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Building Massing Optimization in the Conceptual Design Phase

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ABSTRACT

Taipei is the most densely populated city in Taiwan. Land is very expensive and living environment is crowded. Evaluation of shadow of building allocation and building massing estimate are two most important tasks of an architect in the conceptual design phase. In this investigation, we have interviewed a senior architect at an architectural firm in Taipei and found that in the conceptual design phase, in addition to legal evaluations, combining structure with the floor area and being able to precisely estimate are currently the most important issues to achieve. In order to achieve this objective, this investigation is based on the dimensionless building-massing algorithm and the parameters for legal evaluation of building shadows are introduced into the optimization tool design. The optimization tool is subsequently combined with the genetic algorithm to build a building massing simulation system to simulate the optimal solution. Optimized result is able to locate the best location coordinates and derive an accurate floor area of the building. The result of this investigation is aimed at assisting architects in providing an accurate quantitative analysis of building massing in the design conceptual phase.

Keywords: Building massing, optimization, dimensionless, genetic algorithm.

1. INTRODUCTION

Architect proposing the optimal object measurement solution in the conceptual design phase is the key to a successful development. However, architects usually have insufficient information at this stage, thus making building massing optimization and allocation a difficult task. In accordance with the drawing level of details (LOD) [1] proposed by the American Institute of Architects (AIA) in 2008, the conceptual design phase is categorized as LOD100. In this phase, the architect should complete floor area calculation, cost analysis and solution evaluation. The BIM Handbook [5] defines the conceptual design phase as massing approximation. Chang and Shih propose to include building site analysis, and massing simulation [3]. This investigation proposes that legal limitation is another factor to be considered by an architect in the conceptual design phase.

The optimal solution in this investigation is to be able to derive a massing algorithm for maximum floor area and gross floor area. Building shadow analysis includes shadow length and area. These two legal items are constraints of building mass allocation. In order to investigate the feasibility of this algorithm, this investigation conducts a simulation of five frequently seen building mass types, which are rectangular, L-shaped, square-shaped, H-shaped, and U-shaped. In addition, according to the interview results in this investigation, architects use Excel to calculate the legal area. AutoCAD is used to draw 2D diagrams for legal evaluation. 3D MAX is used to simulate relationship between mass location and the environment, these methods and tools are used currently in the conceptual design phase in Taiwan. Whether or not the project is successful depends on the experience of the architect.

Investigation of rule checking method is also a very important topic in the recent years. Most countries in the world have already started developing BIM and applying BIM to rule checking of buildings [4]. However, rule checking is performed after evaluation of structural properties such as column, beam, block, wall, door and window upon building design completion and computation of safe walking distance of the building [10]. Rule limitations such as the external environment are less investigated. Software flow of the conceptual design phase is proposed in HOK [8], which states that BIM software is less used

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in conceptual design phase. This investigation concludes that conceptual design phase requires a rule evaluation method that can be linked to BIM Software Tool.

2. TOOLS AND METHODS FOR OPTIMIZATION SIMULATION

2.1. Dimensionless Grid

This research designs a building mass structure formed by structural components. Five frequently seen building mass types are optimized and simulated and the types are rectangular, L-shaped, square-shaped, H-shaped, and U-shaped. A set of parameters can be defined for each shape. A grid structure system develops the set of parameters. The grid structure system is used to calculate the fundamental dots. Any grid dot represents a structural column location. Each column location can be moved to any direction in the grid structure. Gap between the structural column locations describes the coordinates of each grid dot, forming a dimensionless grid system (as illustrated in the formation process shown in Figure 1). Unit of every type is applied to the dimensionless grid system to form a type calculation unit.

2.2. Genetic Algorithm and Simulation Tool

Genetic Algorithm is applied to building design optimization to formulate a method that is frequently seen. Past researches applied Genetic Algorithm to structural combination [7]), LEED energy efficiency analysis [2] and green buildings [14]. Optimization flows in these researches are generally the same. Ouarghi uses Neural Network to investigate building shape optimization together with Genetic Algorithm [11]. Daniel adopts DOE-2 and MATLAB to perform building massing parameter generation [13]. Renner's research method and structure is similar to this investigation but this investigation focuses more on optimized simulation of legal and mass allocation plan.

This paper uses Genetic Algorithm to design a set of simulation programs to be able to optimize and precisely estimate the building massing parameters. Genetic Algorithm uses a nature evolution concept to select good units for optimization, which subsequently converges into a best solution. Evolution unit of this research uses the dimensionless grid dot to describe the formation of mass units. This type of mass unit can be freely evolved into good and bad units. Its unique trait is the integration of free and flexible mass allocation to allow all evolution possibilities. Secondly, GA algorithm concept is integrated to generate mass unit parameters. Each mass unit can be mated to form a better generation. Finally, conditions of the building plan are added to form the most optimized solution that abides by the law after several evolutions.

Selection, Crossover and Mutation are the three phases in the Genetic Algorithm flow. This research defines the flow as follows:

1. Selection process:

Mass unit selection calculates good mass units using the legal condition formula. Legal condition formula in this investigation includes building shadow length, and shadow area. Building shadow length, and

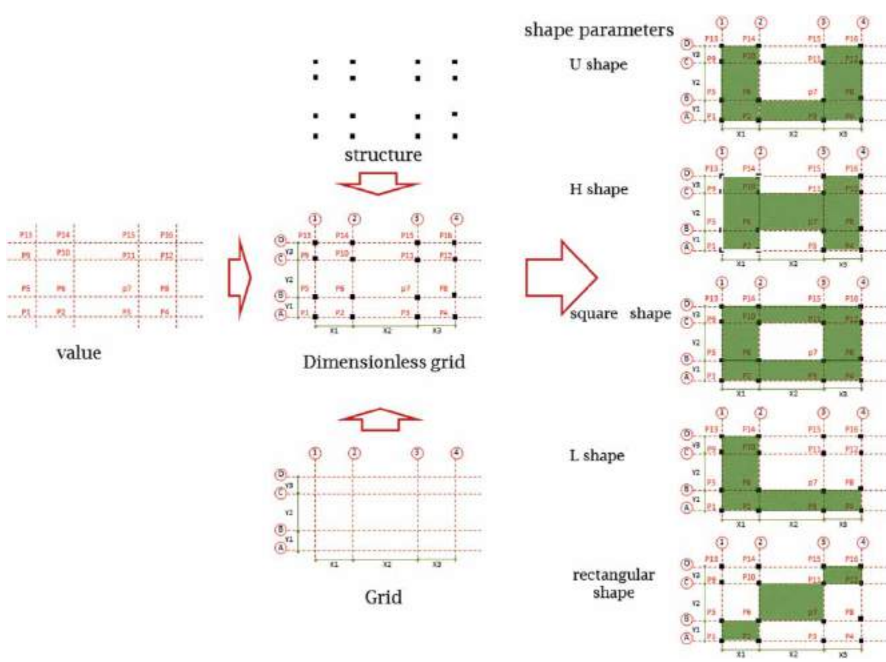


Fig. 1: Dimensionless Mass Unit Formation process.

shadow area are criteria for evaluating external environment. A good unit must pass these two criteria to ensure that new units can be evolved into good units of the next generation.

2. Crossover process

A good unit, upon selected, will start to perform cross comparison between maximum floor area of the building and gross floor area of the building. Area of every mass type can be freely selected and mated to derive mass location based on maximum floor area and gross floor area.

3. Mutation process

This is the last step of the evolution process serving to prevent early convergence of Genetic Algorithm and ensuring the ability of performing comprehensive checking computation. Direction of the grid dot movement is set to no specific direction at the beginning of computation and repeatedly computed with the structural unit. Every mutation will generate a mass close to maximum floor area until the optimal solution is found.

During the analysis of Genetic Algorithm Optimization, we have found that maximum floor area of the building can be fully utilized and at the same time overcomes the legal limitations. Architects, in the conceptual design phase, are able to precisely approximate mass area, solution allocation and component structure to reduce human judgment errors due to decisions made based on past experiences.

The parameters are defined based on the grid structure and added to the structure system with the x-y axial crossing being the column grid dot to form a dimensionless grid system. Finally, the grid variables are applied to each mass type to perform mass type simulation.

Figure 2 shows the basic characteristics and structure of the optimization environment in this research. This research uses Rhino to generate grid dots of mass unit and then uses Rhino's built-in Grasshopper software to generate an appropriate function (defined as legal condition function in this paper) for optimizing a simulation environment so as to ensure consistency between optimized data and simulated mass.

Grasshopper is a plug-in program in the Rhino Environment. Programs are written by various components. Galapagos Software tool is a simulation tool that has the Genetic Algorithm integrated in. Hence, when Grasshopper starts to generate various solutions, Rhino is then able to generate the mass solution locations. After Grasshopper completes algorithm program compilation, the program is then transferred to Galapagos software tool for simulation of the optimal solution of mass unit.

3. MASS PLAN AND EVALUATION OF LEGAL LIMITATIONS

This investigation focuses on a site being evaluated for development. The site is located in proximity to Xikou Elementary School in Ching-Fu Street of Wenshan District, Taipei City (Fig. 3). At the same time,

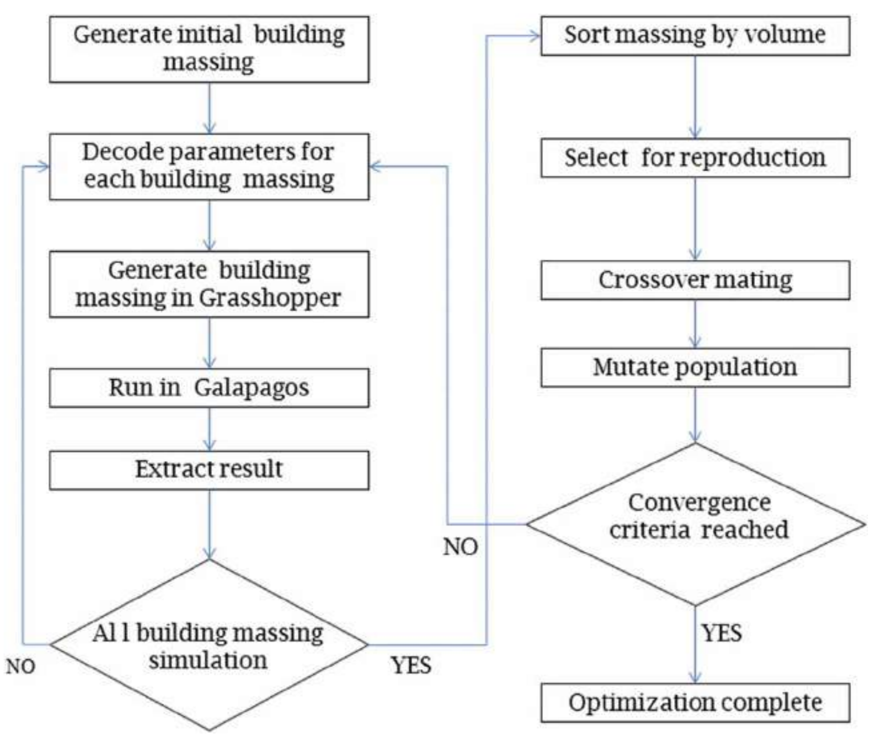


Fig. 2: Flow of Massing Optimization.

Fig. 3: Building Site. The widest road adjacent to the site has a width of 12 meters and the rest are 8 meters. It is a complete standalone site.

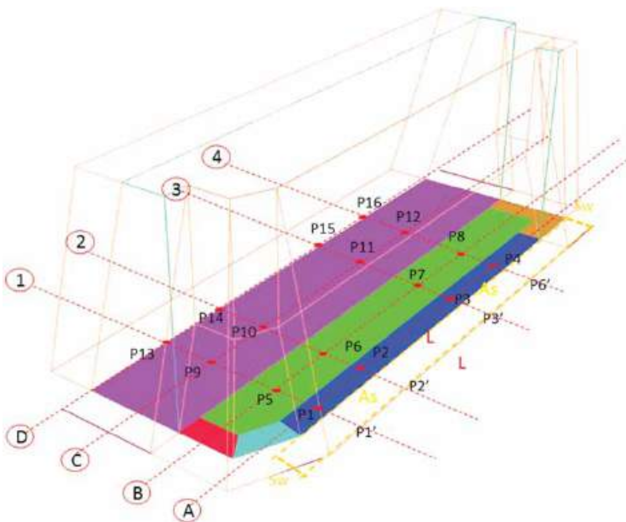


Fig. 4: rule checking Framework: Contents include the structural column plane and legal evaluation categories. 3D transparent frame represents the boundary of legal evaluation.

the site is the most-frequently seen Type-III Residential Land used primarily for residential buildings. This site is chosen because it is a complete standalone site with four sides adjacent to the roads. Each road must be constructed of a set of formula for legal evaluation. This type of site is suitable for constructing a complete legal system framework (Fig. 4). Architects, when performing mass allocation and floor area approximation, must take into consideration of factors such as number of floors, height of the building, maximum floor area, and gross floor area. External environment limitations of the site include building shadow length, shadow area and road width.

This simulation system designs the related algorithm formula based on the external environmental factors and then combines with the building unit structure system and the planned building space requirement to construct an overall evaluation system for optimizing legal limitation simulation as illustrated in Figure 5.

3.1. Mass Building Plan

In Taiwan, buildings with the number of floors exceeding 14 or a height over 50 meters are regarded as tall building by law, which is evaluated differently. Hence, architects, when performing massing evaluation, usually use 14 floors or 50 meters as the boundary for building massing design. This research investigates the algorithm for relationship between general building massing allocation and shadow regulation. Hence, number of floors and building height are defined as constant and fixed at 14 floors and 50 meters respectively and they serve as the basis for estimation of the floor area of the building.

1. Site Coverage Area

Maximum floor area refers to the total shadow projections of every floor onto the first floor of the building. It is called site coverage area. In Taiwan, the Site Coverage Area is regulated. The shadow projection area changes as the shape of floor plan changes. The system computation in this research requires a conditional function with limits. For example, the legal floor space ratio of Type-III residential area is 45% and the formula for calculating the maximum floor area is,

$$\text{Site Coverage Area} = \frac{\text{Max FA}}{\text{A}} \times 100\% \leq 45\% \qquad (1)$$

$$\text{Max FA} : \text{Maximum Floor Area}$$

$$\text{A} : \text{Site Area}$$

2. Gross Floor Area

Gross floor area of a building is the basis for quantitative analysis of building massing. The architect must confirm this task in the conceptual design phase. In Taiwan, developable floor area on each land is fixed and the land purchase cost is expensive. The building site in this research is the Type-III Residential Area in Taipei. Land cost is approximately between NTD 600 thousands and NTD 2.5 millions per square meter (varies according to the land location) [12]. Each square meter of land is almost equivalent to three square meters of floor area(1*225%*1.3 = 2.925 square meters). The legal floor area ratio of a building is 225%. The total floor area formula is,

$$\text{GFA} = \text{A} \times \text{V} \times \text{T} \qquad (2)$$

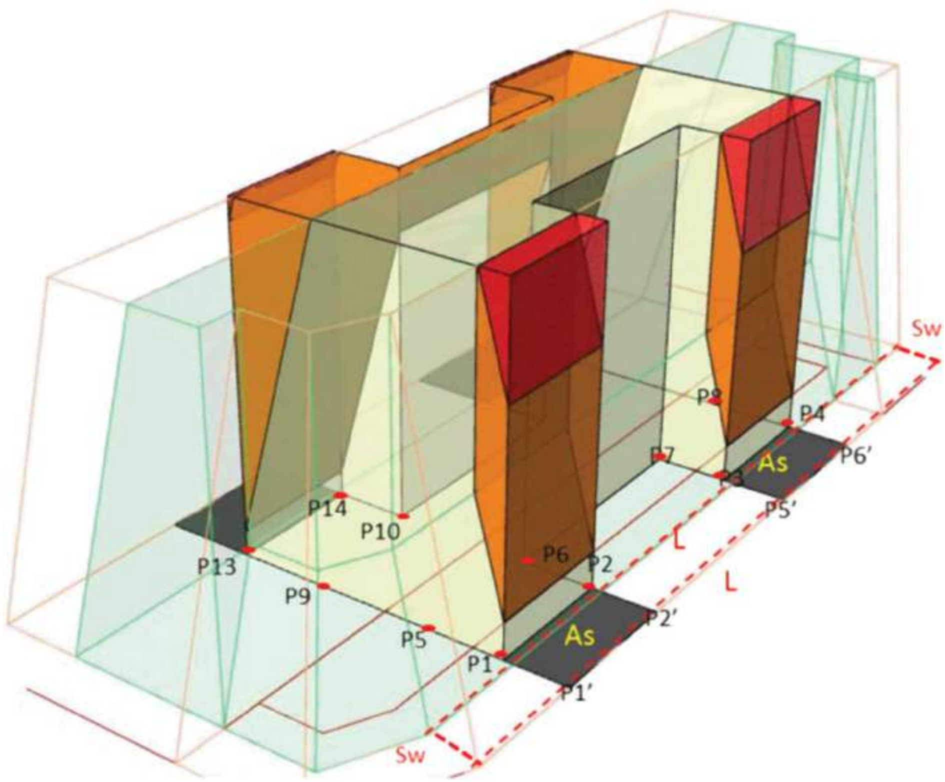


Fig. 5: Building Massing Simulation : Red mass of the simulation result represents bad mass, orange mass are masses requiring optimization, white mass are masses that does not require evaluation.

GFA = Gross Floor Area

A = Site Area V = Legal Floor AreaRatio

T = FAR-exempt Coefficient (Constant defined as 1.3)

3.2. Rule Constraints

1. Road Width and Shadow Evaluation

According to the Taiwan Construction Law & Regulation [9], the width of the road surrounding the building site affects the evaluation range of the building mass shadow within the site. The four sides of the site in this investigation are adjacent to roads, thus the widest road (SW1) will be the starting point for evaluation. Starting from the site boundary that is adjacent to the widest road (L1), the first shadow evaluation line (L1′) is set at 30 meters into the site. This is defined as shadow evaluation area of the primary road. Starting from the site boundary that is adjacent to the second widest road (CL2), the second shadow evaluation line (CL2′) is set at 10 meters into the site. This is defined as shadow evaluation area of the secondary road. The same principle is applied to find the third and fourth shadow evaluation line (CL3′ and CL4′). Four shadow evaluation areas, I, II, III and IV, can thus be constructed in sequence (Fig. 6). Those outside these areas are defined as non-shadow evaluation area, such as the area between L1′ and CL2′ in sections 1 and 2 as illustrated in Figure 7 and the area between CL3′ and CL4′ in section 3 as illustrated in Figure 7. The area formed by L1′, CL2′, CL3′ and CL4′ is defined as non-shadow evaluation area, such as V area of the shadow region as depicted in Figure 6.

Sections 1 and 2 in Figure 7 primarily describe whether mass allocation of shadow evaluation area meets the requirement of the legally regulated evaluation. Mass projection line of Section 1 has exceeded the road range, indicating an error in mass location. Section 2 indicates that the building mass within the site shall retreat by distance D at the minimum in order to comply with the regulation of massing solution. Section 3 indicates that the non-shadow evaluation area can be freely allocated without legal bindings.

2. Calculation of Building Shadow Length

Because the building height in this investigation is constant (H = 50), and Sw is the road width, the perpendicular distance (D) formed by the building mass and the road thus becomes a variable. Calculation of the building shadow length is to derive the most appropriate mass coordinates. In order to calculate D, the road width must first be calculated. In this investigation, the boundaries on the two sides of the road are defined as L1 and L2. From L2, two points, L1-1 and L2-1, are used to calculate the shortest road width. The mass base is the reference point and Pi (i = 1, 2,

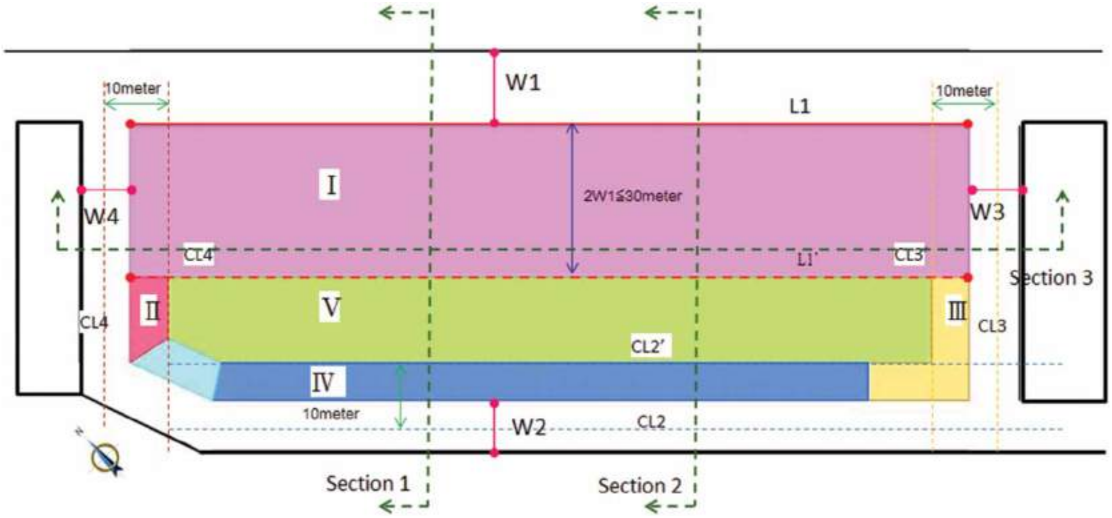


Fig. 6: Shadow Evaluation Regions in Building Site.

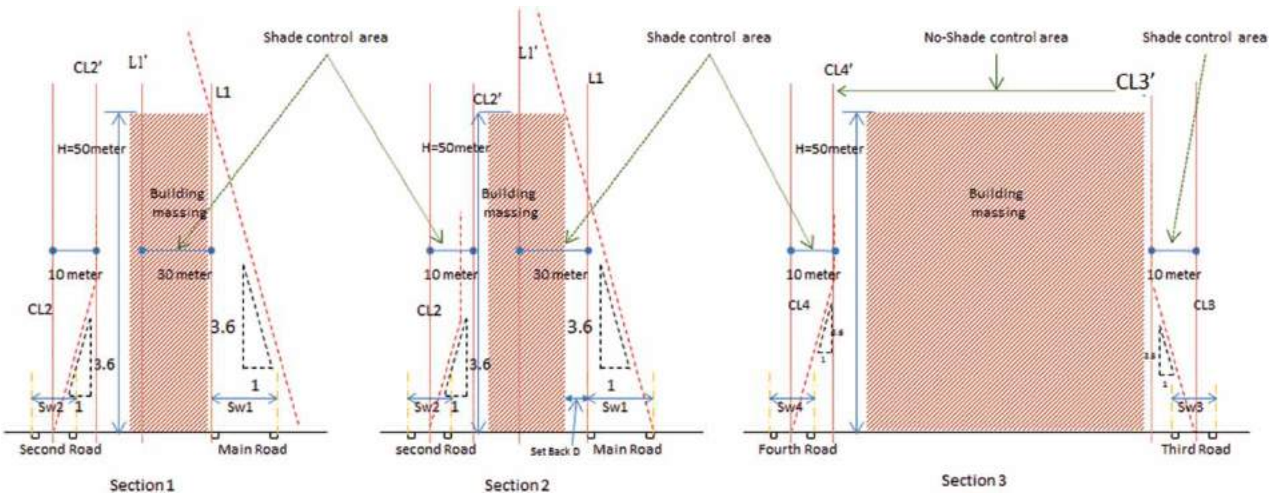


Fig. 7: Diagrams illustrating evaluation of relationship between road, boundary and retreatment

3, 4, 5) is defined as distances from L1-1. Condition of D is that it must be greater than 0. If D is less than 0, then the position of the building is outside the site area. In addition, coordinates of the mass top are Pi', Pi', Pi, and L1′-1, forming a trigonometric relationship with a slope of 3.6:1 in order to calculate the mass shadow length.

$$\frac{T}{H} = 3.6 \quad T = 3.6H \leq Sw + D \tag{3}$$

$D \geq 3.6H\text{-}Sw$ T : Building Shadow Length

H : Building Height

Sw : Road Width

D : Distance between Building Massing and Retreated Road

3. Calculation of Building Shadow Area

After all points of the building mass position are confirmed, each point will have a shadow length of 3.6H projected onto the building site and the road. A_S refers to the shadow area projected in the range of road. Hence, the boundary adjacent to the road is used as a criterion for calculating the area of the building mass shadow projected in the range of road. A_S is not allowed to be greater than half of the area of the road adjacent to the site.

$$As \leq \frac{(L \times Sw)}{2} \tag{4}$$

As = shadow area

L = Length of the road adjacent to site

Sw1 = Roadwidth . . .

4. DESIGN AND APPLICATION OF AN OPTIMIZED SIMULATION SYSTEM

4.1. Simulation System Design

4.1.1. Conditional Program Compilation

In this research, the grasshopper software is used to write a program for the formula of legal limitations. Mesh shadow component is used to design an evaluation line with a slope of 3.6:1, and derive the relationship for determining the slope of the evaluation line and various legally evaluated regions (Regions I, II, III and IV as depicted in Figure 6). Mass allocation will generate the corresponding shadow length and area according to different regions. Length (3) and area (4) formulae are subsequently written to form a legal evaluation framework. Automatic detection (Figure 8) is initiated after the architect configures the control variables of the building height (system sets the height to 50 meters in this investigation).

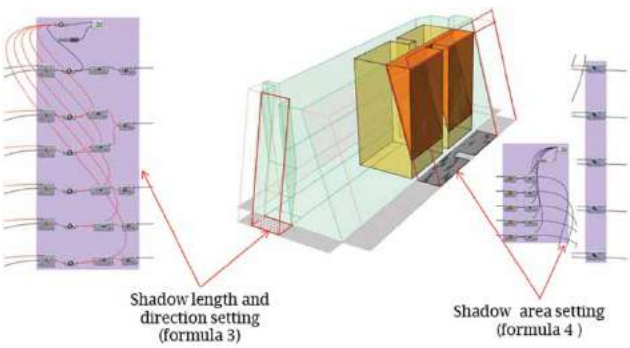


Fig. 8: Component Design Diagram for shadow length and area Programming using Grasshopper of building shadow.

4.1.2. Simulation Flow Establishment.

Flow of the system simulation is designed based on the current operation habits of the architects in the conceptual design phase. The flow includes four parts, building plan information establishment, generation of legal evaluation framework, mass unit calculation and optimization of mass area. Starting from the mass unit, the basic building plan information is embedded in the Grasshopper program (Fig. 10) and then placed in the legal evaluation framework to derive the optimal solution using steps of a three-stage Genetic (Fig. 9).

1. Building plan information establishment: This part includes derivation of formulae and parameters. Formulae include maximum floor area (formula 1), and gross floor area (formula 2); parameters include building mass height, number of floors, and site area. The system design of this research fixed the building mass height to 50 meters, the number of floors to 14 floors and the site area to 5471 square meters. According to the result of formula 2 calculation (5471*225%*1.3 = 16002), the Gross Floor Area has to be as large as 16002 square meters.

2. Legal evaluation framework: This part includes derivation of formulae and parameters of legally evaluated regions. Formulae include mass shadow length (formula 3), and building mass shadow area (formula 4). Parameters include road width, distance deviated from the road center, and shadow slope of 3.6:1. Road widths of the design in this investigation are 8 and 12 meters. Primary road width is 12 meters and the rest of three roads are secondary roads of an 8-meter width. Hence, the legal boundaries are the four retreatment lines forming a 3D evaluation framework.

3. Mass unit calculation: Unit selection is done using simulation of the legally-evaluated framework, which is able to quickly find legal and illegal masses. Good mass unit complies with the regulation. Good units are classified into central region and shadow

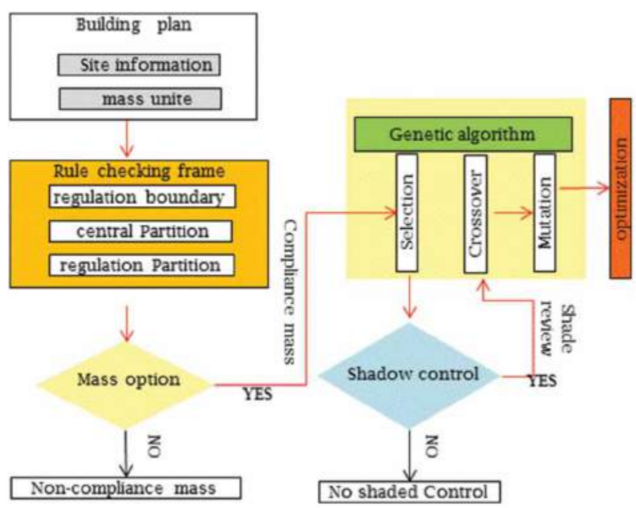


Fig. 9: Massing Optimization System Design Flow: Only mass units compliant to the regulation are allowed to enter the Genetic Algorithm Environment (Galapagos) to be remated for the optimal solution.

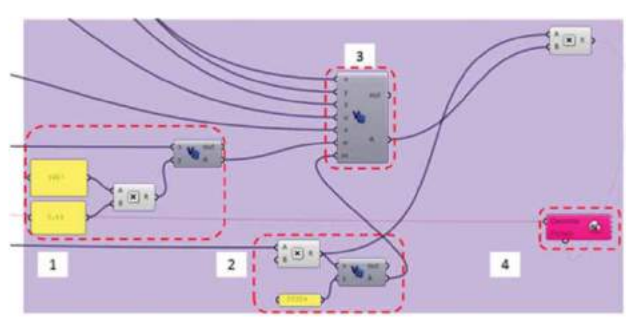


Fig. 10: Optimization Program Components are: 1: Building, 2: Maximum Floor Area, 3: Shadow Area and 4: Optimized Solution Parameters.

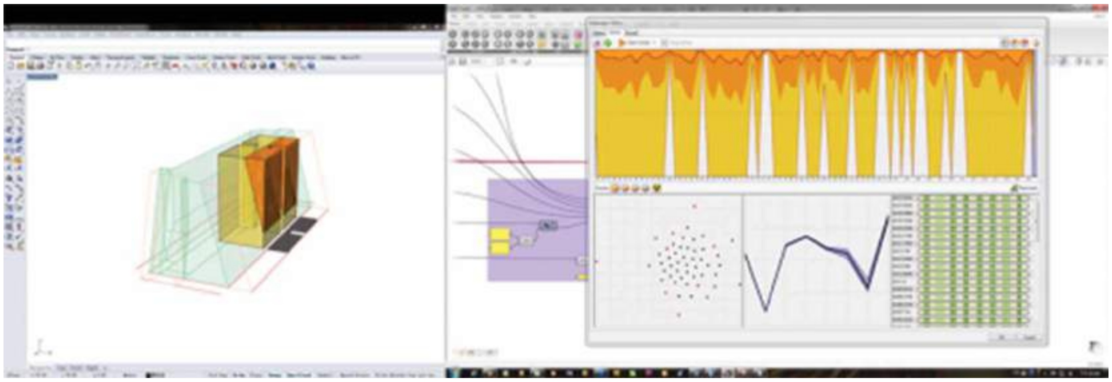


Fig. 11: Flow of Galapagos Optimization.

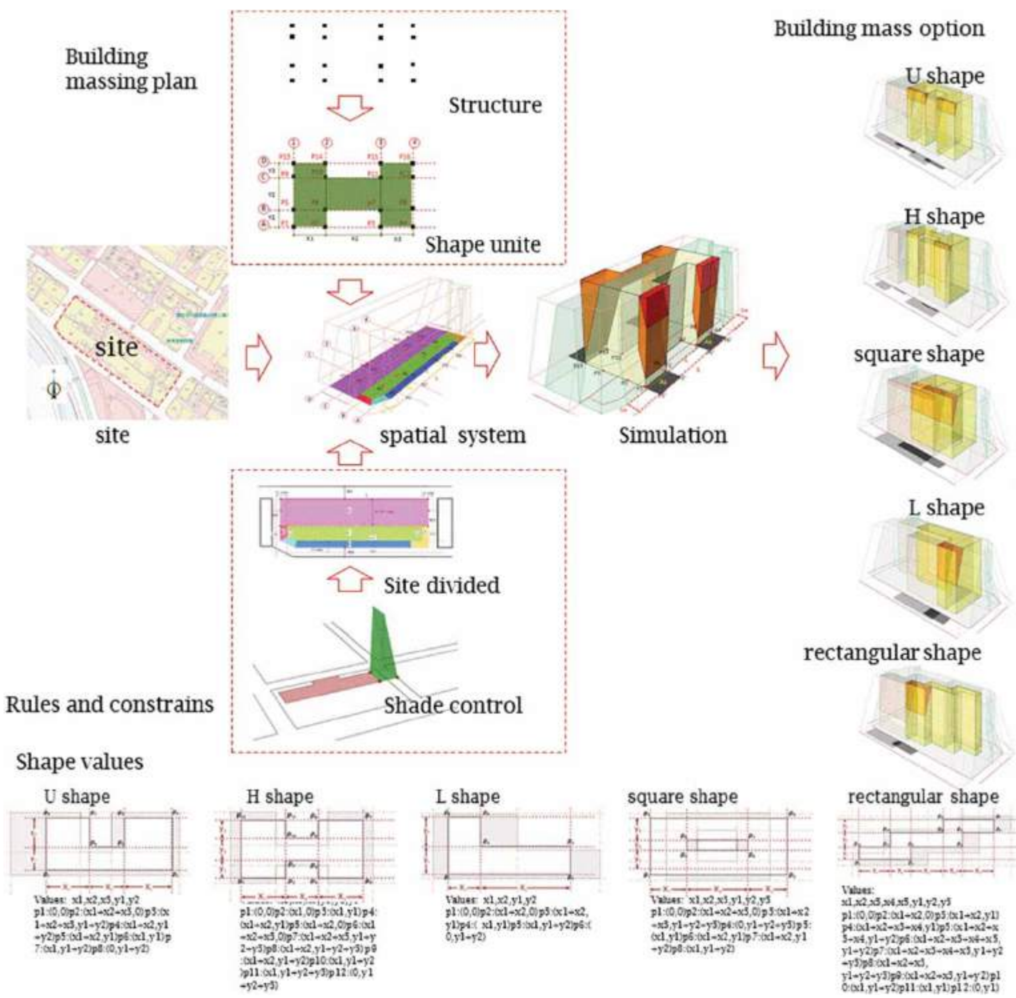


Fig. 12: Illustration Diagram of Massing Optimization System.

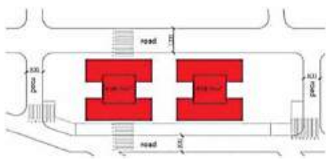
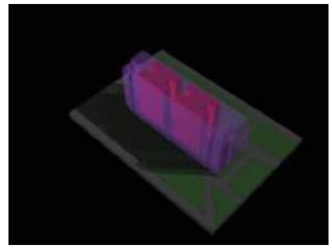
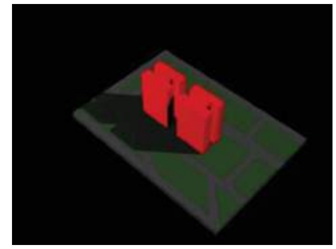
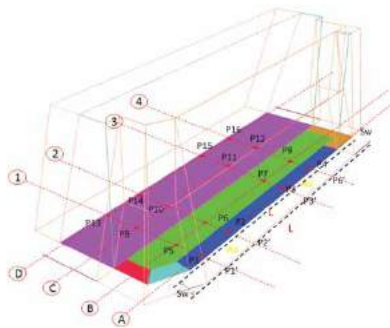
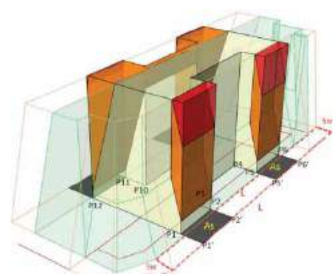
Notes

[1]Firstly, use Rhino software to construct a mass unit to generate a reference point.

[2]Subsequently use Grasshopper software to generate site parameters to ensure that mass can be freely moved around within the site.

[3]Bending points of the sides of each shape are the parameter-generated coordinates.

[4]Every side has at least one column gap or above. By incrementing the column gap, each parameter-generated coordinate on the x and y-axis can be described, such as (X1 + X2,Y1 + Y2).

Items	Legal Evaluation	Environment Simulation	Mass Approximation
General Design Flow	 2D Auto CAD	 3D Max	 Excel and 3D Max
Genetic Algorithm Simulation System	3D Legally Evaluated Framework  rhino	Building massing Shadow Simulation Analysis  rhino	Floor Area Calculation  galapagos

Tab. 1: Conceptual Design Software Application and Analysis.

evaluation region using the Genetic Algorithm according to the mass coordinates. Shadow evaluation region will be required to be adjusted of its allocation solution.

4. Mass area optimization: During the optimization process, only the shadow evaluation region is calculated, thus reducing the massing calculation variables. The region is re-mated (crossover) to derive the appropriate solution of maximum floor area and gross floor area. Galapagos software repeatedly reloads calculation by returning to the origin upon reaching the upper limit of the maximum floor area (as shown in Figure 11). Calculation is repeated together with structural units until convergence is achieved

4.2. Massing Simulation Operation

1. Shape Variable for Algorithm Analysis and Design Table

Shape variable is not equivalent to the number of grid dots. In order to reduce the number of shape variables, the necessary shape variables for every shape must be defined before simulation. Variable location calculation does not need to be applied to every grid dot. This research investigates five types of commonly seen residential buildings in Taiwan and their mass shapes are optimized. The calculation utilizes the same parameters and logic to perform matrix division of five different shapes. Different shapes will generate different numbers of variables (mass shape variables are listed in the table). Mass can freely change its size within the site and under the limitation of the condition. As shown in Figure 12, H-shaped mass can be divided into six column variables according to x1, x2, x3, y1, y2 and y3 and form 12 variable combinations. 12 coordinates, P1 ~ P12, are defined to form a variable H-shape.

2. System Simulation

The system simulation in this investigation is an overall evaluation system that combines building plan, structure system, site information and legally evaluated framework (as shown in Figure 12). Simulation process starts from the building structure. After the architect determines the mass column gap, the simulation system is then able to structure a simulated mass unit. The condition information obtained from the site can be used to configure parameters in the legal program of the system to form a legally evaluated framework. Mass unit can immediately provide the accuracy of the mass allocation result. Initial simulation results show that the approximated mass area

Items	Optimized Solution	Rule checking	Quantitative Analysis	Structure System	Solution estimate	Required Time
General Design Method	3D Max cannot perform precise data analysis.	2DAutoCAD labels 3.6:1, relationship between shadow and mass retreatment.	Excel is used to calculate maximum floor area and gross floor area.	Cannot estimate the system structure.	Cannot precisely estimate; must reserve 3-5% for adjustment (approximately 480 square meters for 3%).	Basic information database construction requires two days; 1-2 hours per solution.
Genetic Algorithm	Galapagos directly calculates the optimal solution.	Real time simulation of 3D legally evaluated framework.	Grasshopper generates parameters for direct judgment of requirement conditions.	Directly generates structure system.	Error margin is not required (error range is 1 square meter only)	Real time parameter adjustment.

Tab. 2: Table of Conceptual Design Analysis.

is close to the allowable maximum floor area. Tolerance is not needed to compensate for the design error. Simulation design in this research derives the optimal solution for the five shapes, proving that the method adopted in this research can indeed assist an architect in finding the optimal massing solution in the conceptual design phase

4.3. Comparison between Genetic Algorithm Simulation and Current Design Method

The current operation flow that the architect utilizes (as shown in Table 1) is that a 2D floor plan is drawn first using AutoCAD, and 3D Max is subsequently used to structure an estimated mass. Approximately 3-5% of the mass is reserved for flexible adjustment. Finally, Excel is used to calculate the area to obtain the maximum floor area and gross floor area. Every mass adjustment must be re-estimated at least once. This research utilizes Genetic Algorithm Software to derive the total floor area on a site, which is 16001 square meters (less than 16002 is the legally allowable area). Table 2 lists the differences between Genetic Algorithm and the general design flow

5. CONCLUSION

This investigation aims to build an optimized simulation method to achieve a breakthrough in the conceptual design phase and overcome the drawback of an architect not being able to derive an optimized massing. This system combines legal information with massing process, which has never been investigated before. Results showed a significant enhancement of the massing preciseness. During the whole design process, it was found that it is difficult to use the general design flow to complete conceptual design phase with one software tool, and error and missing information can easily occur. The solution of this research combines a legal checking tool with an optimized tool to propose cross application of different software tools to achieve the most effective algorithm. However, format conversion between software tools and simplification of massing variables are issues to overcome in the future to enhance more complicated legal checking functions.

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