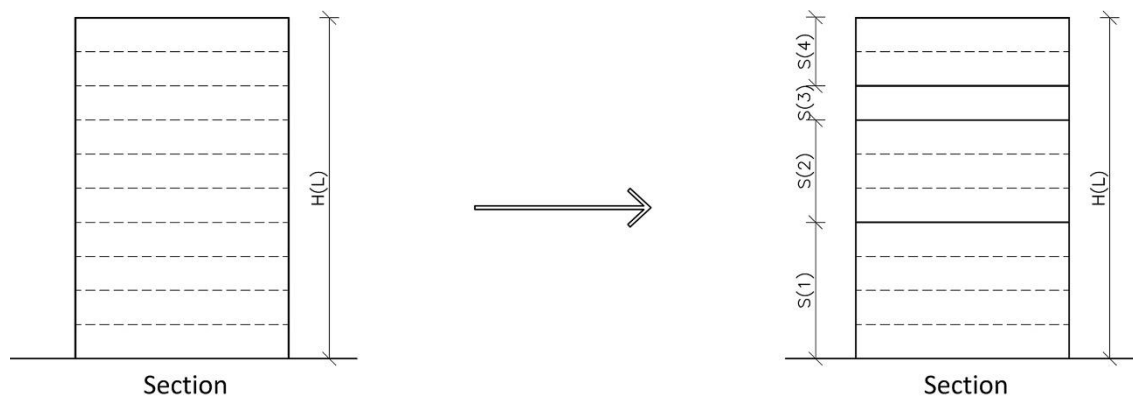
Figure 10. A diagram showing sets of rules, parameters, and number of typologies and rules that construct the socio-spatial grammar.

5.2. Establishing a Computational Tool for the Design of Vertical Residential Buildings

Spatial rules that have specific social meanings extracted from the traditional model were combined with the requirements of vertical buildings, such as the location of the vertical core, the availability of communal spaces, and the arrangement of apartments

on the same floor, to construct a parametric grammar for the design of vertical residential developments. The aim is to provide architects with a tool that produces a contemporary-vernacular vertical development, thus providing a continuity to the existing world and leading the design to be in harmony with the context, climate, traditions, social needs, and requirements of the modern and future time.

A vertical residential building could be defined as clusters of houses arranged vertically. On a basic level, each cluster, which is a vertical segment of the building, represents a horizontal quarter that has specific qualities (Figure 11). Such a vertical arrangement of horizontal neighbourhoods could highly promote the concept of hierarchy and clustering and create a mutual responsibility for common spaces in each segment for encouraging interaction between neighbours.



$S(n)$ is a vertical segment, which consists of (0 to 5) floors

Figure 11. The concept of a vertical segmentation for a high-rise building into horizontal quarters.

A multi-story residential building could be divided into two main zones: First, a public zone; which includes a hierarchal system of common spaces: an entry hall (EN), a vertical circulation core (VC), a main public space (MPS), semi-private spaces between residential units (PVS), and pedestrian pathways (COR) that connect common spaces. A sample of rules for generating a main public space is illustrated in (Figure

12). Second, a private zone, which consists of residential units. To maintain a balance between isolation and interaction inside the apartment, it is recommended to include a private courtyard for each unit. There are different possibilities for the location of such an introverted open space. In high-rise residential buildings, the appropriate location of the courtyard is determined by two factors: (i) the location of the residential unit in relation to other units on the same floor; and (ii) on which floor the apartment is located. For instance, a central courtyard could be sufficient on top floors. However, a courtyard that is attached to one edge of the building is suitable on any floor of the building (Figure 13).

As the constructed grammar is parametric, each derivation process generates different solutions, and makes the process difficult to manage. Moreover, designers seek to express their ideas physically and to generate solutions with a high degree of accuracy in a short amount of time for execution (Segers *et al.* 2001). Therefore, the grammar has been translated into a computational interface and coded using 2D/3D CAD modelling software “Rhinceros 3D” with its plugin “Grasshopper”.

The tool suggests a list of 10 procedural tasks that guide the user through an interactive interface, where the designer can modify a total of 66 unique parameters (Figure 14, Table 2). Each task aims to generate a space or group of spaces that have the same function. Moreover, it allows the designer the ability to control geometric parameters and conditions that respond to different design patterns through dialogue boxes and entities, such as checkboxes, number sliders, and buttons (Figure 15). For example, components that generate the layout of a private courtyard on the ground floor are similar to those that generate a courtyard on the 4th segment. However, the user can change the width, the length, and the location of that space (Figure 16).

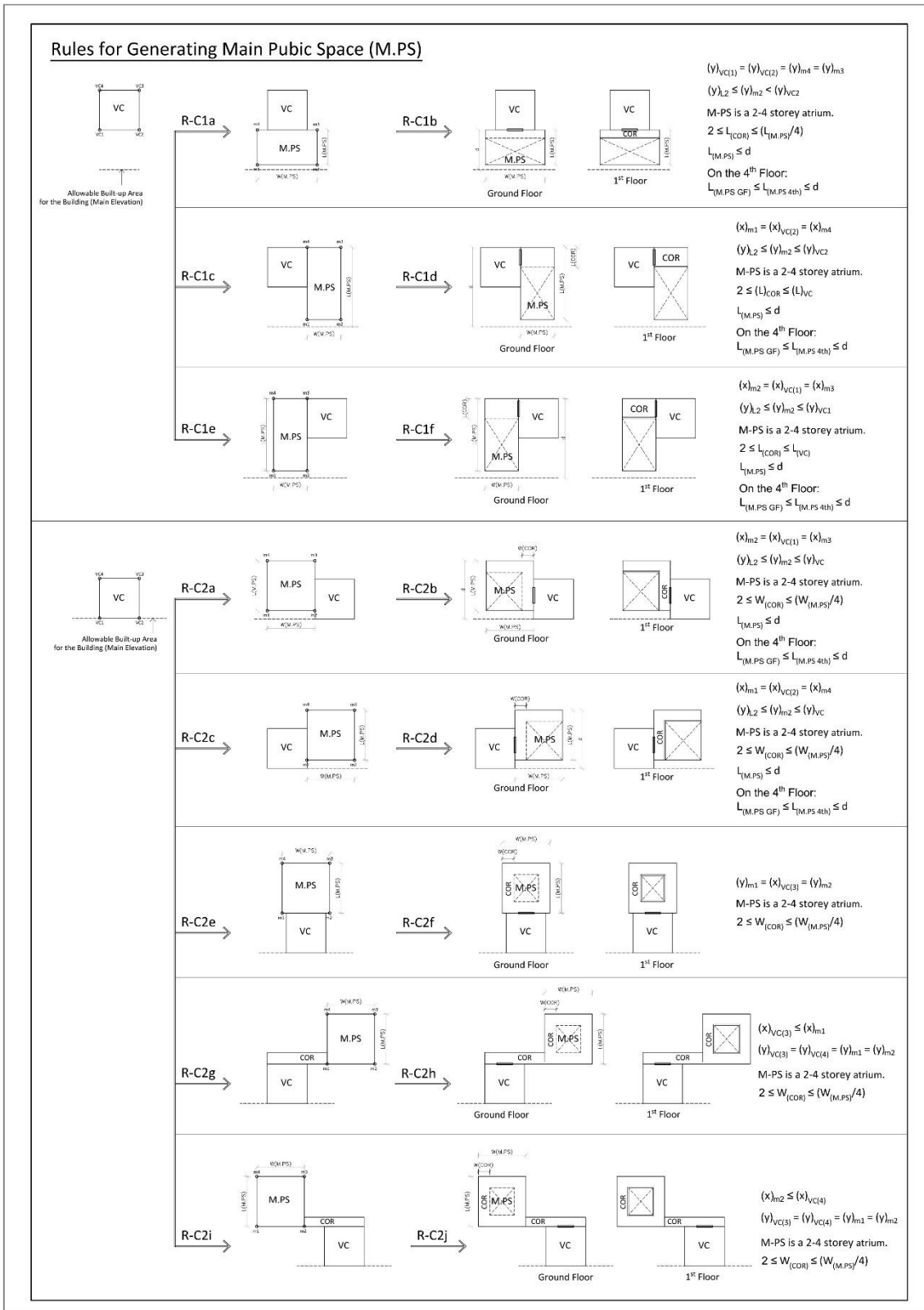


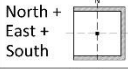

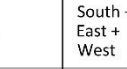

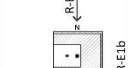


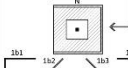
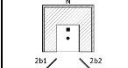

Figure 12. Rules for generating a main public space (MPS).



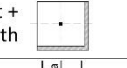


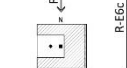
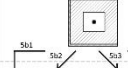
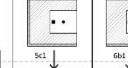
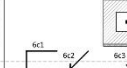
Stage (E): Rules showing Types of Apartments that are located on Floors (except the Top Two Floors)

Descriptions:

Type of apartment and the location of courtyard are based on the location of apartment and number of shared surfaces with other apartments.

Typologies of Apartments (based on number and location of shared surfaces with adjacent apartments)

Apartments attached from Three Sides				
Location of Attached Surfaces	North + East + South	North + East + West	South + East + West	South + North + West
Single-Floor Apartment				
Two-Floor Apartment	1 st Level			
	2 nd Level			

Apartments attached from Two Sides				
Location of Attached Surfaces	West + South	East + South	East + North	
Single-Floor Apartment				
Two-Floor Apartment	1 st Level			
	2 nd Level			







Location of Attached Surfaces		West + North	West + East
Single-Floor Apartment			
Two-Floor Apartment	1 st level		
	2 nd level		

Figure 13. Rules for allocating courtyards inside apartments that are attached to one side.

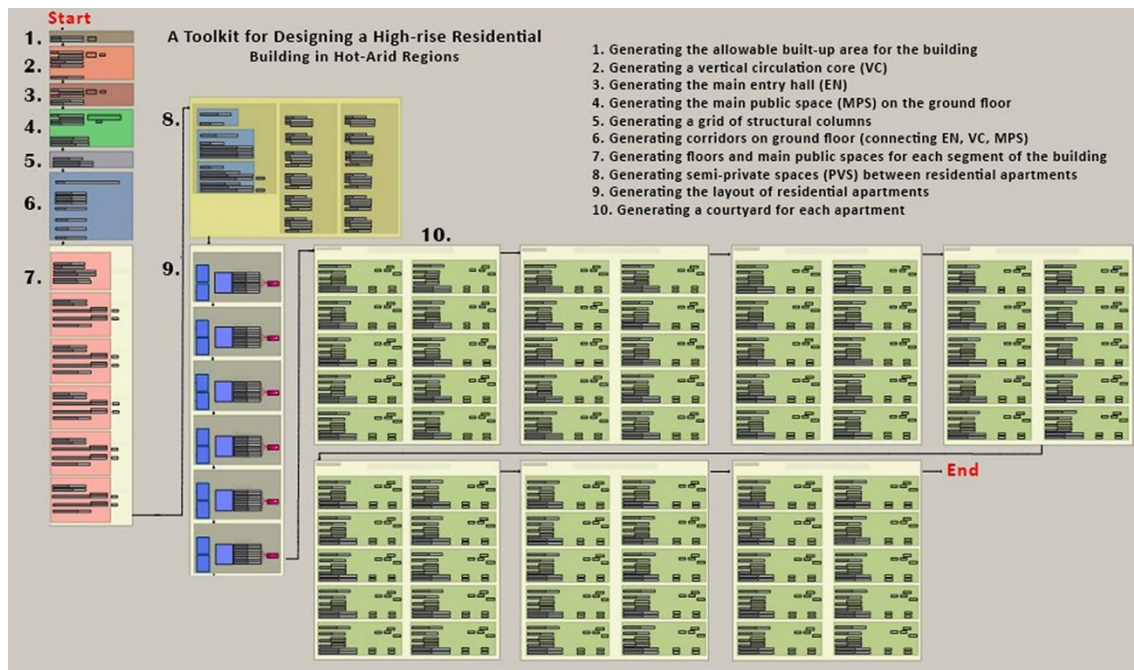


Figure 14. A screenshot of the interface for designing a high-rise residential building in hot-arid regions.

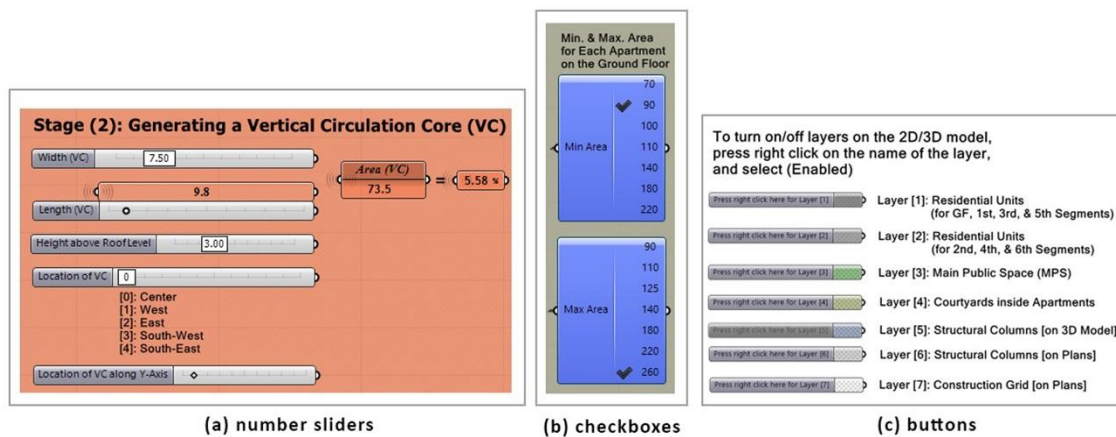


Figure 15. Types of dialogue boxes and entities to control geometric parameters and conditions.

Table 2. Parameters and inputs for each stage in the computational tool for the generation of high-rise residential buildings.

Stages of Design	Inputs	Number of Parameters
1. Generating the allowable built-up area for the building	- Width - Length	2
2. Generating a vertical circulation core (VC)	- Width - Length - Height above roof level - Location	5
3. Generating the main entry hall (EN)	- Width - Length - Location	3
4. Generating the main public space (MPS) on the ground floor	- Width - Length - Location	5
5. Generating a grid of structural columns	- Size of columns - Distances between columns (X-axis) - Distances between columns (Y-axis)	3
6. Generating corridors on the ground floor (connecting EN, VC, MPS)	- Width - Location	6
7. Generating floors and main public spaces for each segment of the building	- Height of each floor - Number of floors on each segment - Width and length of the MPS on each segment - Alternatives for the connection of the MPS with the outside	11
8. Generating semi-private spaces (PVS) between residential apartments	- Width and length of corridors connected with PVS, - Width and length of PVS - Location of PVS	16
9. Generating the layout of residential apartments	- Maximum and minimum Area of apartments on each segment - Width and length of apartments	10
10. Generating a courtyard inside each apartment	- Width - Location	5
Total Number of Parameters		66

Ground Floor: Apartment # (1-W)

Location of Apartment # (1-W)

Not Applicable

Location of Courtyard

2

[0]: No Courtyard
[1]: on West
[2]: on South
[3]: at the Center

Width of Courtyard

7.14

Length of Courtyard

7.14

Position of Courtyard along X-Axis

Position of Courtyard along Y-Axis

Total Area of Apartment (# 1-W) = 155.5

Courtyard Area = 51.0 = 32.8 %

Area of Apartment (excluding Courtyard) = 104.6

Width of Rooms (surrounding the courtyard)

on West: 5.21 on East: 8.65

on North: 4.59 on South: 0.0

4th Segment: Apartment # (1-W)

Location of Apartment # (1-W)

Not Applicable

Location of Courtyard

1

[0]: No Courtyard
[1]: on West
[2]: on South
[3]: at the Center

Width of Courtyard

3.45

Length of Courtyard

3.45

Position of Courtyard along X-Axis

Position of Courtyard along Y-Axis

Total Area of Apartment (# 1-W) = 122.2

Courtyard Area = 11.9 = 9.8 %

Area of Apartment (excluding Courtyard) = 110.2

Width of Rooms (surrounding the courtyard)

on West: 0.0 on East: 3.9

on North: 5.69 on South: 7.48

Figure 16. Parameters that enable the user to change the width, length, and location of a private courtyard in an apartment that is located on: (a) the ground floor and (b) the 4th segment of the building.

It is important to mention that the implementation of the computational model is not intended as a shape grammar interpreter, which should be able to recognize and detect shapes and then apply operations to those shapes (Correia 2013; Trescak, Esteva, and Rodriguez, 2012). However, the Grasshopper model allows for the generation of different design solutions through manipulating parameters for shapes. These shapes have predefined topological relations according to the constructed parametric grammar.

The tool offers architects the ability to evaluate their designs through two types of outputs: (1) drawings and diagrams; and (2) design metrics.

(1) Drawings and diagrams: three-dimensional views and two-dimensional layouts are produced simultaneously in Rhino3D according to the input data by users.

However, these representations are schematic rather than detailed drawings (Figure 17).

(2) Design metrics: to measure the practicality of any generative tool and the performance of each design solution, it is crucial to offer quantifiable and computable metrics that could be used for the evaluation process (Villaggi *et al.* 2017). Therefore, the tool has been developed to produce different measurements and output values automatically. These values include: detailed calculations for the building, detailed calculations for residential units, and detailed calculations for common spaces (main public spaces, semi-private spaces, the entry hall, the vertical circulation core, and corridors) inside the building (Figure 18).

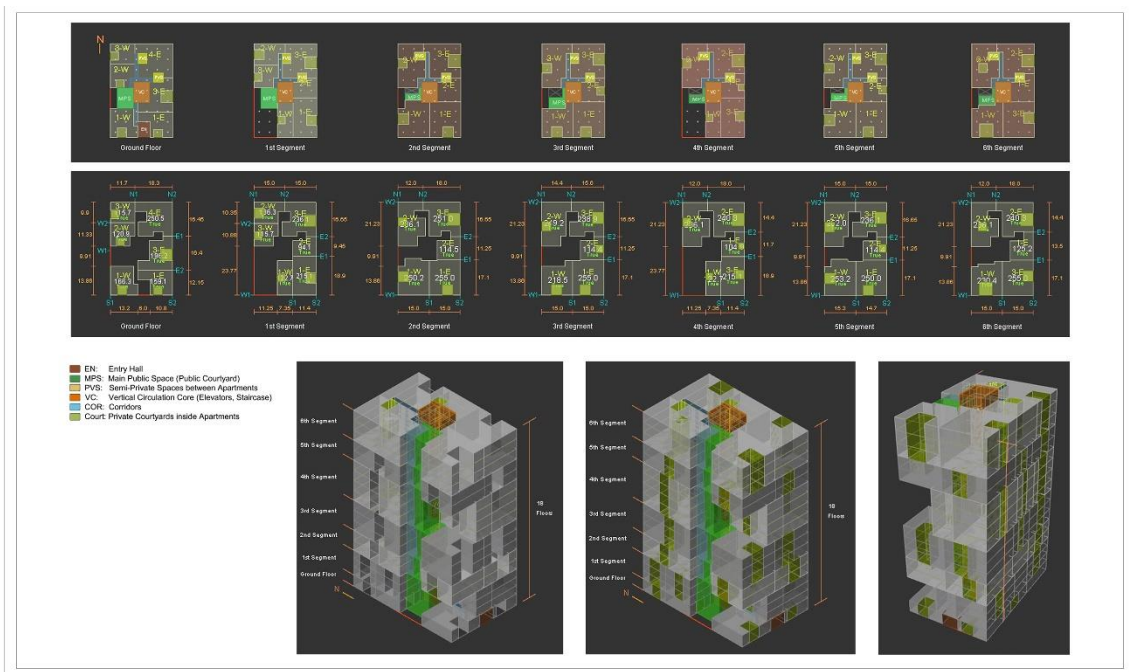


Figure 17. Drawings and diagrams produced by the tool.

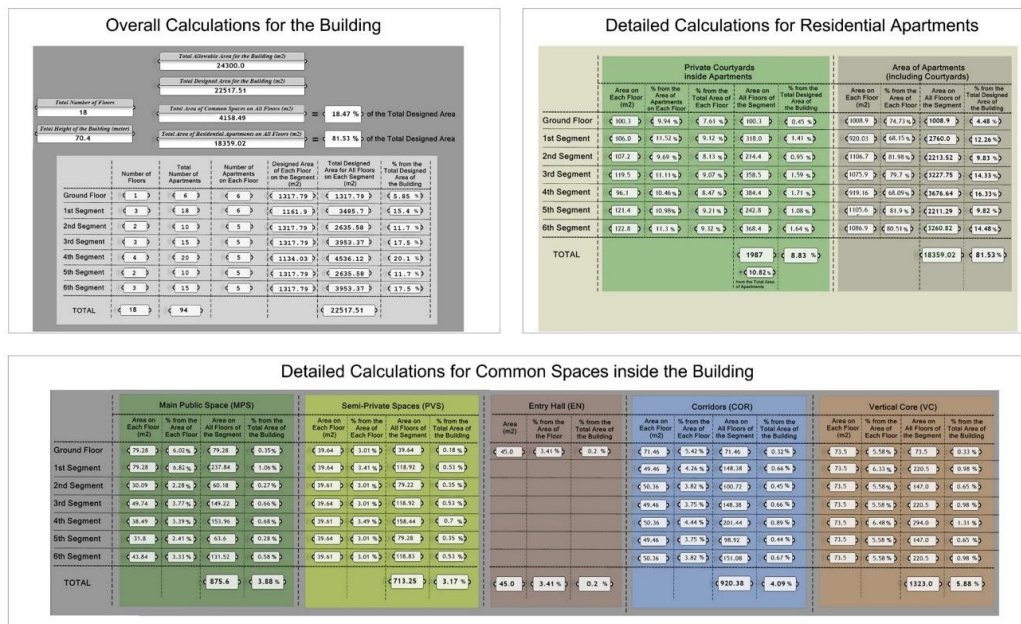


Figure 18. A screenshot showing design metrics produced by the tool.

6. Results

The developed tool was run to check its credibility for generating socially sustainable high-rise alternatives (Figure 19). The different layouts have been analysed spatially to evaluate social qualities of the design (Figure 20):

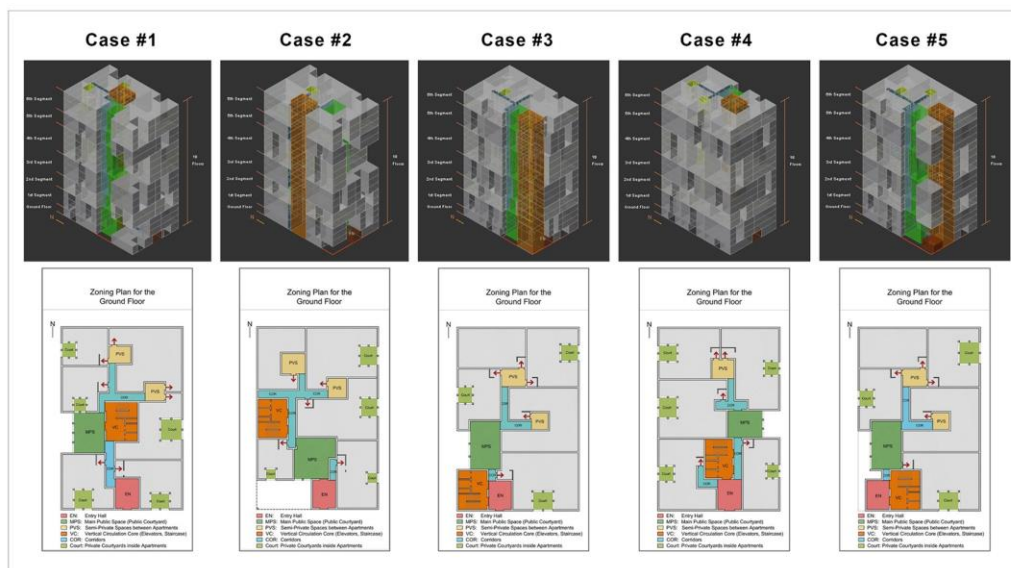


Figure 19. Three-dimensional views and the layout of the ground floor for new solutions generated by the researcher using the developed computational model

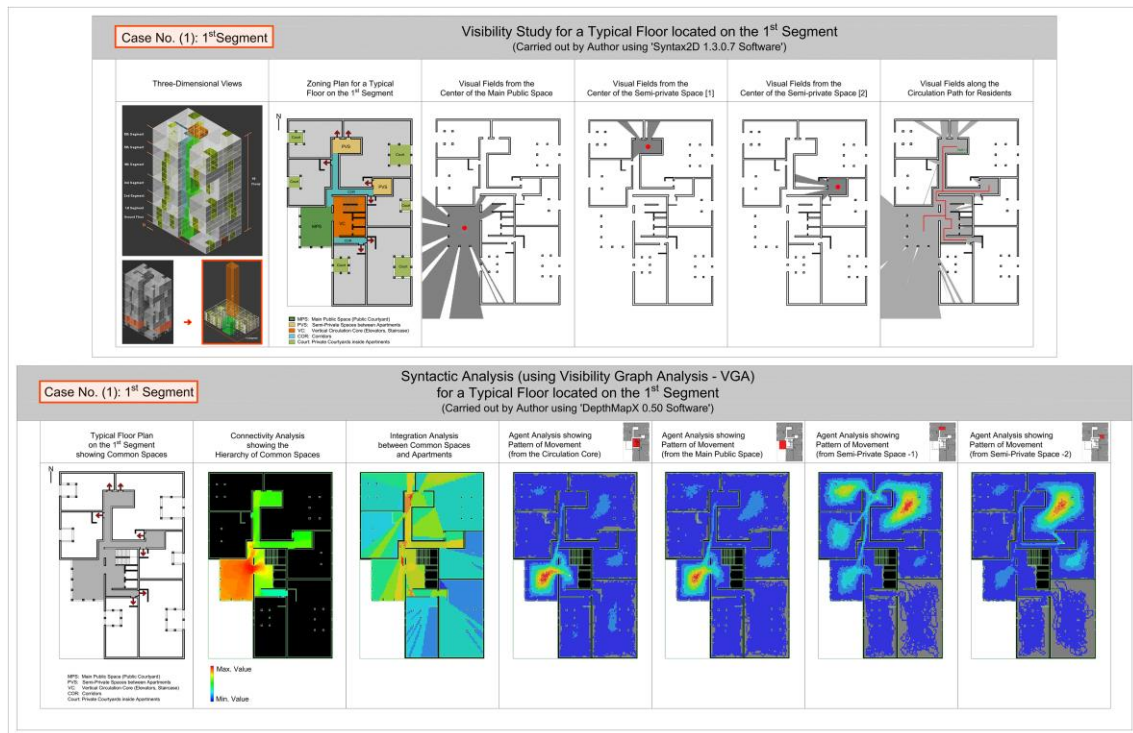


Figure 20. Visibility study and syntactic analysis for the ground floor for Case # 1.

(1) *Visibility graph analysis (VGA)* investigates the spatial configuration of the interior environment by conducting:

- Connectivity analysis for common areas, which creates visibility connections between these spaces to evaluate the hierarchical arrangement of public and semi-public zones. The syntactic analysis showed that the main public space (MPS), the entry hall (EN), and the vertical circulation core (VC) have great connectivity values in comparison to semi-private transitional areas, which are connected directly with residential units (Figure 21). These values range between 10.17 and 13.17 for main public spaces and between 3.00 and 3.55 for semi-private spaces on the ground floor (Table 3).

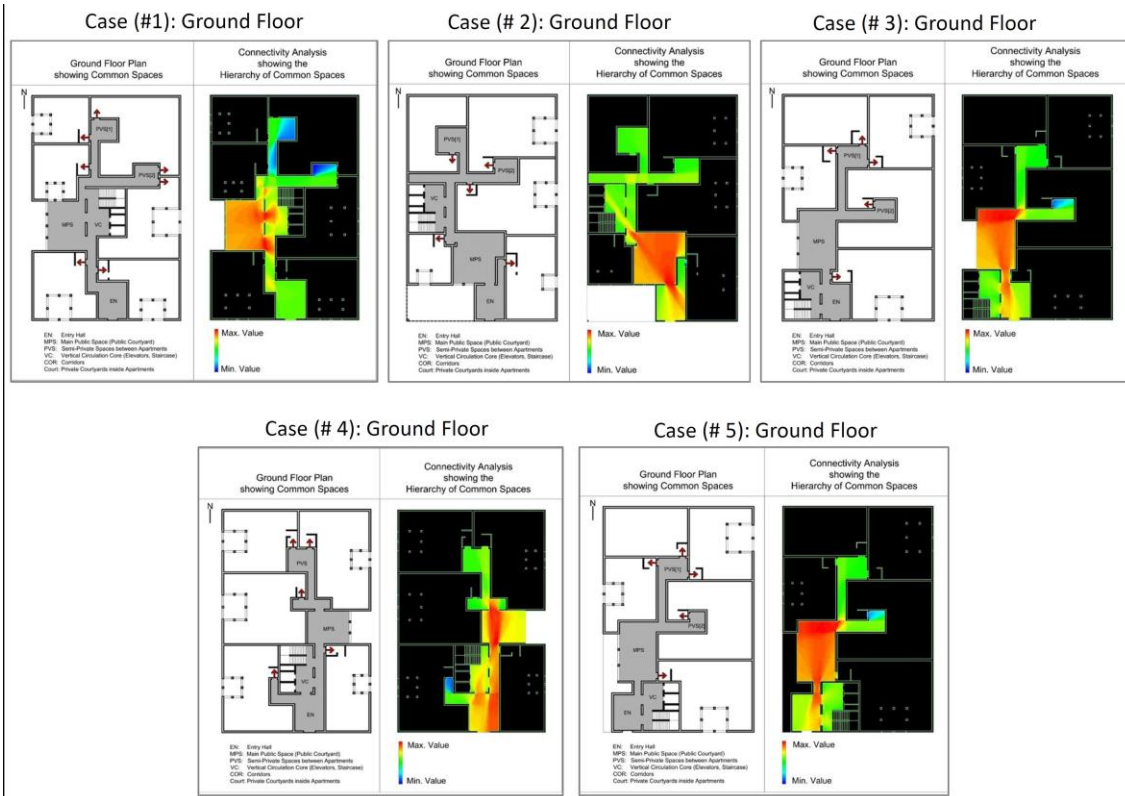


Figure 21: Connectivity analysis showing hierarchy of common spaces on the ground floor for the five cases.

Table 3. Hierarchy of common spaces based on connectivity values.

Cases	No. of Segment	Hierarchy of Common Spaces based on Connectivity Values
Case # 1	Ground Floor	VC > MPS > PVS-2 > EN > PVS-1
	1 st Segment	MPS > VC > PVS-2 > PVS-1
	6 th Segment	MPS > VC > PVS-1 > PVS-2
Case # 2	Ground Floor	MPS > EN > VC > PVS-2 > PVS-1
	4 th Segment	MPS > VC > PVS-1
	6 th Segment	MPS > VC > PVS-1
Case # 3	Ground Floor	MPS > EN > PVS-2 > VC > PVS-1
	1 st Segment	MPS > VC > PVS-2 > PVS-1
	6 th Segment	MPS > VC > PVS-1
Case # 4	Ground Floor	MPS > EN > VC > PVS-1
	5 th Segment	MPS > VC > PVS-1
	6 th Segment	MPS > VC > PVS-2 > PVS-1
Case # 5	Ground Floor	MPS > EN > VC > PVS-2 > PVS-1
	1 st Segment	MPS > VC > PVS-2 > PVS-1
	6 th Segment	MPS > VC > PVS-2 > PVS-1

Key: MPS: Main Public Space, PVS-1: Semi-Private Space (#1), EN: Entry Hall
VC: Vertical Circulation Core, PVS-2: Semi-Private Space (#2)

- Integration analysis, which specifies the degree of integration between common areas and apartments. The analysis showed that public and semi-private spaces in most cases have higher values than residential units (Figure 22). For instance, integration values for the main public space, the vertical circulation core, the semi-private space, and the entry hall for the ground floor in (Case # 4) are 4.07, 4.08, 3.85, and 3.61, respectively. In contrast, residential units on the same floor have lower values, which are ranged between 2.38 and 3.44. In this way, a high degree of privacy for families could be achieved.

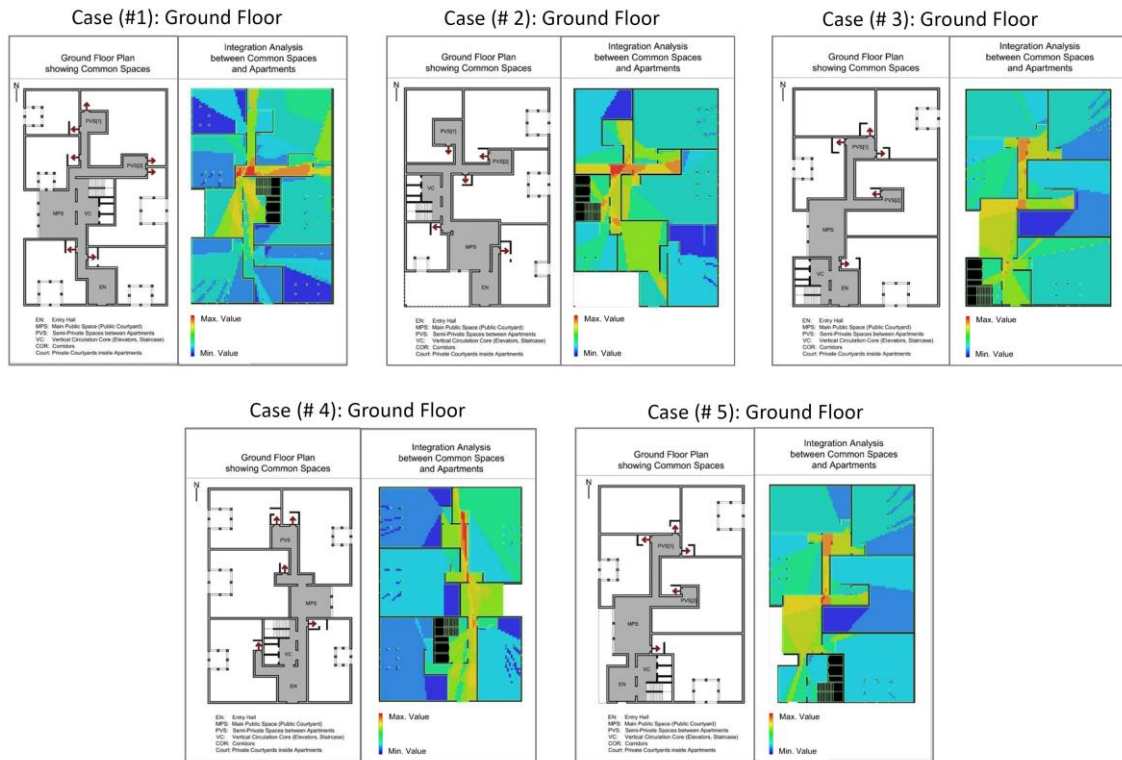


Figure 22: Integration analysis between common spaces and apartments on the ground floor for the five cases.

- Agent analysis, which indicates patterns of movement and the frequent use of spaces starting from the centre of each common area. The analysis showed that each two or three apartments are connected with a

transitional space. Such a mechanism decreases crowding inside the building, as public gathering areas are distributed on the different vertical segments. Moreover, the results of the analysis indicated that the vertical circulation core is not connected directly with entrances of apartments, which adds a social value to the design through preserving the privacy of each family (Figure 23).

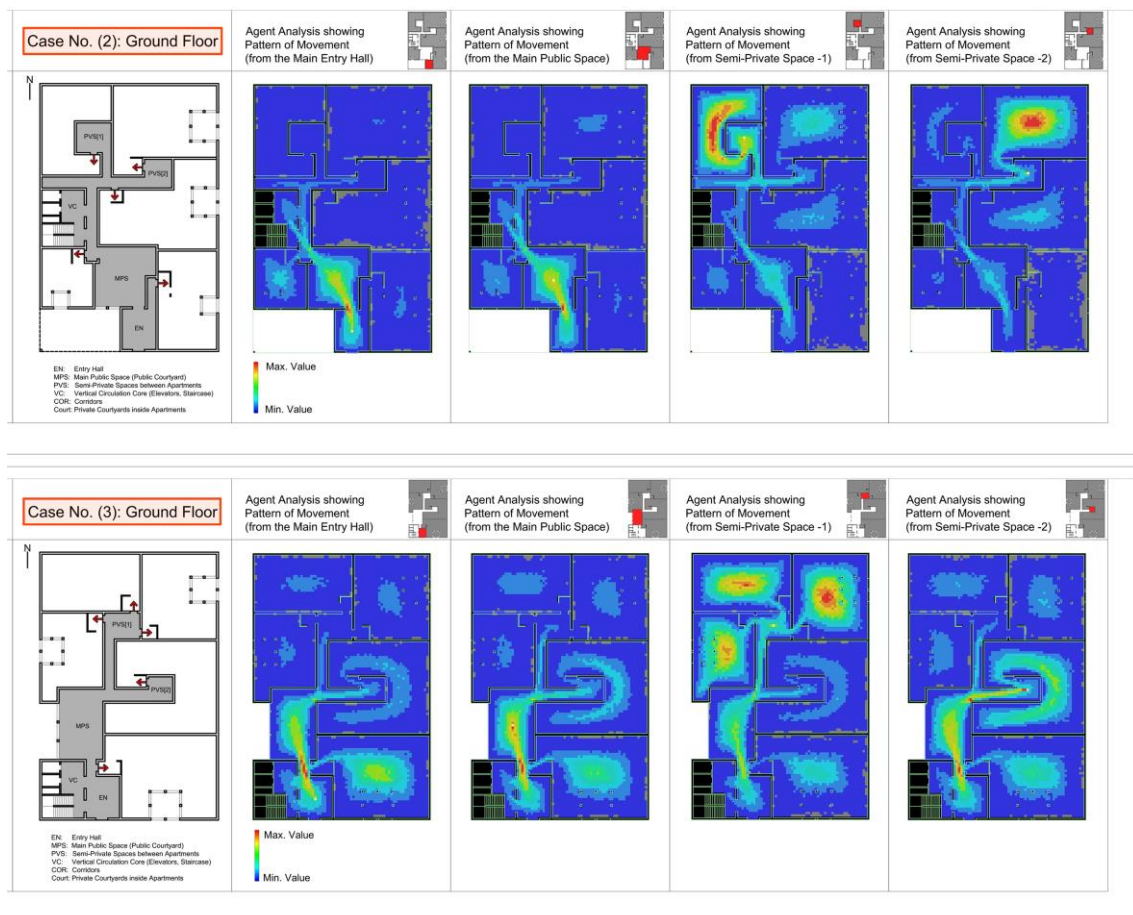


Figure 23: Agent analysis from the centre of each common area on the ground floor for Case # 2 and Case # 3.

- (2) *Isovist* analysis that addresses the visual fields of a person from the centre of each common area inside the building and along the movement path that links these spaces together. This test explores the visual privacy between public and private zones, which is a major indicator of social sustainability in residential

buildings. The isovist analysis of the different solutions showed that the visual fields from the centre of common spaces towards apartments are preserved. Same results were observed from the analysis of the visual fields along the movement path between apartments (Figure 24). Such a quality could be achieved through different mechanisms:

- Common spaces are arranged in a non-linear pattern, which, therefore, breaks the visual fields inside the building.
- Entrances are arranged in a staggered pattern, which maintains the privacy of the family.
- Entrances are connected with corridors or semi-private spaces. Such topological relationships allow for a balance between social interaction and isolation.
- Solid walls are used in front of entrances, which prevents a direct view towards the inside of the apartment.



Figure 24: Isovist analysis for Case # 2 and Case # 3, showing visual fields from the centre of common spaces and along the movement path for residents.

7. Discussion

Achieving social sustainability in residential buildings requires a holistic approach for clarifying spatial qualities that affect the social life inside the house. The information gained from the analytical reasoning process could help designers in problem interpretation and the projection of gained data into new alternatives. For instance, studying the location of each space and measuring distances between functions are useful for analysing accessibility and movement. Moreover, defining the topology of spaces and describing their geometry and scale offer information about their hierarchy, the degree of social interaction that takes place within them, and their ability to provide comfort to their occupants. Such a process creates a type-based database that can be used to improve the social qualities of future developments.

It is worth mentioning that the study adopted a holistic perspective in the development of a parametric tool that views the design as a combination of (a) rationality, which starts with defining the geometric properties and correlations that are associated with parameters, and (b) creativity, where designers can revise parameters and control the application of rules to modify their designs at any stage. Thus, the system allows for the generation of a wide range of new solutions that are within the same stylistic language.

Different benefits could be achieved using the developed interface. Regarding social awards, the hierarchical system of movement from public areas to private zones and the different sizes of public and private courtyards offer a mechanism for decreasing crowding, enhancing social interaction between residents, and enjoying the outside views. Another advantage is that common spaces could be arranged only in a non-linear pattern, thus breaking the visual fields inside the building and maintaining the privacy of the family.

Defining constraints regarding the maximum area of common spaces adds an economic value to the design. This tool offers developers the ability to include public spaces and private courtyards that constitute less than 11% of the area of the building. However, these features are part of the rentable area and aid in selling the apartment quickly. Thus, there is a revenue with no loss area. Furthermore, there is an omission of corridor spaces, which represent less than 5% of the total area.

Regarding environmental rewards, the increased area of external facades obtained by integrating courtyards allows for natural light and air to penetrate the building.

8. Conclusion

The grammar for contemporary vertical developments is built on the benefits of the horizontal arrangement of residential quarters in MENA region, which was achieved through dividing the high-rise building into vertical segments as a representation of neighbourhoods in a traditional fabric. This solution could highly promote the concepts of hierarchy and clustering that create a mutual responsibility for common spaces in each segment, thus encouraging interaction between neighbours. The grammar allows for the generation of a hierarchical system of public and semi-public spaces (public courtyards) on each segment of the building. Moreover, a private courtyard, surrounded by rooms on three sides at least, could be generated inside each apartment.

The developed computational design tool offers designers an alternative method for implementing strategies of social sustainability at the early stage of the design and adds flexibility and creativity to the generation process. The interface provides designers with a catalogue of main spaces that are needed in high-rise residential buildings. Moreover, it allows designers to create different alternatives by modifying

geometric properties and location of design elements. Finally, it offers a search for better solutions according to predefined criteria.

A promising area for future research is to add the cost estimation as one of the factors for the optimization process. In this way, designers can attract the attention of real-estate developers to integrate public gathering spaces and private courtyards in the design of the building. Other issues include the addition of extra details, such as windows, the shape of structural columns, and structural calculations.

Moreover, this tool can be improved by integrating a machine-learning algorithm to allow for an automated optimization process and to supplement the manual process of evaluation by using other computational models. This process can lead to the identification of other best solutions that would have been otherwise unpredictable.

Acknowledgements

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