Section Grammars: An Experimental Study on Decoding Forms of Underground Cities

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Abstract. This study offers two key contributions. Firstly, it introduces the concept and framework of "section grammars" (SecG), which is derived from Stiny's shape grammars. Secondly, it investigates the potential of SecG in generating existing and alternative section layouts for ancient underground cities. The case study focuses on Derinkuyu, which is located in Cappadocia, Turkey. The study thoroughly examines the components of the Derinkuyu underground city, presents its parameters, and explains the rules based on the relations between these components. The study employs these elements and rules to generate an existing satellite city as well as a new synthetic satellite city. Finally, the paper discusses the outcomes of implementing the SecG framework. This study contributes to shape grammar studies by integrating the subtractive (carving) approach and the topological relations observed in underground cities into the proposed framework.

Keywords: Shape grammars, Section grammars, Underground cities, Cappadocia, Derinkuyu

1 Introduction

Architects have long looked to the past for inspiration and knowledge, studying historical precedents to inform their present and future designs. Precedent analysis offers designers deconstructible and abstract structures for ideation and analysis of various concepts in the design process (Clark & Pause, 1996). While there is not a consensus regarding the approach to precedent analysis, multiple efforts have been made to formalize and structure the process. Clark and Pause (1996) propose a graphical method for precedent analysis, encompassing various elements such as structure, natural light, massing, plan to section or elevation, unit to whole, repetitive to unique, geometry, additive and subtractive, and hierarchy categories. By the 1990s, precedent analysis had been discussed as a systematic approach to transferring design and construction knowledge to expert systems (Oxman, 1990; Fang, 1993; Oxman, 1994; Goldschmidt, 1998) through reverse engineering. One crucial requirement shared among diverse precedent analysis methods is the representation of design ideas with a certain level of abstraction, which serves as a fundamental prerequisite for effectively processing information. In this study, underground cities serve as a basis for conducting precedent analysis.

Derinkuyu, an ancient subterranean settlement in Cappadocia, Turkey, offers a unique example of an underground city (Nývlt et al., 2016; Burry & Latifi, 2023). Firstly, the logic of generating the space is not about adding on top of each other, but rather about subtracting and growing downwards. The entrances to the living spaces are positioned at the top, which is unlike the traditional approach. Secondly, Derinkuyu is characterized by intentionally crafted human-made spaces, unlike places that utilize pre-existing natural voids formed over time. Thirdly, the presence of numerous satellite parts within the spatial arrangement results in intricate and complex spatial compositions. This complexity provides a wealth of content for precedent analysis.

This study introduces the concept of section grammars (SecG) as a generative design framework inspired by shape grammars. The implementation of the SecG framework utilizes section drawings, vertical spatial schemas, and the topological relations observed in the Derinkuyu underground city. The city is categorized into three main levels based on Bixio's (2012) classification. The components of this specific SecG framework include ground, main shaft, tunnel, room, bunker, and well. Through this approach, the study aims to investigate and generate spatial configurations that manifest the sectional organization of the ancient underground city.

2 Underground Settlements

For centuries, humanity has adapted void spaces both above and below the ground for the purpose of shelter. Underground settlements have emerged in response to various factors, such as harsh climatic conditions, natural disasters, scarcity of construction materials, and safety concerns (Erdem & Erdem, 2005). Well-known examples of underground cities include Cappadocia in Turkey, Hal Saflieni in Malta, Banpo in China, Mesa Verde in Colorado, USA, and Bulla Regia in Tunisia (Erdem & Erdem, 2005; Bixio, 2012; Bixio & De Pascale, 2017).

2.1 Cappadocia

Cappadocia, historically part of the First Persian Empire, is now located in Nevşehir/Cappadocia, Anatolia, Turkey (Burry & Latifi, 2023). The region of Cappadocia accomodates more than 200 underground cities of varying depths and sizes. These cities encompass a wide range of facilities, including living quarters, chapels, stables, warehouses, workshop areas, ventilation shafts, wells, and circulation tunnels (Hensel & Hensel, 2010). The Cappadocia area is characterized by the presence of lavas and soft pumice volcanic tuffs. These volcanoes have remained active until recent times, contributing to the distinctive geological landscape and the formation of underground cities in the region (Erguvanli & Yüzer, 1978). The volcanic tuffs, due to their relative ease of carving and effective insulation properties, have played an instrumental role in the construction of the subterranean structures in Cappadocia.

2.2 Derinkuyu in Cappadocia

Derinkuyu is one of the best examples of underground complexes in Cappadocia. It was discovered in 1963 due to the renovation works of the houses on the site. According to Erguvanli and Yüzer (1978), the maximum depth of the settlement in Derinkuyu underground city reaches 85 meters below the surface. The Derinkuyu underground city features a total of 52 ventilation chimneys that vary in length and range between 70 to 85 meters (Erguvanli and Yüzer, 1978). The first eight floors of Derinkuyu were cleaned and opened to visitors, while the total number of floors and depth is not clear (Erguvanli & Yüzer, 1978; Okuyucu, 2007; Nývlt, et al., 2016). There is also uncertainty about the number of inhabitants of Derinkuyu. Ergunvanli and Yüzer (1978) mentioned that only the first three floors host 20000, Nývlt et al. (2016) state that Derinkuyu has a capacity of 20000 in total.

Since defining the concept of “floor” is not easy for underground cities, using levels provides a clearer understanding of Derinkuyu's development. Bixio (2012) describes Derinkuyu with 3 main levels including many intermediate levels. The first level begins at the ground and descends to the second level through tunnels. Entrances to the first level are generally situated in buildings above the ground. The second level can be considered a residential zone, with many rooms formed through carving. The third and deepest level is accessed by steep tunnels that chance direction multiple times. The rooms on the third level mostly function as bunkers or redoubts (Bixio, 2012). In brief, the carving-based formation process of Derinkuyu can be summarized as follows: opening a main shaft (Fig. 1, left), placing the rooms and tunnels (Fig. 1b, middle), adding a bunker and well, and connecting distinct complexes under the ground (Fig. 1, right).

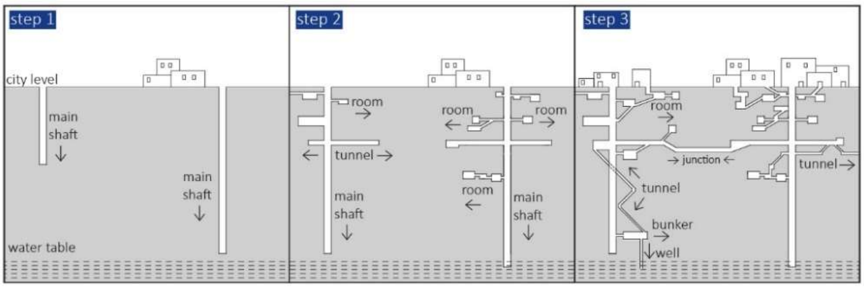


Figure 1. Step-by-step formation of a generic underground city. Source: Adapted and developed based on Bixio, 2012

3 Theoretical Foundations for Section Grammars

3.1 Shape Grammars

Shape grammar is a generative method coined by Stiny and Gips in the 1970s (Stiny & Gips, 1971) that allows for the analysis of design languages having an algorithmic structure and the generation of new designs in the same language. Shape grammar research, focusing on architectural products from a specific period, architect, style, or location, gained momentum starting in the 1980s. While studies on ice ray traces emphasize the elevation of Chinese lattices (Stiny, 1977), Stiny and Mitchell (1978) developed a shape grammar for generating the ground plans of Palladio's villas. In another paper, Çağdaş (1996) introduced a shape grammar capable of generating plan layouts for Traditional Turkish Houses. Shape grammars have also been used to analyze and generate three-dimensional spatial configurations of buildings. The Prairie Houses (Koning & Eizenberg, 1981), Classical Ottoman Mosques (Şener & Görgül, 2008), and Malagueira Houses (Duarte, 2005a; Duarte, 2005b) can serve as examples that work with three-dimensional data.

There are also limited studies that combine subtractive approaches with shape grammars. Analyzing ancient Egyptian rock-cut funerary monuments, Wutte and Duarte (2021) extract linear and symmetrical characteristics of these structures and provide shape grammar rules to generate and reconstruct these rock-cut structures (Wutte & Duarte, 2021). While the study by Wutte and Duarte (2021) introduces a generative model for spatial organization that uses subtractive logic, they employ plan drawings for rule extraction. In another shape grammar-based study, Bidgoli and Cardoso-Llach (2015) introduce the term “motion grammars” while providing a lexicon by classifying the movement of a robotic arm. In their study, the robotic arm performs hot wire cutting and operates a subtractive approach (Bidgoli & Cardoso-Llach, 2015).

3.2 Section Grammars

Previous research and implementations on shape grammar dealt with the plans, elevations, or forms of self-standing architectural products. Unlike the previous works, this paper introduces the term "section grammars" (SecG) for spaces that lack observable forms. Section grammars contribute to shape grammar studies by introducing a subtractive approach. Unlike Bidgoli and Cardoso-Llach's (2015) subtractive approach, SecG employs contextual information and provides spatial layout outcomes. Moreover, this study differs from Wutte and Duarte's (2021) study by focusing on the vertical (section) relationships within the context of underground cities. To develop and test SecG, underground cities are selected due to their step-by-step subtractive (carving) formation process and rich topological relations between the elements forming the underground city. The fundamental attributes of SecG are as follows:

- SecG employs and extends the core principles of shape grammars, such as the initial shape, rules and their application, and a terminating rule.
- SecG operates vertically and starts from the ground level.
- SecG requires the establishment of level-based thresholds.
- SecG includes level-based contractions for elements and rules.

4 Development and Implementation of SecG Framework

4.1 Scope and Limitations

In the scope of this study, one of the Derinkuyu underground cities, specifically Derinkuyu 1 (Fig. 2) introduced by Bixio (2012), was examined. The reason for choosing this particular satellite city was its rich content, which offers valuable spatial relations, rules, and patterns. The main limitations of the case study are listed as follows:

- In underground cities, tunnels and rooms are organized helically around the main shaft. However, this 3-dimensional form cannot be perceived on the cross-section. In the scope of this study, section drawings and vertical relations were considered while the formation in the third dimension was neglected.
- In Derinkuyu 1 underground city, the rooms exhibit diverse forms and functions, ranging from barns to living spaces and kitchens. In this study, all these spaces were categorized as "rooms". This approach enables a comprehensive analysis of the spatial layout and interconnectedness of various functions within the underground city.

- Unlike rooms, the tunnels with different characteristics associated with different rules. For example, the T3 tunnel, which descends than T1 tunnel, and is connected to the bunker, formed different rules.
- While creating the rule set, potential sub-symmetries between two elements are taken into account. For example, while Rule 6 indicates a transition from a room to a T2 tunnel, Rule 6’ pertains to a transition from a T2 tunnel to a room.

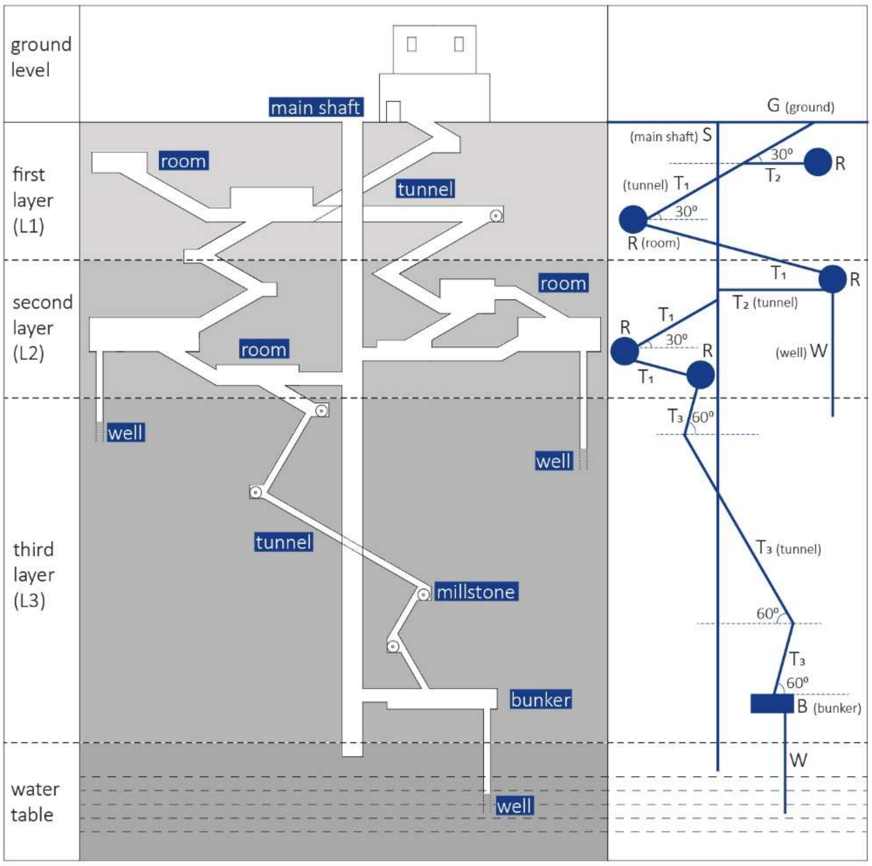


Figure 2. Schematic section and graph representation of Derinkuyu 1 underground city. Source: Adapted and developed based on Bixio, 2012

4.2 Elements, Rules, and Rule Set

To establish a rule set, the first step involves extracting elements and topological relations based on the schematic section (Table 1). Utilizing Bixio's (2012) three-level framework, an analysis of element-level relationships reveals that certain elements are tied to specific levels. As a result, the fundamental elements and rules align with the three-level framework (Table 1& Table 2, ‘level’ columns). The basic steps of the SecG process for Derinkuyu are outlined as follows:

- The initial shape is considered as Ground (G).
- The first rule (R1) that is necessary to start the formation process is to add a main shaft (S) to G.
- The termination rule is adding a bunker (B) to the tunnel located on the third level (T3) (Table 2).

Table 1. Basic elements of Derinkuyu 1 and their representations. Source: Authors

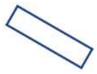
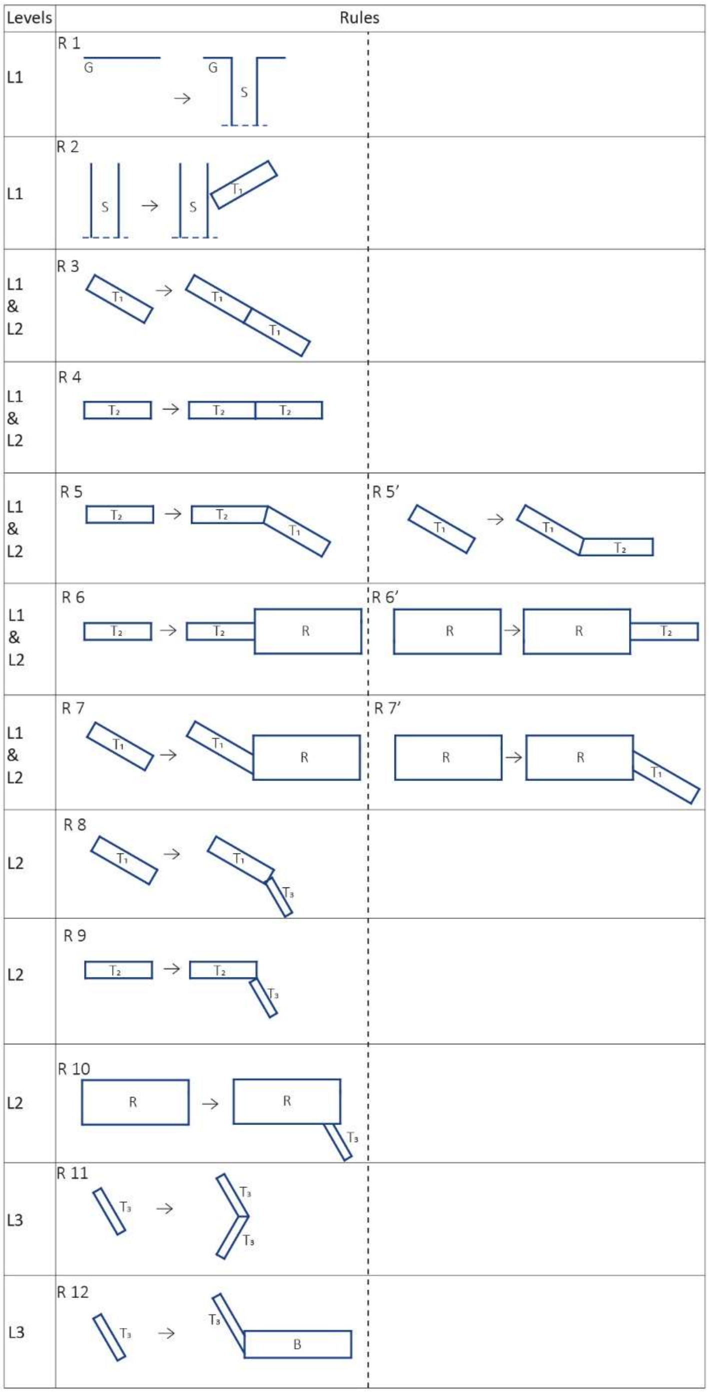
Element Name	Abbreviation	Symbols	Layers	Angle
Ground	G		1	0º
Main Shaft	S		1, 2, 3	90º
Tunnel 1	T_1		1, 2	30º
Tunnel 2	T_2		1, 2	0º
Tunnel 3	T_3		3	60º
Room	R		1, 2	0º
Bunker	B		3	0º

Table 2. Rule set to generate Derinkuyu 1 and Derinkuyu 1-like cities. Source: Authors



4.3 Implementation of SecG

By employing the provided elements in Figure 1 and the established rule set in Table 2, a partial section of the existing Derinkuyu 1 underground city is generated, alongside a synthetic section similar to Derinkuyu 1's satellite city (Fig. 3). The implementation of the framework demonstrates the generative capabilities of spatial layout generation.

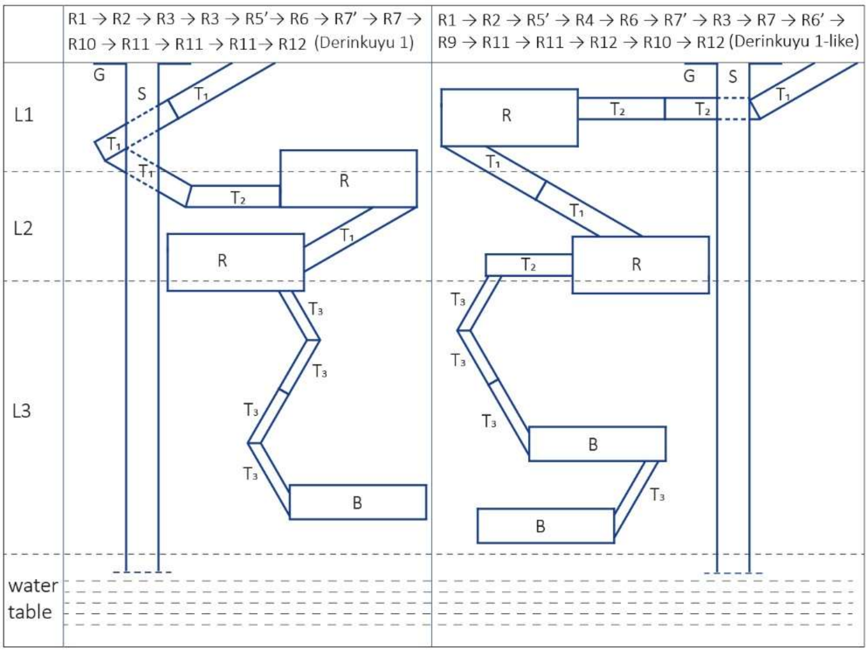


Figure 3. Generated Derinkuyu 1 and Derinkuyu 1-like sections. Source: Authors

5 Conclusion

This paper introduces section grammars (SecG) as a rule-based generative model, which offers new avenues for understanding and designing spatially complex underground cities. This approach is expected to contribute to the development of generative design strategies and vertical city ideas capable of addressing the urbanization and sustainability concerns in the 21st century. Through an analysis of the spatial formations observed in underground cities, architects can gain insights from the past and apply this knowledge to both current and future projects. Moreover, SecG offers a tool for generating novel designs that are not only aesthetically pleasing but also functional and responsive to the specific context and site requirements.

The SecG framework described in this paper was tested by implementing the Derinkuyu case. This study has three main limitations. In this study, only the Derinkuyu underground city was utilized as a case study. The SecG structure is expected to change as the sample set size increases. Second, an orthographic section representation was used to analzye underground cities. The rules and spatial relationships vary when the third dimension is included. Third, preliminary results show that, while it generates an underground city section layout by applying the SecG framework vertically, it lacks the branching typical of underground cities. The current rule set allows formation from the ground level to lower levels in the section (as a single branch) but does not yet support branching. In future studies, the related parameters of underground cities that form helicoids around a central shaft can be investigated.

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