Automated Layout Zoning: A Case of the Campus Design Problem

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Abstract –

Layout zoning is the foremost and crucial step in the design of large-scale greenfield construction projects. While it is known that early design decisions have significant impact on the social and environmental value of the completed facility, much of the relationship between design attributes and values are tacit knowledge. In addition to the challenges, such as the number of design alternatives that can be evaluated in a limited time, traditional methods of design generation and evaluation do not focus on capture of stakeholder defined values and their quantification for effective evaluation of design alternatives. Computational design tools provide several benefits that can be leveraged in automated design generation to overcome the limitations of conventional methods of design. However, the translation of stakeholder defined value to parametric form in automated design generation is not adequately explored in existing works. In this work, generation and evaluation is formulated in a visual programming environment -Grasshopper. The 'growth algorithm' discretizes the available area into numerous land parcels and allocates the parcels to seed nodes until the area requirement is satisfied. The implementation in the case of a real-world campus layout revealed that the script was able to generate layout alternatives with different configurations of zones. Further, from the case study, a set of values and their relationship with design attributes were derived. Using parametric scripting, it was illustrated how the value-based design objectives can be quantified by utilizing the layout solutions produced by the growth algorithm-based script.

Keywords –
Visual Programming; Parametric design; Computational design

1 Introduction

The social, economic, and environmental value of a built facility are significantly influenced by proper planning and design. In addition to addressing the functional and site related requirements, the significance of incorporating stakeholder values in built facility design has been emphasized by researchers [1][2]. However, the traditional methods of design generation and evaluation do not pay adequate attention to value and values in design. This is mainly because they are perceived as intangible design criteria that are difficult to quantify [3]. In the pursuit of theorizing the various types of design values a previous study by the authors derived the following set of ten Architectural Design Values (ADVs) for campus projects. The ten ADVs include Functional, Environmental, Constructability, Design quality, Schedule, Social, Cost, Flexibility, Iconic, and Aesthetic value [4]. A subsequent study showed that the relationship between design attributes and stakeholder values are explicable [5] and hence quantifiable. Additional investigation is needed to investigate the viability of employing such relationships for the evaluation of design options.

Design generation and their evaluation is a challenging task particularly in the layout design phase due to the ill-defined nature of the design problem. Hence, design generation requires significant effort and expertise from the designer. As a result, typically using traditional methods only a limited number of design alternatives can be generated.

The advent of digitization in design has led to an increase in automation of design activities, creation of newer ways of interacting with design, and improvements in the efficiency of the design process through innovative workflows. This study utilizes two closely related concepts, parametric design and generative design, that has gained significant traction in design generation and creative architecture in recent years. Parametric design deals with the generation of design variants using fixed and variable entities [6]. While parametric design has been around even before the invention of computers, generative design is a relatively new concept. As per [7], "Generative Design (GD) is the process of defining high-level goals and constraints and using the power of computation to automatically explore a wide design space and identify the best design options."

A key aspect of GD is the explication and representation of domain knowledge [8]. It is expected that the explicated relationship between design attributes and value can be leveraged in GD frameworks to facilitate automated design evaluation.

Layout design is a necessary first step in the design of a built facility. Several authors have investigated techniques for the automated generation of layout alternatives. These include techniques for locating facilities [9], exhaustive generation of design alternatives [10], topology and geometry representation methods [11]-[15], and learning-based methods [16][17]. Most of the existing works in automated layout design have limitations in terms of constrained geometries. Further, the existing works utilize tangible objectives for evaluation of design alternatives such as energy [19]-[21], daylight [18][19] and structural performance [19][20]. Also, the proposed techniques are more relevant in the detailed design stage of building design.
In the current work, the authors conducted an exploratory study on the design evaluation process of a public university campus in India to empirically understand the layout zoning problem. From the detailed observation of the various stages of the evaluation process, the zoning requirements, and the design attributes to ADVs relationship were identified. In the current problem, the layout was characterized by the presence of uneven or irregular boundaries which is a common feature in large-scale greenfield projects. Since standard methods of layout generation typically rely on rectangular geometries, these methods cannot be directly applied in the current problem.

Hence, the current work attempts to address the need for a method for the automated generation of layout alternatives with various zoning configurations for layouts with irregular boundaries. Secondly, the work explores if the layout alternatives can be evaluated against ADVs. The study was conducted using the real-world case of a greenfield campus design project. Towards this end, a 'growth algorithm' for the automated zoning of a layout was formulated. Further, based on the case study, a set of rules defined by the stakeholders for the quantification of value-based design objectives were derived. The rules were translated to parametric form in a visual programming environment and incorporated with the layout generation script. Based on the results of the script the findings of the study were derived.

Zoning decisions are based on limited design criteria such as distances between the zones and are based on limited information available to the designers at that stage. The other types of values such as cost, flexibility, and design quality could be modelled as the designers are provided with more details. In the later stages, when the design is more detailed and as additional data becomes available, the other relevant factors can be incorporated. While the current work is limited to zoning, it is an exploration regarding the effectiveness and utility of mapping the values-design attributes relationship and their translation to parametric form that will be a future investigation through the detailed design stage using the case of the same project.

This paper is organized into five sections. The second section of the paper gives an overview of the existing works related to layout generation techniques. The third section discussed the layout zoning problem and its evaluation based on the campus development case study. This is followed by the discussion section. The final section of the paper is the Conclusion section.

2 Related works

Various approaches have been used to investigate automated layout design generation and evaluation. The seminal works in layout exploration viewed it as a 'location problem' and focused on the costs associated with moving between locations [9]. Other studies utilized mathematical approaches for generation of layout alternatives such as Quadratic Assignment problems [22] and General Space Planner [23]. However, the above techniques consider only a limited number of architectural aspects such as adjacency, sight, distance, and access in layout generation.

Several investigations on layout design have utilized representation techniques for addressing automated layout generation. These representation techniques include the use of graphs [11][15] and the bubble diagram [12]. Another method that has been popular in layout representations is the shape grammar [13][14]. The main feature of shape grammar is that it generates floor plans through shape rules. However, the definition of rules to reflect the relationship between design components in terms of geometries is challenging, let alone the evaluation of more complex architectural value. The application of each of the representational techniques in automated design generation has specific advantages and limitations with respect to automated building design generation as discussed by [8].

Other methods investigated in floor planning include exhaustive generation of floor plans [10], Expert Systems that provides solutions to a design problem by considering criteria and constraints based on the enumerated solutions in the system [24], constraint-based systems which involves conversion of architectural constraints into mathematical model to determine the placement of a room [25], and physics-based method which utilizes spring-damper forces for defining topology logic [26]. Evaluation of quality of plans based on value in design is not given any attention in the above studies.

Recent studies in automated layout generation utilize learning-based techniques. [27] applied a modified Generative Adversarial Network (GAN), the pix2pixHD, for generating new architectural plans from a set of 100 existing plans. Similarly, [28] developed a GAN based framework for generating new layouts by using 45 plans from the work of Le Corbusier. Optimization techniques such as neuroevolution of augmenting topologies (NEAT) [16][17] and graph convolutional networks (GCN) [25] have been used for translating initial inputs in terms of spatial configurations or design criteria to final optimized floor plans. Most of the above studies focus on building design. Further, there are limitations of these approaches. For instance, in case of NEAT the final layout depends on the initial configurations and at the inputs given at the various iterations of the genetic algorithm whereas in case of GAN the results depend on the characteristics of the training data set [17].

There are a number of studies that deal with the placement of site facilities on the site to address objectives such as material movement cost as discussed in the review paper by [31]. Most of the studies utilize rectangular geometries to represent various facilities. The division of layout to address area requirements of different facilities is explored by researchers. For instance [32] discussed an approach for allocation of layout facilities to satisfy area requirements and evaluate it based on safety and other functional requirements. Similarly, [33] proposed an approach for utilizing freeform geometries in layout facilities planning. In both the studies the approaches did not focus on generation of various design alternatives but to arrive at an optimum solution to satisfy the proximity and area requirements. There are limited studies with respect to the site layout zoning that can be applied to the current problem of layout planning for largescale projects.

In most of the studies reviewed in this section, the geometry of the layouts and their components were restricted to rectangular shapes hence geometrically constrained. Further, the scale of the problems was limited to housing or industrial units. In the existing literature, there is little focus on zoning of large-scale layout such as campus design. Furthermore, it could be challenging to apply the strategies to site layouts with uneven boundaries. The criteria used in the evaluation of layouts are easily quantifiable and relevant to advanced stages of building design and therefore not applicable to the layout zoning problem.

3. Research Methodology

The main activities of the current work are summarized in Figure 1.

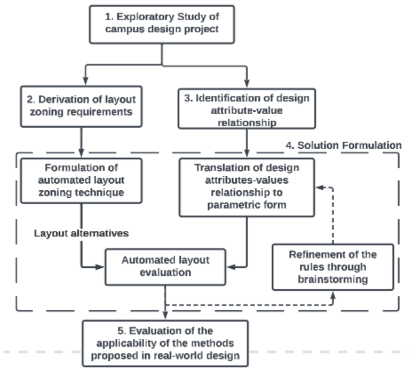

Figure 1: Steps in the current research

Each of the activities shown in Figure 1 are discussed in detail below.

3.1 Exploratory study of campus design project

This section discusses the details of the exploratory case study. In this work, the design evaluation process of a greenfield campus project was studied to empirically understand the requirements of the campus layout zoning problem and to identify the design attribute-stakeholder value relationship. Figure 2 shows the site location plan of the project.

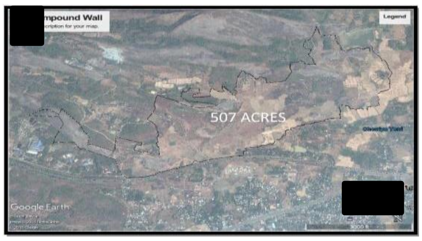

Figure 2: Site location plan

As shown in Figure 2, the total area of the site was 507 acres. The scope of work included development of master plan for the campus. The master plan needed to address a capacity of 20,000 students and was to be developed in three phases over a span of 20 years. Qualitative techniques of data collection were employed as shown in Figure 1 to identify the design requirements and the evaluation criteria.

Figure 3 illustrates the various methods that were used in the exploratory study. Participatory and non-participatory observations of the evaluation of the design concepts provided the main sources of data. In

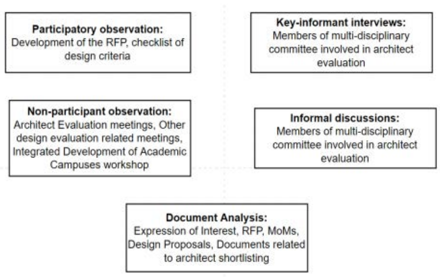

Figure 3: Data collection techniques adopted in the exploratory study

addition, semi-structured in-depth interviews and informal discussions were conducted with eleven key informants who were part of the committee that was the decision-making body in the architect selection process. The duration of the interviews ranged from one to two hours. The key informants included committee members who are experts in the field of Engineering, Architecture, and Construction Management, and the directors of the respective institutes, whose experience ranged from 30 to 50 years in their respective fields. The interviews were audio recorded and transcribed for further analysis. The researcher further had access to project-related documents such as the Expression of Interest, Request for Proposal (RFP), and Minutes of Meetings which were also analysed.

The data analysis process was conducted in two stages. The first stage involved identifying themes and patterns relating to design values in the qualitative data. This analysis led to broad categorization of values which was refined in the second stage of the analysis. In the second stage, the data from participant and non-participant observations was used to map the value categories with the design attributes. The researcher bias was addressed by using multiple sources of data and presenting the results to 2-3 experts who participated in the design evaluation process. The outcomes of the data analysis are discussed in the following sections.

3.2 Derivation of layout zoning requirements

As shown in Figure 2, the layout is characterised by uneven boundaries. The total area of 507 acres needed to be allocated to five zones. The five zones include administrative, academic, hostel, residential, and sports. Based on the proportion of the population that would utilize the five zones the respective approximate areas for each of the zones were calculated. The area requirements were calculated based on the estimate of built up area required for the various buildings in the five zones to meet the target number of users. The estimate was derived based on the data of existing campus projects. The area requirements for the various zones are summarized in Table 1.

Table 1: Zoning requirements

No.	Zone	Area requirement (sq. m)	Number of sub-zones
1	Administration	93104	1
2	Academic	764426	5
3	Hostels	495316	2
4	Residential	626780	2
5	Sports	44690	1

3.3 Layout zoning requirements and the evaluation criteria

As the second objective of the paper was to illustrate how ADV associated with zoning can be converted to parametric form and employed in the evaluation of layout alternatives. The data analysis resulted in the identification of three ADV and their relationship with design attributes relevant to the zoning problem. Table 2 summarizes the ADV and design attribute relationship.

Table 2: ADV and their relationship with design attributes

No.	ADV	Description	Relationship of ADV with design attributes
1	Environmental	Travel carbon footprint	Length of route connecting academic and residential zones
		Vegetation /waterbody exclusion	Areas with vegetation/ waterbody
2	Aesthetics	Academic zone needs to occupy the central position in the campus layout symbolizing the significance of the academic zone while also maintaining the proximity to the entrance of the layout to minimize the view of other zones for visitors	Distances between the centroids of the academic zone and the layout; Distance between the entrance point of the layout and the closest point of the academic zone
3	Social	Proximity between academic, hostel zone, and faculty residential zone to improve social interactions between students and faculty	Distance between the centroids of the three zones

In contrast to the current level, the computation of the various values in the advanced stages of the design will require features that go beyond simple geometrical attributes and are more difficult to quantify.

3.4 Solution Formulation

Figure 4 illustrates the tools used in the solution formulation to translate the design problem to parametric form using the visual programming script.

As shown in Figure 4, there are three main components in the solution framework. The various components were developed in the modelling software, the Rhinoceros [29] and the visual programming software, the Grasshopper [30]. The components are described below.

While the effectiveness of the 'growth algorithm' could be based on the ability of the script to generate layout alternatives, the accuracy of the rules and their translation to parametric form needed verification. As shown in Figure 1, the implementation and the refinement of the rules relating values and design attributes was conducted iteratively through brainstorming with the stakeholders of the project.

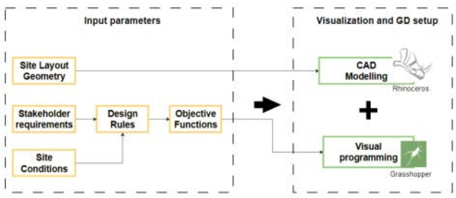

Figure 4: Data collection techniques adopted in the study

Input parameters: The input parameters consist of the following information: the site layout geometry, the stakeholder requirements, and other site related information.

Visualization and GD setup: The site layout geometry was visualized in the modelling environment whereas the design objectives were modelled in the visual programming environment. The logic of translation of the design objectives to parametric form in the visual programming language is described below.

Formulation of automated layout zoning script: The current problem deals with the division of site into five zones while satisfying the area requirements of the zones. In the current work, this was achieved by formulating a 'growth algorithm' using python code within the visual programming environment. Figure 5 illustrates the logic of the 'growth algorithm' and Figure 6 shows the snapshot of the python code used for its execution.

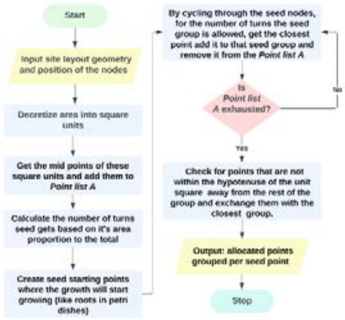

Figure 5: Logic of the 'growth algorithm'

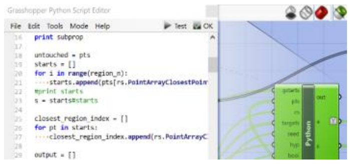

Figure 6: Snapshot of the python code within the visual programming script

In the 'growth algorithm', a change in the position of the nodes will result in a different layout alternative. Figure 7 illustrates the instance of discretization of the layout. As shown in Figure 7 the layout is divided into land parcels. These land parcels are allocated to the closest seed node representing a zone. Figure 8 illustrates the zoning alternatives with the use of different node positions for initiation of the 'growth algorithm'.

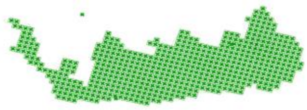

Figure 7: Layout discretization

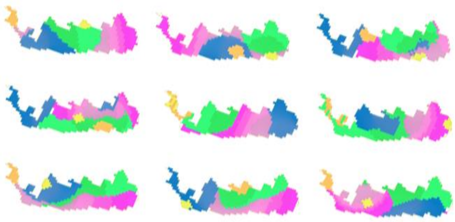

Figure 8: Examples of layout zoning alternatives

As shown in Figure 8, based on different node positions the script generates different layout zoning configurations. However, the formation of a small percentage of land parcels in a different zone in the layouts that were generated by the script.

Translation of design attributes-ADV relationship to parametric form: The translation of the three ADV discussed in Table 2 to parametric form using the visual programming script is discussed below.

Environmental value:

This value mainly deals with the preservation of the natural environment by minimizing the impact of human activities. This value was addressed using two objectives: The measurement of the travel carbon footprint and the areas with natural vegetation. While the measurement of travel carbon footprint could further facilitate its minimization, the vegetation and waterbodies could be preserved by avoiding development activities in the identified areas. The rules for the two evaluations are discussed below.

The travel carbon footprint is linked with the distance between the academic zone (green) and the residential zone (purple). The visual programming script quantified this criterion by generating graphs from the centroids of the zones. The script identifies the longest path of travel between the predetermined zones as shown in Figure 9.

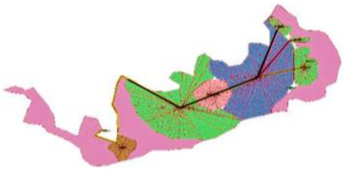

Figure 9: Longest route based on radial graphs

Vegetation/ waterbody exclusion: As summarized in Table 2, the vegetation /waterbody areas can be represented in the layout in terms of geometry. To illustrate the evaluation of this value, a script for the automated allocation of building layouts was first developed. The script automatically creates building layouts in areas other than the vegetation exclusion areas as shown in Figure 10.

Figure 10: Illustration of vegetation areas exclusion

As shown in Figure 10, the script will automatically avoid creating buildings in areas that are covered with vegetation or waterbody.

Aesthetic value:

This value deals with the overall view that a visitor will get when entering the campus. The value focuses on placement of the academic zone at the center of the campus signifying that it is core of the facility while minimizing the distance from the entrance to avoid a visitor viewing other zones while entering the campus. This value consists of two rules. The quantification of the value is based on the distance between the centroid of the academic zone and the centroid of the layout. In this way, the script gives a measure of how far the zone is from the center of the campus. Secondly, shortest distance between the academic zone and a predefined entrance point helps in determining the proximity of the zone from the entrance of the layout. Figure 11 illustrates academic zone location evaluation measurement using the visual programming script.

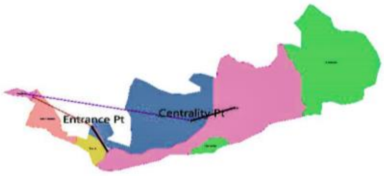

Figure 11: Centrality of the academic zone and its proximity to entrance measure by distances

In Figure 11, the black line shows the distance between the centroid of the academic zone (pink region) and the centroid of the layout. It also shows the shortest distance between the pre-determined entrance point and the academic zone.

Social value:

The social value aims at improving the proximity of three zones: the academic, the hostel, and the faculty residential zones. This value is based on the belief that the closeness of the zones will improve the social interactions between the users of the zones. The distance between the three zones gives an indication about their proximity. The script for measuring the social value computes the proximity of zones by measuring the centroid-to-centroid distances of the set of identified zones.

3.5 Evaluation of the applicability of the solution framework

The applicability of the solution frameworks in the current case study was evaluated through a presentation and discussion session with the architects' group that were involved in the design of the current project. The participants were experts in campus design and had experience ranging from fours years to thirty years. The session followed the Focused Group Discussion guidelines. Overall, the group gave a strong agreement regarding the applicability of the methods used in the study in real-world design process.

Architect 1 articulated the benefit of utilizing the methods used in the current work in exploratory study. Architect 1: *Design is a continuous process. You work something on the paper you translate it on the computer then you keep working on it. The technology helps to produce faster results, you tend to work out many options at one time.*

While emphasizing on the relevance of the quantification of values Architect 2 made the following statement. Architect 2: *What is very critical is how you evaluate it (design alternatives) and although it is very easy to quantify certain things but there are certain things such* *as the feeling that a person would have in this space which gets very difficult to quantify.*

Architect 3 further discussed how the methods used in the study could be useful in utilizing design criteria that are quantifiable along with the criteria that are intangible in nature.

Architect 3: *It cannot be denied it (the methods) is very essential because it must give us the optimal use of resources like space and money. And again, very critical at the same time is that you don't miss out on those factors which might come to you intuitively when you design but you forget when you are actually evaluating them altogether.*

From the discussion it was evident that design exploration activities could benefit from using the methods used in the current work.

4 Discussion

In the current work a technique was formulated for generating zoning alternatives for layout with irregular boundaries and script for the integration of three categories of values was formulated to illustrate the automated evaluation of design alternatives against values. A 'growth algorithm' was proposed for the zoning of layout for a campus design project. The results obtained from the 'growth algorithm' based script showed that to a great extent the script was able to produce different options for zoning of the layout. However, one of the limitations of the 'growth algorithm' was the creation of land parcels of a different zone within a zone. While the algorithm incorporated a mechanism for eliminating the land parcels, a small percentage of it persisted.

The study further illustrated how the generated layouts can be evaluated against a set of ADV. In the current work, the derived logic of ADV evaluation for layout design was translated to parametric form. The presence of land parcels led to inaccurate evaluation results in some instances of evaluation in the current study. However, the work provided evidence that values evaluation can be translated to parametric form. This could be further utilized in automated evaluation of layout alternatives and for arriving at high-performing design solutions.

In the current work, the effectiveness of the "growth algorithm" was evaluated by generating several design alternatives. Based on the design variants generated by the "growth algorithm" through visual examination it was observed that it was capable of generating numerous unique design solutions. To establish evidence for the effectiveness of the "growth algorithm" and the ADV computation, additional empirical investigation may be required.

The algorithms used in the facility layout planning cannot be directly applied to the current work as the current work deals with the zoning of largescale site layout with irregular boundaries for greenfield campus projects. Hence, it is difficult to compare the performance of the existing algorithms to the current work.

The current work discusses the problem of layout zoning automation and their evaluation using the case of campus layout design. The study was based on the recognition that there are several such projects under development globally. The authors believe that the "growth algorithm" and the values evaluation approaches that is discussed in the paper could be applied to any type of AEC project that require zoning of irregular boundaries. Evidence regarding the effectiveness of algorithm to other type of projects will require empirical investigation of the application of the algorithm to other types of projects.

5. Conclusion and Future Work

The current study is based on the need for an approach for automated zoning of layouts with irregular boundaries and further evaluating the zoning alternatives using values-design attributes relationships identified through empirical study of a campus project. The work proposed a 'growth algorithm' based approach for generating zoning alternatives for layouts with irregular boundaries. The work further illustrated that values-design attribute relationship can be utilized for evaluating the alternatives. The study thus demonstrates the feasibility of automating the zoning of layouts and their evaluation against values.

The work provides an approach for stakeholder teams to quickly generate design alternatives for layout zoning and exploring design alternatives through visualization of the layout alternatives and their performance in terms of values. In the current work, the ADV were limited to three as the study focused on illustrating the quantification of the value-based objectives. Further, the design attributes were limited to geometrical aspects. Future study could focus on adopting more rigorous methods for the identification of the comprehensive set of value-based objectives and incorporation of site conditions data. Further, the weightages for the various objectives can be elicited from the stakeholders and incorporated in the automated evaluation process. The use of site constraints could give insights regarding the effectiveness of the method in real-world design. Genetic Algorithm based techniques could be incorporated to provide more controlled generation of high performing design alternatives.

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