# Optimization-Assisted Building Design

## Cases study of design optimization based on real-world projects

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*Computational design optimization has been widely considered a promising technique to help designers address complex design challenges regarding building performance. However, a barrier to applying it to real-world projects is the difficulty in incorporating functional requirements and constraints into the design optimization process. In response, this study presents an optimization-assisted design approach for early-stage architectural design. The approach combines the application of EvoMass, an integrated building mass design generation and optimization tool, and the soft constraint strategy. The combination allows designers to integrate various design requirements and constraints into the optimization, which makes it produce results with higher practical values. To demonstrate the efficacy of the approach, two case studies are presented, which show that the application of optimization facilitates designers to better formulate the design problem and rapidly investigate different design directions for exploration and information extraction.*

**Keywords:** *Generative Design, Optimization, Design Exploration, Design Process, EvoMass, Computational Design, Building Performance.*

## INTRODUCTION

Building performance has become a prominent concern in early-stage architectural design in response to the goal of sustainable urban development, and many architects have begun to adopt the performance-based design approach in their design practice. An important responsibility for architects is to explore alternative design possibilities and compare the performance of these solutions in order to obtain more significant performance improvements. However, when this exploration is conducted manually, time restraints in real-world projects often limit the scope of architects' design exploration, which also makes early-stage design exploration both time-consuming and challenging. The capacity of computational design optimization to assist architects in early-stage design exploration has been demonstrated over the last decade by research advancements in the use of computational design optimization in architecture. Computational design optimization can automate the design generation and exploration process by combining parametric modeling, performance simulations, and optimization algorithms, freeing architects from the time-consuming trial-and-error process of finding high-performing solutions.

### Background

In research, the use of computational design optimization in architectural design has been noticed frequently. Many research studies have been undertaken over the last decade to apply it to architectural design challenges with varied performance targets such as wind environment

(Chronis et al., 2011), sunlight (De Luca, 2017), and energy consumption (Yi & Malkawi, 2012). However, the application of computational design optimization in early-stage architectural design is still quite limited in practice. One of the reasons for this is the dilemma between design effectiveness and variability. This is because function-related design requirements often introduce conflicts with the optimization of building performance, and existing applications of computational design optimization in architectural design are often unable to reconcile both building performance and functional requirements at the same time.

On the one hand, encoding the design requirements as hard-coded rules in the parametric model provides a simple way to avoid generating invalid designs that do not satisfy functional constraints (Janssen, 2005; Wang et al., 2016). This method guarantees that the design obtained by the optimization is valid. However, hard-coded restrictions decrease the parametric model's design variability, limiting optimization to a relatively limited scope for high-performance solutions. Furthermore, hard-coded rules impose unnecessary limits on parametric models, reducing their reusability for other design tasks.

On the other hand, some applications placed more emphasis on design variability and adopted flexible design generation approaches such as free-form (Yi & Malkawi, 2012) and voxel geometries (Si & Wang, 2015). While the design flexibility of these approaches allows the optimization process to examine a large range of design possibilities with considerable changes, the lack of limitations often results in solutions that do not match functional requirements or design codes.

### Paper overview

Considering the limitations of the previous studies, this paper presents a study focusing on the application of computational design optimization to real-world architectural design projects. The study is based on two design cases, in which EvoMass, a building mass design generation and optimization tool in Rhino-Grasshopper (Wang, Chen, et al., 2020a) is used. EvoMass provides more flexibility to be adapted for diverse site conditions and to optimize the design for different performance targets than other building design generating algorithms created for specific design jobs. Over the past few years, EvoMass has been applied to a variety of design tasks and has shown its advantages in assisting designers in early-stage exploration and information extraction.

While previous applications have demonstrated the potential of EvoMass in solving various architectural design tasks, these applications often fell short of the consideration of real-world design constraints related to design specifications and functional requirements. In this regard, this study further exploits the potential of EvoMass in more realistic design scenarios and proposes a design approach incorporating EvoMass with other soft constraint strategies. This approach enables designers to rapidly explore different directions to gather information about the design problem. In addition, the use of soft constraints allows designers to specify various functional requirements during the optimization process. The combination of these two components achieves an optimization-assisted design approach that encourages designers to interact with the computer for co-evolution and human-in-the-loop design.

The proposed approach was developed during our design of two real-world projects where design codes and provisions imposed strong restrictions on the application of the computational design process. Hence, this paper uses these two projects as case studies and demonstrates how the proposed approach can be applied to the design process. As such, one major contribution of this study is to examine and demonstrate the utility of EvoMass in more realistic design scenarios.

## OPTIMIZATION-ASSISTED DESIGN

This study aims to explore the potential of computational design optimization in architectural design, with an emphasis on how optimization can assist designers in design exploration involving functional requirements. As stated above, the approach is based on Rhino-Grasshopper, which makes it easier for design practitioners to use it. Technically, the approach is achieved by using EvoMass and other performance simulation tools such as Ladybugs and ClimateStudio. Regarding requirements related to design codes and regulations, the approach uses soft constraints to transform these requirements into penalty or award functions that navigate and guide the optimization process.

## Design approach

Compliance with design rules such as setback and spacing is one of the most crucial, yet time-consuming, duties for architects. More recently, increased demands for the environment, sustainability, and people's health and well-being have added to the design challenges, making simulation an imperative in design routines. As a result, trial-and-error design processes using simulation verification are becoming increasingly common in most design firms and offices (Figure 1 top). Such design approaches limit the designer's ability to explore numerous design possibilities during the fast-paced conceptual design stage because there isn't enough time to verify that each design option fits all performance goals as well as functional needs and restrictions. Therefore, it is typical to see that designers will soon delve into a specific design scheme and then focus on subtle adjustments to the design to meet all requirements, resulting in the designer's inability to coordinate all aspects of the design as a whole.

The above-mentioned limitations highlight the need for agile and rapid design exploration that allows the designer to investigate different directions at the outset of the design process. In this regard, design optimization can be used to substitute designers' work on design tweaking and code compliance. With this approach, designers can be relieved from repetitive routine tasks and devote more effort to design exploration and ideation. In other words, the computer becomes a co-designer, actively searching for high-performance but also satisfying the design needs of the human designer. At the same time, the human designer reflects on the solution produced by the computer and iteratively indicates a new or more detailed direction for the computer to further explore (Figure 1 bottom). As such, a feedback loop between designers and computers is established.

## EvoMass

EvoMass is the core component in the proposed optimization-assisted design approach. On the one hand, EvoMass's reusability allows it to be applied to a variety of design jobs, relieving the designer of the burden of parametric modeling and speeding up the

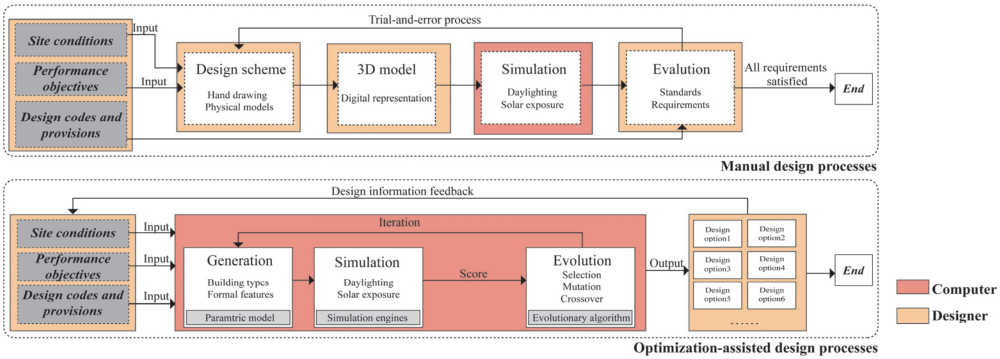



Figure 1
Comparison between manual design and optimization-assisted design workflow

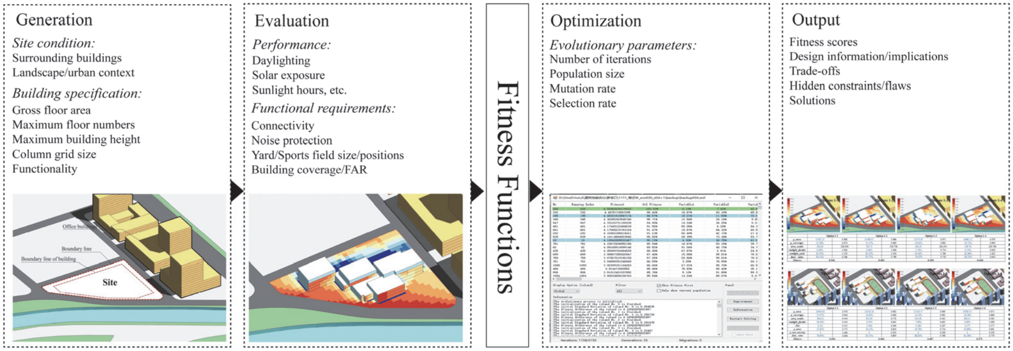



Figure 2
Demonstration of the design workflow

design process. When using EvoMass, designers can customize the generated building design with various user-defined parameters. The design variability of EvoMass, on the other hand, allows the optimization to actively respond to changes in the design target and optimization objectives.

In EvoMass, two generative components encode the subtractive and additive form generation principles respectively (Wang, Chen, et al., 2020b). Because of the geometrical freedom inherited by these two concepts, the produced designs have a lot of topological variety. In addition to the design generation, EvoMass also includes an optimization algorithm called the steady-state island evolutionary algorithm (SSIEA) (Wang, Janssen, et al., 2020). SSIEA integrates an island-based approach and a steady-state replacement strategy into an evolutionary algorithm. The island-based approach subdivides the design population into multiple subpopulations, each guided to focus on different regions in the design space, which is aimed at increasing the diversity in the design population. The steady-state replacement strategy aims to exclude inferior designs from the design population more rapidly, compared with the generational replacement strategy. Thus, this strategy facilitates the fast convergence of the optimization process and shortens the time for the optimization. The combination of the two strategies in SSIEA ensures optimum efficiency and effectiveness when using EvoMass.

## Soft constraints and design workflow

The use of EvoMass lays the foundation for the applicability of the proposed optimization-assisted design exploration, and previous studies have shown that combining EvoMass with other performance simulation tools can enable effective building design optimization for performance improvement. However, employing EvoMass alone is insufficient to produce desirable solutions that satisfy both the demand for improved building performance and functional restrictions. Thus, further intervention is a necessity for the effective application of EvoMass to practice. In the proposed design approach, soft constraints are adopted to establish communication between designers and computers. Soft constraints have been proved to be effective to navigate the design optimization process and compel the optimization to search for the design satisficing various input objectives and constraints (Chen et al., 2022).

By combining EvoMass and the soft constraint strategy, a human-in-the-loop design workflow can be established (Figure 2). In this design workflow, designers first customize EvoMass to regulate the building mass design generation and specify performance objectives and functional constraints for the design optimization. Regarding design optimization, a single-objective optimization mode is used in this approach, where performance objectives and functional constraints are integrated into a fitness evaluation function using weight-product approaches. This study does not apply Pareto optimization to handle multiple objectives since the Pareto set can contain too many options, which could impede designers' information extraction and pattern recognition. The design feedback, from the optimization, can stimulate the designer to further adjust the optimization objectives or design constraints in order to explore other alternative directions. In comparison, such iterative design workflows are often absent in most relevant studies due to the inflexibility of the design tool. Thus, this study can also provide examples of how to apply optimization to realistic design problems.

## CASE STUDY

Two case studies, one for a kindergarten and the other for a primary school, are presented to demonstrate the viability of the proposed design method. Both design tasks are based on real-world design projects that require consideration of a variety of functional requirements and constraints. Moreover, the presented case studies also reflect our actual design process in dealing with these issues.

Regarding the kindergarten design, this is the first task where we applied EvoMass to a real-world design project. Thus, this case study demonstrates how we become aware of the problem in a routine application of computational design optimization and how we applied the soft constraint strategies to coordinate the requirements of performance improvements and functional constraints.

Regarding the primary school design, we learned from the kindergarten design and incorporated multiple functional constraints at the beginning of the design process. In this case study, we applied the workflow to quickly explore two different school planning layouts to test the feasibility of the design.

### Kindergarten design

The project is located in Nanjing, China, and the kindergarten is required to have 15000 $m^2$ with a maximum floor number of four. As shown in Figure 3, there are several high-rise office buildings on the east of the building site, which produce noticeable context shading on the kindergarten site. Since sunlight accessibility is an important factor in kindergarten design, the context shading can cause a critical design challenge for this project.

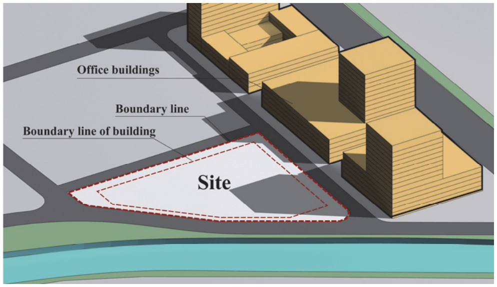



Figure 3
Site condition of the kindergarten project

For the design generation, the user-defined parameters will be set based on common architectural design parameters. The column grid spacing is set to be 6 and 4 (meters) in the X and Y directions; the maximum floor number is four with a 4.2 m floor height.

Considering the design objective, we first target to maximize the sunlight accessibility of the building and the kindergarten yard/playground for outdoor activities. According to the Kindergarten Design Code, nursery units must have at least two hours of direct sunlight from 9:00 to 15:00 on the winter solstice, and more than half of the yard must enjoy more than three hours of direct sunlight. In order to calculate the proportion of the building façade surface and the area of the yard that cannot match the above-mentioned requirements, we translate these two requirements into two performance indicators. As a result, the optimization goal is to reduce the value of these two indicators.

For the optimization, we use the weight product approach to integrate the above evaluation into a single-objective design evaluation function. Figure 4 illustrates the four optimized designs selected from the optimization results. These four design options show a shared tendency that the building spreads alongside the southwest edge of the site in order to maximize its sunlight. In addition, due to the context shading, the northeast corner of the building site is left empty as this region has the least sunlight accessibility.

While these designs effectively address the sunlight accessibility and solar exposure issues, the problem is that these designs typically have a large proportion of the building volume on the fourth floor. The reason for this is that the higher the floor, the less sunlight is blocked by the surrounding structures. These design solutions also reveal a trend to extend the west façade to boost afternoon solar exposure in order to maximize sunlight accessibility. Excessive solar exposure to the west, on the other hand, may cause the building to overheat, increasing the cooling load in the summer.

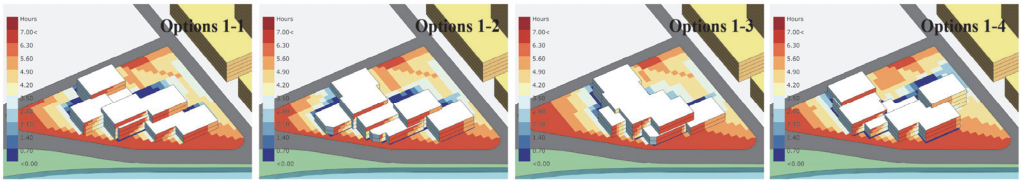
By reflecting on the flaws in the optimized designs, we further added three additional constraints to the optimization. First, we calculate the floor area ratio from the first to the third floor with respect to the GFA of the whole building. Because only the first three floors are accessible to children, this criterion decides whether the first three floors have enough space to accommodate all of the nursery units.

Second, we change the measurement of the sunlight accessibility of the building. We only include the façade surface below the fourth floor in the second stage to avoid the fourth floor's influence on the design results.

Third, maximizing the south-facing façade area is included in the optimization to avoid the design with a smaller south-facing façade area. This constraint is important because it is easier for the design with a smaller south-facing façade to achieve a higher proportion of façade surfaces with sufficient sunlight accessibility. Such designs, nevertheless, have little practical value as only a few nursery units can have south-facing windows.

With the modification of the design evaluation, the performance metrics for the second design optimization run are summarized in Table 1. On this basis, the second optimization run is conducted. Figure 5 demonstrates the result of the optimization. It is worth noting that the inclusion of additional functional metrics has a significant impact on the optimization results.

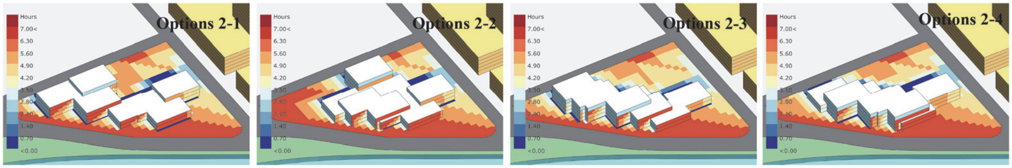
Compared with the results of the first optimization run, the optimized designs of the second optimization run have higher practical value for the subsequent design development. While, in general, the building is spread alongside the southwest edge, changes in the measurement of sunlight accessibility force the design to elongate further along the east-west direction to enlarge the south-facing façade. In addition, the overall building volume is also lowered compared with the optimized design found from the previous optimization result. This provides more space for the designer to arrange the nursery units. However, due to the enlargement of the building massing, the sunlight accessibility of the kindergarten yard is reduced. Hence, these two optimization runs also provide clues to the trade-off between the sunlight




| | Option 1-1 | | Option 1-2 | | Option 1-3 | | Option 1-4 | |
|---|---|---|---|---|---|---|---|---|
| *p_area:* | 15185.25 | 0.988 | 14789.07 | 0.986 | 15373.87 | 0.975 | 14682.52 | 0.979 |
| *p_coverage:* | 32.38% | 0.970 | 31.47% | 0.984 | 28.62% | 0.985 | 30.72% | 0.994 |
| *area_south:* | 326.04 | 3.260 | 310.75 | 3.107 | 261.05 | 2.611 | 329.76 | 3.298 |
| *sunlight_facade:* | 0.00% | 1.000 | 0.00% | 1.000 | 1.74% | 0.754 | 0.53% | 0.856 |
| *sunlight_yard:* | 83.43% | 1.519 | 80.52% | 1.450 | 85.63% | 1.760 | 81.66% | 1.622 |
| *floor_ratio:* | 83.11% | 0.788 | 83.27% | 0.790 | 78.67% | 0.719 | 88.23% | 0.814 |
| *Fitness:* | **0.542** | | **0.483** | | **0.450** | | **0.436** | |

Figure 4
Selected high-performing designs from the first optimization run

Figure 5
Selected high-performing designs from the second optimization run




| | Option 2-1 | | Option 2-2 | | Option 2-3 | | Option 2-4 | |
|---|---|---|---|---|---|---|---|---|
| *p_area:* | 14468.61 | 0.965 | 15052.71 | 0.996 | 14994.34 | 1.000 | 14998.27 | 1.000 |
| *p_coverage:* | 32.85% | 0.962 | 34.86% | 0.929 | 29.88% | 1.000 | 29.17% | 0.992 |
| *area_south:* | 384.33 | 3.843 | 341.76 | 3.418 | 320.73 | 3.207 | 345.75 | 3.458 |
| *sunlight_facade:* | 0.00% | 1.000 | 0.00% | 1.000 | 0.00% | 1.000 | 0.00% | 1.000 |
| *sunlight_yard:* | 80.33% | 0.494 | 82.48% | 0.543 | 83.14% | 0.558 | 80.73% | 0.502 |
| *floor ratio:* | 94.03% | 0.816 | 94.26% | 0.816 | 83.31% | 0.790 | 83.33% | 0.790 |
| *Fitness:* | 1.404 | | 1.370 | | 1.370 | | 1.360 | |

accessibility of the building and the yard.

In summary, the first case study demonstrates a design process that echoes Schon's reflective practitioners (Schön, 1992). In this presented design process, a *moving-seeing-moving* process emerges. Compared to the manual design modification process, the modification in this case study depends on the definition of the optimization problem. Therefore, it is foreseeable that the designer can identify more constraints in the design and adjust the objectives and constraints in design optimization by continuing the reflective design process.

Table 1
Optimization objectives of the first case study

| Optimization objectives | Target value | Abbr |
|---|---|---|
| gross floor area | 15000m$^2$ | *p_area* |
| building coverage | 30% | *p_coverage* |
| south façade area | maximize | *area_south* |
| The proportion of the building façade with less than three hours of sunlight accessibility | minimize | *sunlight_facade* |
| The proportion of the yard area above three hours of direct sunlight | >50% | *sunlight_yard* |

## Primary school design

The second case study describes a primary school project also located in Nanjing, China. As shown in Figure 6, the building site of the project is surrounded by several high-rise residential towers on the west and south, and there is a middle school on the east. According to the design brief, the target GFA of the school is 25000m$^2$.

The Primary School Design Code, like the kindergarten design, stipulates that the school has adequate sunlight accessibility and natural daylighting. Furthermore, as compared to kindergarten design, primary school design must take into account noise reduction and communication between classrooms and other amenities. Therefore, based on the optimization objective defined in the kindergarten project, we include three additional factors.

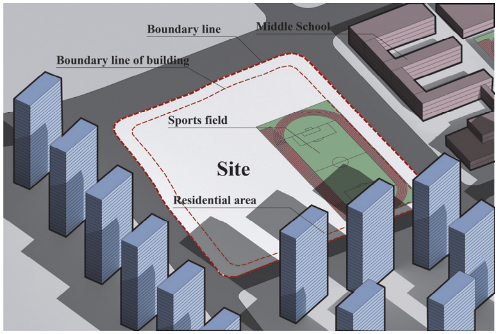
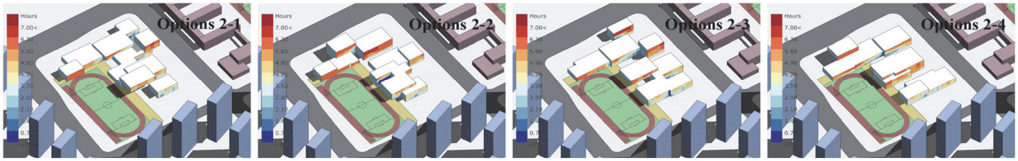



Figure 6
Site condition of the primary school project

| Optimization objectives | Target value | Abbr |
| --- | --- | --- |
| gross floor area | 25000 $m^2$ | *p_area* |
| Building coverage | 25% | *p_density* |
| south façade area | maximize | *area_south* |
| Similar to the first case study | minimize | *sunlight_facade* |
| Spatial Daylight 8 Autonomy | maximize | *sDA* |
| Noise from the sports field | minimize | *p_noise* |
| number of massing | 1 | *p_num_massing* |
| floor area ratio | >75% | *floor_ratio* |

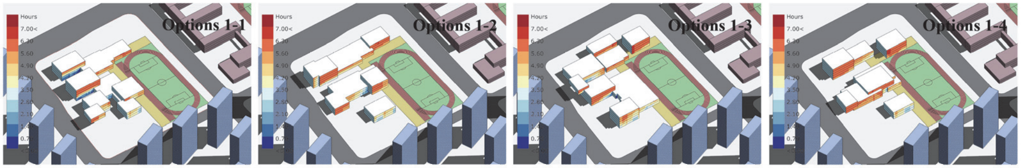
Table 2
Optimization objectives of the second case study

First, spatial daylight autonomy (sDA) determines the daylight accessibility of the building, which indicates the proportion of the interior spaces that can have sufficient daylight. Second, sports fields are frequently the main source of noise in primary schools. Therefore, a buffer zone around the sports field is defined, and the overlap area between the buffer zone and the building is calculated to measure the indoor space that is more likely to be affected by the noise from the sports field. Third, in order to improve connection, the number of building blocks was evaluated, which shows the degree of separation between the buildings. Table 2 outlines the first case study's aims and restrictions, as well as the factors considered in the second case study's optimization. These variables are combined using a weight-product function, just as they were in the first case study.




| | Option 2-1 | | Option 2-2 | | Option 2-3 | | Option 2-4 | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *p_area:* | 24821.36 | 0.993 | 25224.83 | 0.991 | 25126.57 | 0.995 | 25171.15 | 0.993 |
| *p_coverage:* | 25.55% | 0.996 | 21.38% | 0.950 | 23.10% | 0.977 | 24.48% | 0.996 |
| *area_south:* | 785.16 | 7.852 | 904.08 | 9.041 | 924.48 | 9.245 | 843.24 | 8.432 |
| *sunlight_facade:* | 14.07% | 0.457 | 13.58% | 0.463 | 7.46% | 0.559 | 4.13% | 0.647 |
| *sDA:* | 0.481 | 0.281 | 0.579 | 0.379 | 0.560 | 0.360 | 0.526 | 0.326 |
| *p_noise:* | 24.79% | 0.752 | 27.62% | 0.724 | 29.78% | 0.702 | 28.93% | 0.711 |
| *p_num_massing:* | 1 | 1.000 | 2 | 0.500 | 3 | 0.333 | 3 | 0.333 |
| *floor_ratio:* | 85.93% | 0.806 | 80.41% | 0.756 | 88.00% | 0.813 | 84.78% | 0.800 |
| *Fitness:* | **0.605** | | **0.407** | | **0.344** | | **0.333** | |

Figure 7
The layout result of the sports field in the southeast corner and the scores of various indicators (the four best designs)




| | Option 1-1 | | Option 1-2 | | Option 1-3 | | Option 1-4 | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *p_area:* | 24456.61 | 0.978 | 24538.26 | 0.982 | 25772.56 | 0.969 | 24380.13 | 0.975 |
| *p_coverage:* | 21.07% | 0.944 | 20.80% | 0.940 | 24.38% | 0.995 | 18.28% | 0.896 |
| *area_south:* | 844.42 | 8.444 | 856.99 | 8.570 | 846.08 | 8.461 | 848.15 | 8.482 |
| *sunlight_facade:* | 18.46% | 0.414 | 4.31% | 0.641 | 5.50% | 0.605 | 0.00% | 1.000 |
| *sDA:* | 0.512 | 0.312 | 0.564 | 0.364 | 0.497 | 0.297 | 0.577 | 0.377 |
| *p_noise:* | 22.81% | 0.772 | 18.13% | 0.819 | 27.65% | 0.724 | 30.89% | 0.691 |
| *p_num_massing:* | 1 | 1.000 | 3 | 0.333 | 2 | 0.500 | 4 | 0.250 |
| *floor_ratio:* | 76.84% | 0.648 | 85.35% | 0.804 | 81.11% | 0.766 | 81.38% | 0.770 |
| *Fitness:* | **0.504** | | **0.404** | | **0.407** | | **0.372** | |

Figure 8
The layout result of the sports field in the southwest corner and the scores of various indicators (the four best designs)

Aside from the optimization objectives and restrictions, the location of the sports field is also taken into account in this project. The location of the sports field in primary school design is critical in deciding the overall building layout, which can have an impact on the design's performance. As a result, two prospective locations were specified in order to explore the impact of the sports field on this design project, and the design parameters and limitations for the building mass generation were altered correspondingly.

Lastly, the column spacing in the X and Y directions is set to 12 and 8 (meter) in the design generation, which is based on the standard classroom dimensions; the maximum floor number is five with a 4.2 m floor height.

Figures 7 and 8 show the optimization results based on two different sports court locations within the building site. In general, placing the sports field on the southeast side (Figure 7) is more conducive to achieving better results in terms of overall fitness, and the corresponding design typically has higher sDA and sunlight accessibility. Taking both optimization results into account, it can be found that dividing the buildings into three rows is a viable building plan choice (options 1-2, 1-4, 2-3, 2-4). On the contrary, the designs with relatively higher fitness (options 1-1, 2-1) achieve better overall performance, typically due to connectivity. As all the building blocks are mutually connected, this feature benefits the accessibility of the design. However, it undermines the daylight and sunlight accessibility because of the mutual shading between the building blocks.

In this case study, the optimization facilitates the design exploration and allows the designer to investigate two different directions, and additional design exploration can be stimulated after the existing optimization runs. The use of optimization can help designers rapidly identify promising solutions or hidden constraints in the design, without which designers may need to spend more time and effort to find these solutions and constraints. Thus, the computer in this project acts as a co-designer that helps designers to delve into each design direction and provide feedback to designers' decision-making.

## DISCUSSION AND CONCLUSION

The two case studies show that the combination of EvoMass and soft constraint strategies allows for an iterative and human-in-the-loop design process assisted by computational design optimization. In the design process, the computer helps the designer conduct the tedious "number-crunching" for finding satisfying designs and code compliance.

The case studies also demonstrate the applicability of the proposed design approach to practical building projects. From the design perspective, EvoMass' capability of providing timely feedback and abstract design information is key to achieving its utility. In other words, the proposed approach is not intended to provide designers with definite solutions, but, instead, the result of the optimization is aimed at serve as a "medium for reflection" (Wortmann & Schroepfer, 2019).

To conclude, this study presents an optimization-assisted design approach for early-stage architectural design. As shown in the cases, the use of computational design optimization facilitates the designer's design exploration and information extraction. Moreover, in comparison to existing studies, this study is also focused on how to include functional requirements and constraints from the real-world project into the optimization process. The result demonstrates that the inclusion of these requirements and constraints makes the optimization produce results with greater practical values, which assists designers in rapidly identifying promising design directions and hidden constraints.

## ACKNOWLEDGEMENTS

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