B. Dave, A. I. Li, N. Gu, H.-J. Park (eds.), *New Frontiers: Proceedings of the 15th International Conference on Computer-Aided Architectural Design Research in Asia CAADRIA 2010*, 185–194.

SHAPING BUILDING VOLUMES THROUGH LIFE CYCLE COSTS

A constraint programming approach for building volume optimisation

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Abstract. Due to a general freedom in the architectural design process, a wide range of possible alternatives exist; although building-volume designs must also continue to meet numerous, possibly conflicting design requirements originating from various related disciplines. This research addresses problems associated with missing quantitative design aids during the early design stages. It aims to provide designers with solutions that provide optimal cost-effectiveness. The demonstrated building-volume optimisation model minimises life cycle costs by determining optimal-volume dimensions, floor number, building orientation and 'window / wall' opening ratios while satisfying site and building code regulations and design constraints. Results indicate an optimal solution can be found within a practical timeframe. The proposed, novel approach to introduce cost objectives into building-volume design provides designers with a valuable decision support tool in a design domain that is known to be complex owing to multiple design criteria and constraint influences.

Keywords: Decision support; design optimisation; building volume design; life cycle costs and constraint-based design.

1. Introduction

The presented research focuses on the development of a decision support tool for a building-volume optimisation (BVO) model by considering life cycle costs (LCC) as a design objective. The model embeds exterior constraints for building volume design such as site criteria, building code regulations and suggested floor-area boundaries. These are associated with relevant cost declarations over a given study period. Thus, the BVO model not only guarantees constraint fulfillment that determines building volume validity, but also allows an insight into the relationship between building volume design and its relevant costs.

Using a constraint programming technique, BVO through life cycle costs has been established and investigated. The visual, three-dimensional display of optimal or feasible test-result solutions allows for the establishment of a more effective understanding of the BVO model results.

2. Literature review

Scientifically, the design process is understood to be a procedure involving problem definition and solution finding (Rittel et al., 1973). Hence, a common methodology during the architectural programming phase is to develop a design by describing the objectives of what it is expected to be accomplished and by establishing constraints marking possible solution limitations (Gross, 1985). When considering design as a computer-based process, design objectives are often excluded from an automated approach. Instead, processed design solution alternatives remain for later consideration and evaluation by the designer.

Donath and Gonzales (2006) introduced a "building-bulk" design support using a constraint-based, design-declaration method. Likewise, by introducing a "massing-study support," used with a commercial software package, Donath and Lobos (2008) attempted to find feasible solutions by implementing criteria-satisfaction in their approach to solving building design problems. Both methods guarantee a possible design remains within a feasible, theoretical building volume; however, they do not define objectives of how a generated solution could be improved.

An exception to this lack in implementing design objectives was presented by Sowa and Hovestadt (2008). In their research, a "digital support for strategic planning" was proposed, during which the design process for building volume-generation and evaluation could be automated. This proposed method, based on employing existing, reliable data through case-based reasoning helped to define design objectives and allowed design solutions to be generated and improved through evolutionary algorithms.

The intended evaluation and reduction of LCC during the early design stage can be seen as a major economic improvement since design decisions made in the early phases of architectural design are significant, irreversible, and can only be changed later at very high cost (Cherry, 1990). One important aspect when considering LCC is the increasing significance of continuous operation costs over a project's running time, as the percentage of total expenditure steadily increases compared to initial investment at project commencement. However, a major difficulty can be seen in cost establishment during this stage, as it requires either extensive evaluator experience and / or a sufficient database of existing, comparable building information (Leifer et al., 2004).

The implementation of constraint programming (CP) techniques into design-criteria definition and evaluation has recently been introduced to architectural design (Lömker, 2007). One CP advantage is the wide variety of possible constraints including disjunctive, relational, explicit, unary and logical (Hillier et al., 2005). The much greater flexibility in expressing problem constraints greatly increases the ability to more accurately formulate valid models for complex problems such as architectural design. Although, CP is ideally suited for highly constrained problems without an objective function, procedures for finding optimal solutions can be implemented as well when incorporating integer-programming techniques.

Thus, this proposed BVO model has the advantage of implementing design improvement based on financial objectives associated with initial constraint satisfaction of building-volume design. The demonstrated method to optimise building volumes using LCC objectives therefore represents a novel and significant contribution to this effort.

3. Methodology

3.1. BUILDINGVOLUME OPTIMISATION (BVO) MODEL

Unlike common representations of rectangular volumes using width, length and height definitions, building volume in the proposed optimisation model is defined through a rectangular floor-area unit per floor and its perimeter length indicating its exterior surfaces per floor. Though the current setup of the BVO model is based on singular rectangular floor areas, it generally allows setups using combinatorial floor areas per floor as well. The three-dimensional building-volume characteristic is implemented by stacking floor areas on top of each other. The model's advantage can be seen in that it not only satisfies building volume dimensional constraints itself, but also constraints that relate to usable floor-area limitations. Additionally, the separation of building volume into floor areas and exterior surfaces provides significant model data for LCC diversification of individual cost members within the optimisation objectives. This setup, using a floor-area unit per floor, also allows later implementation of optimisation solutions such as floor-area zoning and multi-level floor space layouts.

The BVO model development as a computer-aided design tool is based on optimisation techniques used in operation research. An optimisation model describes a mathematical model that attempts to optimise an objective function without violating resource constraints (Bazaraa et al., 2004). Consequently, the BVO model can be described through its objective function, decision variables and constraints. The complexity of the BVO model can be seen in the computational effort to search for optimal solution based on non-linear objective function and constraint definitions.

3.2. OBJECTIVE FUNCTION

The objective in finding an optimal building-volume design is based on finding the lowest LCC over a study period. For the proposed BVO model, the following cost members have been integrated based on their direct influence on building-volume properties: Construction Costs (CC), Energy Costs (EC), Operation and Maintenance Costs (OMC), and Repair and Renovation Costs (RRC). Thus, the objective function can be stated as:

$$\textit{Minimize}: LCC_{PV} = CC_{PV} + EC_{PV} + OMC_{PV} + RRC_{PV} \tag{1}$$

The subscript "PV" declares that each cost is understood as a present value (Ruegg et al., 1990). Since all members represent real costs appearing during the life-cycle period, all cost members are treated equally. Therefore, the objective function represents the summarised building cost expenditure to be minimised.

3.2.1. Cost specification

In addition, a separation into individual cost constituents per area unit, categorised into horizontal and vertical building elements is proposed.

The construction costs (CC) during early architectural design stages are based on cost estimation. While different cost estimation models are in practice, the most common approach is to calculate construction costs via a predefined cost per floor-area unit. To allow for more accurate feedback, cost estimates can be more rigorously established by separating specific building elements. In this BVO model, a separation into individual construction costs per area unit for the following building elements is proposed: foundations, floor areas for lower, medium and high floor levels, roof areas and exterior surface areas (façade).

For simplification and comparison purposes, actual annual energy costs (EC) can be determined via local electricity cost per KWh and the electric use of HVAC system, lighting and appliances. The activation of building elements is achieved through separation into floor areas and exterior surfaces, including individual window to wall opening ratios per orientation.

The operation and maintenance costs (OMC) can be defined through annual cost estimation. Similarly, to be effective, OMC needs to be established by consequently breaking occurring costs into respective building elements. For example, for higher floor levels, OMC are expected to increase due to increasing vertical infrastructure demands.

Repair and replacement costs (RRC) gradually increase over time due to aging. Typically, these are not indicated annually, but instead over a predefined time. Further, RRC estimation is defined as repair or replacement of individual building system parts. Therefore, RRC calculation depends on earlier assumptions as to when certain building elements will require repair or replacement. While building parts are not directly represented in the BVO, RRC reference is limited to horizontal and vertical cost constituents at a predefined time.

3.3. DECISION VARIABLES

Decision variables in the BVO model are building-volume determinants and are the dimensional representatives of a rectangular floor-area unit per floor. Each unit is defined through its two dimensional position in a Cartesian coordinate system, width and length, along with floor level reference.

Floor-area unit location and expansion on the ground floor level is limited through property constraints. Floor-area units on the following upper levels are primarily restricted in location and dimension by the floor level below. The geometrical model in figure 1 demonstrates an adaptation of an existing space layout problem (Medjodoub et al., 2000), where topological and dimensional constraints have been developed to limit space units.

An additional set of decision variables is required to determine building-façade. The opening ratio is measured between window and solid wall openings on exterior surfaces, separated by their orientation. The ratio determines the amount of openings allowing solar gains through interior spaces. However, while individual openings in the exterior wall need to relate to interior spaces, the opening ratio is theoretical in nature. Therefore, results of an optimisation run are not made visible in later visualisations of the processed BVO solution.

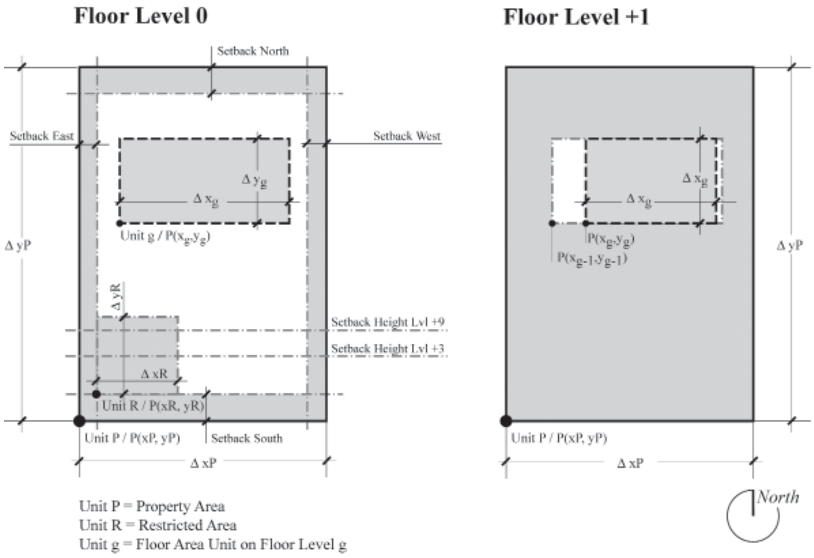

Figure 1. Area units per floor, their location on the ground floor and the following upper floor level.

3.4. CONSTRAINTS

Constraints on the proposed BVO model, guaranteed volume design remains within the theoretical volume. These constraints are defined through regulations originating from building codes, local ordinance and site-specific declarations (Donath et al., 2008), as well individual design intentions. These regulations constitute the search space of the optimisation problem in which the optimal building-shape configuration is to be found. The constraints have been organised into three categories: Property, Topology and Design Constraints.

The following property constraints: "Force to Inside Constraint, Force to Outside Constraint" and "Force to Border Constraint" have been adapted from earlier research concerning space layout problems (Medjodoub et al., 2000; Michalek et al., 2002). In reference to the building volume optimisation model, these constraints are used to define allowable floor-area unit on the ground floor. Additional property constraints are:

- **Setback Regulation Constraint,** limiting the property area according to distance regulations on ground and/or at different height levels,
- **Building Line Constraint,** forcing a building orientation to a specified building line, mostly for building attachment purposes,
- **Site Coverage Ratio,** guaranteeing that only an allowable percentage of the property is to be covered by the planned building volume,
- **Buildable Floor-area Ratio,** limiting total building floor area volume below

an allowable percentage for the specified property, and

- **Building Height Constraint,** ensuring the building height remains under a specified height limitation.

Regarding topological constraints, consecutive floor levels are primarily regulated by the Force to Inside Constraint, guaranteeing that increasing floor level units remain within the boundary of the floor unit below.

Finally, design constraints mostly limit dimensional expansion of rectangular floor-area units. Existing constraints are width, length, width to length ratio and perimeter. Additional design constraints are:

- **Total Floor-Area Constraint,** guaranteeing building volume remains within an earlier defined, allowable range,
- **Building Depth Constraint,** guaranteeing floor-areas receive sufficient natural lighting, the constraint is used on the ground floor level only, and
- **Opening Ratio Constraint,** preventing the search space from increasing unnecessarily, a boundary range, based on designer experience and/or expectation is foreseen.

4. Implementation

To solve this optimisation problem, the software application 'ILOG OPL Development Studio 6.1.1,' an optimisation package, was used in combination with 'Processing.' an open-source programming environment for data presentation and visualisation. For the experiments, specifications regarding construction and electricity costs, as well as climatic and solar radiation data were employed in reference to Bangkok, Thailand. Further, a medium sized, quadratic shaped property was defined, allowing medium to high-rise building volume up to a given building height. Additional property regulations, including setback definitions at increasing height levels and prohibited building area were included. A two-year construction period and a 30-year operation were assumed.

The results in figure 2 demonstrated that an optimal solution could be found with an average running time of less than three minutes, when the range for the allowable building-volume opening ratio was limited beforehand to 40–60%.

All generated solutions remained within theoretical building-volume boundaries, satisfied all constraints and demonstrated continuous improvement in the objective value. Each test run resulted in 15 to 35 feasible solutions.

The resulting visualised solutions illustrate how dimensional changes in building volume led to a continuous LCC improvement. In the demonstrated example, the following building volume improvements during the optimisation process have been documented in figure 3. From the first feasible solution until solution 13, the objective value improved through the optimal distribution of floor areas and exterior surface area reduction. Solution 14 improved due to the reduction of one floor level. Then, similar to the earlier process, the amount of floor areas and exterior surfaces were consolidated. Solution 25 represents another significant change in the optimisation process in which building orientation changed from north–south to east–west. Finally, the

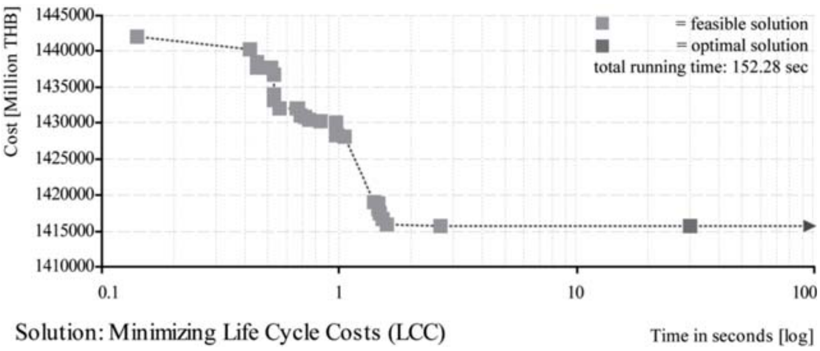

Figure 2. Objective-value solution time for all feasible and optimal solutions found when minimising life cycle costs.

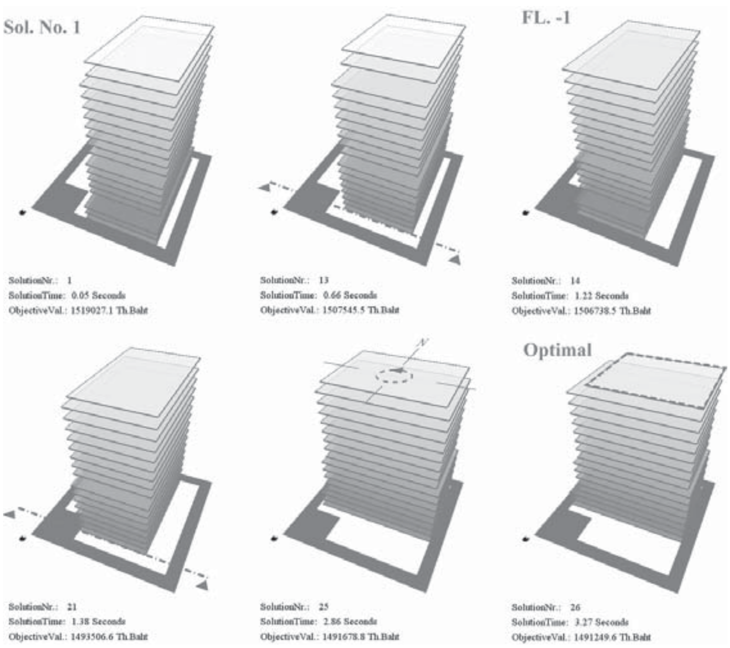

Figure 3: Feasible and optimal solution selection (26) found when minimising life cycle costs.

optimal solution (#26) slightly improved over its successor by decreasing the top floor perimeter, reducing its exterior surface area.

5. Analysis

The proposed BVO model allows designers to investigate building volume dependencies regarding building costs and volume shape. Studies of feasible building volumes indicate a general tendency to generate compact building shapes affiliated to volume design primary cost factors. In construction cost terms, this mainly derives from cost diversification into building floor-areas and exterior surface areas. While floor areas are constrained by lower and upper boundaries, cost minimisation can be primarily achieved through optimal floor-area distribution over available floor levels and exterior-surface area reduction.

The BVO model therefore endeavours to calculate a compact quadratic building volume. A similar tendency can be seen when inspecting energy costs individually, where heat conduction and radiation play an important role. In a tropical climate such as Bangkok, a primary building volume design goal can be seen in reducing exterior surfaces due to continuous exposure to a hot and humid outdoor environment. By considering solar gain only, a reduction in exterior surfaces oriented towards east and west was prioritised in the optimisation process due to solar radiation on these exposed plains. Similarly, the opening ratio, indicating the opening amount and thus influencing solar gain tends towards the need to decrease openings on surfaces exposed in east and west orientations. The results proved that optimal building volume shapes not only depend on a combination of individual cost members, but on individual property constraints and their requirements as well.

Besides LCC, a multi-objective approach achieved through goal programming technique was implemented and tested. The strategy to increase building floor areas could be seen as a more realistic approach, where not only cost minimisation dictates building design but also usable floor area maximisation. Its implementation led to design solution findings that combined cost minimisation with interior floor-area maximisation.

One critical aspect of the demonstrated BVO model can be seen in the quality of the feasible and optimal solutions found. The search algorithms strategy is to find an optimal solution, if it exists. However, the feasible solution findings that were uncovered do not represent a complete set of solutions, nor do they guarantee a possible variety and quality of alternative solutions. With this in mind, and to allow designers a more investigative decision support, a population of solutions that are near to optimal should be made available.

6. Conclusion

The BVO model demonstrates an applicable approach for designers to not only attain a deeper understanding of quantitative design options through constraint definition, but also the ability to strive for meaningful design solutions with respect to optimised building information such as LCC assessments. Its results can provide designers with insight into dependencies between building volume and building costs. The visual display of optimal and feasible solutions employing the demonstrated method allows designers to successfully understand design-optimisation impact and to integrate it into an effective decision support mechanism.

Although the rendered BVO model guarantees the generation of building-volume based on single, rectangular footprints, to allow for a more realistic investigation, ongoing research is concentrating on investigating combinatorial formations of rectangular geometries. Similar to allocation problems, such as space layout design, running time for an optimisation problem is expected to increase significantly.

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