OPTIMIZING CONTAINER HOUSING UNITS FOR INFORMAL SETTLEMENTS

A parametric simulation & visualization workflow for architectural resilience

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Abstract. In rapidly growing cities like Dhaka, Bangladesh, sustainable housing in urban wetlands and slums present a challenge to more affordable and livable cities. The Container Housing System (CHS) is among the latest methods of affordable, modular housing quickly gaining acceptance among local stakeholders in Bangladesh. Even though container houses made of heat-conducting materials significantly impact overall energy consumption, there is little research on the overall environmental impact of CHS. Therefore, this study aims to investigate the performance of CHS in the climatic context of the Korail slum in Dhaka. The paper proposes a building envelope optimization and visualization workflow utilizing parametric cluster simulation modeling, multi-objective optimization (MOO) algorithms, and virtual reality (VR) as an immersive visualization technique. First, local housing and courtyard patterns were used to develop hypothetical housing clusters. Next, the CHS design variables were chosen to conduct the MOO analysis to measure Useful Daylight Illuminance and Energy Use Intensity. Finally, the prototype was integrated into a parametric VR environment to enable local stakeholders to walk through the clusters with the goal of generating feedback. This study shows that the proposed method can be implemented by architects and planners in the early design process to help improve the stakeholder's understanding of CHS and its impact on the environment. It further elaborates on the implementation results, challenges, limitations of the parametric framework, and future work needed.

Keywords. Multi-objective Optimization; Building Energy Use; CHS; Informal Settlements; Parametric VR.

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1. Introduction:

Making cities and settlements sustainable, inclusive, and resilient is one of the UN's seventeen goals for sustainable development. Additionally, ensuring universal access to affordable, appropriate, and safe accommodations for slums is its primary goal (UN, 2015). However, in rapidly growing cities like Dhaka, Bangladesh, sustainable housing has become an increasingly significant problem and does not reflect the concept of an affordable, livable, and equitable city to all its residents (RAJUK, 2015). Within the metropolitan area of just ˜300 square kilometers, Dhaka houses well over 12 million people (BBS, 2009), which is projected to grow to 26 million by 2035 (RAJUK, 2015). Currently, most low-income communities already reside in sub-standard unsustainable conditions in urban wetlands scattered within Dhaka, requiring immediate critical intervention, as the expected population growth is expected to worsen the issue. Worldwide, slums accommodate nearly 1 billion people, representing one-third of the global urban population. Dhaka accommodates a total of 3.5 million slum occupants (Fan et al., 2017), and current materials used for constructing the houses in informal settlements are prone to fire and natural calamities.

Module-based housing out of recycled containers is a construction practice that is currently gaining acceptance in the building industry. Due to the globalization of supply chains, over 17 million used shipping containers exist globally (Steve, 2019). This surplus has initiated a trend towards the usage of these as construction units in architecture. Bangladesh has seaports and riverports, which prompted container housing units to become popular among local urban wetland dwellings. In general, the containers can cut construction times, costs, and waste due to their stackable nature and modular construction (Steve, 2019). However, the container envelope design is critical due to its nature of heat and cold conducting properties. Several previous papers focused on CHS as a sustainable solution to meet the housing demand in slums, but these research projects did not provide an in-depth assessment of container envelope design optimization to achieve high-level building energy performance.

This study proposes a parametric envelope optimization and immersive visualization framework applicable to sustainable informal settlement development. The envelope optimization process was tackled through multi-objective optimization algorithms. On the other hand, the immersive visualization process addressed socio-cultural values via stakeholder feedback. The simulation workflow was implemented in the Korail slum, which houses over 20,000 families adjacent to a lake as one of the largest and densest slums in Dhaka. The living situations in Korail are mostly deplorable due to untenable housing conditions. Korail's residents construct houses using either locally sourced materials or recycled containers, and place their dwellings in unplanned arrangements without considering the impact on the surrounding environment or ecology. Therefore, restructuring the housing provision through different sustainable approaches is a much-needed change to improve these housing conditions. This research assumes that the proposed framework in this study can be employed by architects and planners in the early design stage to help improve the local dweller's understanding of the container housing system.

2. CHS optimization and immersive visualization framework:

2.1. METHODOLOGY

The design optimization and visualization framework to investigate the performance of CHS in this paper (Figure 1) is structured as follows: First, the container cluster pattern was selected through local housing cluster typologies observation in Step 01. Step 02 was comprised of hypothetical container cluster formations and the selection of the design variables. In Step 03, the MOO results were derived from the daylight and energy simulation process. The optimization progression continued until termination, and the optimized design options were integrated with parametric virtual reality (VR) in Step 04.

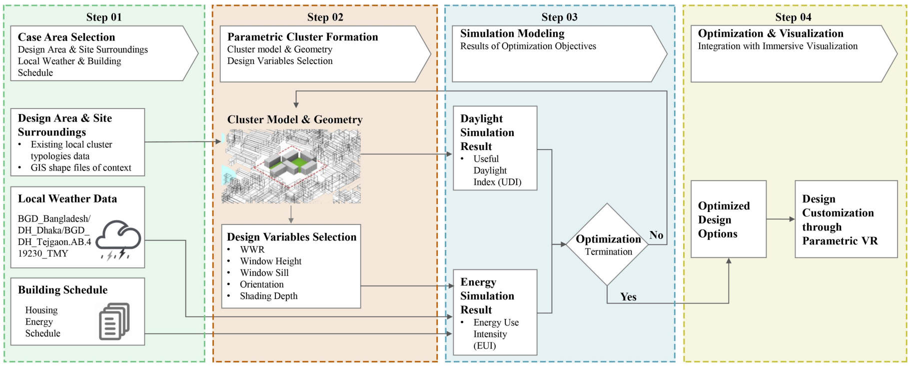

Figure 1. CHS optimization and visualization framework.

2.2. PROTOTYPE DEVELOPMENT

Figure 2 shows the software prototype for simulation and immersive visualization. First, the building footprints were applied as inputs in ArcGIS pro. Then the outputs were taken to the Rhinoceros-Grasshopper platform. Here, parametric simulation modeling and simulations were operated by using Ladybug tools, Octopus, OpenStudio, Radiance, and Daysim cross-platforms. Finally, immersive visualization is an ongoing development using the Unity game engine.

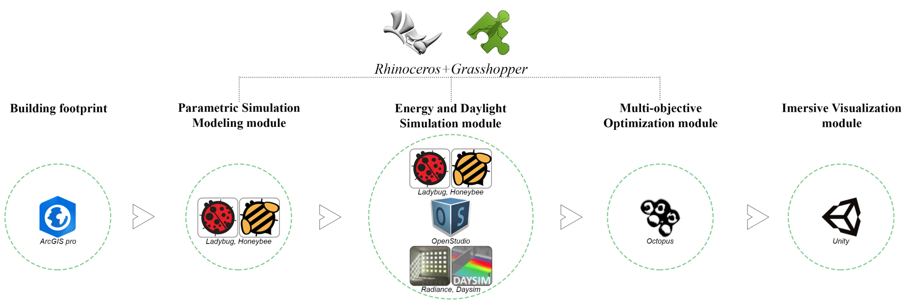

Figure 2. Software prototype for simulation and visualization.

3. Implementation:

3.1. CLUSTER PATTERN SELECTION

Generally, three groups of typological approaches for hypothetical cluster formation can be identified: (a) generic targets with unvarying contexts; (b) existing built urban arrangements; and (c) hybrid targets with unvarying contexts (Natanian et al., 2019), which was applied in this research.

The generic method is guided by vernacular building/block typologies. That type is generated from the traditional courtyard (Figure 3), which family members use for home-based activities, such as work or leisure (Zahir & Aman, 2017). The generic pattern may cause unnecessary experiments due to oversimplifying complex building geometries, and it does not respect traditional settlements. Yet, the existing built urban arrangements require an unnecessary level of details and limit the transferability for site variations. The hybrid approach allows keeping existing constructed municipal arrangements as it impacts the energy performances and confirms the transferability and computational efficiency. Hence, the hybrid method was considered to model the hypothetical CHS clusters for this research.

There are two ways to collect footprint data of the dense areas of the Korail slum. Firstly, from different online sources like Open Street Maps or Grasshopper plugins such as Urbano, Elk, Gismo, and Heron. However, these online sources have two drawbacks: a lack of up-to-date footprint information, and no consideration of the fluid nature of slum architecture. For this study, the second option of collecting dwelling footprint data from the local Bangladeshi government survey institute (BBS) in .shp and .csv formats was used to import data in ArcGIS pro for processing. Hourly weather data 'BGD_Bangladesh/DH_Dhaka/BGD_DH_Tejgaon.TMY', originated from the US Department of Energy was used for the simulation analysis.

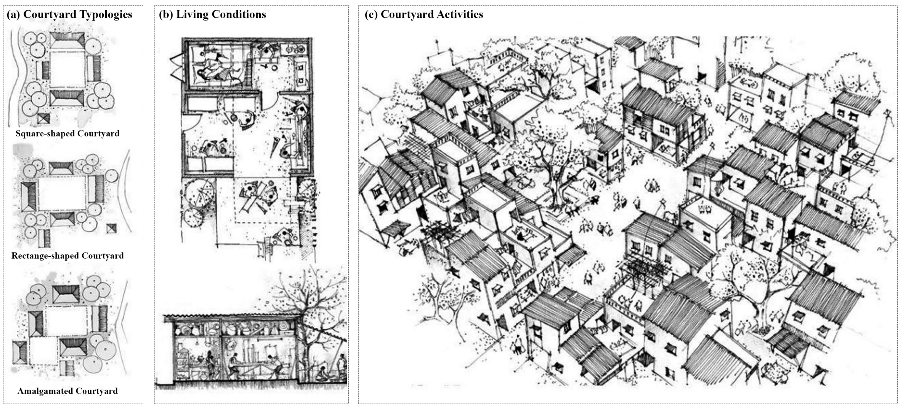

Figure 3. Vernacular housing cluster and courtyard patterns in Bangladesh; (a) courtyard typologies, (b) living conditions, and (c) courtyard activities (Source: Zahir, 2017).

3.2. PARAMETRIC CLUSTER FORMATION

The standard container dimensions were obtained from industry literature and verified on locally available shipping containers in Bangladesh. The number of container houses per cluster was considered following local regulations for standard living measures in affordable housing. A physical survey of 350 families showed that an average family consists of 4-6 persons, and about 200 people live in one cluster in the case area. To model the cluster, one of the three common types of courtyards in Bangladesh, which is the ‘Amalgamated courtyard’ (Figure 3) was considered. In this research, the typologies for the cluster are the single tier to give every family access to the courtyard.

Figure 4. (a) Urban layers, (b) site context, and (c) hybrid typology placed in the existing site.

The hybrid parametric model was developed in the Rhino-Grasshopper platform considering the design variables, which were measured in the multi-objective optimization process. The design variables were: window-to-wall ratio (WWR_North/South/East/West), window height, windowsill, orientation, and shading depth. The range of these design variables was determined through locality survey in the urban wetland areas and location regulations (Table 1). The median value of each variable’s range was considered for the base proposal geometry to compare with the most optimal options.

Table 1. Initial value for the base model and design variables ranges.

	Variables	Initial Value	Range	
			Minimum	Maximum
V1	Shading depth (m)	0.375	0.25	0.5
V2	WWW_North (m)	0.4	0.1	0.7
V3	WWR_West (m)	0.4	0.1	0.7
V4	WWR_South (m)	0.4	0.1	0.7
V5	WWR_East (m)	0.4	0.1	0.7
V6	Window height (m)	1.35	0.7	2
V7	Window sill (m)	0.75	0.5	1
V8	Orientation (degree)	90	0	180

3.3. MULTI-OBJECTIVE OPTIMIZATION PROCESS

A Pareto-front algorithm was considered in this study for the MOO process, which determines the bargain within multiple outcome objectives (Evins, 2013). In this study, multiple outcome objectives - Useful Daylight Illuminance (UDI) and Energy Use Intensity (EUI) - were considered to be optimized for acquiring the insights regarding the best possible options and determining the impact of design variables on the solutions. UDI is measured through the proportion of the number of useful hours to the total yearly occupied hours. EUI is the sum of annual heating, cooling, equipment, and illumination loads. Therefore, a lower EUI value is ideal as it designates a lower energy requirement; and a greater UDI value is wanted as it points to an increased usage of available sunlight. Along with these two outcome indices, the envelope construction cost is another crucial element that stakeholders need to consider. To properly calculate and identify the optimal results, the total cost was analyzed for each iteration using the following formula:

$$\sum C_{\cos t} = C_{wall} + C_{r\infty f} + C_{flr} + C_{glz} \tag{1}$$

For CHS, material properties play a critical role in the optimization process. As an uncommon material for the context, steel is more sensitive to microclimatic impacts of high-density urban wetlands. Therefore, customized CHS material properties were fed into the simulation process to generate more accurate predictions. An average insulation thickness of 12.5 cm was used and kept constant for the entire series of iterations. For the MOO process, the initial cohort's populace extent was 50, meaning 100 design resolutions are arbitrarily nominated from all choices. The termination criterion was considered for this research, which denotes the maximum number of the generation. The limit generation was specified as generation 8. The algorithm randomly selected about 775 solutions from the present population.

3.4. VISUALIZATION

Co-design via immersive media can transform how architects and stakeholders design future places, mainly where vernacular architecture and socio-cultural factors are important (Vosinakis et al., 2018). Tools such as Mindesk and Enscape allow experts to navigate, manipulate, and design in VR with a high level of immersion and enable designers to interact with and modify 3D models of buildings. Few tools exist which empower underprivileged users with technologies to facilitate their design input for prospective eco-friendly dwellings (Chowdhury & Schnabel, 2020).

This paper proposes a parametric VR structure, which caters to future dwellers of these container units. The occupants have unique personal insights and contextual knowledge about their spatial preferences. However, they do not have the technical or design background to use complex computational tools like Grasshopper and Revit. Therefore, the system uses the optimized 3D models that resulted from the MOO simulations as input and moves the model to an immersive customization phase in a VR environment. Here, the user interacts with the container unit where variables that modify its spatial qualities have been pre-determined. The opportunities for design were split into three major categories of variables: interior, exterior, and communal.

Interior variables enable the user to partition spaces, select finishing materials, add and move built-in furniture, and modify lighting options. Exterior variables permit the user to choose paint colors and local cladding materials and manipulate vegetation parameters. Last but not least, the communal assets include the ability to add and modify the placement of gathering areas, leisure spaces, and other shared assets (Figure 5).

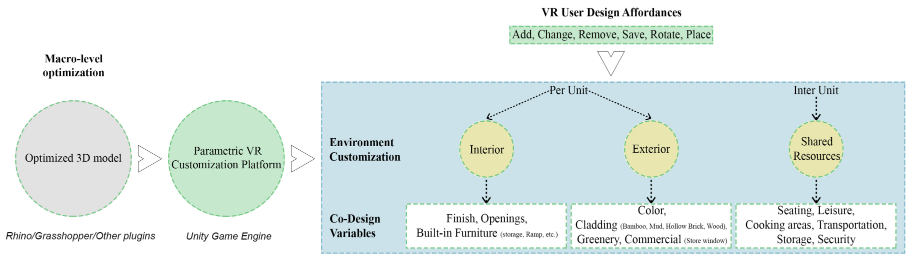

Figure 5. Parametric VR workflow.

This tool aims to address socio-cultural values as an essential aspect of sustainability. If users maximize the functionality of individual units, then this portion of the framework can enhance the efficiency of the units. This is achieved by incorporating the occupants' needs and knowledge into the proposed unit design. The opportunities that VR brings with increased immersion and presence to the participatory design arena is supported by this application (Figure 6).

Figure 6. VR immersion and participatory design.

4. Results & Discussion:

A Pareto optimization aims to find the trade-off front (Pareto-front) between multiple outcome objectives. The Octopus plugin handled the MOO process using Pareto-front algorithms. A scatterplot was generated grounded on the optimization data composed by the iterations in Octopus (Figure 7), in which one individual data point denotes one design option. Due to the eight used predictor variables introduced above, the results are more complicated, and it may be difficult to interpret by measuring scatterplots only. Therefore, parallel coordinates coupled with scatterplots were plotted to analyze the data exported through the TT Toolbox plugin for Grasshopper.

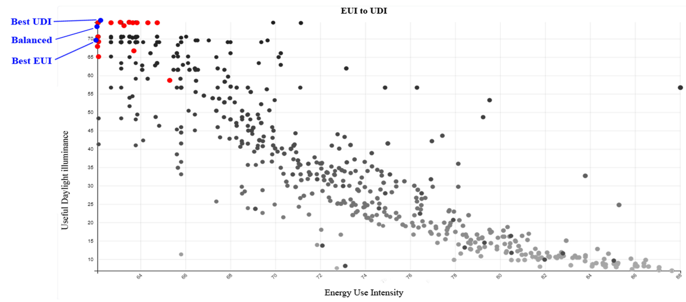

Figure 7. Pareto-front plot for multi-objective optimization.

The data points marked in red are the non-dominant results, which show the optimized products combining UDI and EUI simultaneously. Among several non-dominant optimized options, two optimal options based on EUI, UDI, and one balanced Pareto-front model were bunched in the information plot. Hence, their conduct and shapes demonstrate significant resemblances.

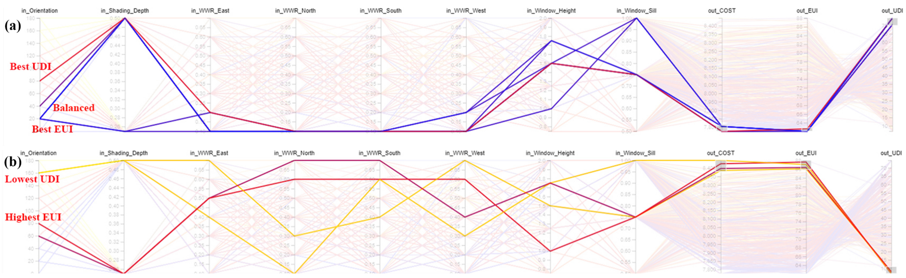

Figure 8. (a) Parallel coordinate plot to show the relationship between optimal solutions, (b) lowest UDI-Height EUI plot.

The low glazing ratios at the South and West walls are the main reason why EUI is reduced. Yet, the highest EUI and lowest UDI are seen by the higher WWR_South and WWR_West. It is worth noting that the iterations with the least energy use have a much lower WWR at the South without reducing useful daylighting. This is caused primarily by orientation, shading depth, and window height. However, the arbitrary distribution on the plot shows it has no impact on EUI. One assumption was that greater window height would be desired for the container's metal envelope to achieve lesser EUI, which was not observed as this results in greater EUI - a surprising finding for a CHS. The results further show that a window height range of 0.75-1.5 meters is satisfactory, and a windowsill at 1 meter provides a more optimal solution than a windowsill at 0.5 meters.

Even though a balanced model balances daylight use and energy consumption, this option is more expensive than the other non-dominant optimized option. This means cost should be another outcome objective in this process to find a better-balanced model. For the base model comparison with the optimized model, the initial values were calculated as one of the optimized Pareto-front models. After inputting the achieved values, greater UDI by about 29%, lesser EUI by about 17%, and lesser costs were achieved, as seen in Figure 9.

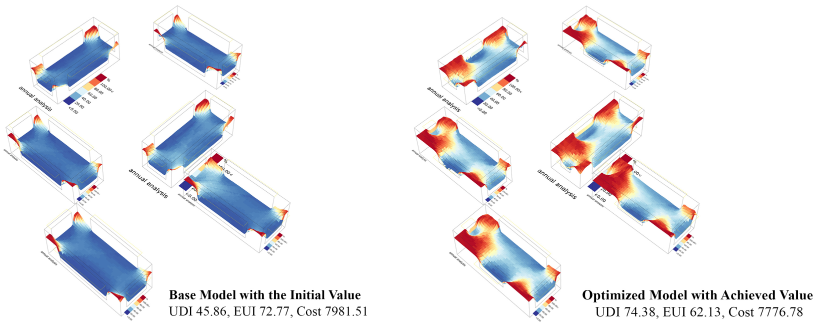

Figure 9. Comparison model of the base model and the optimized model.

Ongoing research and testing are focused on transferring the optimized clusters onto the VR design parametric environment. Special consideration is placed upon creating parametric materials and spatial labeling tools. By maximizing iterative design alternatives and keeping stakeholders engaged in the design process, the virtual environment takes advantage of prior research in this area and VR as a medium for design. (Hopfenblatt & Balakrishnan, 2018).

5. Conclusion:

The purpose of this research was to propose a computer-aided parametric envelope optimization and immersive visualization framework that can measure the most appropriate container cluster options considering sustainable measures. The envelope optimization method was implemented through multi-objective optimization algorithms. Moreover, the immersive visualization process focused on feedback-based customization of the optimized options keeping the stakeholders in the loop. This paper applied the framework to the Korail slum in Dhaka, Bangladesh as a case study.

During this application, several drawbacks of the framework were identified. For instance, more design variables such as insulation thickness and glazing type require consideration. Additionally, outcome objectives such as thermal comfort, airflow, and outdoor courtyard comfort can further enhance the design. Lastly, computing time is another major limitation that can be solved if other intelligent algorithms like Artificial Neural Network (ANN) could be incorporated for more accurate sampling prediction with a higher number of predictive iterations. The use of multiple simulation platforms and plugins adds to the overall processing time. Other limitations include the time required to develop customized VR design tools. Furthermore, a generalized system that is implementable into any project would be appropriate. This approach is more adaptable as such a device can address multiple projects involving multiple cultures, building typologies, and incorporate other problem areas if required. Additionally, advanced technologies such as Mixed or Augmented Reality may provide an improved platform for participatory design since they offer real-world interaction in addition to rich digital content.

The novelty of this research lies in its approach towards the parametric simulation considering the environment and economy for a CHS. Also, feedback-based design through immersive visualization to achieve socio-cultural aspects in the selected context has not been undertaken before. The future scope of this research indicates a more resilient living condition in informal settlements in the urban wetlands.

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