Use of scenario planning approach to explore high-dense, mixed-use function distribution:

A case of financial viability, daylight availability, and solar envelope radiation.

Firus Faizal
A0000345B

Abstract

Scenario planning is an established method in planning theory that considers the growing complexity and uncertainty of the future. Scenarios are typically defined as 2D land-use plans and evaluated using 2D GIS-based tools and human judgement. (de Roo and Porter, 2007).

However, as a large number of developers make use of the scenario planning approach to plan for high dense, mixed-use developments, the developers face five main challenges:

First, the 2D plans that the developers use for the different scenarios cannot be evaluated by existing evaluation tools. These evaluation tools require 3D building models and data, which are non-existent on the plans. Typical evaluation tools currently in use range from daylight availability, envelope solar radiation, urban heat island (UHI), wind ventilation, air pollution, building operational energy tools, etc.

Second, a recent survey showed that when developers use the scenario planning approach, they constantly test for high dense, mixed use developments as part of their strategy (Bartholomew 2007). However, at the present moment, developers only utilize 2D plans, which are insufficient to understand the performance and impact of their high-dense, mixed use development. 3D building models are required to understand these daylight, urban heat island, etc, performances on the high dense development setting.

Third, on high dense, mixed use development, developers tend to explore the different percentage mix and distribution of functional use in that development. This is very limiting on the 2D plans that they traditionally work on and requires the use of 3D buildings to be able to achieve this exploration.

Fourth, for each scenario that the developers develop, they traditionally generate only one single building variant by hand. However, in reality, there are a large number of building possibilities that can satisfy the plan and requirement to every scenario. In fact, to be thorough with each scenario's performance and impact, a large number of building variants must be generated.

Fifth, for each building variant that the developers generate, they must satisfy the local development, building and fire safety regulations. It would therefore be an onerous task when each scenario requires a large number of building variants.

In addition, the problem for developers is that there are currently no clear methods available for generating such models. Existing generative methods and tools for producing development models focus primarily on visualization and are not able to generate the data and information required for the simulations. For example, Esri's CityEngine approach produces attractive building façade visualization using texture maps, but only includes very limited data and information regarding the urban environment and buildings. Sythicity's Urban Canvas does generate urban information models with more data, but the models tend to be highly simplified and are therefore not representative of the actual urban forms that would be built in any specific city. Other existing tools such as CommunityViz, Envision Tomorrow, and INDEX do not explicitly address the generation and evaluation of variants, as well as adhering to local development and building regulations.

This investigation proposes a parametric modelling method to generate 3D models that can be used for scenario-based planning. The method differs from existing methods in two respects. First, the models that are generated include a range of data required for different types of simulations. Second, the

models that are generated are based on existing building typologies selected from specific cities and are therefore representative of actual urban form.

The proposed method consists of series of modelling steps that create a high-dense, mixed use building configuration by manipulating a set of polygons representing different building functions. First, a set of 2D polygons are placed within the plot boundaries according to various constraints that control site coverage, set-backs, heights, and structural construction schemes. Second, the polygons undergo generative steps such as (1) multi-scale partitioning to achieve the required floor areas, (2) routing of human, vehicular and service circulation, (3) placement of critical structural elements and circulations such as lift-cores, escalators/staircases, columns that satisfies the fire safety and construction schemes regulations, and (4) floor-planning of lettable and residential plans. Third, additional data is added to the model defining the materiality of the structural member and envelope cladding as well as the functional distribution within the mixed-use building configuration.

In order to demonstrate the proposed method, a parametric model is developed for an existing mixed-use development in Clementi Town Centre in Singapore with a complex mix of functions. The development consists of a bus interchange on the ground floor, commercial podium, and a number of residential towers on top of the podium is proposed as another scenario which can form as a viable alternative. The demonstration show how proposed method can be used to generate a range of design variants that all follow the typology of the existing mixed-use block and adhering to the same constraints and regulations.

This paper hypothesize that this computational approach to evaluate variants for every single planning scenario is capable to generate a much broader and diverse set of design solutions, allowing developers to be more thorough in their exploration on the early design stage, encouraging more experimentation and exploration.

KEYWORDS
Parametric, Evolutionary Algorithm, Planning, Regulations, City Modelling.

I. Overview

List of Figures

List of Tables

Chapter 1

1 Introduction

1.1 Problem Statement

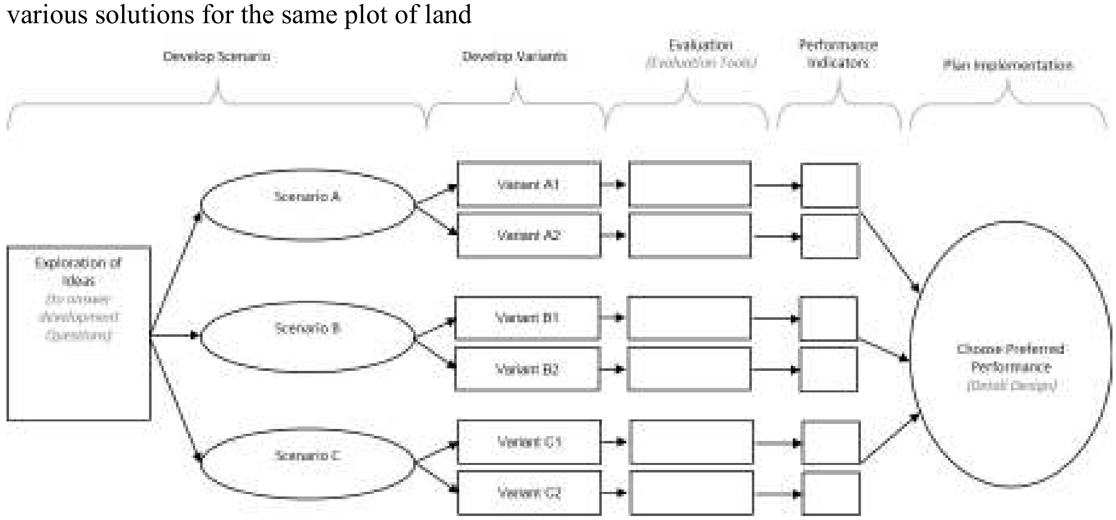
1.1.1 Overview of scenario planning

Scenario planning is an established method in planning theory that creates different possibilities or ‘alternatives’ for the future that could show how a projected area might work in many different ways.

Rather than consolidating on one development design, scenario planning considers several development designs, typically between two or more development designs in parallel (Bartholomew 2005). Each development design considered in parallel is known as a ‘scenario’. Through the exploration of different scenarios for the area, the scenario approach facilitate experimentation amongst the developers, allowing the testing of various ideas and encourages discussion for development possibilities (Corey and Wilson, 2006).

In addition, by creating different planning scenarios, this approach is capable of tackling a variety of complex development issues and uncertainties at the drawing board, leading to various routes and solutions (de Roo and Porter, 2007). The aim behind scenario planning is to explore alternative development designs while taking into consideration of uncertain and complex economical, political, etc drivers of the future.

Fig. 1-1 Scenario planning workflow through three scenarios, through various routes, leading to various solutions for the same plot of land

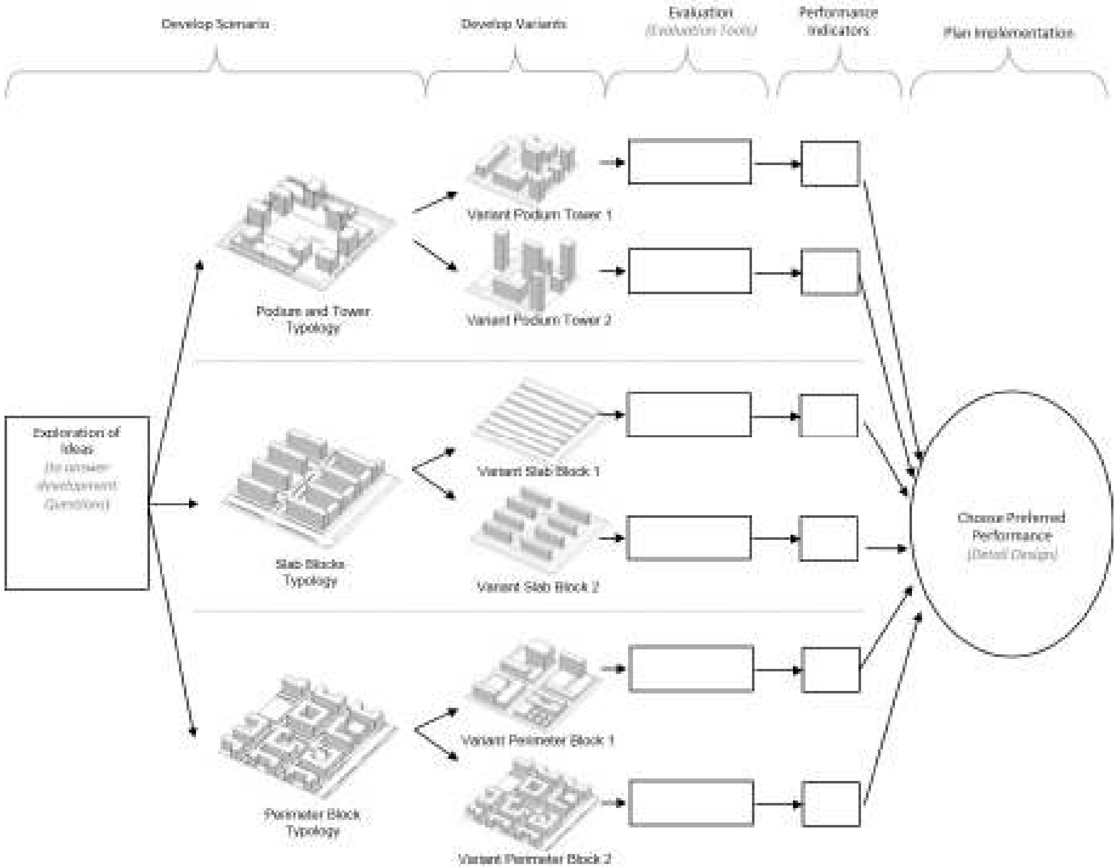


Scenarios: A situation or a sequence of events, based on certain assumptions and factors (variables) chosen for that situation. Scenarios are used in estimating or evaluating the probable effects of one or more of these variables as part of the evaluation.

Scenario Planning Approach: Scenario planning approach is a technical approach in planning theory that takes the development issues as predefined, focusing on development content and goals through the synthesis of various possibilities, alternatives or routes in the development process for how a projected area might work in many different ways. The issues might be predefined, but the outcomes become situation and context dependent. The result is a cyclical process with evaluative feedback loops that incorporates the development process with new facts or new issues that emerge as the scenarios are being evaluated. This approach can be seen as a response to the lack of certainty in development and therefore a response to 'bounded' rationality, instead of an acceptance of uncertainty. Rather than producing blueprint plans, this approach produces planning evaluations which are often tactical progress reports with performance or impact indicators.

1.1.2 An example of scenario planning for this investigation

Fig. 1-2 The different scenarios can be encoded as exploring different types of typologies, while the generation of variants generate numerous alternatives (variants) to each given scenario.



In this investigation, the scope of a scenario and its variants can be exemplified as such:

(1) A scenario:

comparison of different typologies

ie: Scenario A explores podium and tower typology while Scenario B focuses on slab block typology whereas Scenario C is looks into the perimeter block typology.

(2) Variants

Numerous variants are generated for each single scenario and they generate a large number of different development alternatives that is constrained on the development rules of each scenario.

ie: Variants of Scenario A generates numerous podium and tower development that has different performance and impacts but all variants to Scenario A will always be generated as podium and tower developments.

1.2 Problem Identification

1.2.1 Primary Problem: Lack of use of 3D models

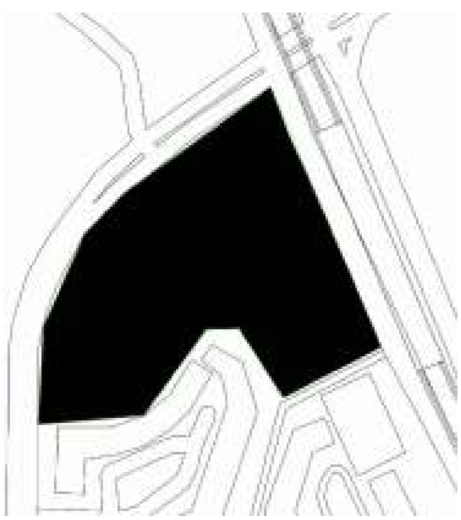
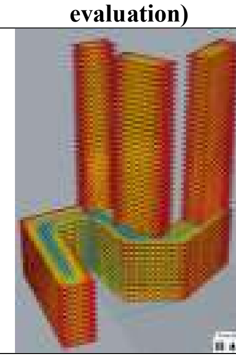
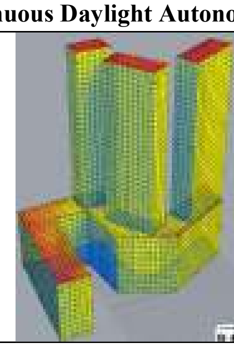
The primary problem is that the typical developer does not use 3D models when it comes to developing for complex high dense mixed-use development. In a survey done by Bartholomew (2006), developers only depended on 2D plans for the planning of high dense mixed-use development (refer to Chapter 3: Literature Review).

On the contrary, this thesis argues that the use of 3D models to assist planners in planning complex mixed-use development is critical to their understanding of how the development will perform, especially in the case of a high dense development. A high density mixed-use development has very significant impact in the developer's pursuit of sustainable goals. Presently, developers are expected to create sustainable developments, example, developments that uses less energy and artificial lighting, reduce Urban Heat Island (UHI), as well as to maximize the Return-On-Investment ROI, etc.

In addition, in Chapter 2: Case Study, the thesis investigates the impact of high dense mixed-use development on the performance of daylight availability, Urban Heat Island (UHI) and envelope solar radiation.The case study was able to establish that at plot ratio of 3.0 and above, planners require the use of 3D models to effectively plan for high dense developments.

In summary, developers need to know quickly how the different types of developments on the 2D plans that they produced are better than another in terms of performance, so as to be able to conduct more experimentation and exploration of different developments to encourage innovation.

Fig. 1-3 The missing 3D data required for evaluation to be carried out

Scenario A (2D plan from plans)	**Missing 3D data and model**	**Evaluation Tools (requires detailed 3D models for evaluation)**
		
		Continuous Daylight Autonomy cDA
		
		Solar Envelope Radiation

1.2.2 Secondary Problem: Lack of use of 3D variants to thoroughly explore scenario planning analysis

The second problem is that the evaluation conducted through this manner is not thorough as each scenario only generates only a single variant or proposal.

- For a more thorough evaluation for any given scenario, numerous variants need to be generated. Considering only 1 variant before evaluating a particular scenario as ‘good’ or ‘bad’ risks a premature dismissal of that particular scenario in its entirety.

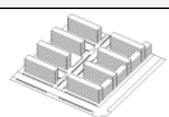
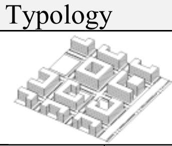
- Developers require more experimentation and exploration in order to come up with innovation, hence, this supports a need to explore more variations for each scenario.

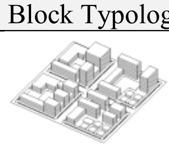
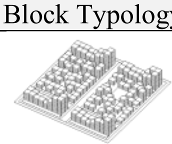
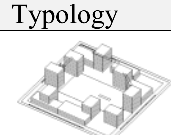
- In addition, each variant that the developers explore will have a different performance during the evaluation stage

- Thus, each scenario requires many more variants for a more thorough evaluation of each scenario

In order to illustrate this problem, the thesis put forward six possible scenarios that any given developer can consider for the same site. As an example, the six scenarios below that satisfies a plot ratio of 2.0 are (1) slab typology, (2) perimeter block typology, (3) block-mixes typology, (4) high density perimeter block typology, (5) fine grain block typology and (6) podium and tower typology. There are other typologies and scenarios that any developer can investigate and the list for different scenarios is inexhaustible.

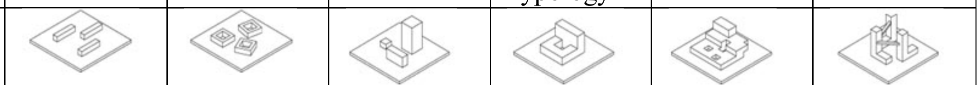
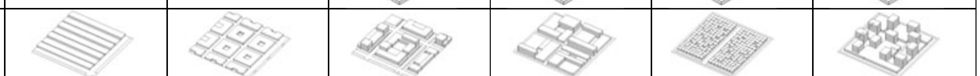
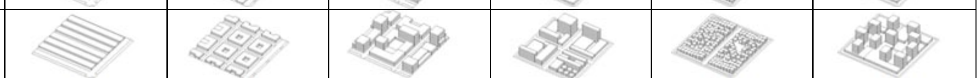
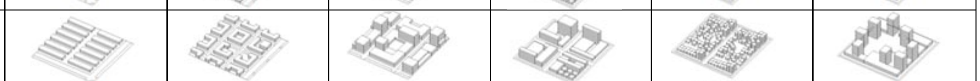
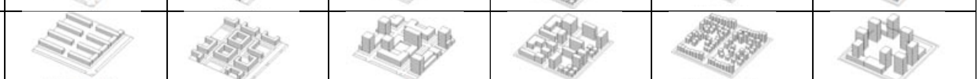
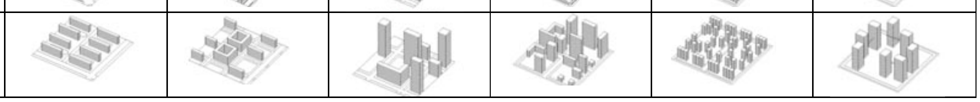
Fig. 1-4 Six development scenario can be designed into 6 different variants

[01] Slab Typology		[02] Perimeter Block Typology		[03] Block Mixes Typology	
					
FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn	FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn	FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn

[04] High Density Perimeter Block Typology		[05] Fine Grain Block Typology		[06] Podium and Tower Typology	
					
FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn	FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn	FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn

However, since the developers did not specify the percentage of the site coverage (% of SC), the possibility of different variants having different site coverage percentages can be generated. While the plot ratio remains at 2.0, the site coverage percentage can range between 20% to 100%. Therefore, instead of six other variants, there can be a few hundreds of variants that can satisfy the initial requirement of plot ratio 2.0!

Fig. 1-5 Numerous variants can be generated that satisfies the development scenario's requirement of plot ratio 2.0

	[01] Slab Typology	[02] Perimeter Block Typology	[03] Block Mixes Typology	[04] High Density Perimeter Block Typology	[05] Fine Grain Block Typology	[06] Tower Typology
General Typology						
85.0% Site Coverage						
75.0% Site Coverage						
62.5% Site Coverage						
50.0% Site Coverage						
37.5% Site Coverage						
20.0% Site Coverage						

Therefore, for a more thorough evaluation, numerous variants for any given scenario should be generated. Computational techniques can be employed to generate these variants automatically and the parametric modelling technique is employed in this research to achieve the generation of numerous variants.

In addition, for any given scenario, many variants can be created that differ in their performances. Therefore, in order to be able to thoroughly evaluate a particular scenario, planners need to be able to not only generate, but also to evaluate a wide range of variants. As a requirement, the generated variants must vary significantly from one another and yet satisfy local development and building regulations. Hence, a search based procedural content generation would be required. This would be proposed in chapter 4 (research proposition) and implemented in chapter 6 (demonstration).

Scenario planning is a planning domain where the application of parametric modeling techniques could be highly beneficial. In other design related domains such as architecture design, the parametric modeling techniques have been successfully used to explore architecture design variants at the early design stage.

Therefore, being able to apply parametric modeling techniques to generate and evaluate variants for every planning scenario early on in the early planning stage would be beneficial to the developers before arriving at a final detailed scheme.

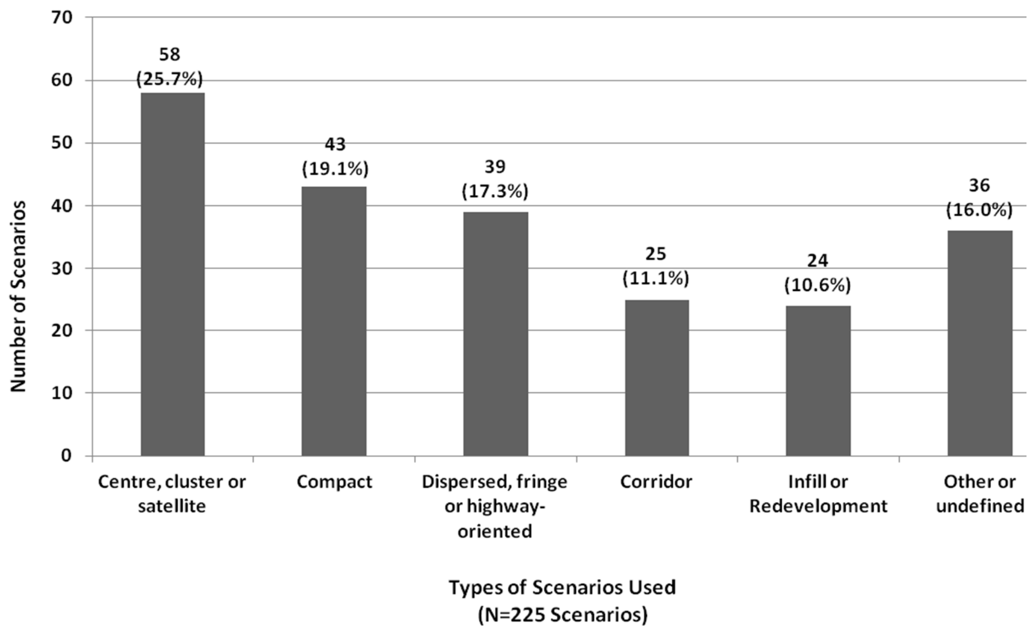
1.3 Scenario planning approach and mixed use developments

1.3.1 Frequent adoption of mixed-use developments in scenario planning

Bartholomew, illustrates that the most common scenario planning approach involved the densification of existing cities or sub-cities, and their strategies typically involves the use of mixed-use development projects.

- Bartholomew analyzed 225 scenario plans in the United States between the years 1980 to 2005. The survey was focused to characterize the types of scenarios that was conducted by developers through clustering similar types of scenario planning studies. The results characterized five most common types of scenario planning:

Fig. 1-6 Types of scenario planning projects conducted in the United States from 1980 to 2005



  - (1) Centre, cluster or satellite development scenarios (25.7% out of 225 scenarios). Bartholomew categorized these planning scenarios which involves the planning of a multi-nodal, sub-centre focused strategy to accommodate new growth.

  - (2) Compact development scenario (19.1% out of 225 scenarios). This planning scenario plans for the more uniform intensification in density to result in a more compact city development.

  - (3) Dispersed, fringe or highway-oriented development scenario (17.3% out of 225 scenarios). This planning scenario is defined by Bartholomew to be the equivalent to the ‘sprawl’ development.

  - (4) Corridor development scenario (11.1% out of 225 scenarios). This planning scenario focuses growth along a transportation corridor in a uniform distribution.

- (5) Infill or redevelopment scenario (10.6% out of 225 scenarios). This planning scenario focuses growth into a single central city.

It can be noted that 125 out of 225 (55.5% out of all surveyed projects) scenario planning project is focused on land densification developments. The land densification projects span from densifying centres, sub-centres, infill, redevelopment and mixed-use development project. However, mixed-use development, while being a densification project, proves to be most challenging.

1.3.2 Frequent use of 2D plans for mixed use developments in scenario planning

In the same survey, it is highlighted that while developers planned for high dense, mixed-use developments, they are still dependent on 2D plans to represent these developments.

- An illustration of one of the project surveyed involves varying the dispersal (sprawl) away from the city centre versus a redevelopment (densification) into and towards the city centre.

Fig. 1-7 Land use element that was varied between the 3 scenarios was the dispersion (sprawl) or compactization (compact/infill)of residential development.

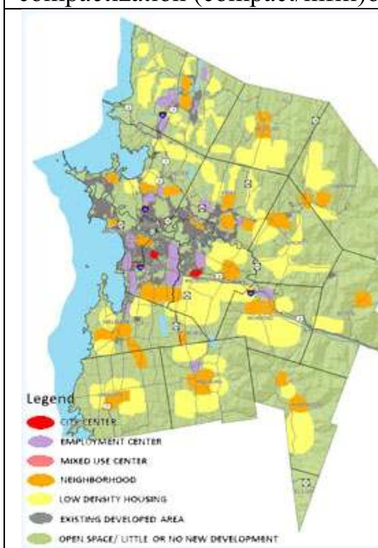


Fig 1-3 (A)

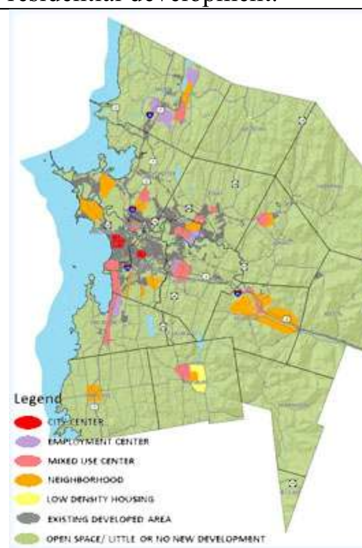


Fig 1-3 (B)

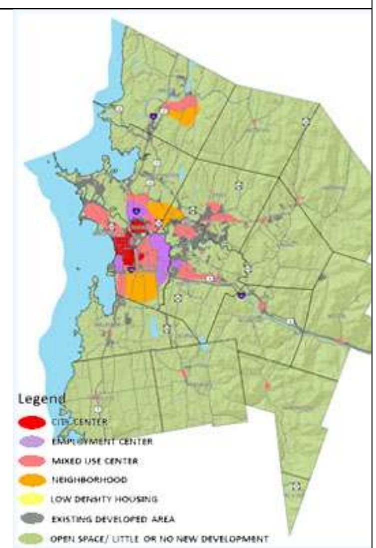


Fig 1-3 (C)

- An important point about the survey shows how mixed-use developments (shaded in pink) is used to mitigate sprawl development (shaded in yellow). The use of mixed-use development is one of the many strategies that developers utilize to reduce sprawl by densifying the city centres. As much as 40% of the land is planned as mixed-use development (Fig 1-3 (C)) instead of the sprawl plan in Fig 1-3 (A).

However, it is to note that while the developers can actually plan mixed-use development on 2D plan, the developers are limited in being able to understand the performance and impact of the mixed-use development over the other types of development. In the Bartholomew's example, we observe how developers have to achieve high sustainability performance and goals that cannot be evaluated on the

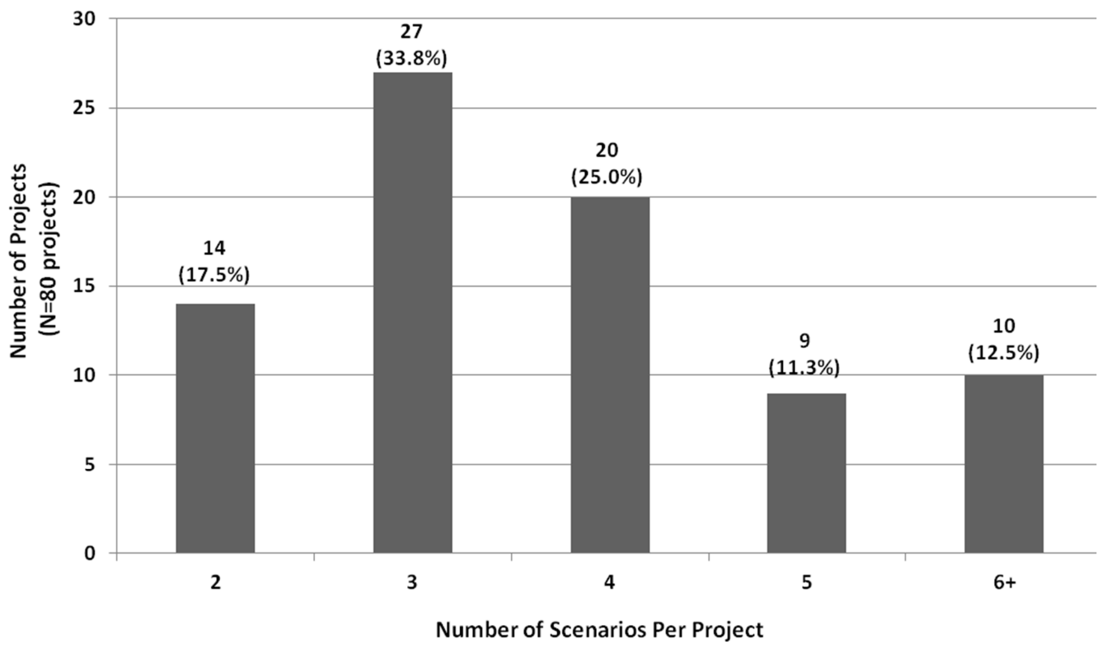
2D plan. In order to evaluate mixed-use development in terms of its performance, 3D models are required to be generated and evaluated.

1.3.3 Number of scenarios typically used in the scenario planning approach

Bartholomew also pointed out that the two most frequent number of scenarios considered in the scenario planning survey is between three scenarios (33.8% out of 80 projects) to four scenarios (25.0% out of 80 projects).

In addition, the planners to do not explore variants to each planning scenario. By not exploring more variants to each planning scenario, the planners are unable to thoroughly explore and experiment with numerous other variants to the possible development of their 2D plans.

Fig. 1-8 Typical number of scenarios used by planners in conducting scenario planning projects



1.3.4 High-dense, mixed-use developments impact significantly on urban performance

A change in urban mixed-use function distribution has a significant impact on urban performance. Drummond and Herndon in 2011 discovered that by changing the mixed-use function in a development will result in:

(1) a change in access to daylight
(2) a change in solar envelope radiation
(3) a reducing of risk in returns-on-investments ROI
(4) a reduction on automobile dependence,

(5) a better support for the public transit system,
(6) a reduction on sprawl development,
(7) a better preservation of more open space instead of being developed,
(8) an intensification of economic development
(9) a reduction on the costs associated on maintaining sprawling infrastructure in low density development.

In this research, there are three main urban performance indicators that are investigated which are significantly impacted by the change in mixed-use functions in a development.

• In densification, daylight availability may be reduced. This is due to the fact as the development becomes denser, certain taller buildings within the development might restrict access to daylight. (American Planning Association 2006).

• A denser development would also affect the solar envelope radiation reading of the development. This would be dependent on the layout, density and urban form of the development. (American Planning Association 2006).

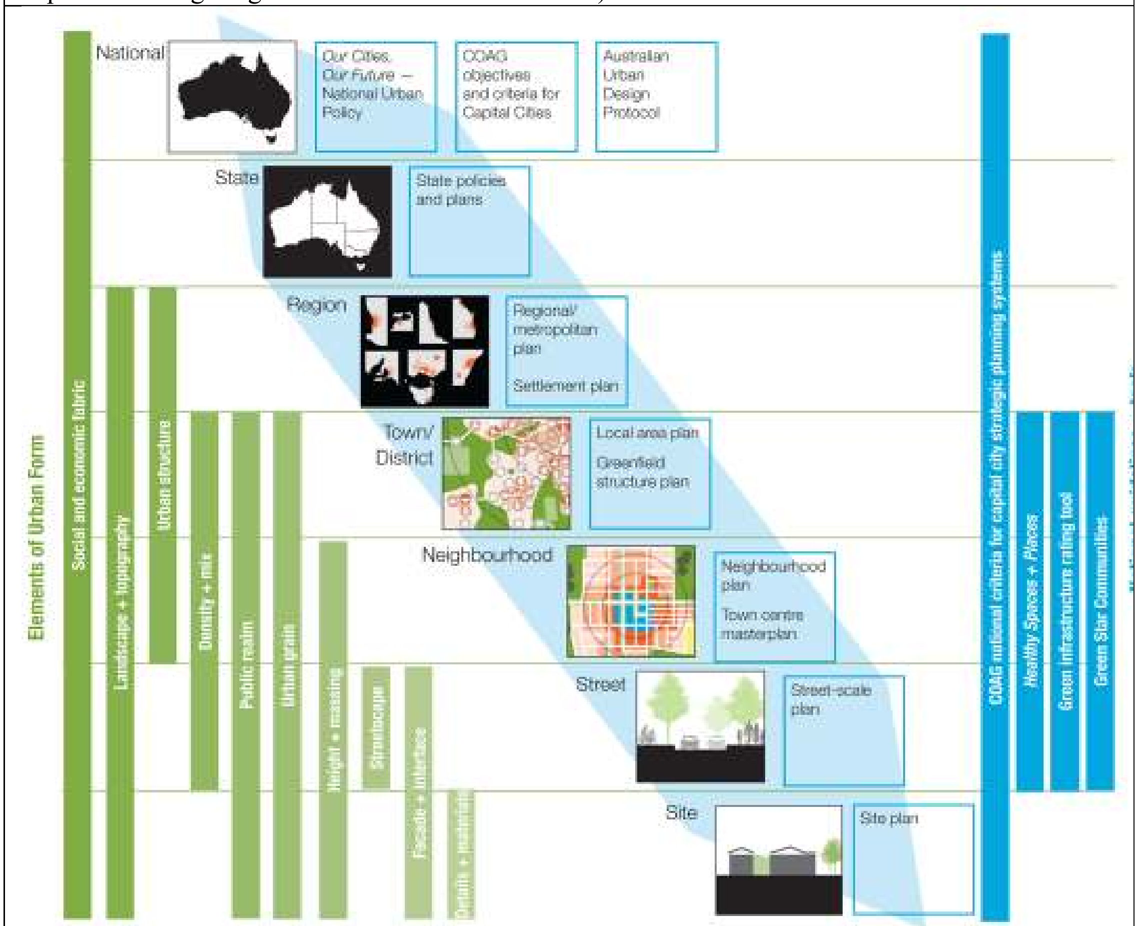
• The third development performance indicator which is significantly impacted when mixed-use function is changed is the reduction in risk on returns-on-investments (ROI). Mixed-use developments promote a diversification of the risk in a development to a developer, which may also result in a synergistic functional relationship when complementary functions are co-located together in a development. (American Planning Association 2006).

Again, the investigation stresses that these performances can only be properly evaluated using 3D building massing. Traditional tools such as the 2D GIS, which are used by many developers, does not allow evaluaton in daylight, envelope radiation and calculation of ROI to be evaluated. Thus, this research develops a method to generate and evaluate numerous 3D variants which allows planners to understand the performance and impacts of high dense mixed use development. In Chapter 2, the case study was able to establish that at plot ratio of 3.0 and above, planners require the use of 3D models to effectively plan for high dense developments.

1.3.5 Research Planning Scale

In terms of planning scale, this research focuses on the Site Plan Scale. This planning scale is defined by a subzone accommodating 1,000 population served by a commercial center, which in this investigation, is represented in the form of Clementi Town Centre. To better illustrate the different planning scales, below is an example of how the Site Plan Scale relates to the rest of the planning scales:

Fig. 1-9 An urban design protocol for Australian cities, creating places for people. Department of Infrastructure and Regional Development, Australian Government (Source: http://urbandesign.org.au Last Visited: 30 June 2015)



Thus at the Site Plan, the planning tasks that are involved are:

(1) height and massing development
(2) structural and envelopes
(3) materials
(4) routing of human, vehicular and services
(5) facades, details and interfaces

In order to meet the objectives of this research, only the first four planning tasks required on the Site Plan are focused on: (1) height and massing development, (2) structural and envelopes, (3) materials and (4) routing of human, vehicular and services.

1.4 Research Objectives

1.4.1 Overall Research Objective

The main research objective is to develop a computational workflow to (i) conduct scenario planning at the site plan scale (ii) in evaluating a few key scenarios consisting of different functional distribution within a development. Subsequently, these developments with different functional distribution must be evaluated to understand its performance and impacts.

Primary Research Objective

To evaluate a developer's 2D site plan, a large number of evaluation tools require 3D models, which are missing from the 2D site plan. These missing data (3D models) must be generated in order for evaluation to be carried out.

- Hence, 3D models must be generated for evaluation to take place

Secondary Research Objective

The developer team will generate a few key scenarios which explores different functional distribution on a 2D plan. However, for each given scenario, numerous 3D models or variants can be generated. In addition, each variant has different performance and impact that the planner might not have considered that must be evaluated.

- Therefore, to be able to thoroughly evaluate a single scenario, numerous variants to that scenario must be generated.
- In order to generate a large number of 3D variants, generative techniques by means of parametric modeling is used. This aspect significantly reduces the time required to generate the large number of 3D models, when compared by hand.

Overall, main focus of this research is to generate and evaluate numerous 3D variants for each scenario that must also meet the local development, building and fire safety regulations.

1.5 Research Methodology

1.5.1 Overview

This research methodology can be broken down into three key stages: (1) conceptualization, (2) implementation and (3) evaluation.

Fig. 1-10 Methodology

Research Methodology

(1) Conceptualization
- (A) Literature Review
- (B) Software Review
- (C) User Method
- (D) System Architecture

Prescriptive Research Methods

(2) Implementation
- (A) Development of 'proof-of-concept'

Prescriptive Research Methods

(3) Evaluation
- (A) Performance Testing
- (B) Analytic and Statistics
- (C) Validation (replicate existing typologies)

Descriptive Research Methods

Conceptualization

In the conceptualization stage, the (A) literature review looks into the expert opinion on the subject while the (B) software review looks into state-of-the-art tools in the field. The (C) user method looks into a design method that integrates synergistically both the human and computational system in a coherent framework. (D) The system architecture provide an implementation plan to be executed. The conceptual stage of the research methodology is predominantly based on prescriptive research methods.

Implementation

The implementation stage involves the development of a prototype "proof-of-concept' system. A generative technique is proposed to generate a dense mixed-use development through three typologies. The stage of the research methodology is predominantly based on prescriptive research methods.

Evaluation

The evaluation stage includes testing of the system's performance (performance testing). Subsequently, analysis and statistics of the system's performance is evaluated. This would then lead to the validation stage, where the generative system should be able to generate a real-life typical development (ie, all the typologies generated should be able to reflect on real developments). Different from the previous two stages, the evaluation stage is predominantly based on descriptive research methods.

Table 1-1 Function distribution search-based design framework

General Research Stages (Livari et al., 1998)	**Detailed Research Framework** (Nunamaker et al., 1991)	**Research Proposition**	**Thesis Chapter**
Conceptualization Stage	(1) Conceptual Framework	(A) Design workflow for urban planners and developers	3
Implementation Stage	(2) System architecture	(B) Computational system consisting of workflow using parametric modelling	5
	(3) Analyse and design the system	(C) Prototype system	
	(4) Build prototype system		
Evaluation Stage	(5) Evaluate the system	(D) Clementi Town Centre Demonstration	5

1.6 Primary Research Impacts and Contribution

The investigation contributes in two ways:

• (1) enhancing the generation of high-dense, mixed-use development in an automated manner (see Section 1.6.1)

• (2) enhancing the scenario planning approach (see Section 1.6.2)

1.6.1 Enhancing the generation of high-dense mixed-use development in an automated manner

Traditionally, the development of high-dense, mixed-use development is a very complex and difficult problem. It takes a significant amount of time to develop a high-dense, mixed-use development by hand. The problem compounds further when numerous variants must be developed and yet strictly adhere to the voluminous amount of development, building and fire safety regulations.

On the other hand, while it takes a significant amount of time to develop a high-density, mixed-use development by hand, it can also take more time to develop a parametric model of a high-density, mixed use development. Only when numerous variants must be developed does it make sense to invest first in the development of a parametric model.

Thus, this research contributes by facilitating the generation of numerous variants of high-dense, mixed-use development in an automated manner, thereby allowing developer to focus more on the different variant types that are generated that they would like to explore and evaluate, rather than spend time hand making each variant.

In addition, the contribution of the research is as follows:

- Contribution of a novel approach to generate and evaluate function distribution in numerous variants to a given high dense, mixed-use development. Literature on this topic is very little.

- Enhance the automated generation of 3D models from 2D plans in scenario planning.

1.6.2 Enhancing the scenario planning approach

The other contribution is to enhance the scenario planning approach with computational support. Rather, this research contributes to the scenario planning approach in a synergistic way – tasks that require predominantly creative and subjective judgment are handled by the planning team while tasks are predominantly repetitive and objective can be assigned to the computer.

However, the development of a parametric model is less creative and subjective, yet this process cannot be assigned to the computer. For this reason, a parametric modelling team is required to manually create the 3D design schema and parametric model alongside the developer team before assigning the repetitive and objective tasks to the computer.

- In assigning the repetitive and objective tasks to the computer, the first benefit of this study reduces the likelihood for human error, concurrently speeding up this aspect (as compared to the time taken when repetitive tasks are done manually by hand).

- The second benefit is that this investigation allows a thorough evaluation for any given planning scenario.

- The third benefit encourages exploration, experimentation and innovation in the planning process.

- The forth benefit comes in the form of variants being evolved to obtain a higher performance than the planners would have conceived.

Chapter 2

2 Literature Review and Background Research

2.1 **Introduction**

The goal of Chapter 2 is to introduce the evaluation techniques to be considered in the computational architecture and its demonstration presented in the later chapters (Chapter 3 and Chapter 5 respectively). In evaluating the numerous variants of 3D models for high-density, mixed-use developments, evaluation techniques of

(1) financial viability (see section 2.2),
(2) daylight availability (see section 2.3), and
(3) solar envelope radiation (see section 2.4)

are presented in this chapter.

In addition, the background research relating the need for the generation and evaluation of 3D models for high-density, mixed-use developments is also presented. The background research attempts to answer the question to which degree of plot ratio is the use of 3D models in high-dense, mixed-use development necessary?

The background research illustrates that developers require the use of 3D models in the planning of high-dense, mixed-use developments should they require to evaluate envelope solar radiation performance and continuous daylight autonomy CDA at development plot ratios of 1.0 and 3.0 respectively.

2.2 **Financial Viability Literature Review**

2.2.1 Introduction of Financial Viability

The financial viability of a development is typically conducted through a pro-forma calculation, which uses a return-on-investment (ROI) analysis. Financial quantification of the land costs, the construction costs, and the speculated profits derived from the rent or sale for all property types: office, industrial, retail, residential or mixed-use, is required in the ROI analysis.

In this research, a simplified financial viability calculation using return-on-investment (ROI) analysis is considered to be used in the evaluation of 3D models. The ROI analysis technique is discussed in detail in the following section 2.2.2 and its demonstration is illustrated in Chapter 5.

2.2.2 Importance of ROI evaluation as a means to measure the financial viability of a development

The evaluation of financial viability through the calculation of return-on-investment (ROI) analysis is important to allow developers to understand the amount of financial profit that the development can return. In this research, the ROI can be maximized through reducing the costs of construction, while keeping the speculative rent/ sale price and land costs constant for different development variations. Since, each 3D model variants have different ROI performance values, it becomes effective for developers to compare how the different design variants perform in terms of its corresponding ROI performance.

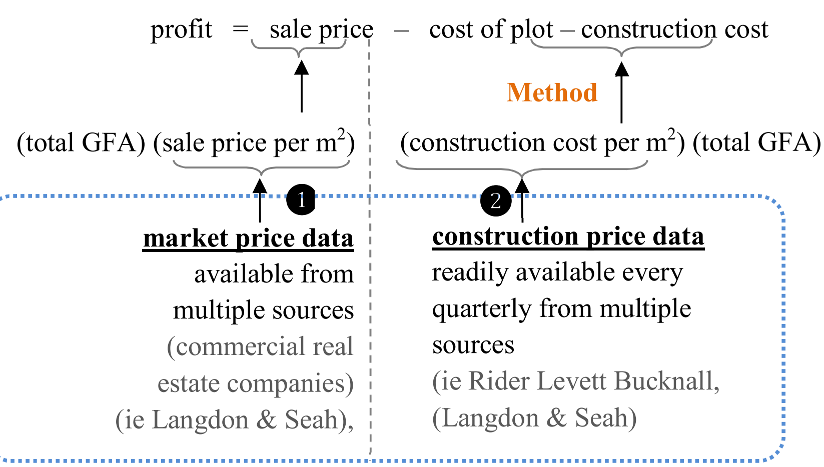
2.2.3 Return on Investment (ROI) Analysis

The Return-On-Investment (ROI) is a financial term that refers to the percentage of invested money returned to the developer after the deduction of construction and land purchase costs, as follows:

ROI = profit / (cost of plot – construction plot) x 100%

Where ***profit*** is calculated as follow:

$$\pi = (p)(q) - (Fn + wq)$$



ROI = profit/investment cost

= (sale price – cost of plot – construction cost) / (cost of plot – construction cost)

= [(lettable area X price per sq metre) – (cost of plot) – (volume of concrete X cost of concrete + surface area of cladding X cost of cladding)] / [(cost of plot) – (volume of concrete X cost of concrete + surface area of cladding X cost of cladding)]

ROI = [(lettable X $15,251) – ($119,000,000) – (ConcreteVol X $104.00 + SurfaceArea X $138)] / [$119,000,000 - (ConcreteVol X $104.00 + SurfaceArea X $138)]

The schematic diagram above illustrates a workflow proposal to calculate the profitability of a planning proposal. The equation first begin with the simple profit = sale price – cost of plot – cost of construction. Focusing on the 2 components (1) sale price and (2) construction cost, more detailed data is required.

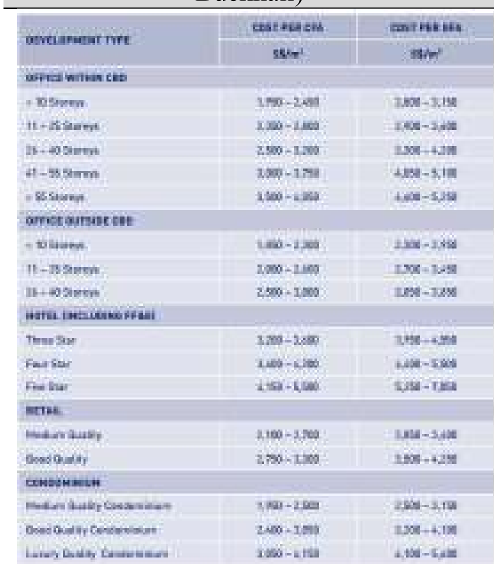
Traditionally, a heuristic, generalized market data can be obtained from commercial real estate sources such as construction cost per meter square values from real estate companies (ie Langdon & Seah, etc).

However, in this research, this heuristic, generalized approach does not consider the numerous variations of 3D models generated parametrically (see computational architecture, Chapter 3 and demonstration, Chapter 5). When numerous 3D model variations are generated through the use of parametric modelling, different construction costs are generated, especially so when numerous variants require different volumes of materials such as volume of concrete as well as require different cladding area requirement due to different building massing generated leading to different building perimeter factors and thus different façade area calculations.

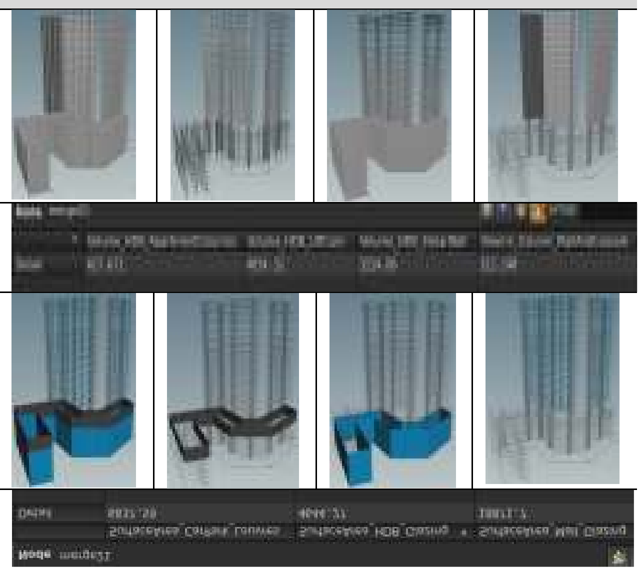
In short, the different 3D variants would generate different construction costs, thereby, this research argues that it is not sufficient, or rather, inaccurate, to depend on a heuristic, general construction cost-per-meter-square value as available from real estate companies. It is necessary for the calculation of construction costs to be evaluated in the generation pf parametric models (see Chapter 5).

Fig. 2-1 Market driven data (Inaccurate) vs 3D Model Data (accurate)

Inaccuracy from a heuristic, generalized Construction Cost per m^2 in Singapore, leading to an inaccurate calculation of return-on-investment ROI (Source: Singapore Construction Prices 2012, Singapore Report, Rider Levett Bucknall)	**Accuracy from 3D Models Construction Cost per m^2 data, leading to a more accurate calculation of return-on-investment ROI** (See Chapter 5)



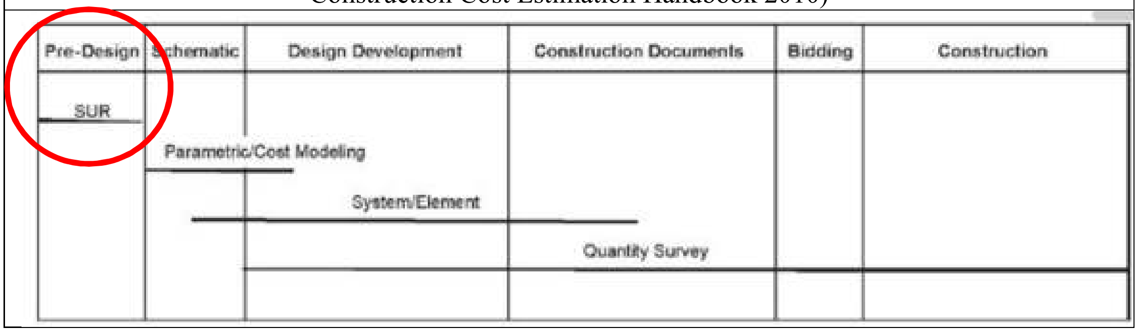
DEVELOPMENT TYPE	COST PER CFA S$/m^2	COST PER GFA S$/m^2
OFFICE WITHIN CBD		
< 10 Storeys	1,950 – 2,450	2,600 – 3,150
11 – 25 Storeys	2,300 – 2,800	2,900 – 3,400
26 – 40 Storeys	2,500 – 3,200	3,300 – 4,200
41 – 55 Storeys	3,000 – 3,750	4,050 – 5,100
> 55 Storeys	3,500 – 4,050	4,600 – 5,350
OFFICE OUTSIDE CBD		
< 10 Storeys	1,650 – 2,300	2,300 – 2,950
11 – 25 Storeys	2,000 – 2,600	2,700 – 3,450
26 – 40 Storeys	2,500 – 3,000	3,050 – 3,650
HOTEL (INCLUDING FF&E)		
Three Star	3,200 – 3,600	3,950 – 4,350
Four Star	3,400 – 4,200	4,400 – 5,000
Five Star	4,150 – 6,000	5,250 – 7,050
RETAIL		
Medium Quality	2,100 – 2,700	2,850 – 3,400
Good Quality	2,750 – 3,300	3,500 – 4,250
CONDOMINIUM		
Medium Quality Condominium	1,950 – 2,500	2,600 – 3,150
Good Quality Condominium	2,400 – 3,050	3,200 – 4,100
Luxury Quality Condominium	3,050 – 4,150	4,100 – 5,400



2.2.4 Construction Cost Evaluation Technique

In the American Institute of Architects AIA Construction Cost Estimation Handbook, the cost estimation of a building construction can be done on the pre-design stages, where the cost estimation takes into consideration the costliest construction: (1) the building shell, (2) building core (structure) and (3) functional floor area of a building. Cost Estimation at the Pre-Design stages of a building is known as Single-Unit Rate (SUR) Estimating Methods, with 4 different techniques. One of the techniques, Functional Area Method (FAM), calculates the cost of construction of the building by calculating the construction costs of the shell, core and functional build out of the building.

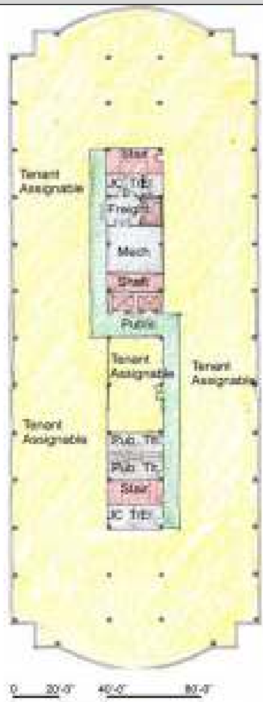
Fig. 2-2 Construction Cost Estimation Techniques during the early design stage. (Source: AIA Construction Cost Estimation Handbook 2010)



This technique has been used frequently in federal GSA General Services Administration buildings in the United States during the pre-design stages where the architects uses hand-drawn sketches to calculate the construction costs of a building before embarking on a selected project. The merit of this technique is that it consistently yields the least construction costs to build federal and governmental buildings.

Fig. 2-3 Construction cost estimation using the Functional Area Method (Building Shell, Core and Functional Space Build Out) used by GSA buildings to control a building construction cost at the pre-design stages (source: GSA Unit Cost Study)

Architect's Hand-Drawn Sketches	**Functional Area Method (Building Shell, Core and Functional Space Build Out) to Estimate Construction Costs of a Building at the Pre-Design Stage**



Low Rise Office Shell Type Level 2 thru 3 Floor Plan

LOW-RISE OFFICE BUILDING
BUILDING AREA

FLOOR	USF Office	USF Parking	USF SUB-TOTAL TENANT SPACE	USF Public Space	USF Common Space	USF Wall Thickness	USF SUB-TOTAL NON-TENANT SPACE	GSF TOTAL NON-PARKING AREAS	GSF Inside Parking	TOTAL BUILDING GROSS AREA
BASEMENT		19,152	19,152	0	6,948	740	7,688	7,688	19,152	26,840
1ST FLOOR	20,388		20,388	3,742	3,360	840	7,942	28,330	0	28,330
2ND FLOOR	22,360		22,360	1,600	2,640	740	4,980	27,340		27,340
3RD FLOOR	22,360		22,360	1,600	2,640	740	4,980	27,340		27,340
TOTAL	65,108	19,152	84,260	6,942	15,588	3,060	25,590	90,698	19,152	109,850
TOTAL ROUNDED	66,100	19,200	84,300	6,900	15,600	3,100	25,600	90,700	19,200	109,900

STRUCTURAL AREA

FLOOR	SLAB ON GRADE	OFFICE / CR SUP. SLAB	ROOFING	TERRACE	TOTAL STRUCT.
BASEMENT	26,840				26,840
1ST FLOOR	1,490	26,840			28,330
2ND FLOOR		27,340	990		28,330
3RD FLOOR		27,340			27,340
ROOF			27,340		27,340
TOTAL	28,330	81,520	28,330	0	138,160
TOTAL ROUNDED	28,300	81,500	28,300	0	138,200

SKIN AREA

SKIN AREA	HT	EXT PERIM	EXT TOTAL	1.25 X EXTERIOR TOTAL*
BASEMENT	16.00	740	11,840	14,80
1ST FLOOR	18.00	840	15,120	18,90
2ND FLOOR	13.50	740	9,990	12,49
3RD FLOOR	13.50	740	9,990	12,49
PARAPET	2.00	740	1,480	1,85
SUBTOTAL			48,420	60,53
FOUNDATION			11,840	14,80
TOTAL FINISHED SKIN			36,580	45,73

* 1.25 Factor to account for the articulation of the exterior wall

Estimating construction cost through the technique of Functional Area Method (Building Shell, Core and Functional Space) yields a few key benefit that considers certain changes in the masterplan proposals:

(1) Changes in the building geometry, affects the building envelopes (building shell) which would affect the construction costs.

(2) To estimate the construction cost for the building shell, wall material and glazing consideration must be accounted for in its calculation. Thus, the technique is sensitive to the external wall materiality, glazing specification and window to wall ratio.

(3) The surface area of the building shell is accounted for because the construction costs is dependent per m^2.

(4) In estimating the construction cost of the building core (structure), calculation of the structural members of the building such as (I) basement (II) all floor levels (III) roof (IV) terraces and (V) lift cores considers how tall a building is, in affecting its construction cost. In short, the taller a building is planned for in the plan proposal, the higher the cost of construction for that building will be.

Fig. 2-4 Cost of materials and Cost of Key Construction Trades in Singapore (Langdon & Seah 2012)

Singapore – hourly cost of labour (including overheads)	2010 SGD	2011 SGD	2011 USD
Group 1 tradesman – eg plumber, electrician	23	23	18
Group 2 tradesman – eg carpenter, bricklayer	20	20	16
Group 3 tradesman – eg carpet layer, tiler, plasterer	20	21	17
General labourer	12	15	12
Site foreman	30	30	24

Singapore – costs of materials	2010 SGD	2011 SGD	2011 USD
Concrete 30 mpa (m³) (1,500m³ job)	126	152	121
Reinforcement bar 16mm (tonne) (120 tonne job)	1,500	1,770	1,406
Concrete block (400 × 200) per 1,000 (>10,000 block job)	800	808	642
Standard brick per 1,000	230	253	201
Structural steel beams (tonne) (>100 tonne job)	5,200	5,200	4,132
Glass pane 6mm (m²)	35	56	44
Softwood timber for framing 100mm × 50mm (m)	13	13	10
Plasterboard 12mm (m²)	21	22	17
Emulsion paint (litre)	20	20	16
Copper pipe 15mm (m) (>1,000m job)	12	13	10
Copper cable (m) (3C + E, 2.5mm PVC) (>100,000m job)	2	2	2

Singapore – key trades (excluding preliminaries and builders' margins)			
Excavate basement (m³) (1,000m³ job)	21	21	17
Excavate footings (m³)	50	50	40
Concrete in slab (m³) (1,500m³ job)	200	242	192
Reinforcement in beams (tonne)	1,500	1,770	1,406
Formwork to soffit of slab (m²)	30	31	25
Blockwork in wall (m²) (10,000 block job)	35	35	28
Structural steel beams (tonne)	5,200	5,200	4,132
Pre-cast concrete wall (m²)	110	110	87
Curtain wall glazing incl support system (m²) (1,000m² job)	500	500	397
Plasterboard 13mm thick to stud wall (m²) (5,000m² job)	21	25	20
Single solid core door incl frame and hardware (no) (50 door job)	800	824	655
Painting to walls primer + 2 coats (m²)	8	8	6
Ceramic tiling (m²) (1,000m² job)	70	70	56
Vinyl flooring to wet areas (m²) (500m² job)	150	150	119
Carpet medium tufted (m²) (4,500m² job)	70	70	56
Lighting installation (m²) (>5,000m² job)	200	200	159
Copper pipe 15mm to wall (m) (>1,000m job)	27	27	21
Fire sprinklers (per m²) (5,000m² job)	80	80	64
Air conditioning incl main plant (m²) (>5,000m² job)	260	260	207

(5) In estimating the functional space build out, the technique considers how certain changes in building function or building use would affect the construction cost of a building. This means that when a developer plans for different mix of functional spaces on the masterplan proposal, he would incur more construction costs due to the nature of the space. For example, a commercial space tend to cost more than a residential space for every m² of build out due to the level of finishing required.

Note however that the data required to calculate a *pro forma analysis* is voluminous. The below tabulation is the data required to carry out a *pro forma analysis* where the (1) revenue, (2) costs (3) mortgage and (4) pro forma summary are necessary to calculate the Return on Investment (ROI) for the financial conviction that a plan proposal is economically viable.

Table 2-1 Types of data required to calculate Return-on-Investment (ROI)

Revenue		**Cost**			
		Building Cost		Land Cost	
Office Revenue		Office Construction Cost		Land Acquisition Cost	
Total m²	m²	Office Floor Area m²	m²	Cost per Acre	$
Market Rate	$	Cost per m²	$	Number of Acres	ACRE
Total Rent	$	Office Costs	$	Total Land Acquisition	$
Occupancy Rate	%				
Occupied m²	m²	Retail Construction Costs		Land Improvement Cost	
Actual Rent	$	Retail Floor Area m²	m²	Cost per Acre	$
		Cost per m²	$	Number of Acres	ACRE
Retail Revenue		Retail costs	$	Total Land Improvement Cost	$
Total m²	m²				
Market Rate	$	Residential Construction Cost			
Total Rent	$	No. of Lots	No.		
Occupancy Rate %	%	House Floor Area m²	m²		
Occupied m²	m²	Construction Cost of House	$		
Actual Rent	$				

Residential Lease Revenue	
Total No. of Units	No.
m^2 per Unit	m^2
Monthly Rent per m^2	$
Total m^2	m^2
Monthly Rent	$
Annual Market Rate	$
Total Annual Rent	$
Occupancy Rate	%
Occupied m^2	m^2
Actual Rent	$

Acreage Summary	
Total Acres Developed	ACRE
Total Acres Acquired	ACRE
Open Spaces Remaining	ACRE

Mortgage	
Mortgage % of Costs	%
Mortgage needed	$
Equity needed	$

PRO FORMA SUMMARY

Office Space		Retail Space		Residential Space	
Market Rent Income	$	Market Rent Income	$	Market Rent Income	$
Loss to Vacancy	$	Loss to Vacancy	$	Loss to Vacancy	$
Actual Rent Income	$	Actual Rent Income	$	Actual Rent Income	$
Total Office Revenue	$	Total Retail Revenue	$	Total Retail Revenue	$
Actual Operating Expenses per m^2	$	Actual Operating Expenses per m^2	$	Actual Operating Expenses per m^2	$
Actual Operating Expenses Total	$	Actual Operating Expenses Total	$	Actual Operating Expenses Total	$
Net Operating Income for Office Space	$	Net Operating Income for Retail Space	$	Net Operating Income for Retail Space	$

Total Net Operating Income (NOI)

Debt Service		Cash Flow		Internal Rate of Return
Amortization	$	Pre-Tax Cash Flow		Cap Rate
Interest	$	Pre-Tax Annual Return on Investment (ROI)	%	Initial Investment
Total Principal and Interest	$		%	Before Tax Cash Flow (Annually for 10 Years)
	$		$	Reversion
			$	Internal Rate of Return

2.2.5 Conclusion of Financial Viability Literature Review

In conclusion, in evaluating a high dense, mixed-use development in terms of its financial viability, a heuristic, generalized calculation of construction cost-per-meter-square is an inaccurate way to measure the return-on-investment ROI when numerous 3D model variants are generated.

On the other hand, it will be more accurate to extract the actual volume of building and cladding material required from the 3D models generated (see Chapter 5) and subsequently derive a more accurate construction cost and its corresponding return-on-investment ROI value. In this way, the developers can compare the financial viability of any given 3D variant to one another when different building massing or design are generated while keeping its gross floor area GFA value constant. They can begin to understand that different massing or design would mean different construction costs and therefore impact the return-on-investment ROI.

2.3 Daylight Availability Literature Review

2.3.1 Introduction of Daylight Availability

The daylight availability of a development refers to the amount of daylight falling on a working plane positioned 1-meter above ground in a development. In specificity, there are two types of daylight availability evaluation that is being explored in this thesis:

(1) continuous daylight autonomy (cDA)
(implemented in Chapter 5 for demonstration)

(2) spatial daylight autonomy (sDA)
(NOT implemented in Chapter 5 for demonstration)

In this research, both the continous daylight autonomy (cDA) and spatial daylight autonomy (sDA) are evaluated on the 3D models in the background research (see section 2.6) as a means of preliminary investigation.

However, only continous daylight autonomy (cDA) method is implemented in the demonstration (Chapter 5) as an evaluation of the numerous 3D models.

2.3.2 Importance of continuous and spatial daylight availability (cDA) analysis to measure the daylight availability of a development

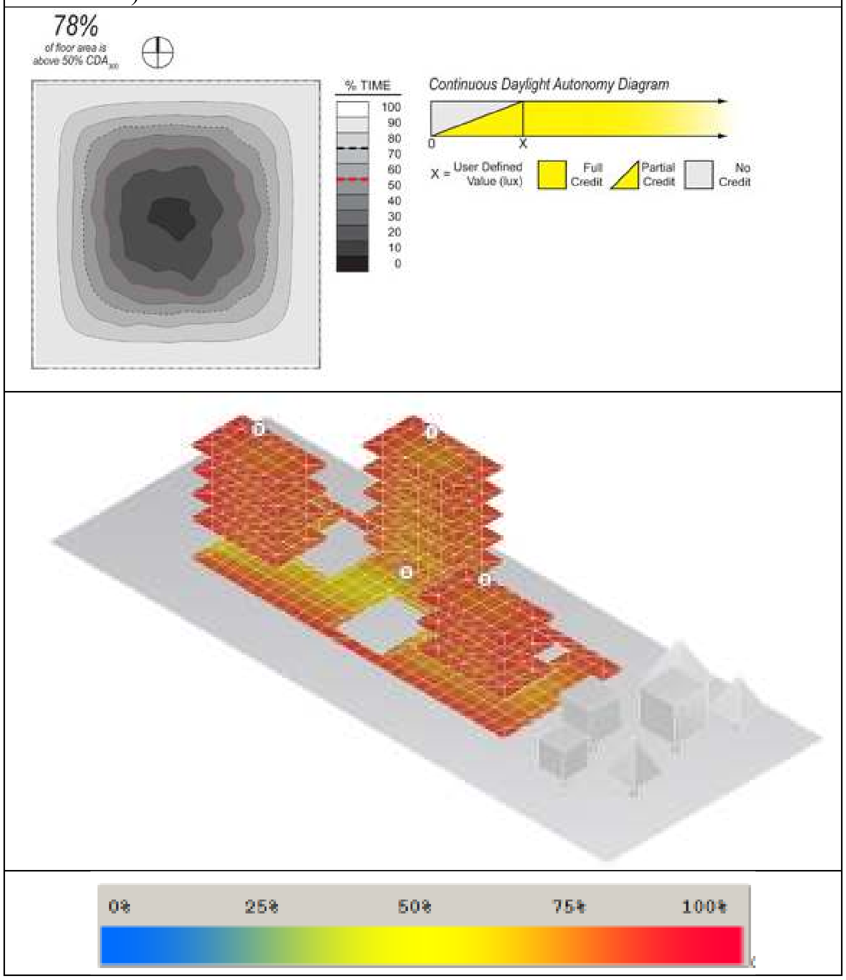
The measure of daylight availability is important to the developer as a means to understand areas of the development that are over-lit, sufficiently or under-lit, which is directly related to the design of the built geometry.

- Thus, the challenge of the development is to reduce areas of the building that suffers from over-lit or under-lit daylight conditions and to maximize areas of the development with sufficiently daylight areas, in accordance to the luminance level as required by the development’s illuminance requirements (ie, an industrial development requires 1000lux of illuminance level while a residential may require only 300lux).

2.3.3 Continuous Daylight Availability (cDA) Evaluation Method

Continuous Daylight Autonomy (cDA) was developed in 2006 by Zach Rogers as a basic modification of Daylight Autonomy. In Continuous Daylight Autonomy, partial credit is given to values below the user defined threshold. If the user defined threshold is 300 lux (or Daylight Autonomy threshold, DA300) and a specific point on the working plane exceeded 300 lux 50% of the time on an annual basis, then the cDA300 might result in a value of approximate 55-60% or more.

Fig. 2-5 Continuous Daylight Availability
(Source: http://patternguide.advancedbuildings.net/using-this-guide/analysis-methods/continuous-daylight-autonomy) (Last Visited: 30 June 2015)



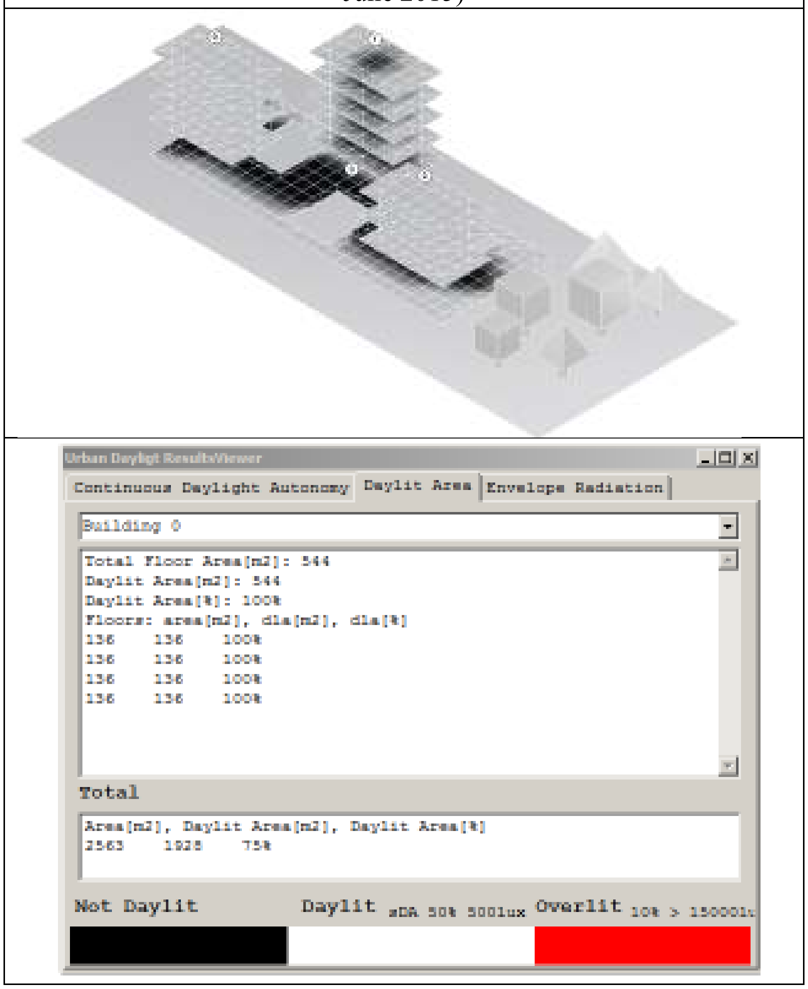
For example, say a certain interior grid point has 150 lux due to daylight at a given time step, DA300 would give it 0 credit for that time step whereas cDA300 would give it 150/300=0.5 credit for that time step. For the graphs above, we selected a Continuous Daylight Autonomy threshold of 300 lux (cDA300). The graphical percent values represent the percentage of the floor area that exceeds 300 lux for at least 50% of the time giving partial credit for time steps below 300 lux.

2.3.4 Spatial Daylight Availability (sDA) Evaluation Method

In the evaluation of Spatial Daylight Availability (sDA), the evaluation tool measures "How much of "of a certain" space or building is adequately daylit?" to analyze daylight sufficiency in a development.

In this metric, a certain illuminance threshold has to be achieved at least 50% of the occupied hours to consider a space adequately daylit and is reported as daylit area or a percentage of floor area that is daylight. While the metric is a simple one, it can provide useful information consolidated to one number; e.g."40% of the design variant's area is daylit". Thus, the evaluation is able to highlight underperforming areas in terms of daylight availability quickly.

Fig. 2-6 Spatial Daylight Availability
(Source: http://archsim.com/documentation/dla/) (Last Visited: 30 June 2015)

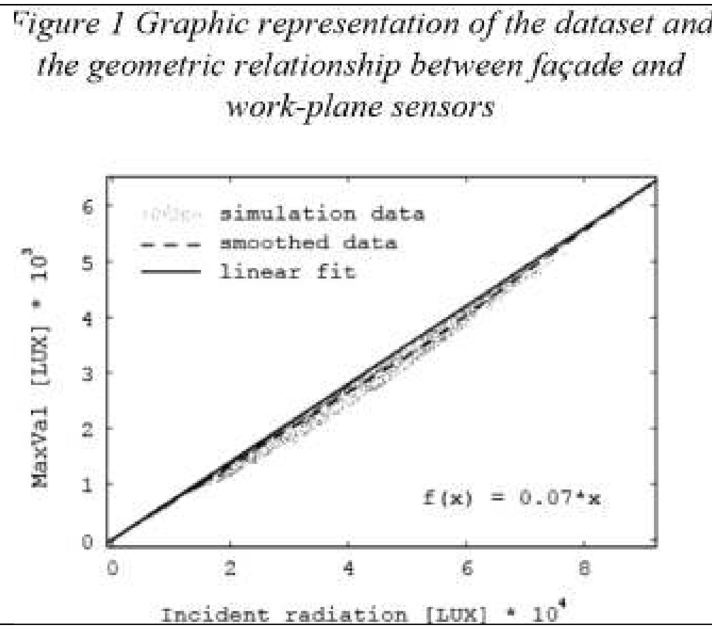


2.3.5 Evaluating Continuous and Spatial Daylight Availability using the tool ARCHSIM.

In order to conduct Continuous Daylight Availability and Spatial Daylight Availability, especially for evaluating the daylight availability of large urban designs, ARCHSIM by Christopher Reinhardt and Timur Dogan was used. The tool automates exterior DAYSIM simulations for all the buildings in the model. Given the solar radiation on the façade, the tool uses a generalized impulse response to calculate the interior illumination on an hour by hour basis.

Fig. 2-7 Generalized light propagation algorithm.

Generalized impulse-response to calculate interior illumination fromgiven solar radiation on a building's façade.(Source: Reinhardt, Christopher and Dogan, Timur, 2012)



The method used in evaluating daylight availability involves locating a sensor point 1 meter above every floor in the building (to represent light falling on the table).For every floor, the sensor points are spaced at 5 meters apart from one another, hence in a given building, the sensor points are an array spaced at 5 meters from each other horizontally and spaced by the height of the building vertically (6 meters vertical height sensor point spacing for a production building, 3.6 meters for a residential and 5 meters for a commercial building.). In Reinhardt's generalized light propagation algorithm, the incident radiation of the building's façade becomes the input and the algorithm (represented as a graph in Fig , approximates the interior illuminance in as much as 84 times faster than the commonly used method of daylight availability calculation in Radiance, yet is under 9.3% RMSE error under diffuse sky conditions.

2.3.6 Conclusion of Daylight Availability Literature Review

In conclusion, in evaluating a high dense, mixed-use development in terms of its daylight availability, a 2D plan is insufficient to measure the daylight availability and 3D models are required. This is so as the continuous and spatial daylight availability (cDA and sDA) analysis requires the placement of both horizontal and vertical sensor points inside the building floor plates within a 3D model. However, this leads to another question: Since the generation of 3D model may require more time, then at which density or plot ratio is the use of 3D models in a high-dense, mixed-use development necessary to facilitate the evaluation of cDA and sDA? The research attempts to answer this question in the following section 2.5 (Background research: The plot ratio problem).

2.4 Solar Envelope Radiation Literature Review

2.4.1 Introduction of Solar Envelope Radiation

Solar envelope radiation is the amount of solar radiation energy received on a building envelope during a given time period. This is also sometimes called insolation (INcident SOLar RadiATION) and is in terms of energy accumulated per day or per year (kWh/m2/yr).

In this research, the solar envelope radiation analysis is evaluated on the 3D models in the background research (see section 2.6) as well as in the demonstration (Chapter 5) as an evaluation of the numerous 3D models.

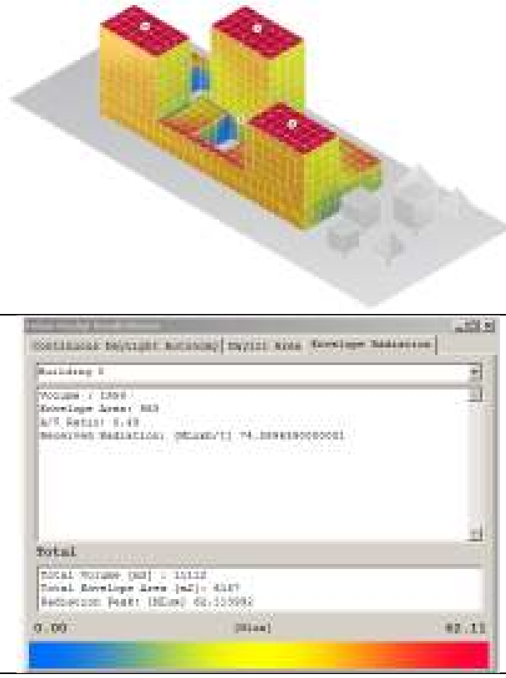
2.4.2 Importance of solar envelope radiation analysis of a development

The solar envelope radiation analysis allows developers to understand the amount of solar energy received on the building envelope in a typical year at a specified location. For a given plot of land, numerous design variants can be generated that ranges in numerous development massing and orientation, thus, each design variant has different building envelopes that are exposed to different amount of direct and indirect solar radiation. Hence, developers can effectively compare different design variants in terms of their solar envelope radiation performances through this analysis.

2.4.3 Solar Envelope Radiation Evaluation Method

In the evaluation of solar envelope radiation, sensor points are attached to the development's external envelope: inclusive of the building roof, façade, windows, doors and internal facades that receive solar radiation. Sensor points are attached in fixed intervals horizontally, while on the vertical intervals, the sensors are placed on every floor and roof, corresponding to the different floor heights due to the development's functional use (ie, industrial developments may have a floor height of 6 meters while a residential development have a floor height of 3.6 metres, thus the vertical interval of the sensor points requires to be placed on every floor level will have a smaller interval in a residential development than an industrial development).

Fig. 2-8 Solar Envelope Radiation
(Source: http://archsim.com/documentation/envrad/) (Last Visited: 30 June 2015)

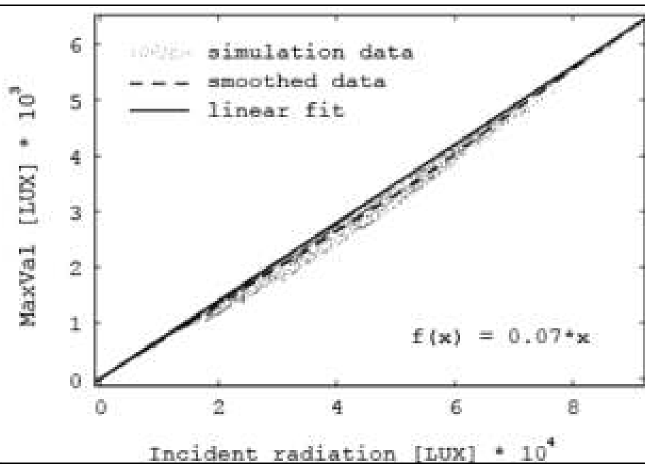


2.4.4 Evaluating Solar Envelope Radiation using the tool ARCHSIM.

ARCHSIM was again used in this analysis. Reinhardt and Timur's generalized impulse-response light propagation algorithm not only evaluates the illumination value, but also generalizes the solar radiation on a building façade. Through the use of this algorithm, the researchers were able to significantly speed up the analysis time required, by as much as 84 times as opposed to present insolation calculations done in Radiance.

Fig. 2-9 Generalized light propagation algorithm.

Solar Envelope Radiation analysis significantly faster through the use of the generalized light propagating algorithm .(Source: Reinhardt, Christopher and Dogan, Timur, 2012)



2.4.5 Conclusion of Solar Envelope Radiation Literature Review

In conclusion, in evaluating a high dense, mixed-use development in terms of its solar envelope radiation, a 2D plan is insufficient to measure the solar envelope radiation and 3D models are required. This is so as the solar envelope radiation analysis requires the placement of both horizontal and vertical sensor points on the building envelope of a 3D model. However, this again leads to another question: Since the generation of 3D model may require more time, then at which density or plot ratio is the use of 3D models in a high-dense, mixed-use development necessary to facilitate the evaluation of solar envelope radiation? The research attempts to answer this question in the following section 2.5 (Background research: The plot ratio problem).

2.5 Background research: The plot ratio problem

2.5.1 Introduction

With the literature review focusing on the selection of evaluation techniques for consideration to be used in the computational architecture and demonstration of the research, a background research is conducted. The goal of the background research is to achieve two aims:

(1) To answer the question at which degree of plot ratio is the use of 3D models in high-dense, mixed-use development necessary?

(2) To use the selection of evaluative techniques such as the continuous daylight availability (cDA, see Section 2.3) as well as the solar envelope radiation evaluation techniques (see Section 2.4) through the use of the evaluative tool, ARCHSIM. This is critical to the computational architecture section (Chapter 3) and the demonstration section (Chapter 5) of the research. The evaluation technique of financial viability using the return-on-investment ROI analysis is not used in the background research but implemented in the demonstration (Chapter 5).

In the background research, developers typically plan on 2D plans (Bartholomew, 2005). 2D planning is useful to plan for mono-functional landuse plans (see section 1.3.2, Frequent use of 2D plans for mixed use developments in scenario planning). However, 2D plans are very limiting when it comes to developing sites into a high-dense, mixed-use development.

- 2D plans are very limiting as both a planning and communication tool on the development of mixed-use developments. Rather, developing using 3D models can offer an easy and clear way in communicating the development intent of mixed-use development.

- The use of 3D models effectively allows developers to understand problems or building performance at higher plot-ratio or density. For example, it is much easier to visualize the building performance through the use of daylight availability and solar envelope radiation performance across the vertical height of the development. A 2D plan will not be able to illustrate this performance or problem.

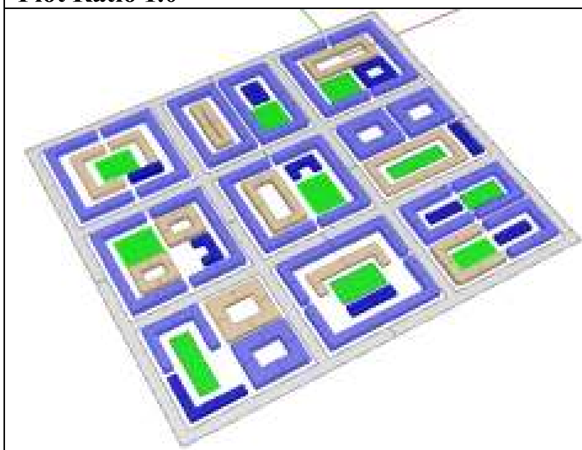
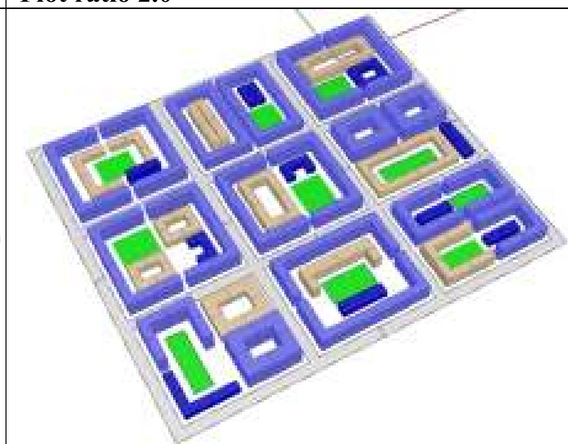
When planning high dense, mixed-use developments, 2D site plans are insufficient due to the fact that they do not allow proposals to be fully understood and evaluated. In particular, as the plot-ratio increases, certain performance issues start to have a more significant impact. In order to take these performance issues into account, 3D models must be generated and evaluated.

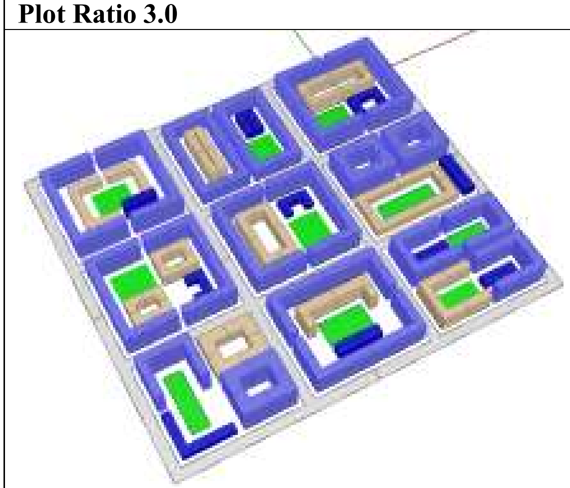
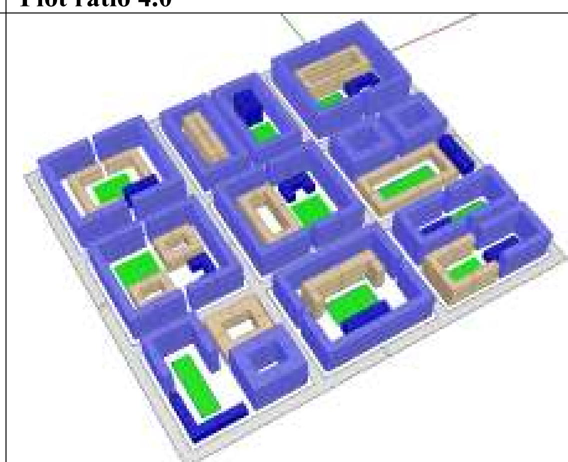
2.6 Establish the degree of density (plot ratio) requiring the use of 3D models in planning

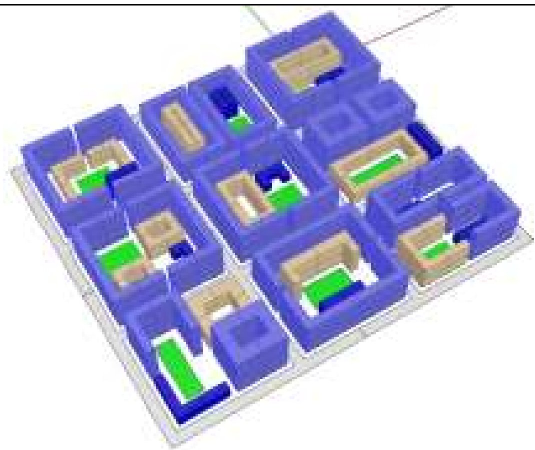
2.6.1 Courtyard Typology with five different densities

In this case study, a typology- the courtyard type- is presented below as the plot-ratio problem case study. In the Courtyard Typology, a total of five different Plot ratios are studied: Plot ratio 1.0, 2.0, 3.0, 4.0 and 5.0.

Fig. 2-10 Three by three grid of courtyard typology mixed-use development with different plot ratio (from 1.0 to 5.0)

Plot Ratio 1.0		**Plot ratio 2.0**	
			
Typical Height of Development: **1 to 2 floors**	Gross Floor Area **20,982 m²**	Typical Height of Development **3 to 5 floors**	Gross Floor Area **41,964 m²**

Plot Ratio 3.0		**Plot ratio 4.0**	
			
Typical Height of Development: **5 to 7 floors**	Gross Floor Area **62,946 m²**	Typical Height of Development **7 to 10 floors**	Gross Floor Area **83,928 m²**

<table>
<tr><td colspan="2">Plot Ratio 5.0</td><td colspan="2">Legend</td></tr>
<tr><td colspan="2" rowspan="5"></td><td></td><td>Production function</td></tr>
<tr><td></td><td>Residential function</td></tr>
<tr><td></td><td>Commercial function</td></tr>
<tr><td></td><td>Recreational function</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Typical Height of Development:
8 to 13 floors</td><td>Gross Floor Area
104,910 m^2</td><td></td><td></td></tr>
</table>

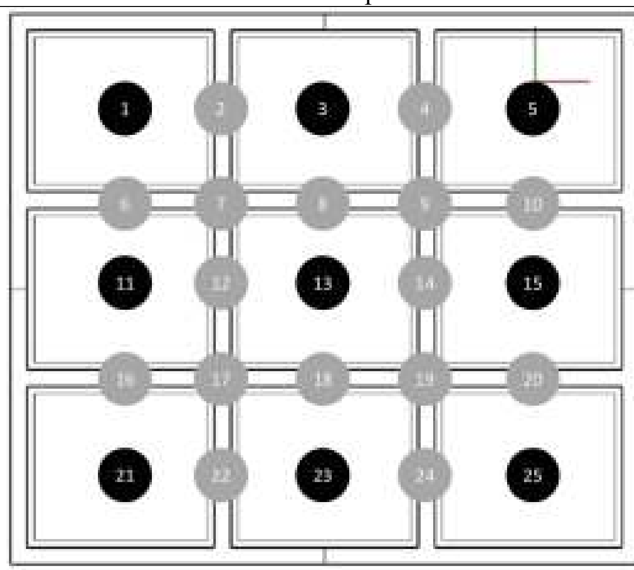
2.6.2 Urban Heat Island (UHI)

Methodology

In determining at which density does a development affect the Urban Heat Island readings, the STEVE tool is used to evaluate the five plot ratios. For every plot ratio, sensors points are placed at 1.6metres above the ground level and are distributed in the centroid of the plots (represented by black sensor points) as well as on the road network (represented by grey sensor points).

The evaluation tool used for the evaluation of urban heat island (UHI), is the STEVE tool. In the STEVE tool, the method used for the evaluation of the 3D model is through the placement of 25 sensors point spaced at 5 metres away from each other. The sensor points are placed 1.6metres above the ground level,and they give five different readings: Tmax, Tmin, Tavg, Tavg-day and Tavg-night. These five readings are taken at all of the 25 sensor points and are given an average to summarise the performance of the development. The sensor points are also placed on the roads as well as the plot sites to detect any thermal difference between the developments.

Fig. 2-11 25 Sensor Points for each Plot ratio development

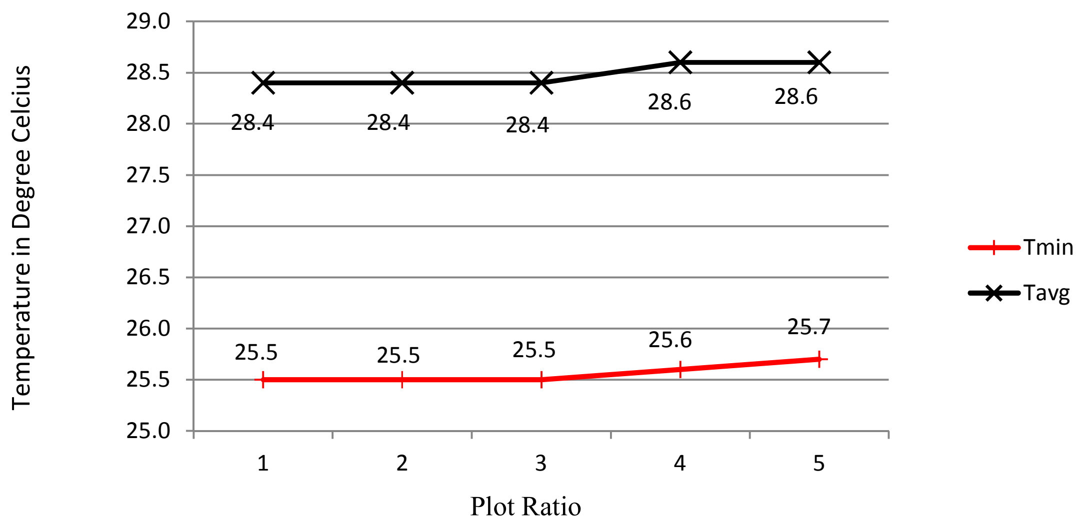


Results

When it comes to comparing the performance of Urban Heat Island (UHI) for the development having different plot ratios, there is no difference in the Urban Heat Island values between plot ratio 1.0, 2.0and 3.0. However, there is a difference in the Tmin and Tavg values when the development is at developed at the plot ratio of 4.0 and 5.0.

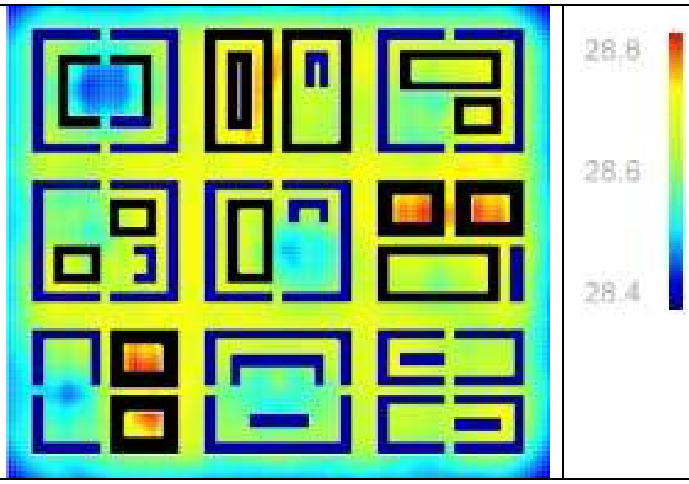
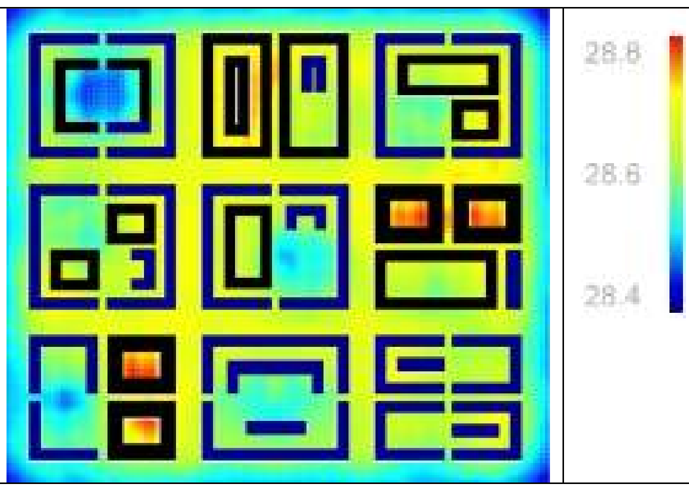
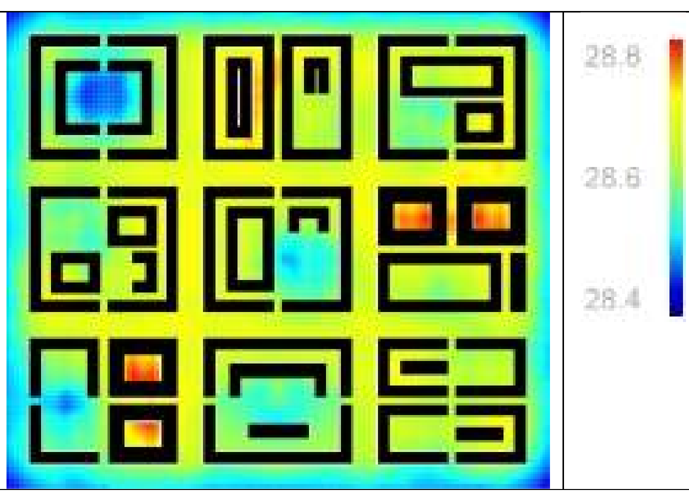
At plot ratio 4.0, the Tavg increased by 0.2^0C (from 28.4^0C to 28.6^0C). The Tmin value for the development at plot ratio 4.0 increased by 0.1^0C (from 25.5^0C to 25.6^0C) while the Tmin value for the development at plot ratio 5.0 inceased by 0.2^0C (from 25.5^0C to 25.7^0C).

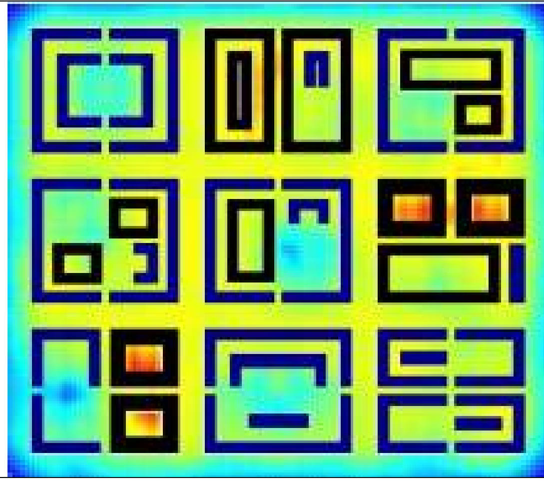
Table 2-2 Tmin and Tavg values across the 5 different plot ratio development

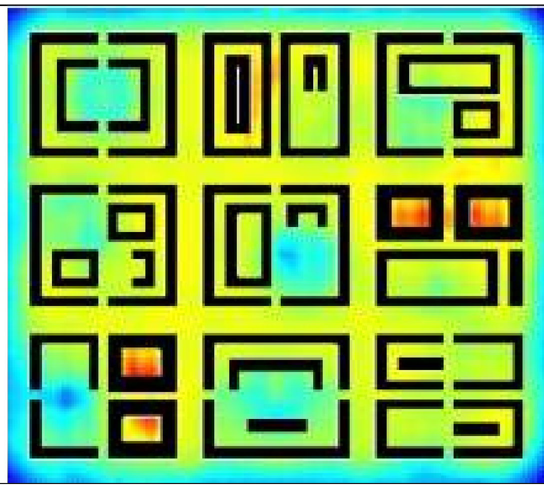


Below are the simulation visualization. As one visually inspects the visualization results, there is almost no difference between the development at plot ratio 1.0, 2.0 and 3.0. However, the visualization shows more warmer readings (represented by a shift from blue to yellow colour) when the development becomes more dense at plot ratio 4.0 and 5.0

Fig. 2-12 Urban Heat Island results for courtyard typology

Plot Ratio 1.0		Tmin	25.5 ^{0}C
		Tavg	28.4 ^{0}C
		Tavg-day	30.1 ^{0}C
		Tavg-night	27.5 ^{0}C
		Tmax	33.3 ^{0}C
Plot Ratio 2.0		Tmin	25.5 ^{0}C
		Tavg	28.4 ^{0}C
		Tavg-day	30.1 ^{0}C
		Tavg-night	27.5 ^{0}C
		Tmax	33.3 ^{0}C
Plot Ratio 3.0		Tmin	25.5 ^{0}C
		Tavg	28.4 ^{0}C
		Tavg-day	30.1 ^{0}C
		Tavg-night	27.5 ^{0}C
		Tmax	33.3 ^{0}C

<table>
<tr><td rowspan="5">Plot Ratio 4.0</td><td rowspan="5"></td><td rowspan="5"></td><td>Tmin</td><td>25.6 ^{0}C</td></tr>
<tr><td>Tavg</td><td>28.6 ^{0}C</td></tr>
<tr><td>Tavg-day</td><td>30.1 ^{0}C</td></tr>
<tr><td>Tavg-night</td><td>27.5 ^{0}C</td></tr>
<tr><td>Tmax</td><td>33.3 ^{0}C</td></tr>
</table>

<table>
<tr><td rowspan="5">Plot Ratio 5.0</td><td rowspan="5"></td><td rowspan="5"></td><td>Tmin</td><td>25.7 ^{0}C</td></tr>
<tr><td>Tavg</td><td>28.6 ^{0}C</td></tr>
<tr><td>Tavg-day</td><td>30.1 ^{0}C</td></tr>
<tr><td>Tavg-night</td><td>27.5 ^{0}C</td></tr>
<tr><td>Tmax</td><td>33.3 ^{0}C</td></tr>
</table>

Conclusion:
To which degree of plot ratio is the use of 3D models in planning necessary?

Hence, for the case of the performance of the Urban Heat Island (UHI), there is a difference in the performance of the development at the higher density at plot ratio 4.0 and above. The use of 3D modelling to assist planners to complement 2D planning is critical when planning involves a density of 4.0 and above.

2.6.3 Continuous Daylight Autonomy cDA

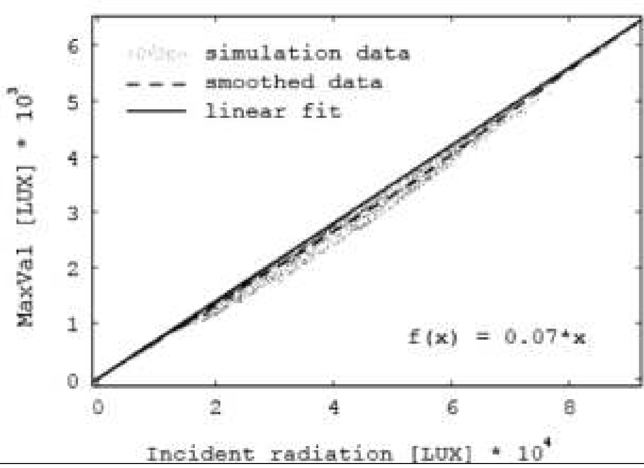
Methodology

For evaluating the daylight availability of developments, ARCHSIM by Christopher Reinhardt and Timur Dogan was used. The tool automates exterior DAYSIM simulations for the development in the model. Given the solar radiation on the façade, the tool uses a generalized impulse response to calculate the interior illumination on an hour by hour basis.

Fig. 2-13 Generalized light propogation algorithm.

Generalized impulse-response to calculate interior illumination fromgiven solar radiation on a building's façade.(Source: Reinhardt, Christopher and Dogan, Timur, 2012)

Figure 1 Graphic representation of the dataset and the geometric relationship between façade and work-plane sensors



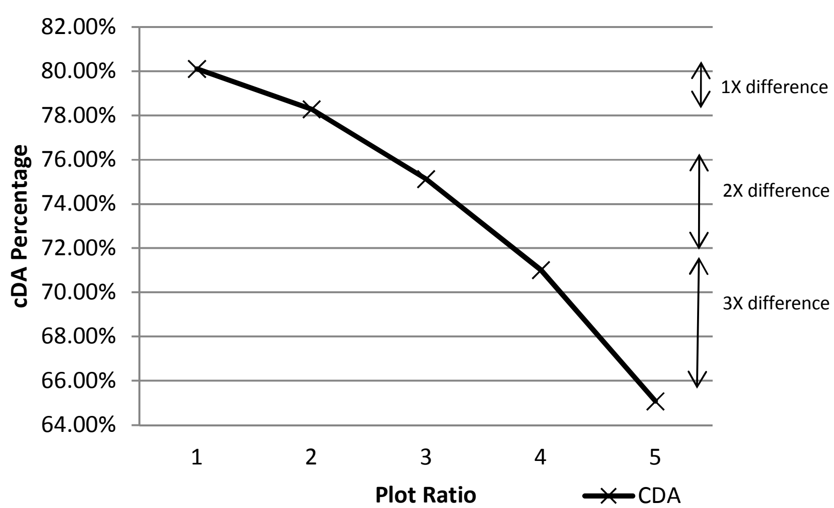
The method used in evaluating daylight availability involves locating a sensor point 1 metre above every floor in the building (to represent light falling on the table).For every floor, the sensor points are spaced at 5 metres apart from one another, hence in a given building, the sensor points are an array spaced at 5 metres from each other horizontally and spaced by the height of the building verticslly (6 metres vertical height sensor point spacing for a production building, 3.6 metres for a residential and 5 metres for a commercial building.). In Reinhardt;s generalized light propogation algorithm, the incident radiation of the building;s façade becomes the input and the algorithm (represented as a graph in Fig , , approximates the interior illuminance in as much as 84 times faster than the commonly used method of daylight availablilty calculation in Radiance, yet is under 9.3% RMSE error under diffuse sky conditions..

Results

When it comes to comparing the performance of continuous daylight autonomy for developments having different plot ratios, it appears that there is a larger difference when the development becomes more and more dense.

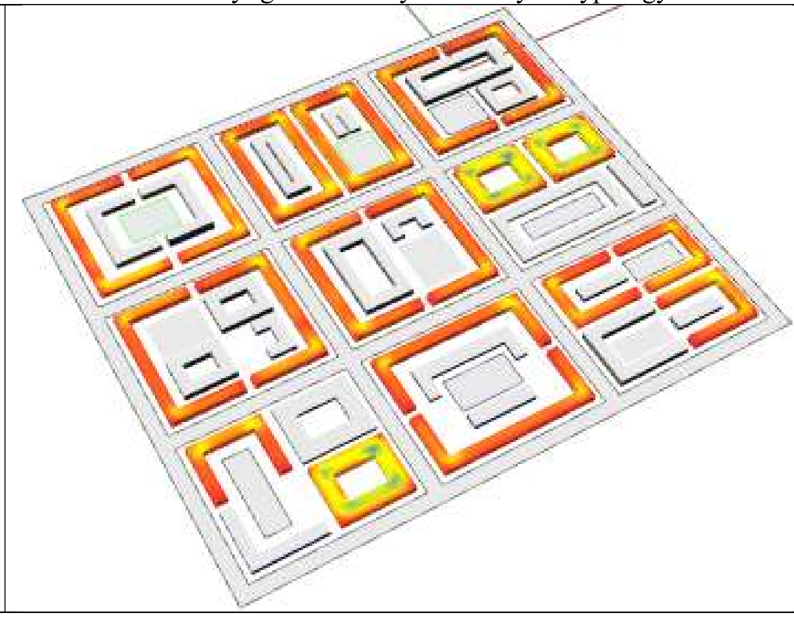
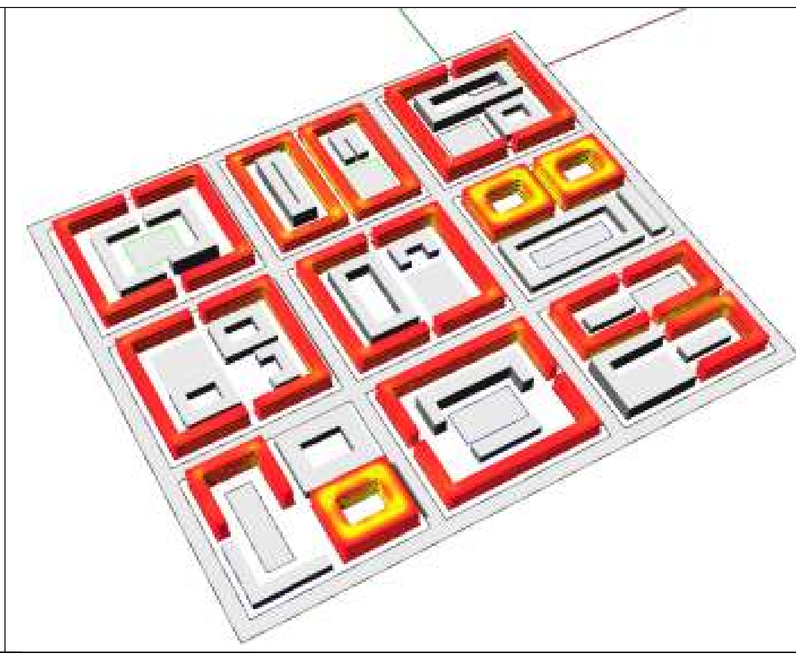
The results suggest that there is a much larger difference between the denser plot ratios of 3.0, 4.0 and 5.0. The difference between continuous daylight autonomy values between the developments at plot ration 1.0 and 2.0 is 1.83% (1 times difference). However, the difference between continuous daylight autonomy values of the developments at plot ratio 3.0 and 4.0 is 4.11% (2 times the difference), while the difference of continuous daylight autonomy values between the developments at plot ratio 4.0 and 5.0 is 5.93% (almost 3 times the difference).

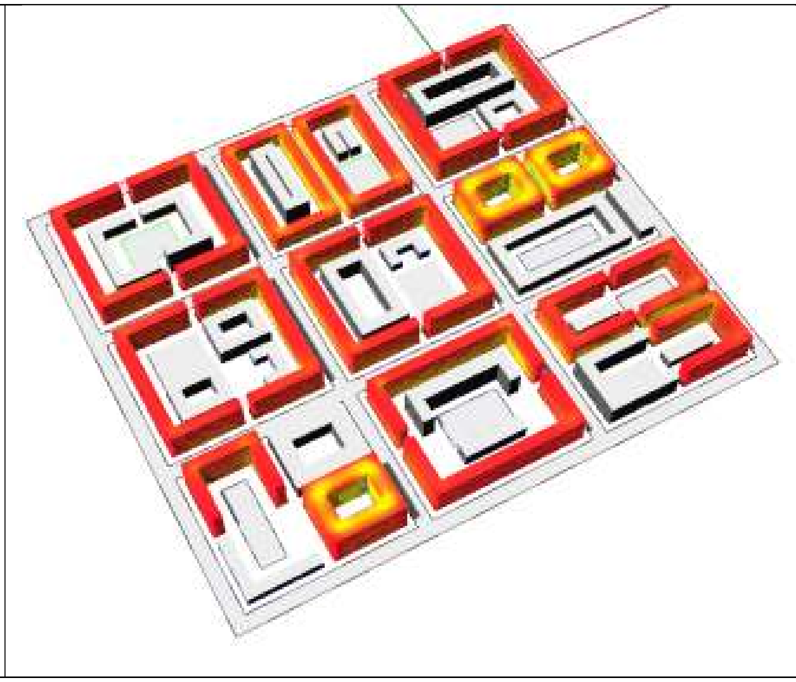
Table 2-3 Continuous daylight autonomy values across the 5 different plot ratio development

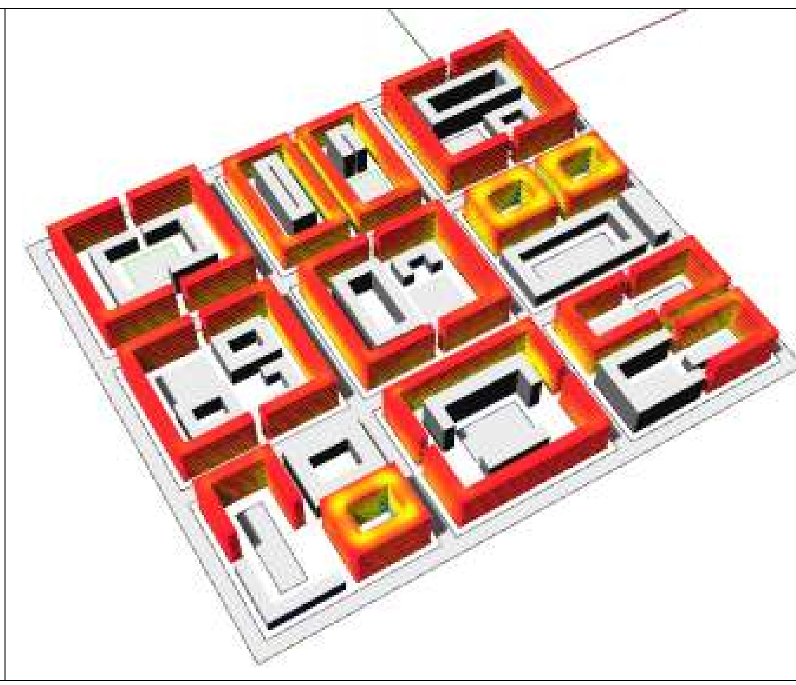


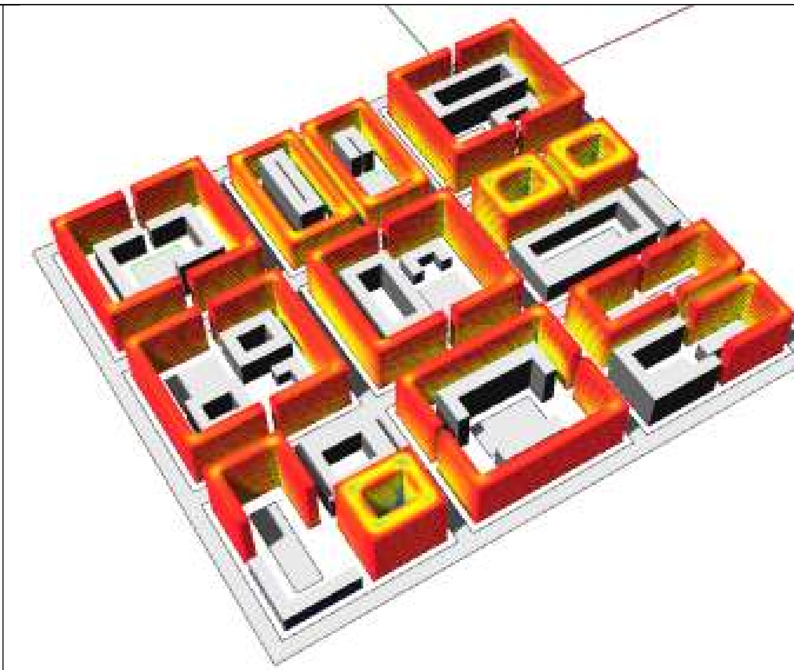
Below are the visualization to the continuous Daylight Autonomy simulation results. As one visually inspects the results, it can be observed that the higher dense development show simulation readings with poorer daylight autonomy values (represented by more and more yellow colour). Another note worthy observation is that as the development becomes more dense, the floors on the lower portion of the buildings tend to show results of poorer daylight autonomy.

Fig. 2-14 continuous daylight autonomy for courtyard typology

Plot Ratio 1.0		cDA	80.11%
			
Plot Ratio 2.0		cDA	78.28%
			

Plot Ratio 3.0		cDA	75.12%
			

Plot Ratio 4.0		cDA	71.01%
			

Plot Ratio 5.0		cDA	65.08%
			

Conclusion:
To which degree of plot ratio is the use of 3D models in planning necessary?

Hence, for the case of continuous daylight autonomy, the performance differs greatly with higher densities. In fact, at plot ratio 3.0 and above, the lower floors of the development begins to receive poorer daylight availability than the upper floors.

When planners work on 2D plans alone, they are unable to understand this repercussion of daylight availability. hence it is imperative t complement the use of 3D modelling and evaluation from plot ratio 3.0 and above.

2.6.4 Spatial Daylight Autonomy sDA

Methodology

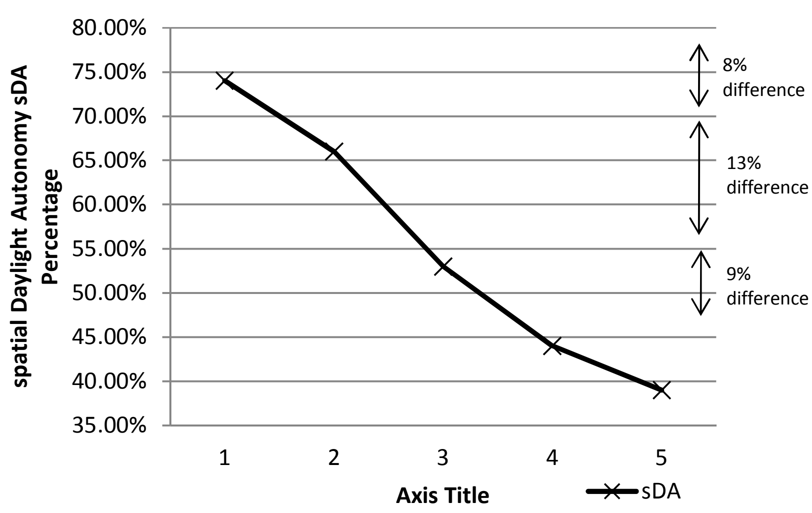
Using the same evaluation tool as in calculating continuous daylight autonomy, the same method was used: sensor points are spaced 5 metres apart horizontally and on the vertical sensor spacing, the sensors are separated by the eight of every floor (6 metres vertical height sensor point spacing for a production building, 3.6 metres for a residential and 5 metres for a commercial building.). Again, Reinhardt;s generalized light propogation algorithm was used to calculated the spatial daylight autonomy values of the interior illumination

Results

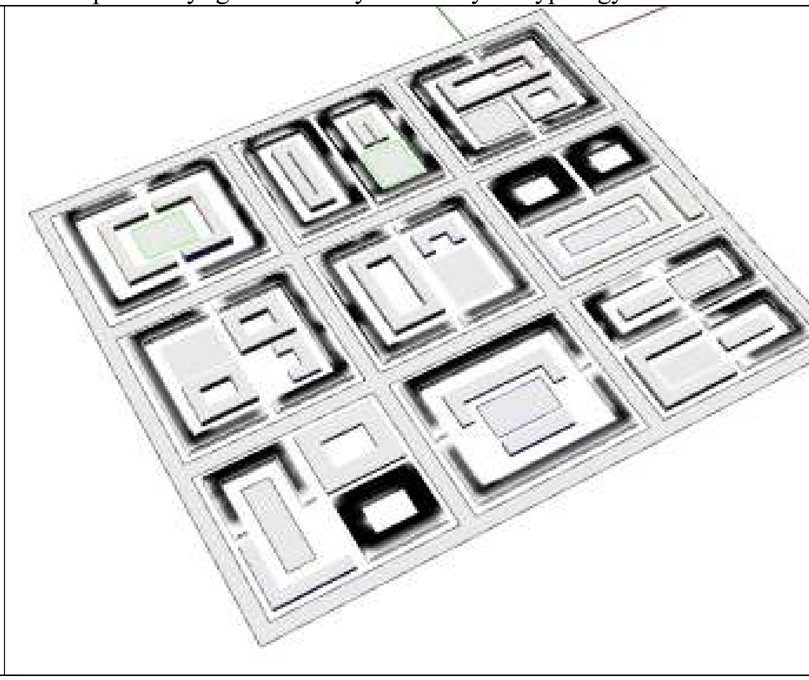
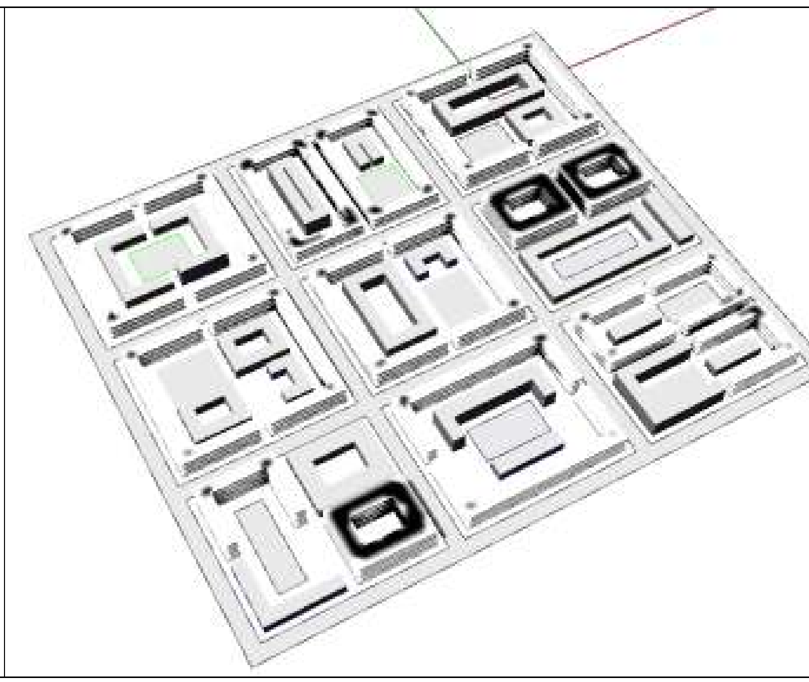
When it comes to comparing the performance of spatial daylight autonomy for developments having different plot ratios, it appears that there is a larger difference when the development is more dense than plot ratio of 1.0

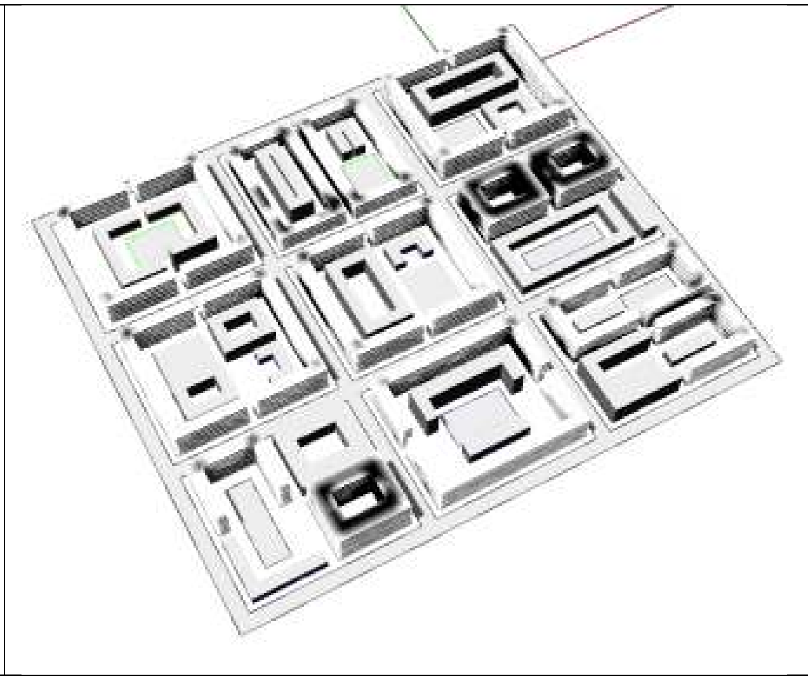
The difference between the spatial daylight autonomy values between the developments at plot ration 1.0 and 2.0 is 8.02% . However, the difference between spatial daylight autonomy values of the developments at plot ratio 2.0 and 3.0 is 13.00% , while the difference of spatial daylight autonomy values between the developments at plot ratio 3.0 and 4.0 is 9.00%.

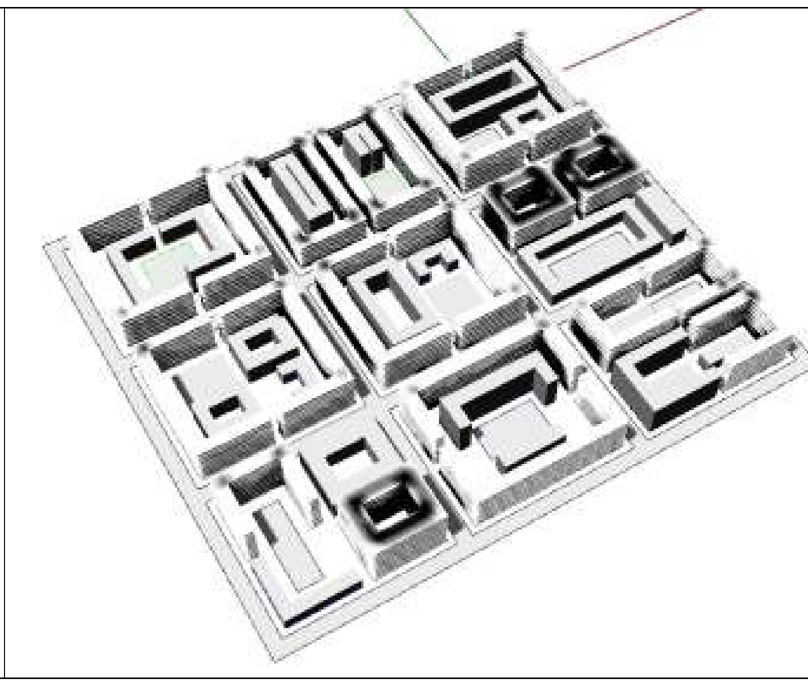
Table 2-4 Spatial daylight autonomy values across the 5 different plot ratio development

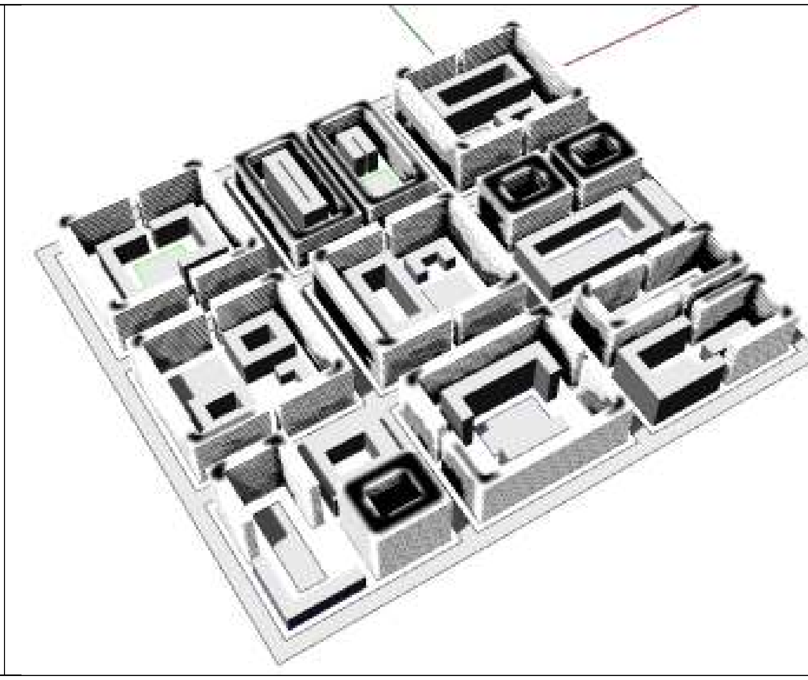


Below are the visualization to the spatial Daylight Autonomy simulation results. As one visually inspects the results, it can be observed that the higher dense development show simulation readings with poorer daylight autonomy values (represented by more and more black colour). Again, note that as the development becomes more dense, the floors on the lower portion of the buildings tend to show results of poorer daylight autonomy.

Fig. 2-15 Spatial daylight autonomy for courtyard typology			
Plot Ratio 1.0		sDA	74.02%
			
Plot Ratio 2.0		sDA	66.00%
			

Plot Ratio 3.0		sDA	53.00%
			

Plot Ratio 4.0		sDA	44.00%
			

Plot Ratio 5.0		sDA	39.00%
			

Conclusion:
To which degree of plot ratio is the use of 3D models in planning necessary?

Hence, for the case of spatial daylight autonomy, the performance differs after the density of plot ratio 1.0. In fact, at plot ratio 1.0 and above, the lower floors of the development begins to receive poorer daylight availability than the upper floors.

When planners work on 2D plans alone, they are unable to understand this repercussion of daylight availability. hence it is imperative to complement the use of 3D modelling and evaluation from plot ratio 1.0 and above for the case of spatial Daylight Autonomy.

2.6.5 Envelope Solar Radiation

Methodology

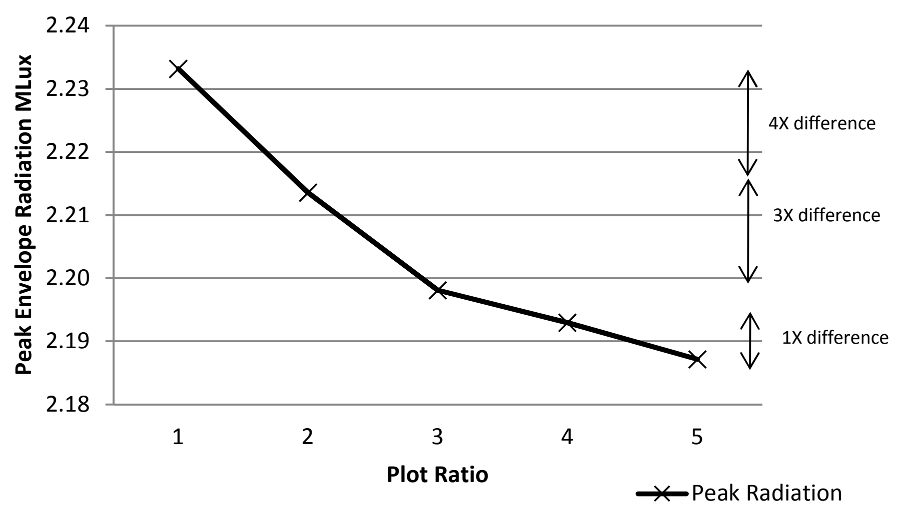
ARCHSIM was used again. In order to evaluate the envelope solar radiation, sensor points are attached to the building envelope (roof and façade). The sensor points are also spaced at 5 metres apart horizontally and on the vertical sensor spacing, the sensors are separated by the eight of every floor (6 metres vertical height sensor point spacing for a production building, 3.6 metres for a residential and 5 metres for a commercial building).

Results

When it comes to comparing the performance of envelope solar radiation for the development having different plot ratios, it appears that there is a difference for every given development at all the plot ratios.

Rather, the results suggest that there is a much larger difference between the lower plot ratio of 1.0, 2.0 and 3.0 while the difference becomes smaller as the development densifies between plot ratio 4.0 and 5.0. The difference between peak envelope solar radiation values between the developments at plot ration 4.0 and 5.0 is 0.005786MLux (1 times difference). However, the difference between peak envelope solar radiation values between the developments at plot ratio 2.0 and 3.0 is 0.015459MLux (3 times difference), while the difference between peak envelope solar radiation values between the developments at plot ratio 1.0 and 2.0 is 0.019649MLux (almost 4 times difference).

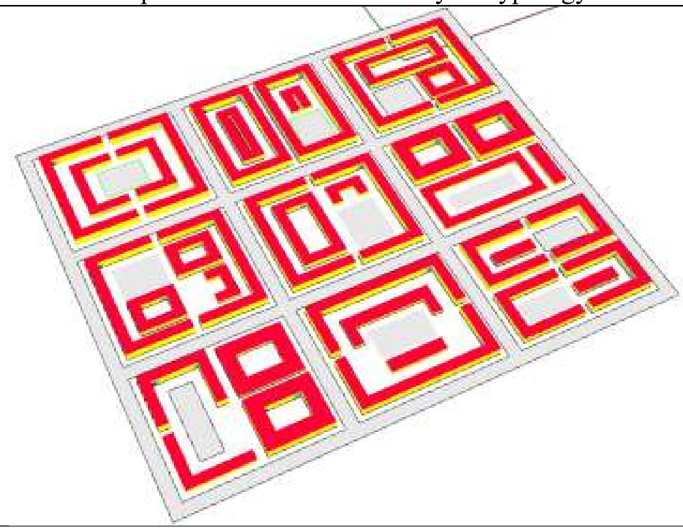
Table 2-5 Peak Envelope Solar Radiation values across the 5 different plot ratio development



Below are the visualizations to the envelope solar radiation simulation. As one visually inspects the visualization results, it can be observed that the lower plot ratio development show simulation readings with higher envelope radiation (represented by red and yellow colours). Another noteworthy observation is that the buildings on the lower plot ratio do not shade one another as is the case for the developments at plot ratio 4.0 and 5.0.

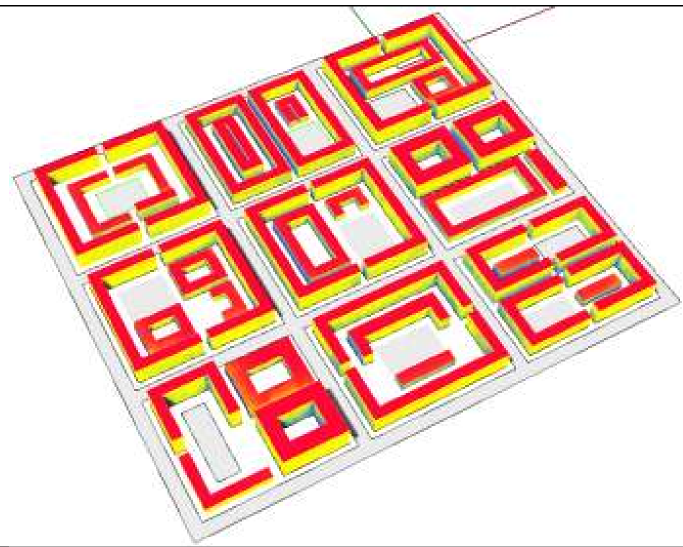
Fig. 2-16 Envelope solar radiation for courtyard typology

Plot Ratio 1.0



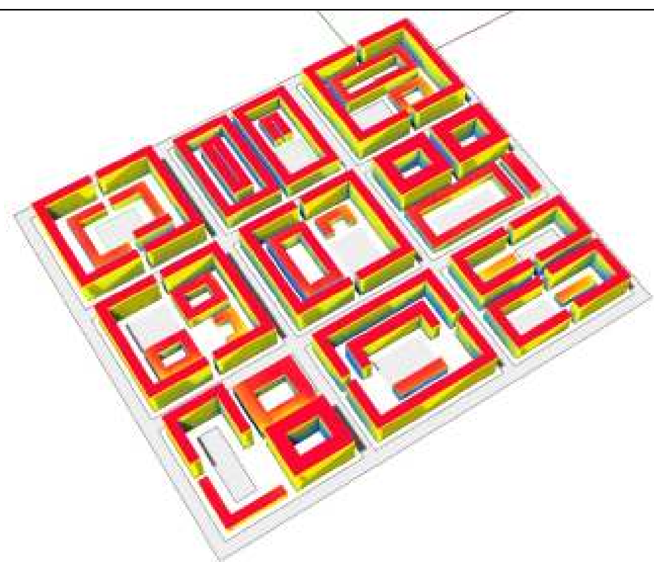
Peak Radiation	2.233214 Mlux
Envelope Area	240,320 m^2

Plot Ratio 2.0

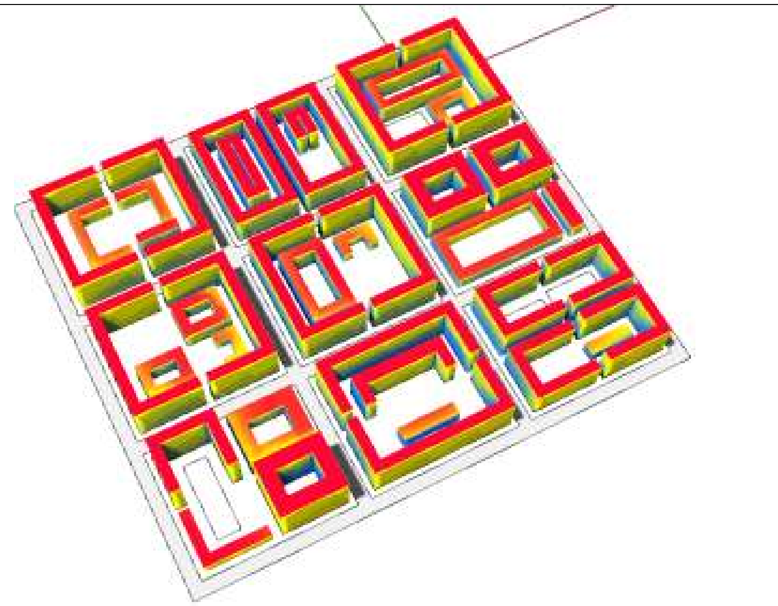


Peak Radiation	2.213565 Mlux
Envelope Area	495,320 m^2

Plot Ratio 3.0



Peak Radiation	2.198106 Mlux
Envelope Area	633,977 m^2

Plot Ratio 4.0		Peak Radiation	2.192935 Mlux
		Envelope Area	782,186m^2
			

Plot Ratio 5.0		Peak Radiation	2.187149 Mlux
		Envelope Area	933,126 m^2
			

Conclusion:
To which degree of plot ratio is the use of 3D models in planning necessary?

Hence, for the case of envelope solar radiation, it is more critical to begin involving the use of 3D modelling and evaluation to assist planners at all densities. In fact the low density development are more acutely affected by the performance of the envelope solar radiation, and this is not discernable on the 2D plan. Only through the use of 3D models and evaluation tools can then the planners be able to observe the performance of their development.

2.6.6 Case Study Conclusion

To which degree of plot ratio is the use of 3D models in high-dense, mixed-used development necessary?

In general, the usage of 3D models is necessary when developers work at higher densities. However, it depends on the type of evaluation that the developers are interested in:

- to design developments that attempt to mitigate solar radiation on its envelope, developers have to work on 3D models from plot ratio 1.0 and onwards.
- For daylight availability, such as spatial daylight autonomy, 3D models need to be involved as soon as developers are working above density 2.0 or
- For continuous daylight availability, a density of 3.0 requires the use of 3D Models.
- Developers mitigating Urban Heat Island has to create 3D models when they are working at density of 3.0.

Table 2-6 Establishing which plot ratio is the use of 3D models necessary in planning

To which degree of plot ratio is the use of 3D models in planning necessary?	
Type of Evaluation	Recommended Usage of 3D Modelling and Evaluation at which density (Plot Ratio)
Urban Heat Island (STEVE tool)	Plot Ratio 3.0 and higher
Envelope Solar Radiation	Plot Ratio 1.0 and higher
Continuous Daylight Autonomy CDA	Plot Ratio 3.0 and higher
Spatial Daylight Autonomy SDA	Plot Ratio 2.0 and higher

Therefore, from the case study as above, the demonstration on Clementi Centre will be demonstrated using a plot ratio of more than 3.0.

Chapter 3

3 Research Proposition

3.1 Overview of Research Solution to Problem Statement

3.1.1 Research Workflow Proposition

In order to achieve the overall aim as set out as above, the primary objective is to develop a workflow that allows the generation and evaluation of numerous 3D design variants for each planning scenario. These design variants will all have the same overall areas for different functions, but will distribute these functions in varying ways. This workflow is referred to as the *Function Distribution Design* (FDD) workflow.

The *Function Distribution Design* (FDD) workflow consists of three parts:

- (A) a five-design-steps workflow
- (B) a computational system
    - (i) overall computational architecture
- (C) generative techniques

3.1.2 Design Workflow

(A) Five-Design Steps Workflow

The five-design steps workflow forms the first part of the *Function Distribution Design* (FDD) workflow. The design workflow explicitly prescribes the way of designing a type of product, and particularly in this research, the process that is structured as a set of tasks to be carried out by the developer team in a very specific order.

The proposed design workflow defines a scenario planning procedure for using parametric modeling techniques to generate and evaluate numerous 3D variants. The major five steps that are guided by the design workflow are defined as below. While the research proposes a five-design step workflow, the middle three are exemplified in the subsequent demonstration ("codify scenario", "generate variants", "analyze variants"):

(1) Develop scenario
The first design step accommodates the developers' working methods to generate a few scenarios and specifies the starting point, the development of the planning scenario which must be manually set by the developers.

- While this constitutes as a design step, the research does not prescribe a (design) method for this step, and will not be exemplified in the subsequent demonstration.
- This step accommodates the developers' working methods that deals with the developers' subjective creativity and discretion in developing specific scenarios that they would like to investigate.

(2) Codify scenario
The second step of the workflow combines two steps:
Step (a) 3D design schema and Step (b) is codifying the design schema into a parametric model.

- In Step (a), a 3D design schema, which is also a design task, is generated by the modelling team, adhering to the planning scenario's investigation criteria, and is designed alongside the developer team.
- In Step (b), the modelling team codifies the 3D design schema in Step (a) into a parametric model. In addition, the research specifies a number of sub-steps with relevant techniques identified, as part of the computational architecture (see Chapter 3, 3.1.3 (B) Computational Architecture). The computational architecture also specifies a number of techniques for the evaluation of the design variants.

(3) Generate variants
Once the parametric model is codified, numerous variants of each planning scenario are generated by the parametric models.

(4) Analyze variants
Thereafter, the numerous variants of each planning scenario are analyzed in terms of its performance and constraint satisfaction.

(5) Detail design
Variants that satisfy the constraints are represented as several possible options for further detailed development

- The last step identifies the result of the workflow that can be further considered and developed by the developers. However, while this constitutes as the last design step, the research does not prescribe a method for this step as well, and will not be exemplified in the subsequent demonstration.

Thus, in prescribing the five-design steps workflow, this research offers a clear, process-driven workflow that defines the subsequent demonstration.

The design workflow is a conservative one, where it conforms to the processes used by the developers in practice. The only instance of deviation from the developer's design workflow is when it becomes absolutely necessary to ensure the success of the computational aspect of the design workflow. By doing so, the design workflow reduces an imposition of changes and interruptions onto the developer team, thus increasing the appeal and adoption of this approach in practice.

The design method is arranged to be synergistic:

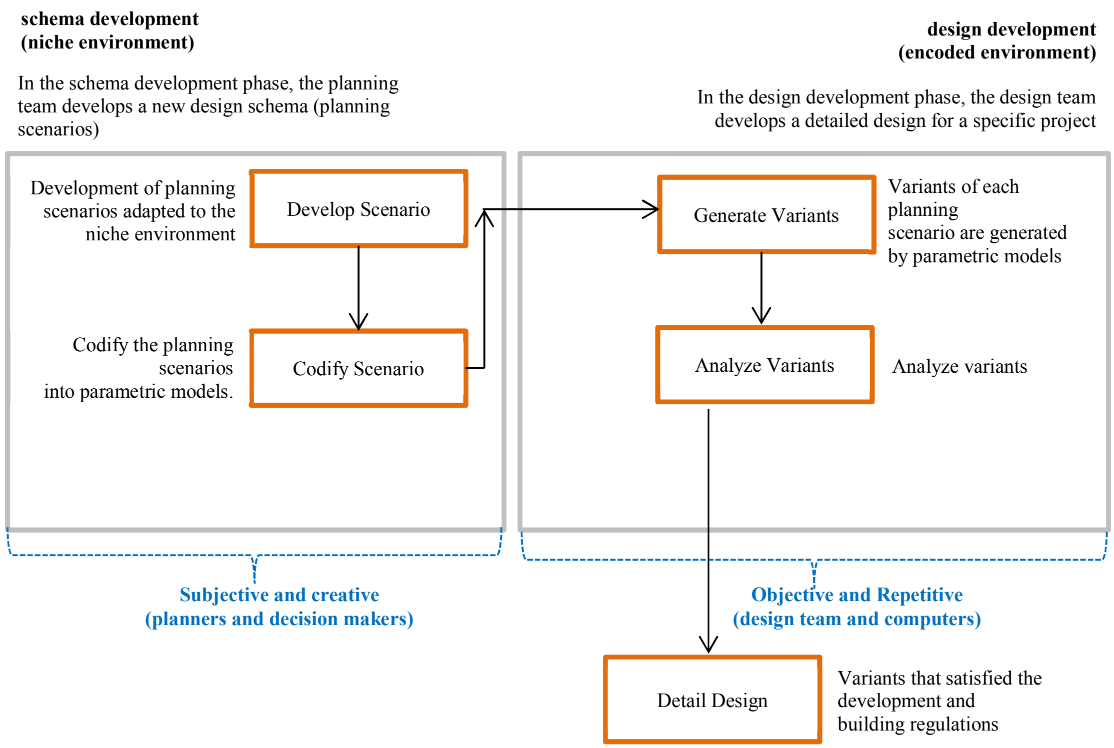
• The scenario planning stage (schema development stage) allows the developer team to focus on the tasks that are predominantly creative and subjective. The tasks of developing and codifying the schema (planning scenarios) are predominantly a creative and subjective task.

• On the other hand, the design development stage allows the computational system to focus on tasks that are predominantly repetitive and objective. Generating and evaluating variants for each planning scenario is predominantly a repetitive and objective task.

• However, the development of a 3D design schema and parametric model *(see Chapter 3, 3.1.2 Design Workflow, Step (2) Codify Scenario, Step (a) 3D Design Schema and Step (b) Parametric Model)* is less creative and subjective, yet this process cannot be assigned to the computer. For this reason, a parametric modelling team is required to manually create the 3D design schema and parametric model alongside the developer team before assigning the repetitive and objective tasks to the computer.

However, it is to note that while it takes a significant amount of time to develop a high-density, mixed-use development by hand, it can also take more time to develop a parametric model of a high-density, mixed use development. Only when numerous variants must be developed does it make sense to invest first in the development of a parametric model.

Fig. 3-1 Proposal of Design Method

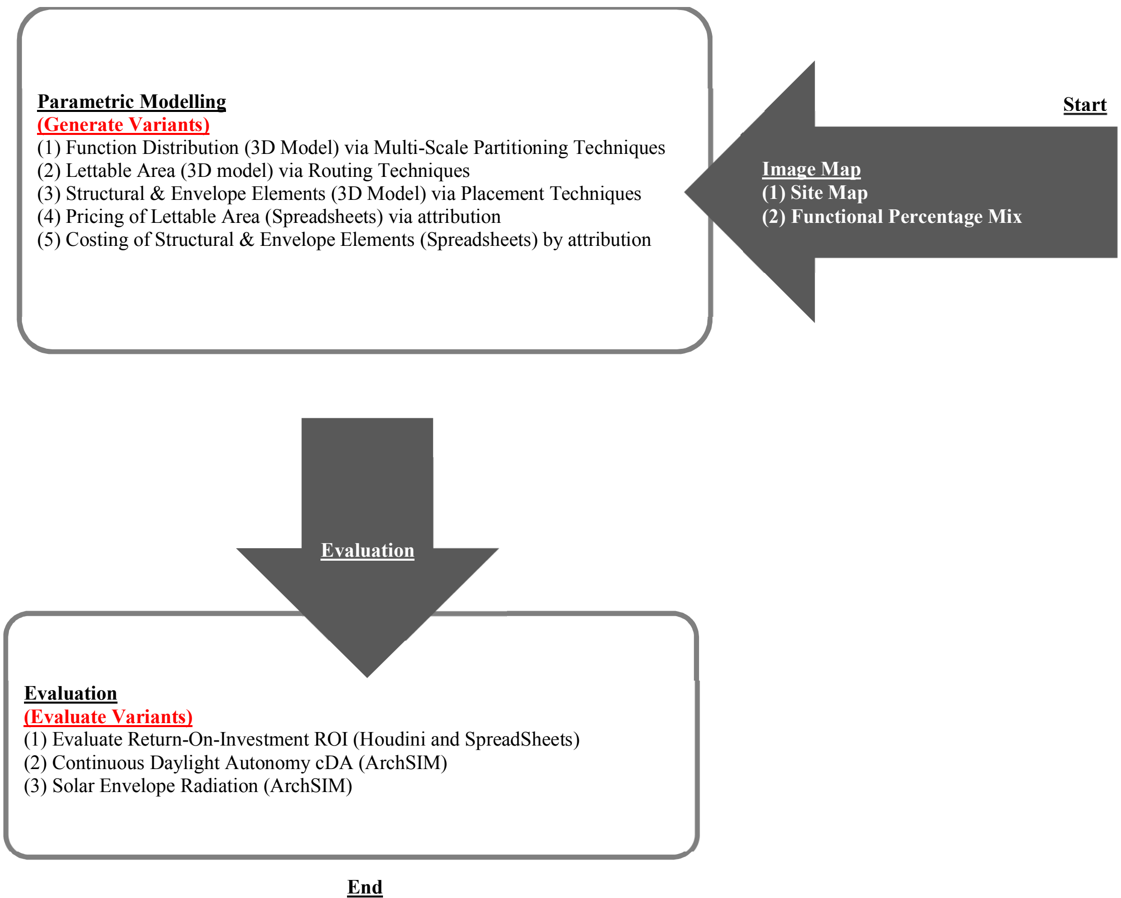


(B) Computational Architecture

(i) overall computational architecture

The computational architecture is the second part of the *function distribution design (fdd) workflow*. This provides an implementation plan and is required in the design development stage in (A) design workflow. The computational architecture uses the generative techniques (see following section) as part of its development step attribution:

Fig. 3-2 Proposal of Computational Architecture

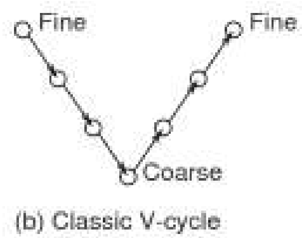
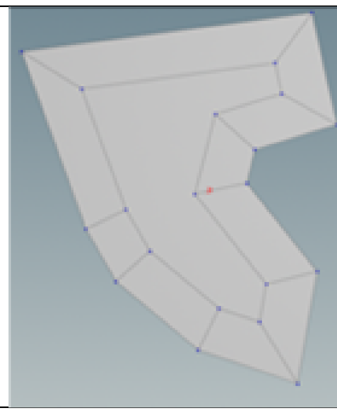
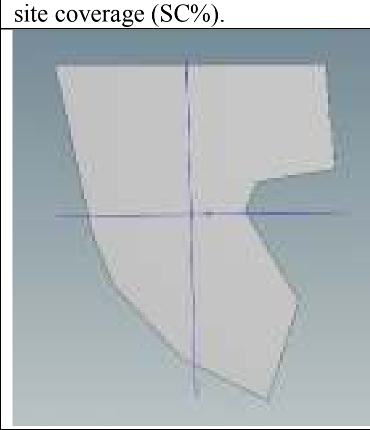
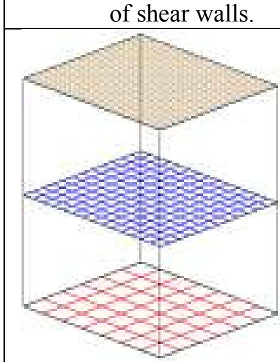
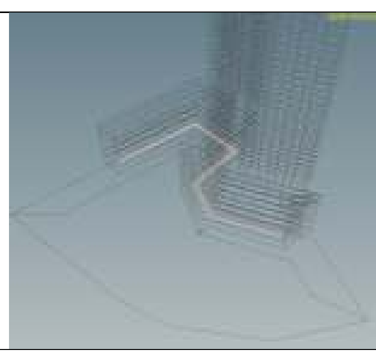
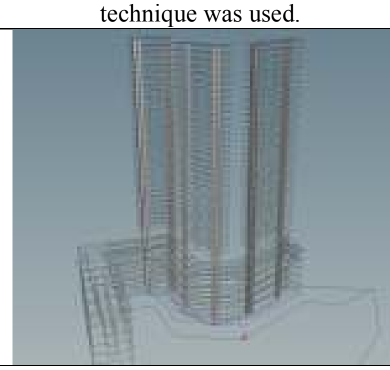


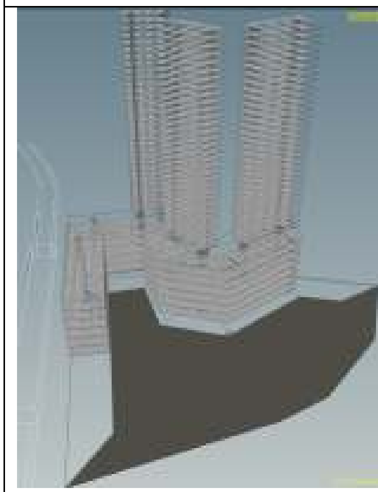
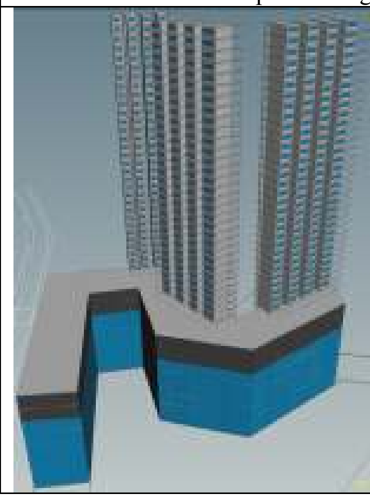
(B) Computational Architecture

(ii) generative techniques
(using parametric modelling techniques)

The prototype system is the third part of the *Function Distribution Design* (FDD) workflow. This provides a more detailed implementation plan for the parametric modeling aspect and is required in the design development stage in (A) design method. The system uses a set of constraints (development and building regulations) as part of the generative techniques in the parametric modeling. The diagram below shows the significant components of the generative techniques as part of the proposition.

Fig. 3-3 : The seven generative steps used to generate the high-dense, mixed-use development.

Step 1: Multi Scale Partitioning technique using the 'classic v-cycle' approach.	**Step 2**: "Fine" partitioning of base 2D plane as ground plane using 'insets' technique	**Step 3**: "Coarse" partitioning using WSA White Space Allocation technique to control percentage of site coverage (SC%).
		
Step 4A: Structural construction scheme gridding. Bus interchange utilizes grid scheme of 24 metres, while mall utilizes the 12metres scheme and HDB apartments at 7.2 metres and use of shear walls.	**Step 4B**: Routing (human, vehicular and service routes) through the structural construction scheme. 'Rip-Up and Reroute' technique was used.	**Step 5**: Placements of structural elements such as liftcores, staircase, escalators, shear wall, columns are distributed under fire safety and construction schemes regulations. The 'simple placement instance' technique was used.
		

<table>
<tr><td>Step 6: Floor-planning of HDB apartments using ‘square of squares’ technique</td><td colspan="2">Step 7: Output metrics in spreadsheets (Houdini)</td></tr>
<tr><td rowspan="2"></td><td>Step 7A: Calculation of lettable/ tenable floor areas</td><td>Step 7B: Calculation of volume of structural concrete used in construction and surface area of materials used in envelope cladding</td></tr>
<tr><td></td><td></td></tr>
</table>

3.1.3 Research Hypothesis

The hypothesis of this research is that by computationally supporting the scenario planning approach to explore high-dense, mixed-use function distribution in a semi-automated manner, planning scenarios can be thoroughly explored in the search space and evaluated by developers, in a more systematic way.

3.2 Research Requirement

3.2.1 Controlled Variability

A critical requirement of the variants that are generated using this method is controlled variability. The variants that are generated must share a 'kinship-of-forms', or have similar character but vary significantly in terms of certain attributes, especially attributes pertaining to configuration and/ or organization of every variant. Thus, each variant would therefore have different performance when subjected to the evaluation stage.

- A simple illustration would be the 'kinship-of-forms' among the trees and plants in a forest. The trees and plants may appear to share similar character on a superficial level. However, they significantly vary from one another in terms of certain attributes, on the configurational and organizational level, hence allowing the varying plants different performance.
- The generation of variants in terms of design variability should not be overly restricted nor should it be unrestricted and too constrained. This variability problem requires striking a balance between an approach to generate variants that are neither too restrictive nor unrestrictive.
    - When the design variability is highly unrestricted, the output may be too unpredictable/ chaotic and risks not being a sensible/ acceptable variant. In addition, it may become problematic for the evaluation process or it may not be meaningfully compared to one another.
    - When the design variability is overly restricted, the output may risk excluding the best possible designs.

Thus, it is important that the generative steps proposed in this investigation achieve controlled variability that satisfies three main considerations:

(a) the generative process must be capable of generating designs with the required mixed-use functions and distribute the functions as defined by the functional constraints

(b) the generative process must be able to generate designs that share similar character but significantly vary from one another in terms of configurational and organizational attributes

(c) the generative process generates complex urban designs that are represented using high-level semantic constructs that are constrained to guarantee only plausible urban designs are generated.

Many generative program that have unrestricted variability describes designs using low-level geometric primitives. However, evaluation and simulation programs require designs to be specified as complex representations that use high-level semantic concepts to describe an urban design. This forms a mismatch in evaluation requirements and attempting to infer high-level semantic constructs from low-level geometric primitives is far too complex.

Therefore, the generative steps that describe the urban designs must be able to generate variants that use high-level semantic concepts and constructs that characterize a city such as a building, windows, walls and roads. Hence, a parametric model is therefore, used in this thesis.

3.2.2 Influence and Impact of this Workflow

This workflow allows a significant influence at the early design stages through six aspects:

• (1) influence the planners to explore, experiment and innovate at the early design stage

As an early design stage exploration workflow, this allow the developers to seed the first ideation through allowing the flexibility to explore, experiment and innovate. The adoption rate is expected to be high amongst developers because the tool leverages on the ease of use of parametric modelling to encode the design scheme (scenarios) to generate and evaluate numerous design variants.

• (2) influencing the developers to cognitively understand how design decisions affect design performance from a 3D modelling standpoint when the scenario planning approach is enhanced from a 2D to a 3D modelling environment

Traditionally, developers exploring high-dense, mixed use development had to depend only on 2D plans. This does not allow them to cognitively understand the performance and impact of their decisions on the plan.

However, this tool influences the planner to consider many other design outcomes by being able to visually and cognitively understand how the 3D model of the high-dense, mixed-use development would have an impact and performance as a result of their design decisions.

• (3) influencing and enhancing the scenario planning process to be a more systematic and thorough method of exploration

The tool influences the scenarios that the developers create by allow them to thoroughly evaluate each scenario through the use of numerous design variants.

Traditionally, developers using the scenario planning approach would evaluate a scenario based on a single variant, of which that single variant may risk producing spurious results, as it could be an outlier.

However, through this tool, developers are now able to generate numerous design variants to a given scenario, allowing all the different performance to the different design variants to be statistically analyzed, influencing a statistical validity as well as ensuring that a systematic and thorough exploration was conducted.

• (4) influence the discovery of unthought of design solution in the search space

The tool also allows developers to discover of unthought of design solutions during their exploration in the design search space. As the tool allow a great range of design variations, some of the design solution are unthought of by the developers which at the same time, satisfies the regulatory constraints as encoded in the parametric model.

• (5) influence the design variants to obtain a higher performance than the developers would have conceived

With the unthought of design solutions, this tool may generate design variants to obtain a higher performance that what planners could have conceived by hand. Hence, in terms of influence, this tool may allow developers to discover higher performing design variants.

• (6) influence a synergistic way to leverage on the subjectivity of the developers and the objectivity of the computer

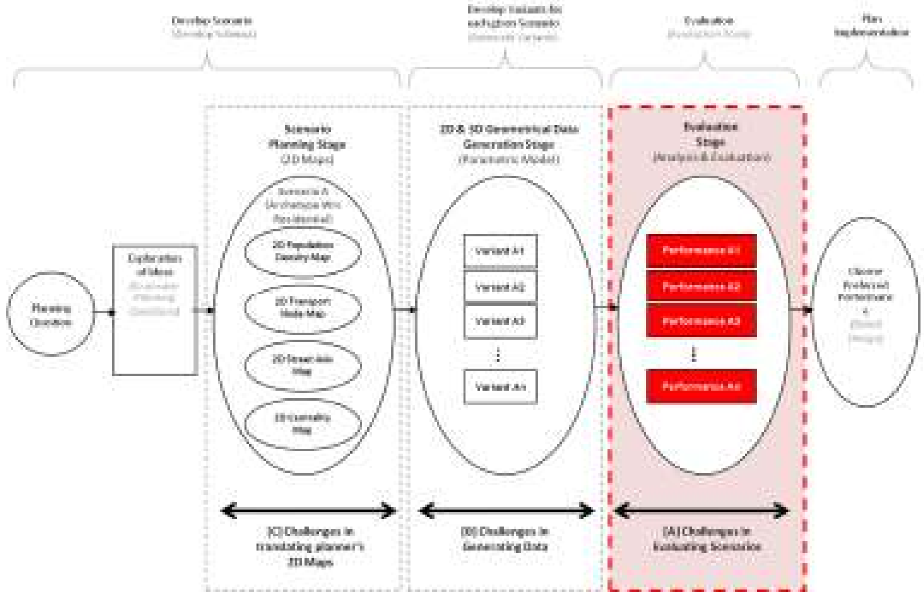
The tool influences the scenario planning process by leveraging on the unique strengths of the developers and computers in a synergistic way – tasks that require predominantly creative and subjective judgment are handled by the developing team while tasks are predominantly repetitive and objective can be assigned to the computer.

Hence, in summary, while there is no guarantee that the developers may not built what this tool can generate, the influence and impact on the urban environment is quite large. This tool facilitates developers to experiment, explore, innovate in a systematic, thorough procedure, which allows them to cogitate from a 3D standpoint, and generate unthought of design variants that are of a higher performance.

3.3 Challenges

3.3.1 Challenges: Evaluating Scenarios

Fig. 3-4 Challenges in evaluating scenarios



The next challenge is (1) evaluating the scenarios. In this challenge, the research looks into what types of evaluations (analysis and simulations) are required to be carried out and what type of data do these evaluation tools would need.

Many evaluations require more detailed 3D geometrical data representing the developments, while other evaluation tools may require less detailed data, such as 2D geometrical data.

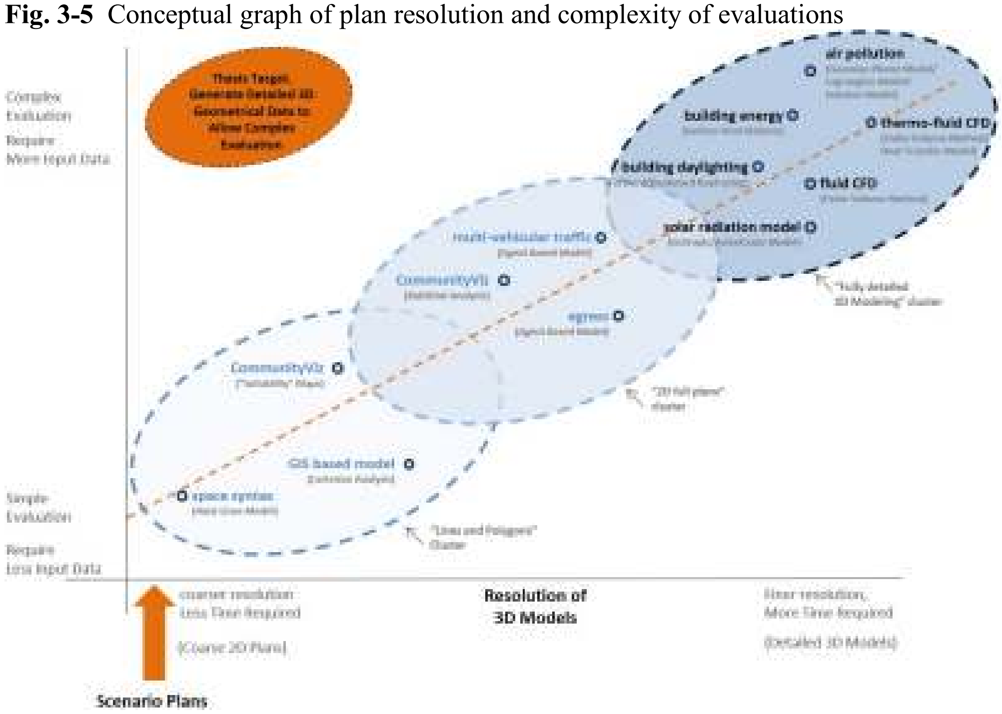
Below is a list of evaluation tools that require different resolutions of geometrical data that is required in order to carry out an evaluation:

Table 3-1 Evaluation tools requiring different resolutions of geometrical data

Types of Data Input Required for Evaluation Tools	Types of Evaluation	Existing Evaluation Tools
3D (Geometrical) Data	Fluid CFD	SCStream
		Fluent
	Building Energy	EnergyPlus
	Daylighting	Radiance
		UMI Urban Modelling Information
		CITYSIM
		TOWNSCOPE
	Air Pollution	CALPUFF
		AERMOD
		CALMET MM5
		MOVES (Motor Vehicles Emission Simulator)
	Sky View Factor	SVF Tool (DEMTools/QGIS)
		DIVA (Rhino)

	Solar Access (PhotoVoltaic Solar Accessibility)	TOWNSCOPE
		SOLENE
	Urban Heat Island	STEVE Tool (NUS)
	Urban Shadow	SHaDEM (DEMTools/QGIS)
2D (Geometrical) Data	Accessibility	UNA Toolbox
		ArcGIS Network Analysis
		Confeego
		AJAX
		Space Syntax
	Agent Based Modeling	UCL DepthMap
		AnyLogic
	Transportation	MATSIM
		PARAMICS
		CORSIM
		AImSUM
		Dynameq
	BuildOut Analysis	CommunityViz
	Pro Forma Analysis	UrbanSIM
		Excel Spreadsheet

Fig. 3-5 Conceptual graph of plan resolution and complexity of evaluations

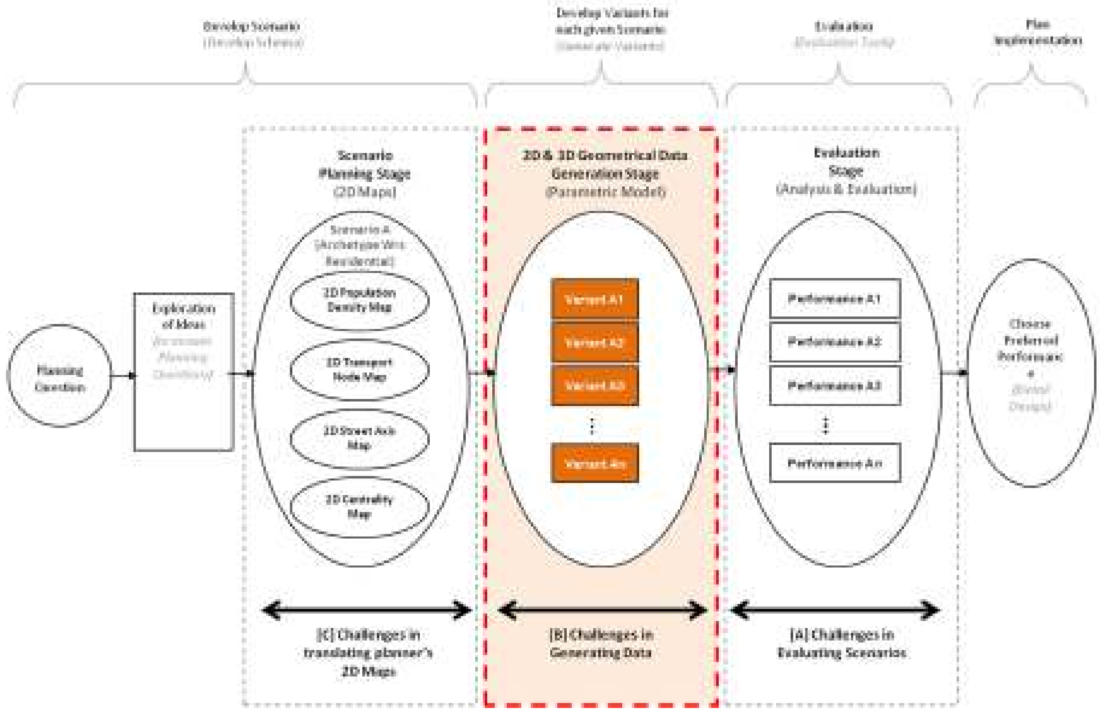


The conceptual graph shows how the investigation aims to use coarse 2D plans to generate detailed 3D models in an automated manner using parametric techniques, which subsequently would allow complex 3D evaluations to be made. The thesis target would be the 'orange spot', meaning that for any given coarse 2D site plan given by the developer, an evaluation of the performance of the different types of buildings can be evaluated without the developer needing to generate numerous 3D models. This saves time and effort on the developer's part to solicit the 'good' over the 'bad' developments.

3.3.2 Challenges: Generating the Data required for Evaluation

The subsequent challenge would be generating the data required for these evaluation tools. Here, the research asks for what different forms of data (e.g. the scenario versus the variants data requirements) which would be required to be generated. The generated data are necessary input for the evaluation tools to carry out evaluations, but does not exist and is very time consuming to generate by hand

Fig. 3-6 Challenges in generating the data required for evaluation



In the following two tables, the types of data that are required by scenarios and variants are presented. These data are necessary to be able to generate the scenarios, followed by their corresponding variants. Without these data, the evaluations cannot be executed and thus, it is imperative for the investigation to highlight these data sets before any further work can begin:

Fig. 3-7 Types of data required by scenario

Data Types	Detailed Data Types	Examples
Location Data	Geo-Referencing	latitude & longitude (1.352083, 103.819836)
Sky dome Data	CIE sky	latitude & longitude (1.352083, 103.819836)
Terrain Data	Elevation	Topographical countour lines
	Hydrography	Water catchment area
		waterbodies (streams, river, drains, canals, etc) (water network locations and dimensions)
		reflective water bodies
	Ground	reflective ground
Road Infrastructure Data	Roads network and geometry	Pedestrian Pavement (network location and dimensions)
		Vehicular Roads (network location and dimensions)
		Cycling Lane (network location and dimensions)
		Green Buffer (network location and dimensions)
Existing Infrastructure	Tall Obstructions	surrounding existing buildings
		elevated structures (overhead bridges, flyways, etc)
Population Data	Residential	Number of residents
		number of residential units
	Commercial (Office and Retail)	number of commercial units
		number of commercial jobs
	Industrial	number of production units
		number of production jobs
Site Boundary Data	Site Lot	Number of internal parcellations Lot Dimensions (width and length)
	Site Parcellation	Parcel Dimensions (width and length)
		Adjacent landuse (affects boundary offset values)
Land Use Data	Infrastructure	Infrastructure (Roads, trains lines, etc)
	Single-Use functional land use	Production, Residential, Commercial, etc) land use
	Mixed –Use functional land use	Mix-Use Development (i) percentage mixture and (ii) functional distribtution).
Landscaping Data	Trees	Location, height and dimension of trees
		presence of heritage trees

Fig. 3-8 Types of data required by variants

Data Types	**Detailed Data Types**	**Examples**
Orientation Data	Building Orientation	North, South, East, West
Building Data	Floor Area Ratio (Plot Ratio)	Plot Ratio 1.0
	Building height limit	60 metres (max.)
	Site Coverage	80% site coverage
Shading Data	Ubiquitous shading	tall obstructions
	Contextual shading	small buildings
	Local Shading (attached to buildings)	building sunshades
Window Data	Window-to-Wall ratio	WWR %
	Infiltration rates	post occupancy evaluation libraries
Window Blinds Data	blinds deployment	at lux threshold value and blinds % coverage of windows
Interior Illuminance Data	target illuminance fr different function use of interior spaces (residential, production,commercial, etc).	(i) perimeter target illuminance (ii) core target illuminance (iii)tolerable maximum lux values)
Envelope Material Data	Window material	building material specifications in RADIANCE/ DAYSIM libraries
	Wall material	
	Roof material	
	Floor material	
Envelope Thickness Data	Window thickness	refer to 3D model
	Wall thickness	
	Roof thickness	
	Floor thickness	
Interior Fitting Data	Furnishing	interior furnishing and finishing specifications in RADIANCE/ DAYSIM libraries
	Interior finishing	
	Interior lighting fixtures	heat gains and electrical power demand
	Interior electrical appliances	
	Cooling, ventilating and heating systems	HVAC specification library
Site Offset Data (Development Control) (URA Regulations, 2011)	Nuissance Buffer	Noise buffer
		Pollution buffer
	Minimum Boundary Setback	Green buffer
		Front boundary buffer
		Side boundary buffer
		Rear boundary buffer
		Roof Eave Line
	Site offset from roads	Category 1- Expressway =15.0 m
		Category 2 – Major Arterial A = 7.5 m
		Category 3 – Major Arterial B = 5.0m
		Category 4 & 5 – Other Major Roads, Minor Roads & Slip Roads =5.0 m

Height Control Data (Development Control) (URA Regulations, 2011)	Floor-to-floor height control	Residential floor-to-floor height control
		Commercial floor-to-floor height control
		Industrial floor-to-floor height control
Quantum Control Data (Development Control) (URA Regulations, 2011)	Quantum Control	Predominant Use ≥ 60% (min.)
		Ancillary Use Use ≤40% (max.)
Noise Control Data (Development Control) (NEA Regulations, 2012)	Site offset	Setback of bus-interchange from facing MRT Station/track =35 metres
		Setback of bus-interchange from facing MRT with use of end-walls facing MRT tracks/station =25 metres
Structural Control Data for Bus Interchange (Building Control) (LTA 2013)	Driveway (Bus Interchange)	min. bus one-way driveway ≥ 12.0m min bus two-way driveway ≥ 24.0m
Building Construction Scheme Control Data (BCA 1999)	Structural construction scheme for each individual function	Bus-Interchange: 12 to 24 metres
		Production: 12 to 24 metres
		Commercial: 6 to 12 metres
		Residential 6 to 8 metres
Floor Area Control Data (Building Control) (URA Regulations, 2011)	Minimum Floor Area for different functions	Bus Interchange ≥ 25,000.0m^2 **(**min.)
		Production Single strata ≥ 150. 0m^2 **(**min.)
		Commercial ≥ 50. 0m^2 **(**min.)
		Residential ≥ 50. 0m^2 **(**min.)
Fire Safety Control Data (Building Fire Control) (SCDF 2013)	Travel Distance	Max. Travel Distance (m) (one-way travel)
		Max. Travel Distance (m) (two-way escape)
		Max Dead End (m)

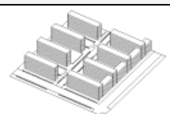
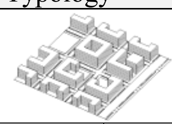
3.4 Choosing between Scenarios and Variants

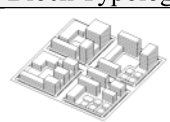
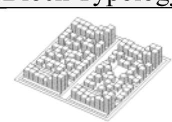
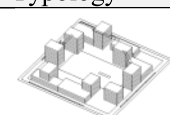
3.4.1 Choosing between scenarios

In this investigation, the scenarios that may be considered are exploring the below six typologies for the site in Clementi Town Centre: (1) slab typology, (2) perimeter block typology, (3) block-mixes typology, (4) high density perimeter block typology, (5) fine grain block typology and (6) podium and tower typology.

However, only one scenario is tested in this investigation, which focuses on the most predominant development typology found in Singapore, which is the (6) podium and tower typology.

Fig. 3-9 Six development scenario can be designed into 6 different variants

[01] Slab Typology		[02] Perimeter Block Typology		[03] Block Mixes Typology	
					
FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn	FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn	FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn

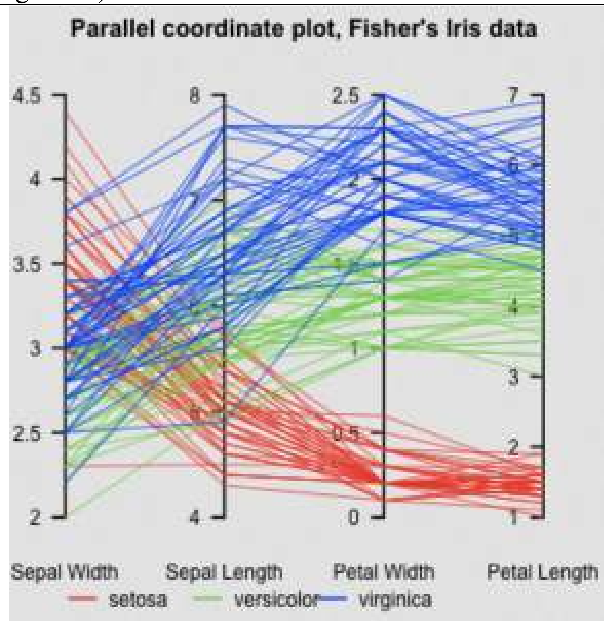
[04] High Density Perimeter Block Typology		[05] Fine Grain Block Typology		[06] Podium and Tower Typology	
					
FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn	FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn	FAR SC % Functional Mix	= 2.0 = 62.5% = 73% Live, 9% Work, 17% Play, 1% Learn

However, as a means of best practices, when developers work with a few scenarios, they would eventually come to the point of having to choose between the scenarios when the evaluations are completed. There are two techniques used in choosing between scenarios:
(1) parallel coordinates plot
(2) pareto frontier comparison

• (1) parallel coordinates plot

Parallel coordinates allow planners to choose scenarios by comparing its performance on many dimensions. Each vertical axis represent a dimension and the points on the axes are the performance results of each dimension.

Fig. 3-10 Parallel Coordinate Plot
(Source: Fisher's Iris data, https://en.wikipedia.org/wiki/Parallel_coordinates. Accessed on 31 Aug 2015)



◦ This technique is an established statistical data visualization technique that relies on discernable pattern or trendlines across the dimensions.

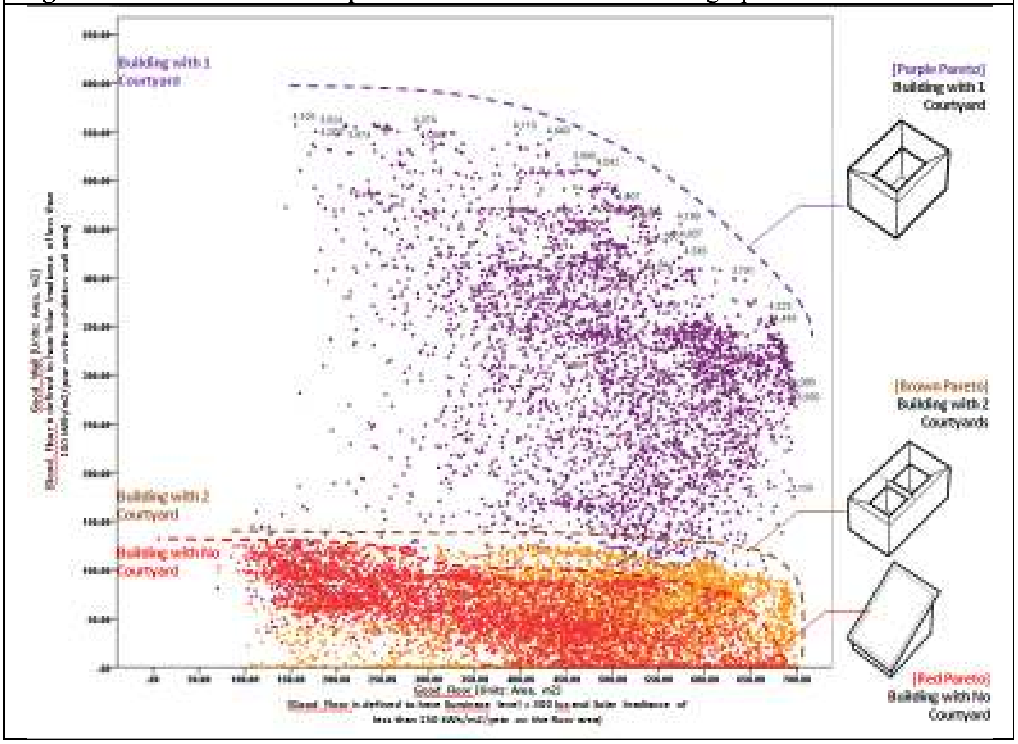
◦ The planner can choose one scenario over another by analyzing which dimensions is of interest to the planner. Then, the planner can discern at that dimension any discernible patterns or trendlines which might suggest how a particular scenario is superior to another at that dimension.

◦ However, one criticism of this technique is that the plots produced can be very chaotic. This may confuse the statistically untrained planner. For this reason, the second technique, pareto frontier comparison, can be a better visual accompaniment to the parallel comparison plot.

• (2) pareto frontier comparison between scenario on the same normalized graph

In the second technique, pareto frontier comparison can be done between scenarios on the same normalized graph. This technique is meant to be a visual accompaniment to the first technique for the statistically untrained planner.

Fig. 3-11 Pareto frontier comparison on the same normalized graph



◦ In the pareto frontier comparison graph as above, three different scenarios of three different buildings are evaluated. Each scenario has its own pareto frontiers:

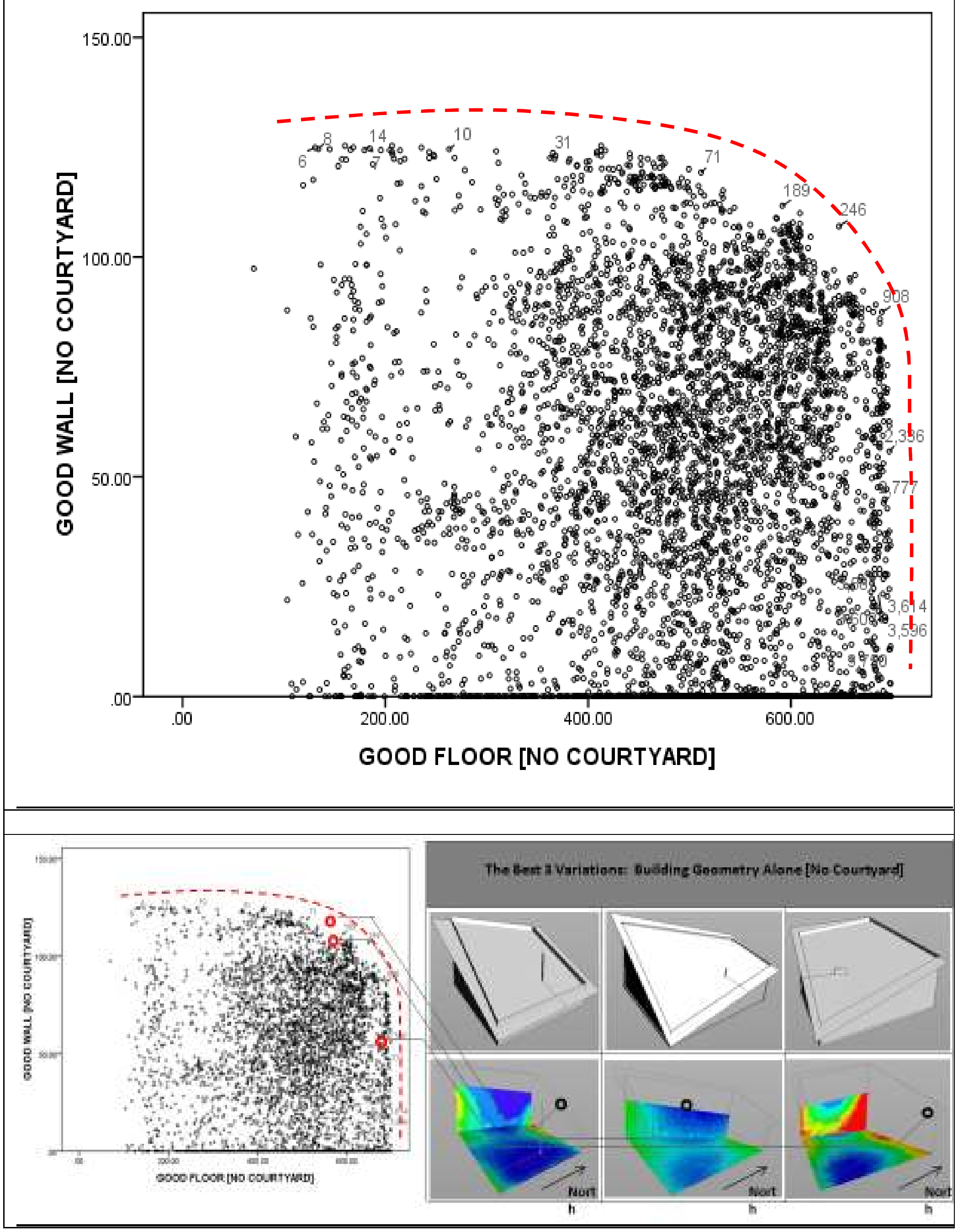
(1) red pareto frontier for the scenario of building with no courtyard,
(2) brown pareto frontier for the scenario of building with two courtyards and
(3) purple pareto frontier for the scenario of building with one courtyard.

From here, the planner can choose one scenario over another by choosing the scenario with the better performing pareto frontier.

3.4.2 Choosing between variants

The generative process will generate numerous design variants which would then be evaluated, resulting in design variants with varying performance scores. These design variants with varying performance scores are then analyzed using a technique known as pareto ranking. Planners can then choose between different variants from the pareto frontiers, or the boundary of high performing variants (marked in red dashed line, Table 1-6, below).

Fig. 3-12 Pareto front comparing variants



• In pareto ranking, the design variants with varying scores are typically plotted on a two-axis graphs.

> ◦ In this two–axis graph, both the x and y axes are performance scores on two different objectives such as daylight performance scores and solar insolation scores.
>
> ◦ Each design variant is a black dot plotted on the graph. As the graphs moves to the right, the performance scores on the x-axis increases, and as the graphs moves to the top, the performance scores on the y-axis increases. Thus, the black dots towards the top-right portion of the graphs have high performance values on both objectives.
>
> ◦ These high performance design variants on the top-right portion of the graph would eventually form the pareto frontier (marked in red dashed line).

• Thus, the planner can choose between the high performing design variants by choosing the design variants closest to the pareto frontier.

Chapter 4

4 Case Study

4.1.1 Usage of scenario planning approach for mixed-use development in Clementi Town Centre in Singapore.

The site of study is a high-dense, mixed-use development in Clementi Town, Singapore. While the building has been completed recently, also known as Clementi Town Centre, it serves as a study for this investigation to generate alternatives or variants to the existing building. At the same time, almost all of the variables such as height, functional uses, set-backs and structural construction schemes are kept unchanged between the proposed scenario and existing development. In summary, the investigation aims to create another scenario to the existing Clementi Town Centre, and generating numerous development alternatives (or variants) that satisfies the same constraints and regulations.

The existing Clementi Town Centre development has been designed as per the following configuration:

(1) a bus interchange of floor area 10,000m^2
(2) a four-storey shopping mall podium of floor area 25,000m^2
(3) a two-storey carpark facility of floor area 2,000m^2
(4) three HDB flats/ tower accommodating 372 apartment units.
Each apartment unit ranges in floor area from 65m^2 to 120m^2

Fig. 4-1 Site Map Location of Clementi Town Centre

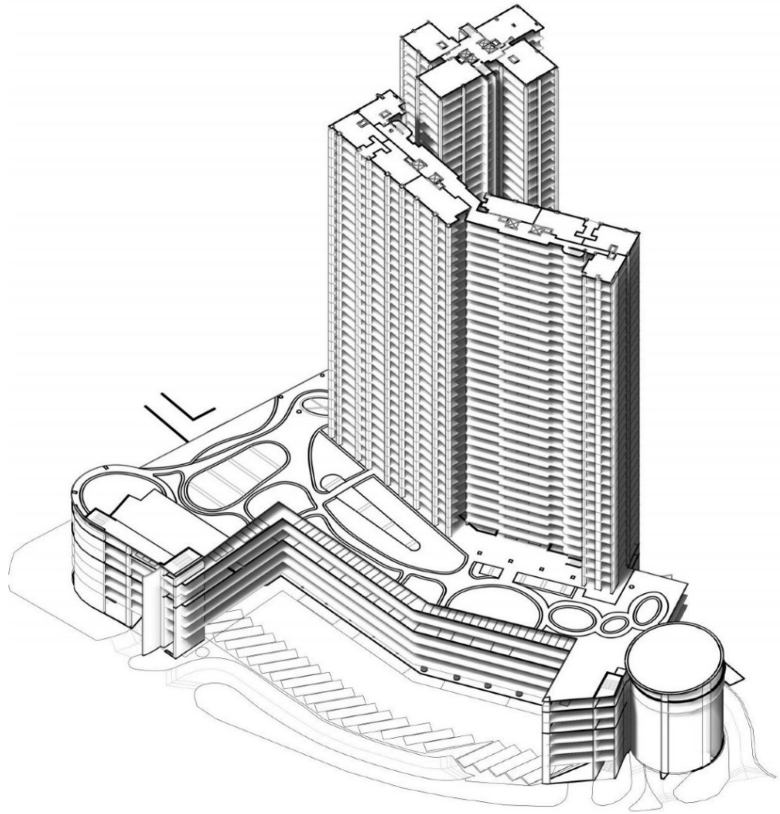
Fig. 4-2 Building Map in relation to exisiting Clementi MRT station and its adjacent roads

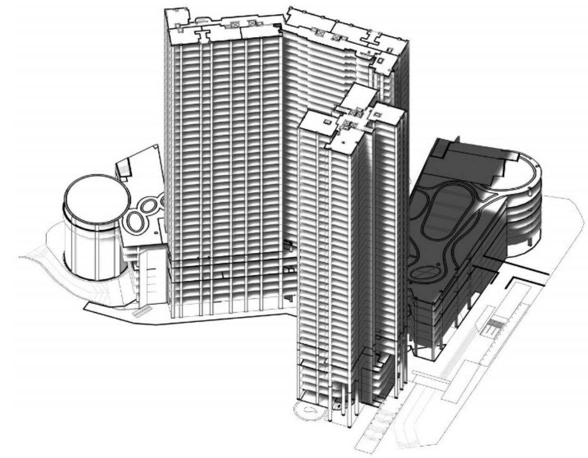
In order to comprehend the complex development, Clementi Town Centre has been modelled in 3D and its floorplans shown as below. Below are drawings of the complex, high-dense, mixed-use development.

Clementi Town Centre is divided into four main functional use:

(1) Ground Level -Bus Interchange
(2) Level 2 to 5 – Shopping Mall
(3) Level 6 to 7 – Carpark
(4) Level 8 – Podium Green Roof
(5) Level 9 to 40 – HDB Flat apartments

Fig. 4-3 3D model of Clementi Town Centre





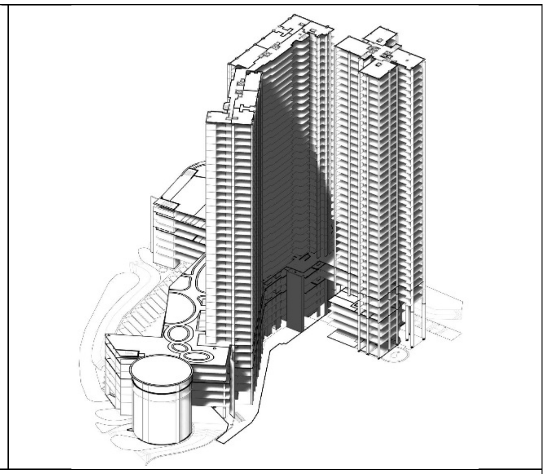
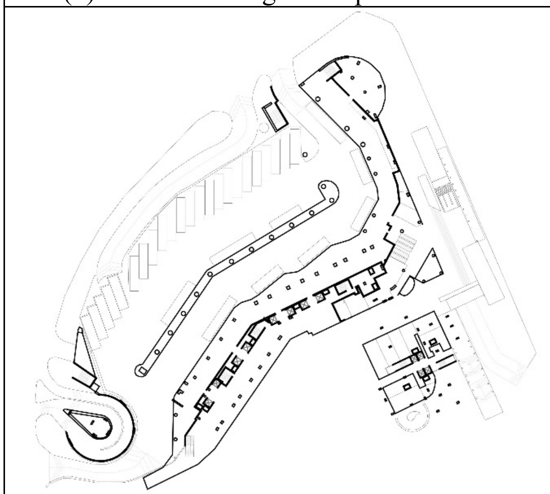
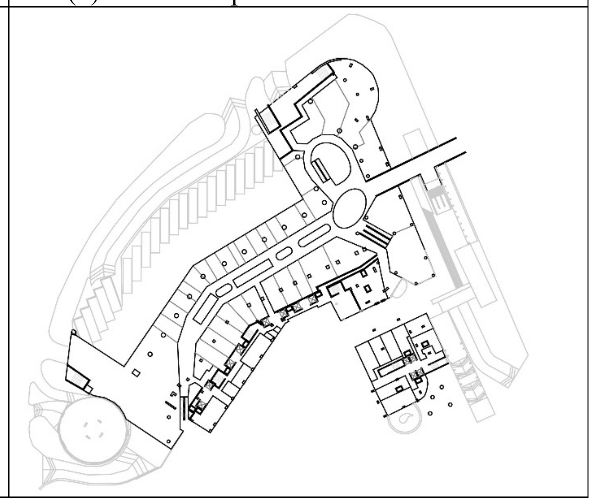


Fig. 4-4 2D floorplans of Clementi Town Centre

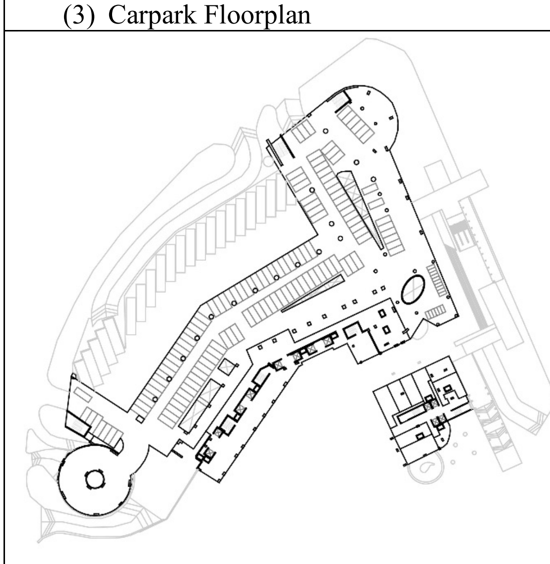
(1) Bus Interchange Floorplan



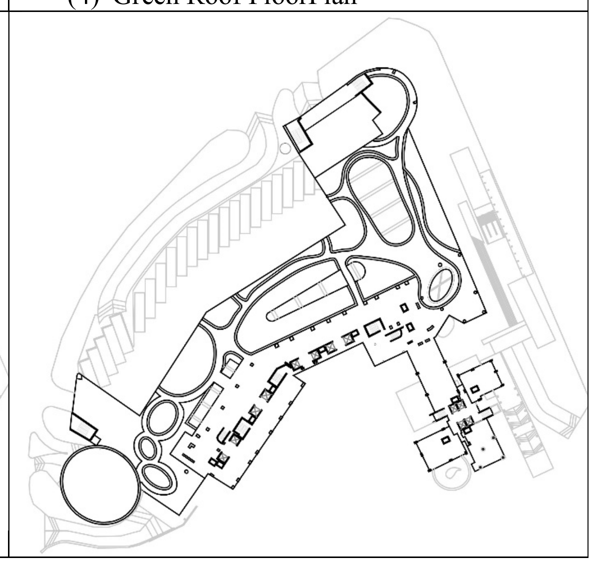
(2) Mall Floorplan

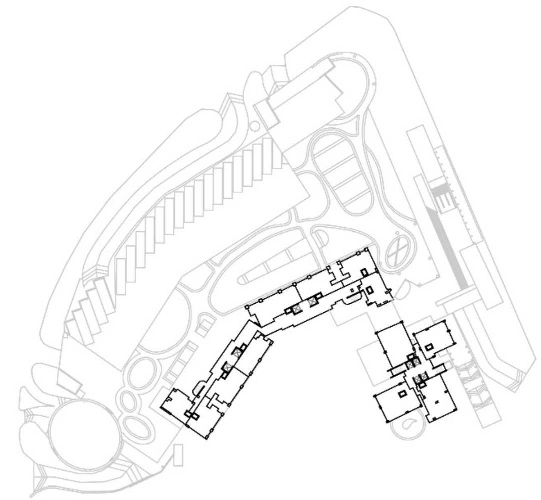
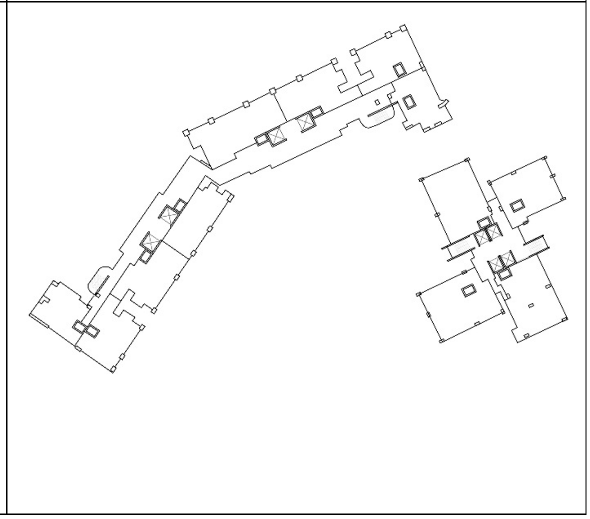


(3) Carpark Floorplan



(4) Green Roof FloorPlan



(5) HDB Flats Apartments	(6) HDB Flats
	

4.2 **Regulations**

4.2.1 Introduction

However, there are numerous constraints that these scenarios and variants must adhere to should they be considered by developers to be implemented in reality. The constraints are defined by the local codes and regulations as stipulated by the regulating authorities. Below are the following regulating bodies that will impact the constraining of the model. In 1.3.2, more details will be illustrated on the regulations that developers must comply in order to have their developments to be approved for construction:

(1) Urban Redevelopment Authority (URA) regulates the development and functional control of a building

(2) Building and Construction Authority (BCA) regulates the construction scheme of a development

(3) Singapore Civil Defense Force (SCDF) enforces the fire safety code and regulations.

(4) National Environment Agency (NEA) regulates the environmental regulation and noise control, since the site requires the development of a bus interchange that has both environmental and noise pollution to the adjacent residential estates

(5) Land Transport Authority (LTA) controls the development of the bus interchange and its functional requirements.

4.2.2 Development regulation: URA Development Control for Different Functions in Mixed-Use Development Requirements

The Urban Redevelopment Authority of Singapore has imposition on the minimum development control on different functions that developments must satisfy. This involves on the height restrictions, minimjum floor areas, land area and landscape replacement areas.

Table 4-1 URA Development Control for Different Functions

	Residential	Commercial (Office)	Commercial (Retail)	Production	Recreational
Height Restriction	Max.3.6m (GPR 1.4 Sites) Max.3.6m (GPR 1.6 and above) Max. 5.0m (1^{st} Storey)	Max. 5.0m	Max. 5.0m	Max. 6.0m (storey height control areas) No Control (area without storey height control)	N.A.
Minimum Floor Area	50.0m2 (HDB shoebox units)	50.0m2	50.0m2	Single strata units must not be less than 150m2	N.A.
Land Area (Plots)	1000m2 (stand alone flat development) 600m2 (party wall flats)	N.A.	N.A.	Min 5 hectares (for Business Park)	N.A.
Landscape Replacement Area (Overall Greenery Provision, as % of site area)	N.A.	N.A.	N.A.	N.A.	GPR ≤1.4: 30% 1.4< GPR <2.8: 35% GPR ≥2.8: 40%

4.2.3 Building regulation: BCA Structural Requirements for different functions in mixed-use development

In Singapore, the Building and Construction Authority (BCA) and the Singapore Structural Steel Society (SSSS) has published a joint resource book, A Resource Book for Structural Steel Design & Construction, which stipulates the allowable structural steel schemes for a multi-storey building to be constructed here. They present a rule-of-thumb sizing to structural steel flooring systems to be constructed in accordance to the needs of different functions in a development. As for concrete construction schemes, the Building and Construction Authority BCA has also provided a Singapore Standard on Code of Practice for Structural Use of Concrete - CP65 : 1999. Below is a summary of Singapore's allowable steel and concrete structural schemes for different functions in a development.

Table 4-2 BCA Structural Requirement for different functions

	Residential	Commercial (Office)	Commercial (Retail)	Production	Recreational
Steel Construction System	5m to 9m (Steel beam)	6m to 16m (tapered composite beam)	6m to 16m (tapered composite beam)	12m to 25m (presstressed composite beam)	N.A.
Concrete Construction System (two-way stsem/ flat plate)	6m to 9m (reinforced flat plate)	8 to 12m (prestressed flat plates)	8 to 12m (prestressed flat plates)	12m to 24m (5kPa to 2 kPa) (single T-beam) 10m to 16m (5kPa to 2kPa) (double T-beams)	N.A.
Imposed Action (Dead Load Only)	2kPa	2kPa to 5kPa	2kPa to 5kPa	2kPa to 5kPa	N.A.

4.2.4 Fire safety regulation

There are numerous fire safety codes contained in the Singapore Fire Code 2013, however, one of the fire safety codes, the maximum travel distance, is one of the most significant regulation that will impact the design geometry of the development. In addition, different functions of a development has different maximum travel distances.

Below are the fire safety requirement as stipulated by the latest Singapore Fire Code 2013:

Table 4-3 Fire Safety Maximum travel distance and maximum dead end, Fire Code 2013, Singapore

Fire Code 2013	Max. Travel Distance (m) (one-way travel)		Max. Travel Distance (m) (two-way escape)		Max Dead End (m)	
Type of Occupancy	Unsprinklered	Sprinklered	Unsprinklered	Sprinklered	Unsprinklered	Sprinklered
Production	15	25	30	60	15	20
Commercial (Office)	15	30	45	75	15	20
Residential	15	30	30	75	15	20

4.3 Constraints

4.3.1 Development and Building Regulation Constraints

There are many constrains that need to be applied to the parametric model. The constraints are the local development and building regulations. Generating variants that satisfy development and building constraints can be challenging. These constrains are subsequently encoded in the parametric model in chapter 6 (demonstration).

Table 4-4 Development Control of Industrial Buildings in Singapore

Control	Control Category	Specification	Dimension
Development Control	Nuisance Buffer	Business B1	no buffer
		Business B2	50.0m (minimum)
		Business Park	no buffer
	Minimum Development Setback (for Detached, Semi-Detached and Terraced Industrial Development)	Green Buffer (all boundary lines)	2.0m
		Road Buffer (front boundary line)	4.5m
		Side Buffer (side boundary lines)	4.5m
		Rear Buffer (rear boundary line)	4.5m
		Roof Eave Line (all boundary lines)	2.0m
	Floor-to-floor height control	Applicable only to industrial estates with Storey Height Control SHC	Cannot exceed 6.0m
	Quantum Control (for single-use and multi-user industrial/ warehouse/ utilities/ telecommunication developments)	Predominant Use (warehouse, manufacturing, production, services, repair, assembly, workshop, storage, e-business, core media activities	60% (minimum)
		Ancillary/ Secondary Use (commercial uses, canteen, ancillary offices, meeting room, M&E services, childcare centre, internal toilets)	40% (maximum)
		Industrial canteens	capped at 700sqm or 5% of proposed GFA
		Showrooms	1st storey of development only
		Business Park Zones	15% of GFA of a Business park development is allowed for 'White' uses

			Minimum 85% must be retained for Business Park component, out of which min 60% = pure Business Park uses and max 40% = ancillary uses

Table 4-5 Development Control of Traffic Network in Singapore

Road Buffer Control	Category 1- Expressway	15.0m (Min width of buffer)	5.0m green buffer, 10.0m physical buffer
	Category 2 – Major Arterial A	7.5m (Min width of buffer)	3.0m green buffer, 4.5m physical buffer
	Category 3 – Major Arterial B	5.0m (Min width of buffer)	3.0m green buffer, 2.0m physical buffer
	Category 4 & 5 – Other Major Roads, Minor Roads & Slip Roads	5.0m (Min width of buffer)	3.0m green buffer, 2.0m physical buffer

Table 4-6 Building Fire Control of Industrial Buildings in Singapore

Control	Control Category	Specification	Dimension
Building Fire Control	Travel Distance	Max. travel distance (one-way escape) (Unsprinkled)	15.0m
		Max. travel distance (one-way escape) (Sprinkled)	25.0m
		Max. travel distance (two-way escape) (Unsprinkled)	30.0m
		Max. travel distance (two-way escape) (Sprinkled)	60.0m
	Capacity (No. of persons per unit width (x) where (x)=0.5m	Door Opening (to outdoors at ground level)	100 person per unit width (x)
		Door Opening (to other exit)	80 person per unit width (x)
		Door Opening (to staircases)	60 person per unit width (x)
		Door Opening (to ramps, corridors, exits, passageways)	100 person per unit width (x)
	Minimum Width	Stairs	1.0m
		Corridors	1.2m
	Maximum Dead End	Corridors (Unsprinkled)	15.0m
		Corridors (Sprinkled)	20.0m

4.4 Performance

4.4.1 Performance: Different Indoor Illuminance Performance for different functions in mixed-use development

The indoor illuminance level recommendations were originally implemented with the intention of improving worker safety in industry, offices as well as the learning environment in schools (CITE). As these recommended illuminance levels have energy implications, many recommendations have been revised to a lower value, particularly during the oil crises in the 1970s and the recent sustainable movement to reduce energy consumption. Examining the recommended illuminance values from 19 different countries from 1930s to 1999, Evan Mills and Nils Borg compiled the range of recommended indoor illuminance for the different functions required.

This research adopts using the average indoor illuminance levels where the levels will be used to define different functional use of the building.

Table 4-7 Recommended indoor illuminance levels

	Residential	Commercial (Office)	Commercial (Retail)	Production	Recreational
Range of Average Recommended Illuminance Levels in 19 countries (Mills and Borg 1993)	100 to 500 lux	300 to 500 lux	300 to 1000 lux	300 to 4000 lux	N.A.
Illuminance levels adopted in this research	300 lux	500 lux	750 lux	1500 lux	N.A.
Occupancy Schedule for Indoor Illuminance	Always Occupied	Weekdays 9am to 5pm	Always Occupied	Always Occupied	N.A.

Fig. 4-5 Survey of recommended range of recommended illuminance levels across 19 countries

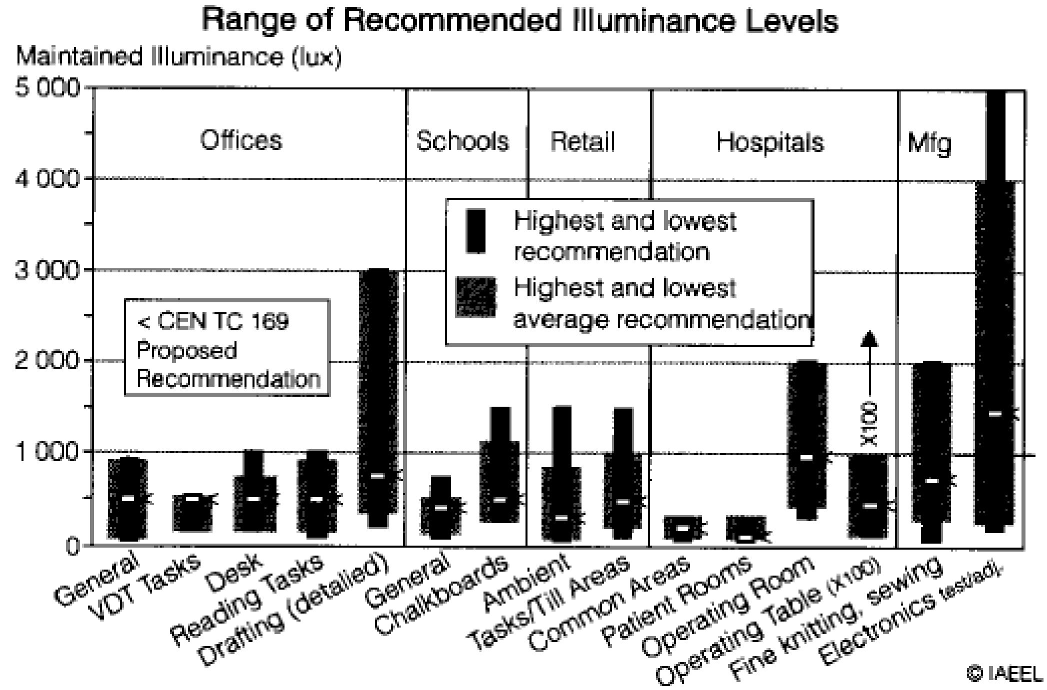


Figure 1— Range of recommended illuminance levels (19 countries). Note: values for hospital operating tables have been reduced by 100x in order to scale to other values. Values of the black bars reflect the extreme high and low endpoints of all national recommendations for a given task. The shaded bars indicate the average values of recommendations when they are expressed as ranges.

4.5 Requirement of Demonstration

A design scenario

A basic design scenario has been developed to demonstrate how it might be encoded. The scenario is for a high-dense, mixed-use development that comprises of four typical but different functions:

(1) a bus interchange of floor area 10,000m^2
(2) a 4-storey shopping mall podium of floor area 25,000m^2
(3) a 2-storey carpark facility of floor area 2,000m^2
(4) two to three HDB flats/ tower accommodating 372 apartment units.
Each apartment unit ranges in floor area from 65m^2 to 120m^2

The design scenario is constructed using typical modern concrete constructed for high-dense mixed-use development:

(1) concrete *flat slab and column construction* are used.
Presently, other construction techniques such as one-way or two-way or waffle slab are not implemented as a majority of developers in Singapore prefer flat slab and column construction technique over the other techniques due to being a more time-efficient construction technique (Langdon & Seah Singapore, 2014)

(2) The site is assumed to be flat and open and the site is assumed to be substantially larger than the building.

Character of design schema

The character of the design schema is best understood by considering a set of examples. Below shows a range of designs created using the generative process that will be described in the next section. The main feature of these designs is their variability in terms of the following:

(1) The geometry of the design consists entirely of flat planar faces. There are no curved walls or roofs
(2) The windows are of three basic types.
- Presently the windows located on the shopping mall are single glazed curtain windows extending from floor to ceiling of each given floor of the mall.

- The HDB flats have standard openable single glazed windows from 1.6metre to 2.0 metres, which are standard on a majority of HDB construction.

- The carparks do not have enclosed glazing. They however have vertical aluminium louvres spaced at every 50 millimetres to assist in natural ventilation but provide visual screening from the unsightly carpark.

Chapter 5

5 Demonstration

5.1 Introduction

This chapter demonstrates the process of encoding a design scenario. This chapter introduces a design scenario that generates numerous variants, as a particular family of designs which strictly adhere to local development, building and fire-safety regulations. The constraint-ing, development, generation of variants and evaluation of these variants have been implemented and the results tabulated on graphs.

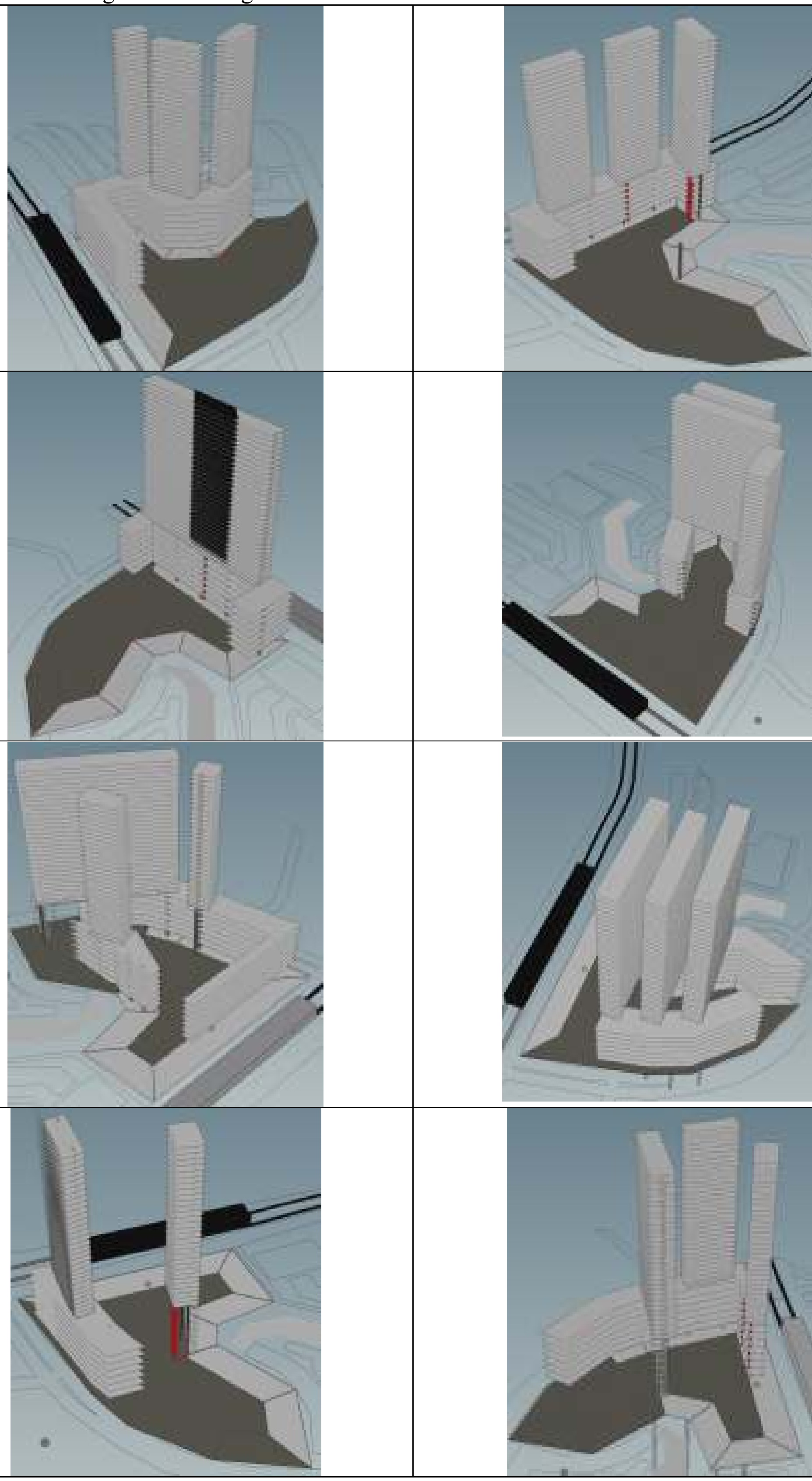
5.1.1 Developmental routine

Controlled variability
In this demonstration, the design team must create a developmental routine that is capable of producing controlled variability, where a balance between over-restricting variability that results in the generation of predictable designs and under-restricted variability that results in a system with poor performance. In order to achieve controlled variability, a generative process needs to be defined that consists of a carefully crafted set of rules and representations.

Evaluation Techniques
The evaluation techniques used in this demonstration are:
(1) Return-on-investment (ROI) analysis in order to quantify the financial viability of the planning scenario
(2) Continuous Daylight Availability (cDA) analysis in order to quantify the daylight availability and
(3) Solar Envelope Radiation analysis in order to understand the heat absorbed by the variants in this planning scenario.

Once the numerous 3D design variants are generated by the parametric model, the design variants are evaluated using the three analysis of (1) ROI analysis, (2) Continuous Daylight Availability (cDA) and (3) Solar Envelope Radiation analysis as stated above.

Fig. 5-1 A set of generated designs



5.2 Generative Steps

5.2.1 General pathway as main direction for generative steps development

In order to define the generative steps for the model, a general pathway of how the generative steps must flow should be specified. Below is a diagram of a general pathway:

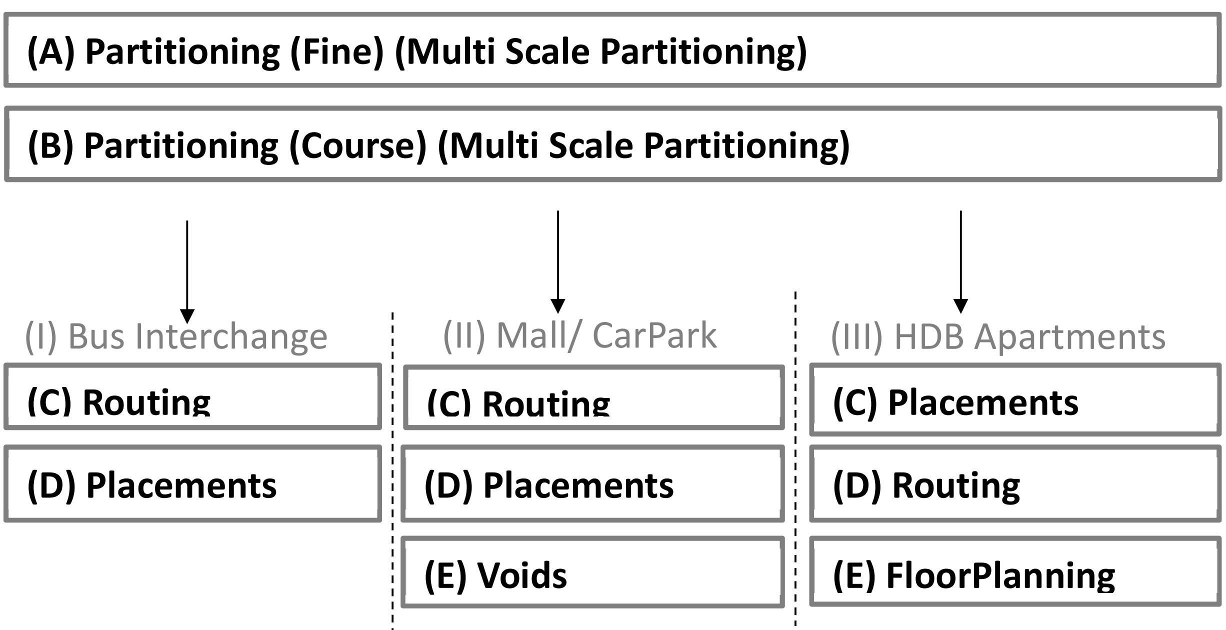
(1) First, the site plan of the development is (A) finely and (B) coarsely partitioned. These fine and coarse partitioning techniques form multi-scale partitioning approach to the site.

(2) Next, the three different building functions of (I) bus interchange, (II) Mall/Carpark and (III) HDB Apartments are separated as they have different sequence of modelling techniques.

(3) The bus interchange requires (C) routing followed by (D) placements techniques while the mall/carpark follows the same routing and placements sequences followed by the addition of voides.

(4) The HDB apartments requires (C) placements and (D) routing followed by (E) floorplanning techniques.

Fig. 5-2 Generative steps of general pathway



5.2.2 Generative steps for Clementi Town Centre

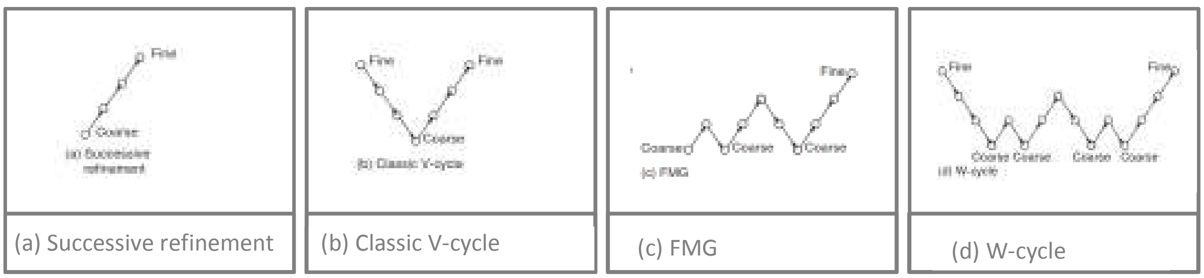
(A) Partitioning (Fine) (Multi scale partitioning)

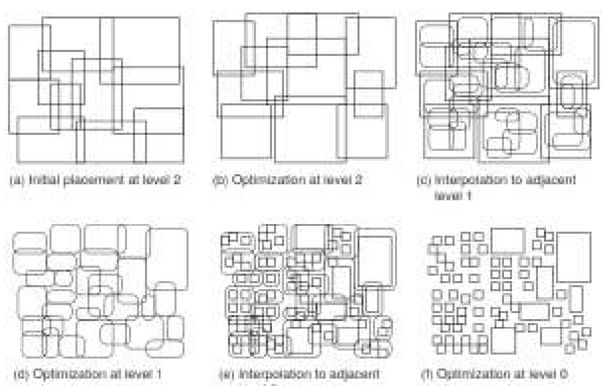
Step 1: Multi Scale Partitioning technique using the 'classic v-cycle' approach

(i) The first generative step involves the use of multi-scale partitioning. This is very important to control how the development would eventually be distributed on the site plan.

(ii) A total of four types of multi scale partitioning was tested for the site: (a) the successive refinement, (b) classic V-cycle, (c) FMG and the (d) W-cycle. After a series of trial and error, the (b) classic V-cycle proved to be the best technique that does not produce implementation errors in the Houdini environment without sacrificing the procedural modelling in achieving its objectives

Fig. 5-3 Multi scale partitioning techniques experimented in model. (Source: Handbook of Algorithm for Physical Design Automation, Taylor and Francis Group, 2008)





(a) Successive refinement

Step 2: generate base 2D plane as 'ground plane' on buildable area of site which is then partitioned finely using the "inset" technique (2D base plane must take into account the offsets as regulated by NEA and URA)

(i) The first step involves offsetting the regulated setbacks as required by the local authorities.

NEA site offset regulation (for bus interchange) (NEA guideline, 2012)

- Setback of bus-interchange from facing MRT Station/track = 35 metres
- Setback of bus-interchange from facing MRT with use of end-walls facing MRT tracks/station = 25m

URA site boundary offset regulation (URA guideline, 2011)

- Road Buffer (front boundary line) = 4.5 metres
- Side Buffer (side boundary lines) = 4.5 metres
- Rear Buffer (rear boundary line) = 4.5 metres

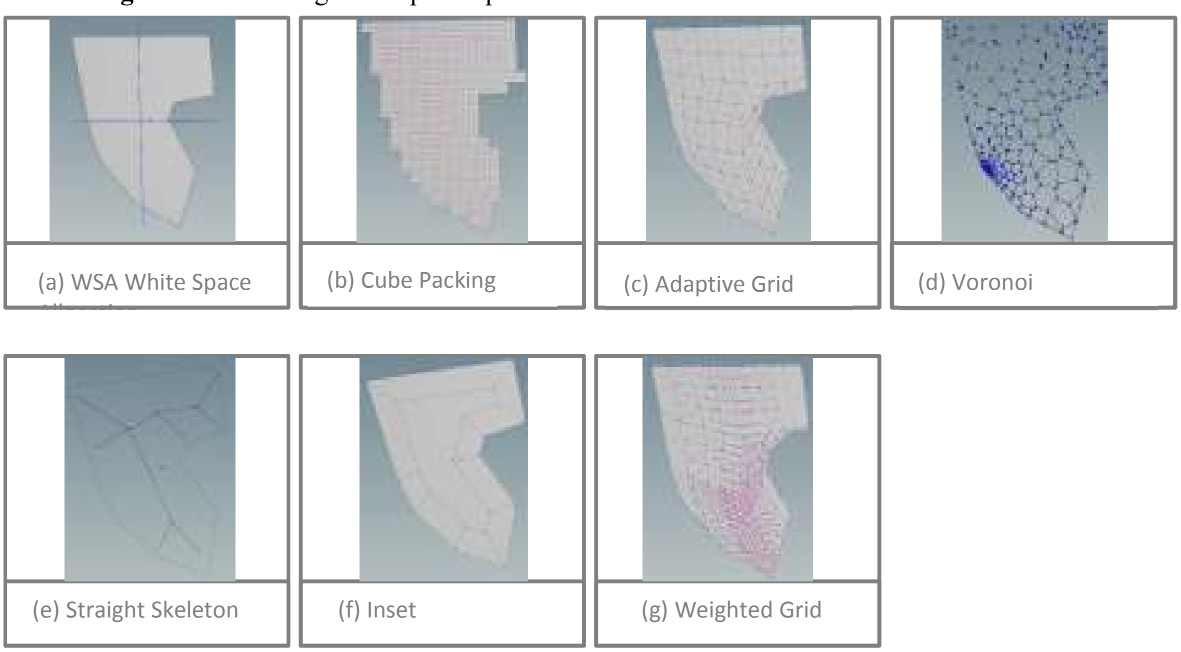
URA site offset from roads (URA guideline, 2011)

- Category 1- Expressway
- Category 2 – Major Arterial A = 15.0m (Min width of buffer)
- Category 3 – Major Arterial B = 7.5m (Min width of buffer)
- Category 4 & 5 – Other Major Roads, Minor Roads & Slip Roads = 5.0m (Min width of buffer)

(ii) Partitioning of the base 2D grid plane is done in such a way that the 3D grid do not exceed the setback boundaries of the White Site. Subsequently, as the 2D grid is modified on the subsequent generative steps, the resultant development may or may not occupy the entire site.

(iii) Seven different well-established partitioning techniques was applied on the site to understand its efficacy (a) WSA white space allocation, (b) cube packing, (c) adaptive grid, (d) voronoi splitting, (e) straight skeletion, (f) inset and (g) weighted grid. The technique (f) inset was chosen because of its ability to distribute the development on certain locations of the site without being too 'uniformly' distributed.

Fig. 5-4 Partitioning techniques experimented in model



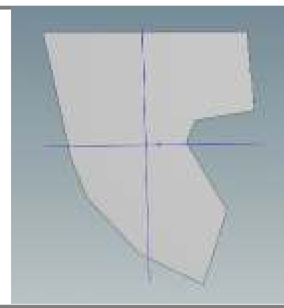
(B) Partitioning (Coarse) (Multi scale partitioning)

Step 3: control over amount of site coverage

To allow control on site coverage as a parameter, the base 2D grid plane can be reduced in buildable area. This is necessary as planners are required to define how much of the site would be developed. The site has a range of being buildable from 20% to 100% site coverage.

(i) As the buildable site is reduced/increased, the technique (a) WSA white space allocation is selected as being the best technique to control the coarse partitioning.

Fig. 5-5 Coarse partitioning implemented to control site coverage



(a) WSA White Space Allocation

(C) Routing (Bus interchange and mall/carpark)

Step 4A: structural construction scheme gridding

(i) In order to allow routing of human circulation at the bus interchange and mall, as well as the vehicular routing at the carpark function, the floorplates must be segmented into the different structural construction scheme and height restrictions to each different function. Thus three functional grids are generated which affects the routing dimensions in terms of width and height

(ii) The specific development regulations from BCA, URA and LTA are encoded through the different sizing of the functional grid. This includes the different structural construction scheme and height regulations.

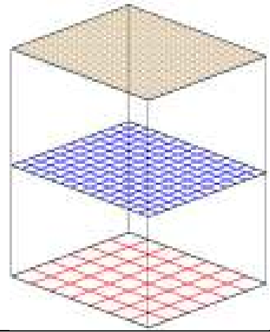
LTA site regulation (for bus interchange) (LTA guideline, 2009)

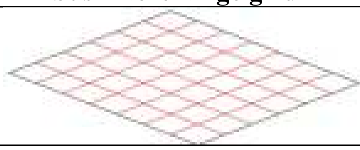
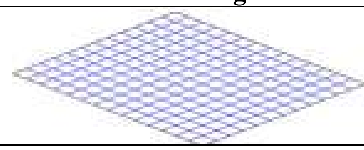
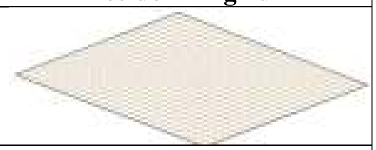
- min. bus one-way driveway ≥ 12.0m
- min bus two-way driveway ≥ 24.0m
- Bus interchange ≥ 10,000 m^2 (LTA minimum recommendation)
- Bus interchange height ≤ 60.0 m

URA site boundary offset regulation (URA guideline, 2011)

- commercial area: min area ≥ $50.0m^2$
- commercial height regulation ≤ 5.0 m
- residential floor area: min area ≥ $50.0m^2$
- residential height regulation ≤ 5.0 m

Fig. 5-6 Floorplates must be segmented into the different structural construction scheme and height restrictions to each different function**.**



Functional Grid 3A: bus-interchange grid	Functional Grid 3B: commercial grid	Functional Grid 3C: residential grid
		

Legend

(red)	**Bus-Interchange function**	Production cuboid dimension: 24.0m (length) X 24.0m (breadth) X 60.0m (height) LTA height regulation (bus-interchange): ≤ 60.0 m	(LTA regulation: : min. bus one-way driveway ≥ 12.0m : min bus two-way driveway ≥ 24.0m Bus Interchange: ≥ 10,000.0m^2 (LTA minimum recommendation)
(blue)	**Commercial function**	Commercial cuboid dimension: 12.0m (length) X 12.0m (breadth) X 5.0m (height) URA height regulation (commercial): ≤ 5.0 m	Floor Area per Cell = 144.0 m^2 (URA regulation (commercial) : min area ≥ 50.0m^2)
(orange)	**Residential function**	Residential cuboid dimension: 7.2m (length) X 7.2m (breadth) X 3.6m (height) URA height regulation (commercial): ≤ 3.6 m	Floor Area per Cell = 50.4m^2 (URA regulation (residential) : min area ≥ 50.0m^2)

(iii) As site coverage is changed in Step 2, the three functional grids in Step 3 must change by equal amount. That means should the planner decide for a development with a site coverage of 50%, then the three functional grids too, must only allow a coverage of 50%. In other words, the three functional grids must mirror the ground level grid's proportions.

Step 4B: generate routes for the human, vehicular and services at the bus interchange, mall and carpark functional areas.

(i) For the bus interchange, the routing for the human circulation is rather straightforward. The human circulation is directly adjacent to the bus depot. However, the human circulation for the mall needs to be placed in the middle of the mall to allow double loading of shops flanking on both sides of the human circulation. This is to increase the amount of lettable areas for the shop to be surrounding a given human walking strip.

(ii) The vehicular circulation for the carpark is similar in its conceptualization as the human circulation in a sense that parking lots should ideally be double loaded flanking alongside any given vehicular route so as minimize the vehicular route but maximize the number of parking lots.

(iii) The service cores for the mall and carparks have to ideally be aligned on the same side and directly above one another: ie the service cores of the mall and the carpark are located on the section of the floorplan and be vertically overhead one another. This is to allow a minimization of the service core routes and the ease of placing service lifts.

Fig. 5-7 Routing techniques implemented in model

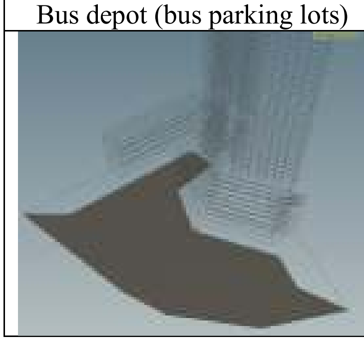
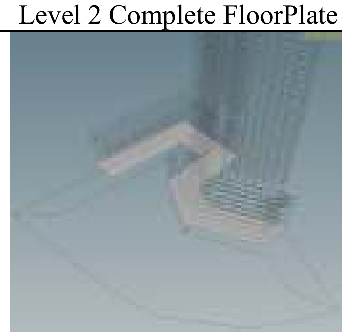
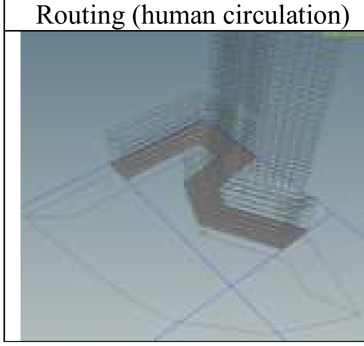
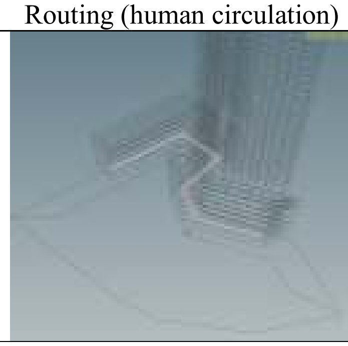
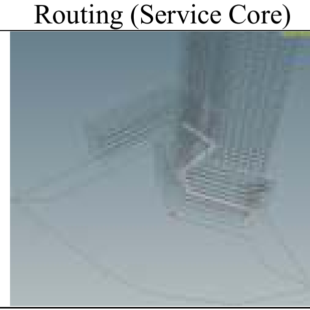
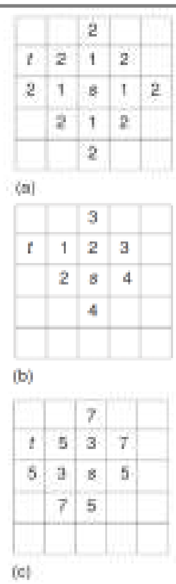
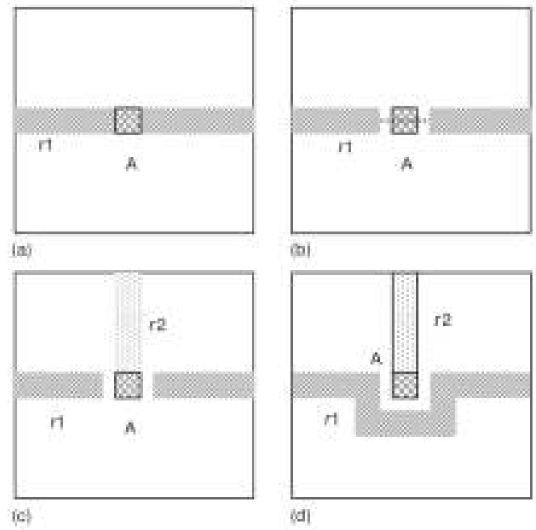
Bus Interchange	Mall	CarPark
Bus depot (bus parking lots)	Level 2 Complete FloorPlate	Level 6 Complete FloorPlate
		
Routing (human circulation)	Routing (human circulation)	Routing (vehicular circulation)
		
	Routing (Service Core)	Routing (Service Core)
		

Fig. 5-8 Two routing techniques experimented in the model. (Source: Handbook of Algorithm for Physical Design Automation, Taylor and Francis Group, 2008)



(a) Wavefront expansion between source (s) and target (t)



(b) classic rip-up and reroute

(iv) A total of two types of routing techniques was tested for the model: (a) the wavefront expansion, and the (b) classic rip-up and reroute. Both techniques were experimented for the routing of the human, vehicular and service core circulation, however, the wavefront expansion technique proved to be extremely difficult to implement without resorting to overly complex expression equations. Rather the classic rip and re-route technique was much easier to implement. Below is an implementation of the human, vehicular and service core routes in the model.

(D) Placements (lift cores and escalators) (bus interchange, mall and carpark)

Step 5: Placements of structural elements such as liftcores, staircase, escalators, shear wall, columns are distributed under fire safety and construction schemes regulations.

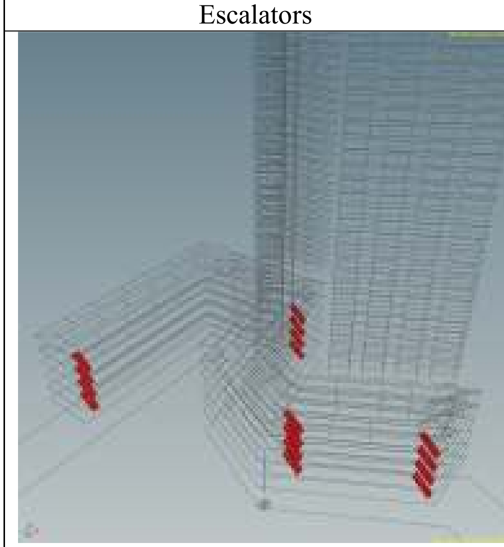
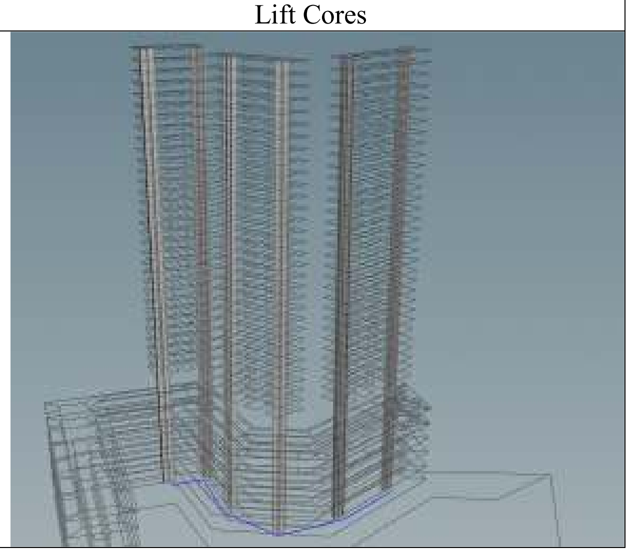
(i) Once the human, vehicular and service core routes are established, there is a need to allow vertical circulation between the levels of the development. Lift cores, escalators are required to be distributed or placed along the routes. However, the placement of the liftcores and escalators are must be critically spaced out to meet the requirements of the fire safety codes in Singapore.

Fire safety (commercial) (Fire Code, 2013)
Commercial one way travel distance (unsprinklered) ≤ 30 metres
Commerical two-way travel distance (sprinklered) ≤ 75 metres
Residential one way travel distance (unsprinklered) ≤ 30 metres
Residential two-way travel distance (sprinklered) ≤ 75 metres

(ii) The placement of columns, shear walls and flat slabs are regulated by the Building and Construction Authority of Singapore (BCA). The parametric modelled is encoded with the allowable structural construction scheme by BCA.

BCA Code of Practice for Structural Use of Concrete (CP65 1999)
Residential 6m to 9m (reinforced flat plate)
Commercial 8 m to 12m (prestressed flat plates)
Bus Interchange 24m

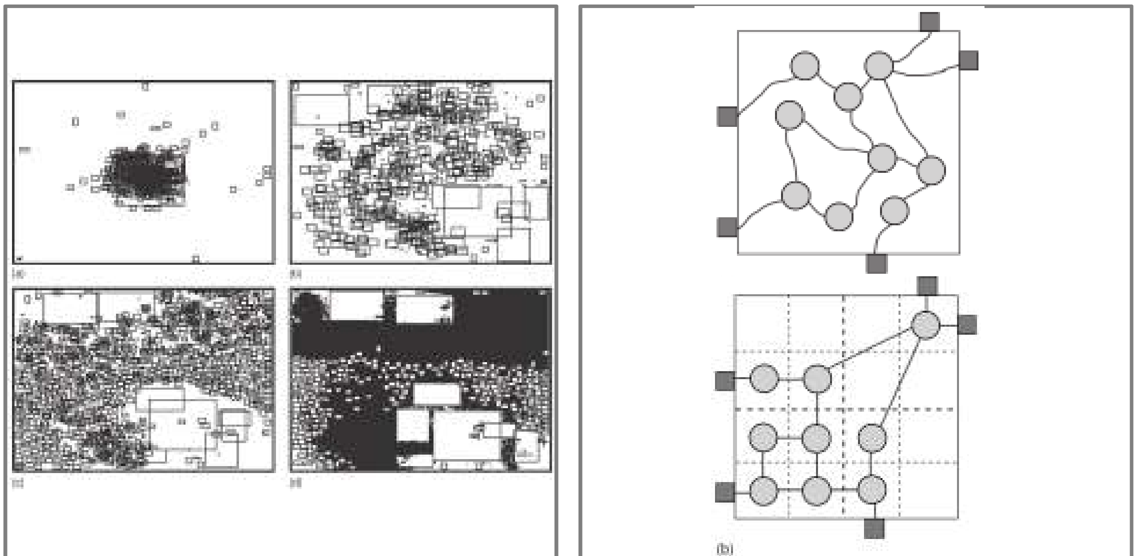
Fig. 5-9 Placement technique implemented that connect bus interchange, mall and carpark

Escalators	Lift Cores
	

(iii) A total of two types of routing techniques was tested for the model: (a) force-directed placement, and the (b) simple placement instance. The (a) force-directed placement technique is far too complex to be implemented. In addition, the routes are already known and it would be much easier and practical to implement the second technique, (b) simple placement instance. Thus, above is an implementation of the placement of lift cores and escalators, all separated to satisfy the fire regulation safety distance. The function of the placement of the lift cores and escalators are to allow vertical circulation between the bus interchange, mall and carpark.

(iv) Using the simple placement instance technique, the lift cores connecting from the ground level of the bus interchange to the HDB apartments are separated by a distance of 30 metres. Each tower would then have two lift cores that are not apart by 30 metres.

Fig. 5-10 Placement techniques.
(Source: Handbook of Algorithm for Physical Design Automation, Taylor and Francis Group, 2008)



(a) Force-directed placement	(b) Simple placement instance

(E) FloorPlanning (HDB Apartments)

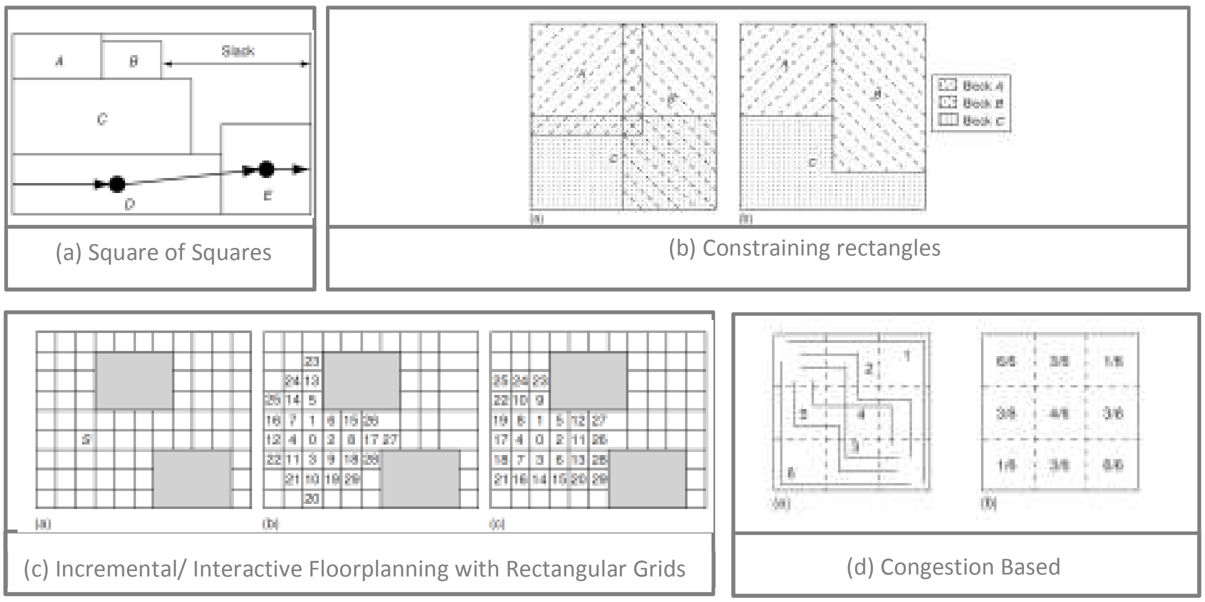
Step 6: Floorplanning of the HDB Apartments

(i) Once the vertical circulation is established between the bus interchange's lobby to the HDB apartments, there is a need for floorplanning of the HDB apartments. A total of 372 HDB apartments units needs to be generated and the floor areas of each HDB apartment unit has to vary between 65m^2 to 120m^2, representing a typical three-room HDB apartment (65m^2) to a five-room HDB apartment (120m^2).

Fig. 5-11 Square of squares techniques implemented into model

(ii) A total of four floorplanning techniques: (1a) square of squares, (b) constraining rectangles, (c) grid interaction and (d) congestion based techniques. The easiest to implement is the (a) square of squares techniques and is implemented in the above model.

Fig. 5-12 Floorplanning techniques.
(Source: Handbook of Algorithm for Physical Design Automation, Taylor and Francis Group, 2008)

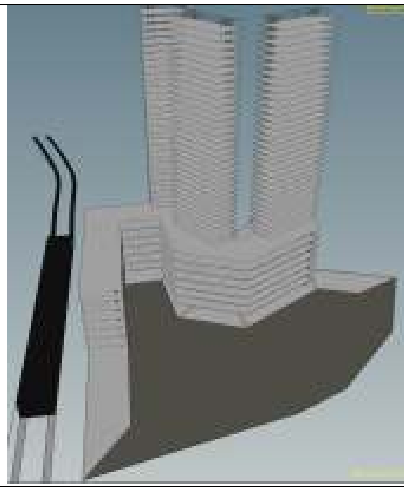


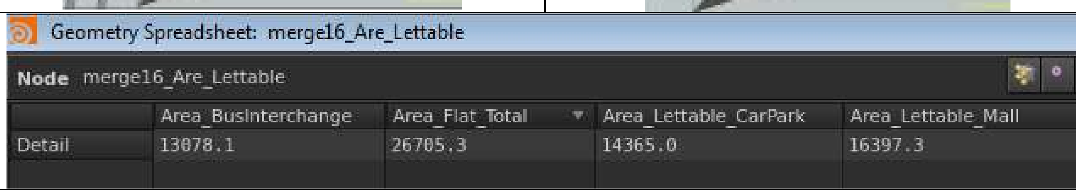
(F) Output Metrics (Bus interchange, mall, carpark and HDB apartments)

Step 7A: Lettable floor areas of bus interchange, mall, carpark and HDB apartments.

(i) With the 3D model of the development completed, the model allows a customized output metric that calculates the lettable or tenable area. This metric allows further calculation of the floorplan efficiency or the evaluation of the lettable area to optimize the Return on Investment (ROI) of the development.

Fig. 5-13 Lettable Area Calculation

(i) Massing of Development	(ii) Lettable/ Rentable Floor Area of Development
	



Geometry Spreadsheet: merge16_Are_Lettable

Node merge16_Are_Lettable

	Area_BusInterchange	Area_Flat_Total	Area_Lettable_CarPark	Area_Lettable_Mall
Detail	13078.1	26705.3	14365.0	16397.3

(ii) In the model encoded in Houdini, a customized spreadsheet is created for the model to automatically calculate the total lettable of each of the different functions:

(1) bus interchange lettable floor area
(2) HDB apartments lettable floor area
(3) mall shops lettable area
(4) carpark lettable area and subsequently the number of parking lots

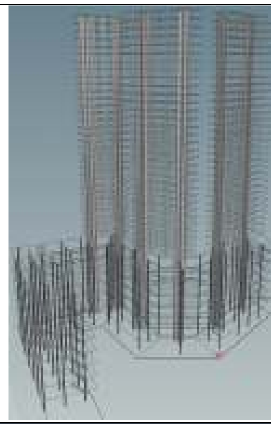
Step 7B: Volume of concrete used for structural components and surface area of cladding used for envelope materials

(i) The parametric model also allows a customized output metric that calculates the volume of concrete used for the development's construction as well as surface area of envelope cladding material. This metric allows further calculation of the cost of the development, thereby allowing a calculation on the Return on Investment (ROI) of the development.

Fig. 5-14 Constituents of development (volume of concrete used in structure of development)

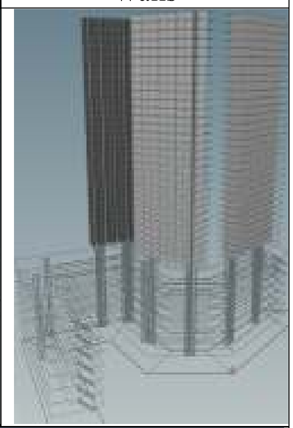
(i) Overall concrete massing

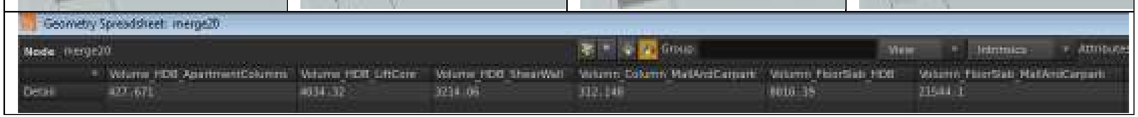
(ii) Concrete Columns



(iii) Concrete Flat Slabs

(iv) Concrete Shear Walls



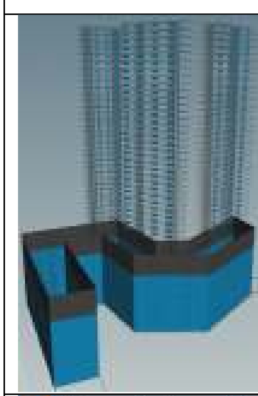

Geometry Spreadsheet: merge20

Node merge20 | Group | View | Intrinsics | Attributes

	Volume_HDB_ApartmentColumns	Volume_HDB_LiftCore	Volume_HDB_ShearWall	Volumn_Column_MallAndCarpark	Volumn_FloorSlab_HDB	Volumn_FloorSlab_MallAndCarpark
Detail	427.671	4034.32	3214.06	312.148	8016.35	21544.1

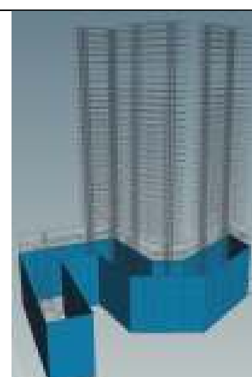
Fig. 5-15 Constituents of development (cladding elements)

(i) Overall glazing

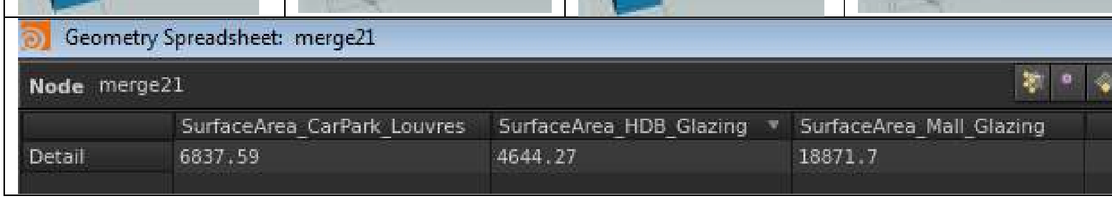


(ii) Carpark aluminium louvres

(iii) Mall glazing



(iv) HDB glazing


Geometry Spreadsheet: merge21

Node merge21

	SurfaceArea_CarPark_Louvres	SurfaceArea_HDB_Glazing	SurfaceArea_Mall_Glazing
Detail	6837.59	4644.27	18871.7

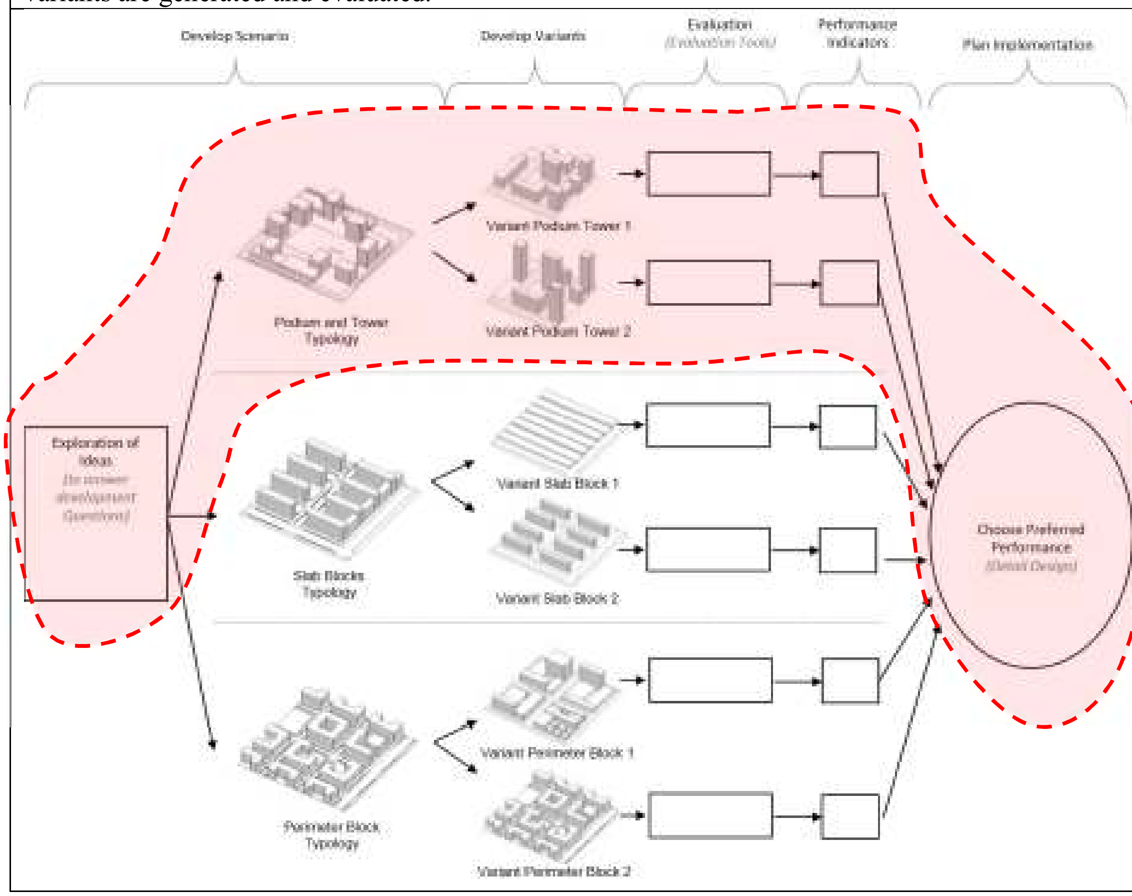
5.3 **Implementation**

5.3.1 Results

In this implementation, the scenario of exploring podium and tower typology was chosen. The other scenarios of other typology were not implemented so as to allow the demonstration to only focus on a single scenario, and its subsequent 3D variants.

In this demonstration, a total of eight podium and tower variants are generated. The main aim of generating and visualizing these designs is to verify the character of design and the variability that can be achieved, and that the development, building and fire safety regulations are not violated.

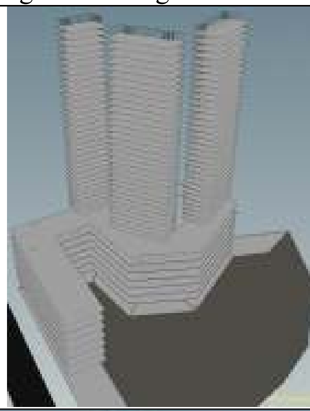
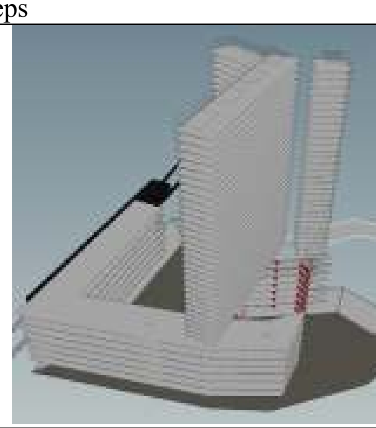
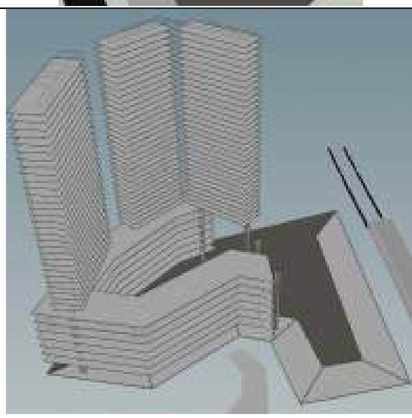
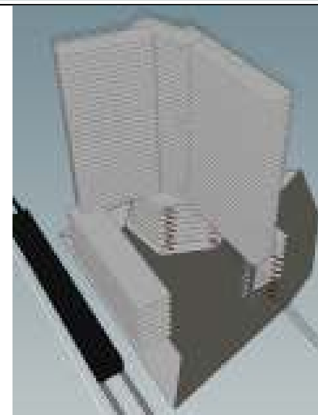
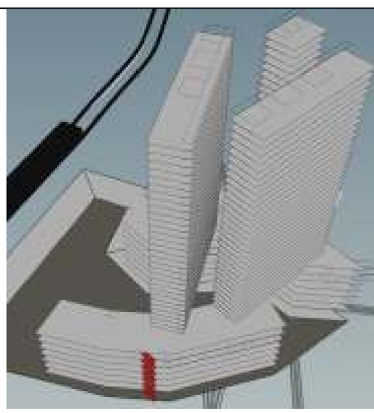
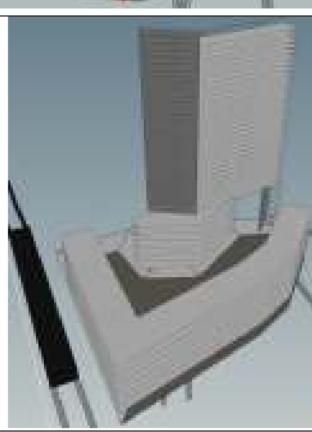
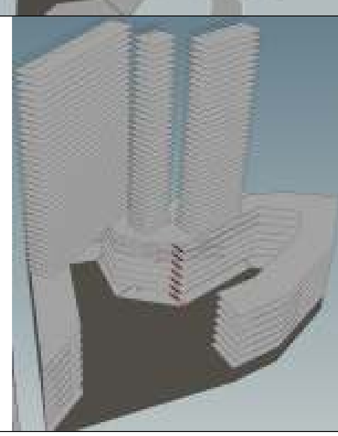
Fig. 5-16 A scenario of exploring podium and tower typology was implemented and 8 design variants are generated and evaluated.



In the following page, the eight generated variants are presented. An interesting feature is that while the HDB flats are usually developed above the podium block, a few variants have the HDB flats straddling between two other podiums.

Initially, it might come across as awkward, but the development seems plausible as the staircase cores satisfies the fire safety regulations and there are sufficient liftcores and staircases for these variants. While it may not be typical, there are a few rare executive HDB flats facing in front of Tampines Junior College, Singapore, that has almost similar design of straddling two different podiums, allowing human and vehicular traffic to pass under the straddling block. While these design is not typical, it definitely has been constructed in Singapore, hence these variants are acceptable.

Fig. 5-17 Eight variants generated from the generative steps

Variant 01		**Variant 05**	
Variant 02		**Variant 06**	
Variant 03		**Variant 07**	
Variant 04		**Variant 08**	

5.3.2 Controlled variability

One of the important requirements of the designs generated is to achieve controlled variability. This is to ensure that unthought, challenging and unexpected designs to be generated and prevent the designs to vary in highly unrestricted ways, as that would mean that the generative system has deteriorated – chaotic forms, designs that differ fundamentally from one another that it affects the semantic level of representations- is avoided at all costs.

The generative process must fulfil four key criteria to achieve controlled variability:
(1) capable of generating designs with the required level of complexity
(2) designs should have a kinship of character
(3) designs should differ significantly in terms of overall organization and configuration
(4) should not generate chaotic forms that is semantically not possible for ranking or evaluation

Thus, the generative steps in this demonstration fulfils all four criteria through the careful control of the variability of the design variants.

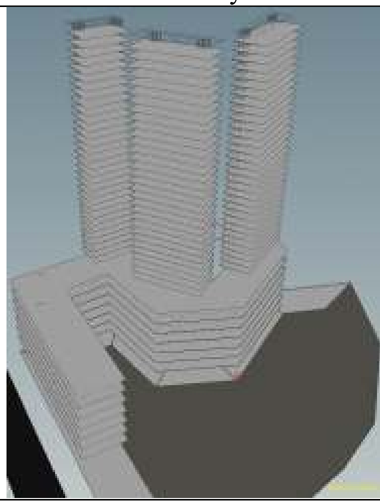
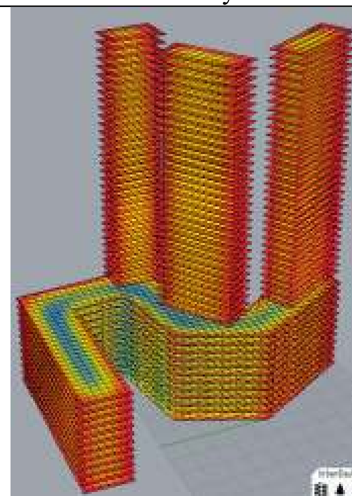
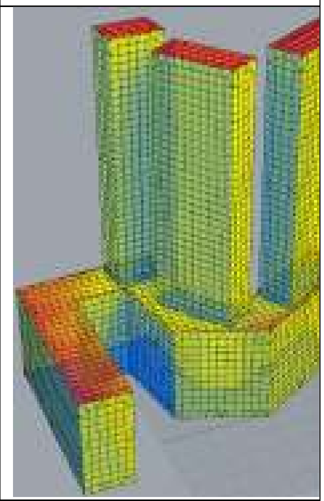
5.3.3 Variants evaluated by external 3D evaluation tools.

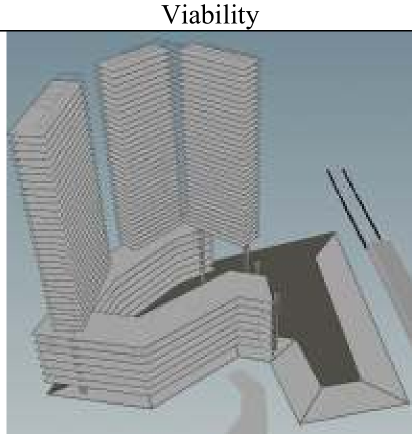
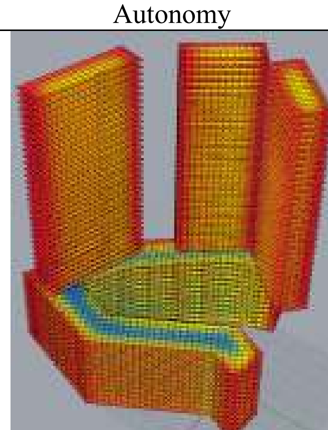
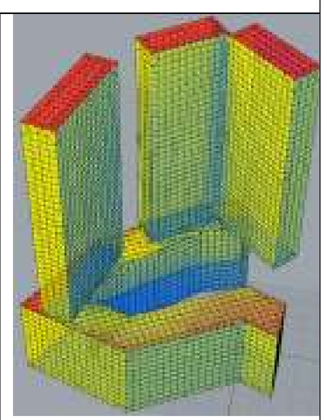
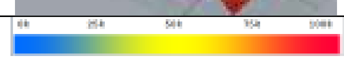
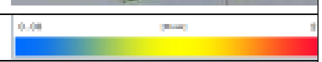
While the generated design variants are not chaotic in form, the variants are tested for any form of semantical mismatch with other 3D evaluation tools. The variants are evaluated for daylight availability and solar envelope radiation with Christopher Reinhardt's daylight evaluation tool, ArchSIM.

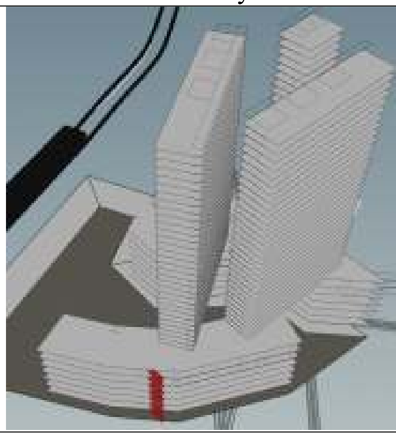
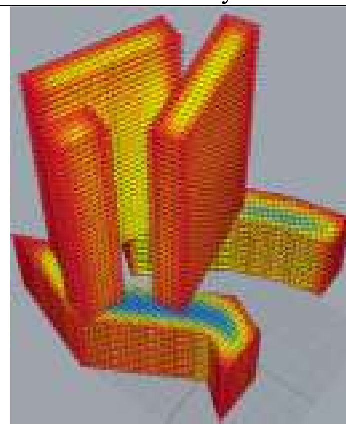
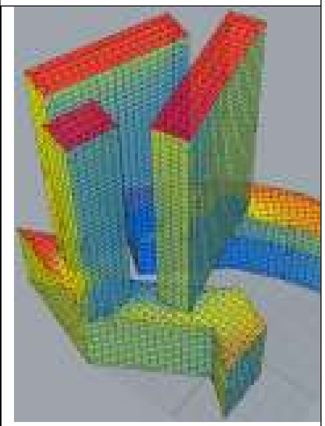
The results on the following pages display that the evaluation of the generated variants are possible, signaling that the complex, high dense mixed-use development generated through this approach can potentially allow developers to be more thorough and systematic in their exploration of any particular scenario.

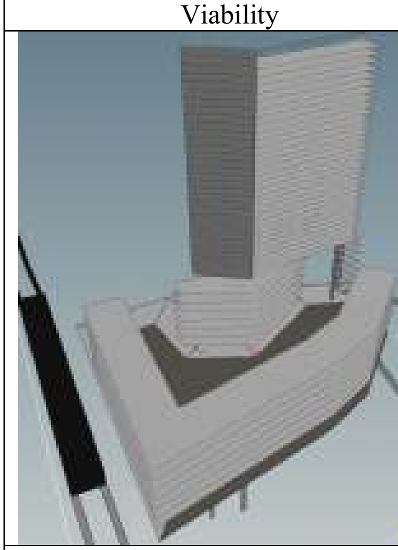
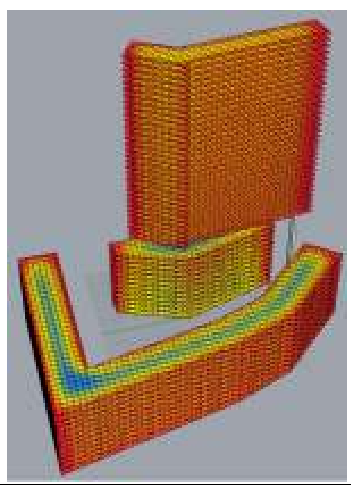
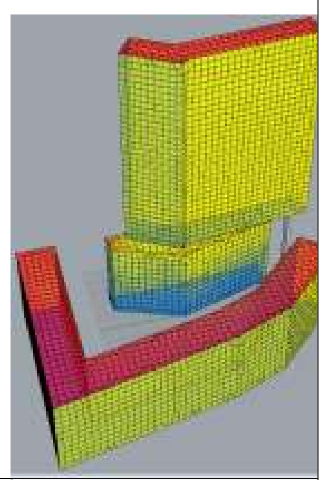
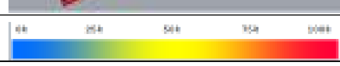
In fact, this demonstration has achieved the aim of this investigation to empower developers to generate 3D developments from a 2D plan and at the same time generate numerous variants that can be evaluated in terms of their performance.

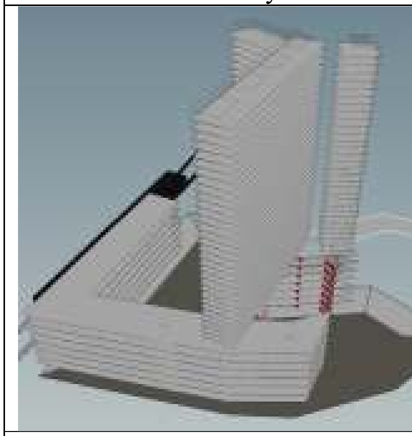
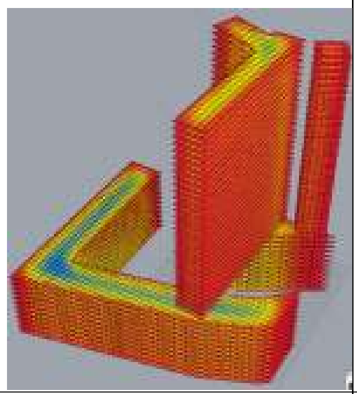
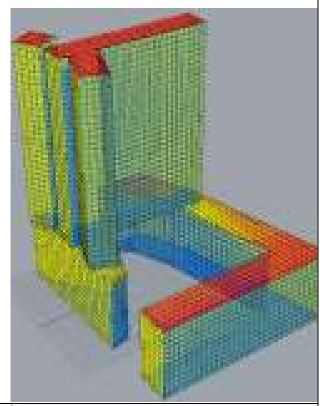
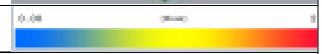
As a means of further evaluation, the results of these evaluations are graphically plotted to demonstrate how developers can further the use of the evaluation results into statistical analysis. Examples of statistical analysis that can be done using the results of these three evaluations are presented in the following pages.

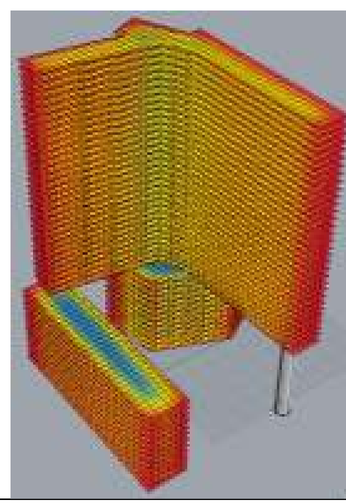
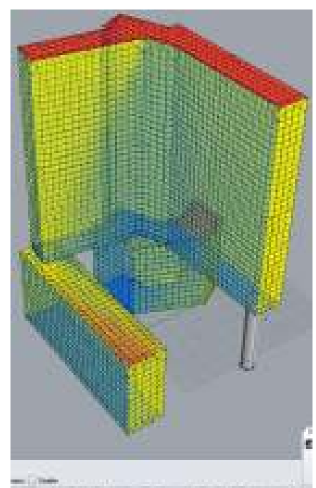
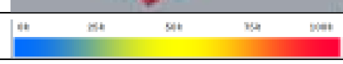
<table>
<tr><td colspan="5">Fig. 5-18 Results of variants' evaluation</td></tr>
<tr><td colspan="5">Variant 01</td></tr>
<tr><td colspan="3">Financial Viability</td><td>Continuous Daylight Autonomy</td><td>Envelope Radiation</td></tr>
<tr><td colspan="3"></td><td></td><td></td></tr>
<tr><td colspan="3">ROI = 9.55%</td><td></td><td></td></tr>
<tr><td>Total Lettable Area</td><td>Total Volume of Concrete</td><td>Total Surface Area Cladding</td><td>Group CDA</td><td>Radiation Peak:</td></tr>
<tr><td>70,545 m²</td><td>37,541 m³</td><td>30,352 m²</td><td>72.31%</td><td>[MLux] 2.09801</td></tr>
</table>

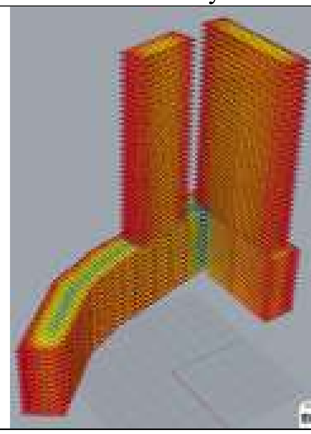
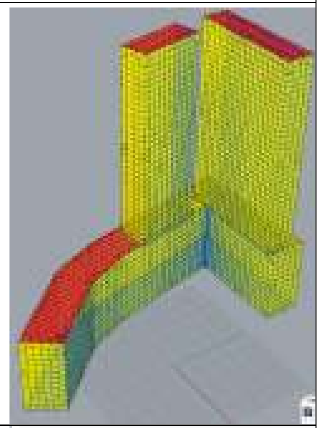
<table>
<tr><td colspan="5">Variant 02</td></tr>
<tr><td colspan="3">Financial Viability</td><td>Continuous Daylight Autonomy</td><td>Envelope Radiation</td></tr>
<tr><td colspan="3"></td><td></td><td></td></tr>
<tr><td colspan="3">ROI = 9.91%</td><td></td><td></td></tr>
<tr><td>Total Lettable Area</td><td>Total Volume of Concrete</td><td>Total Surface Area Cladding</td><td>Group CDA</td><td>Radiation Peak</td></tr>
<tr><td>80,304m²</td><td>37,703m³</td><td>31,019m²</td><td>69.96%</td><td>[MLux] 2.09823</td></tr>
</table>

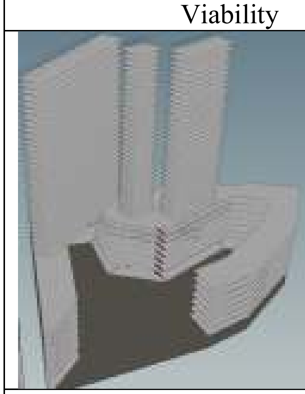
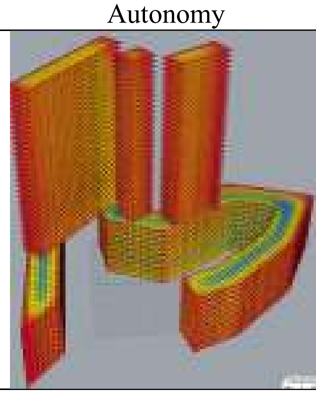
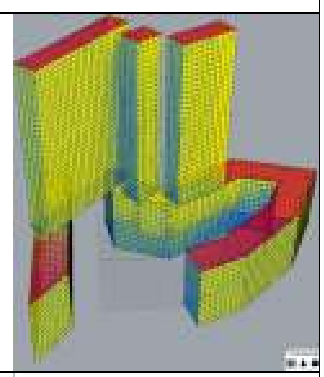
Variant 03				
Financial Viability			Continuous Daylight Autonomy	Envelope Radiation
				
ROI = 7.16%				
Total Lettable Area	Total Volume of Concrete	Total Surface Area Cladding	Group CDA	Radiation Peak
60,476 m^2	36,533 m^3	30,112 m^2	62.86%	[MLux] 2.099522

Variant 04				
Financial Viability			Continuous Daylight Autonomy	Envelope Radiation
				
ROI = 5.17%				
Total Lettable Area	Total Volume of Concrete	Total Surface Area Cladding	Group CDA	Radiation Peak
46,435 m^2	43,092 m^3	13,738 m^2	63.5%	[MLux] 2.098069

<table>
<tr><th colspan="5">Variant 05</th></tr>
<tr><td colspan="3">Financial Viability</td><td>Continuous Daylight Autonomy</td><td>Envelope Radiation</td></tr>
<tr><td colspan="3"></td><td></td><td></td></tr>
<tr><td colspan="3">ROI = 10.42%</td><td></td><td></td></tr>
<tr><td>Total Lettable Area</td><td>Total Volume of Concrete</td><td>Total Surface Area Cladding</td><td>Group CDA</td><td>Radiation Peak</td></tr>
<tr><td>104,620 m^2</td><td>43,241 m^3</td><td>37,509 m^2</td><td>68.51%</td><td>[MLux] 2.098297</td></tr>
</table>

<table>
<tr><th colspan="5">Variant 06</th></tr>
<tr><td colspan="3">Financial Viability</td><td>Continuous Daylight Autonomy</td><td>Envelope Radiation</td></tr>
<tr><td colspan="3"></td><td></td><td></td></tr>
<tr><td colspan="3">ROI = 8.56%</td><td></td><td></td></tr>
<tr><td>Total Lettable Area</td><td>Total Volume of Concrete</td><td>Total Surface Area Cladding</td><td>Group CDA</td><td>Radiation Peak</td></tr>
<tr><td>71,285 m^2</td><td>33,087 m^3</td><td>23,882 m^2</td><td>59.32%</td><td>[MLux] 2.098594</td></tr>
</table>

Variant 07				
Financial Viability			Continuous Daylight Autonomy	Envelope Radiation
				
ROI = 6.18%				
Total Lettable Area	Total Volume of Concrete	Total Surface Area Cladding	Group CDA	Radiation Peak
53,679 m^2	34,865 m^3	24,053 m^2	69.49%	[MLux] 2.099072

Variant 08				
Financial Viability			Continuous Daylight Autonomy	Envelope Radiation
				
ROI = 10.40%				
Total Lettable Area	Total Volume of Concrete	Total Surface Area Cladding	Group CDA	Radiation Peak
82,893 m^2	45,540 m^3	36,962 m^2	68.91%	[MLux] 2.099978

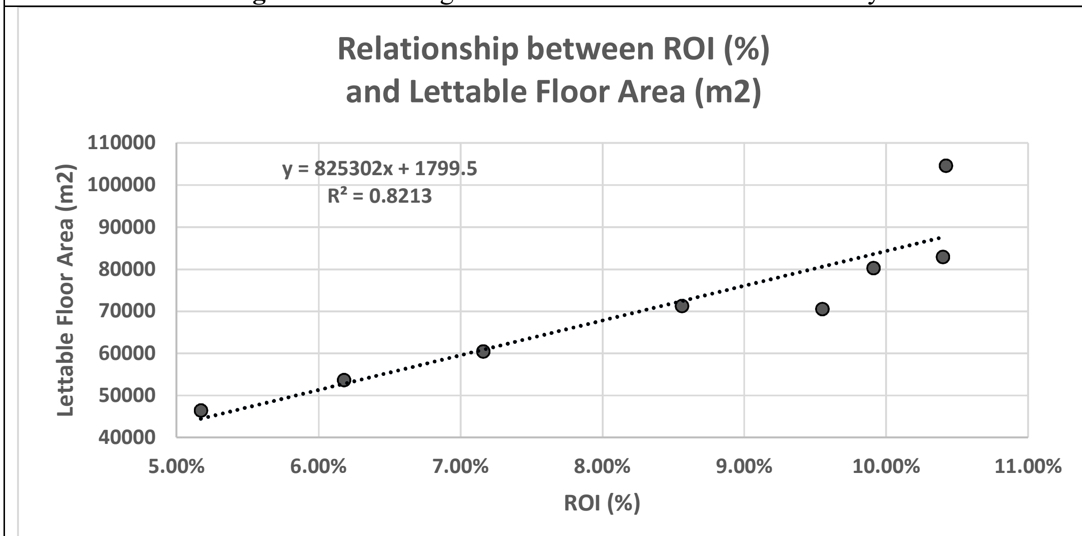
5.3.4 Furthering evaluation results into statistical analysis

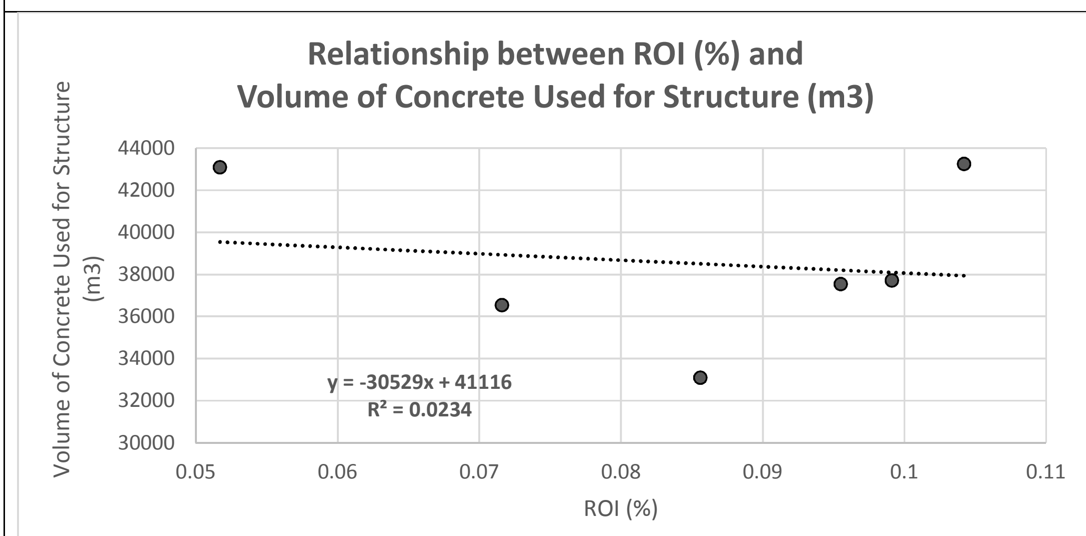
With the result from the evaluation of the variants, developers can graphically plot these results onto a chart and conduct statistical tests. However, in this demonstration, only eight variants are created. In actual fact, more variants should ideally be generated to allow the graphs to reveal a pareto-front. Example of a pareto-front graph can be seen in chapter 1 (choosing between variants).

However, should developers only have the time resources for a small number of variants, they can conduct simple statistical tests such as linear regressions, etc. Below are examples of how the variants's evaluation results are plotted to excavate possible correlationships.

Example of statistical analysis: developers can begin to understand how the Return-on-Investment (ROI) is positively and strongly correlated to the amount of lettable floor area available for rent and how negatively but weakly is the correlation between the ROI and volume of concrete used in the development.

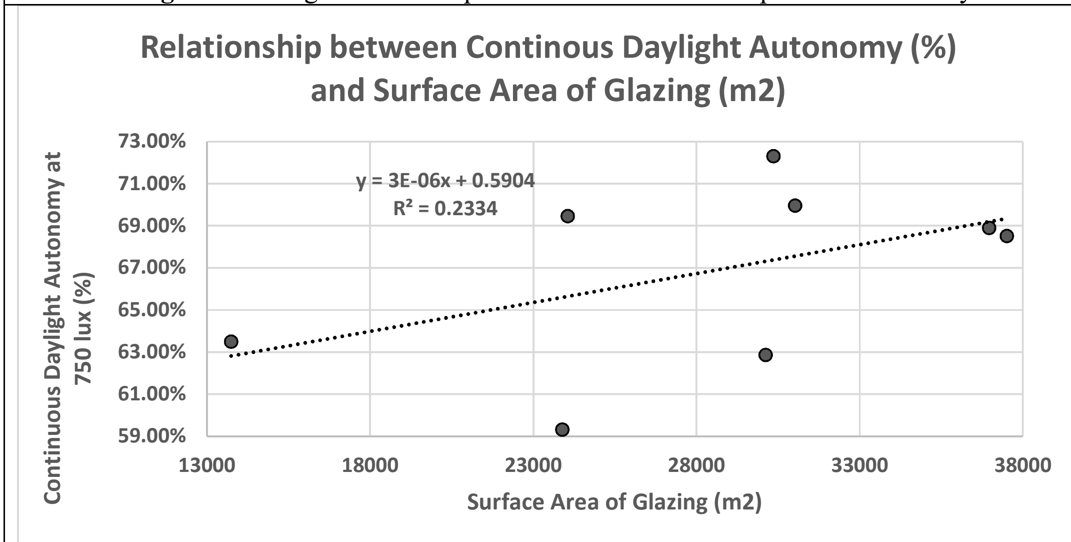
Fig. 5-19 Furthering evaluation results into statistical analysis

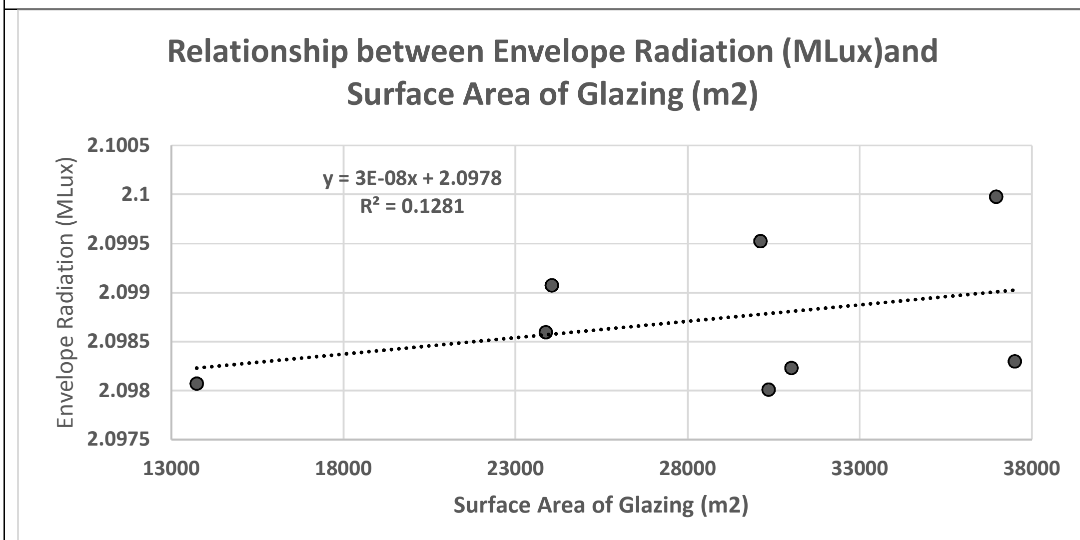




In addition, developers can also extract the variants's variables from the parametric modelling spreadsheets to conduct deeper analysis. An example is shown below where statistical analysis is used to understand how a variable might relate to the evaluation results, such as the surface area of glazing to the amount of continuous daylight autonomy that the variants receives. Or even the comparison of two variables such as the analysis between envelope radiation and surface area of glazing.

Fig. 5-20 Using sub-data in spreadsheets to conduct deeper statistical analysis





5.3.5 Summary

This chapter has demonstrated the process of encoding a design scenario. The aim of this demonstration is to support the proposed generative steps in the parametric modelling:

- An example development scenario has been created for a high-dense, mixed-use development. The overall form, the organization of spaces all vary significantly.

- A generative process has been described for generating parametric models in the example scenario. This process consists of a series of transformations that gradually transform a 2D polygon into a 3D development, subsequently numerous 3D variants are generated and evaluated.

- The variants are evaluated in terms of evaluation tools that require the use of 3D data, such as the calculation of Return-on-Investments (ROI), daylight availability in the building as well as solar envelope radiation.

- The controlled variability of the generated variants displayed the desired four key criteria: (1) generated plausible podium and tower developments with sufficient complexity typical of buildings, (2) the generated variants share the same character but (3) vary significantly from one another and (4) they maintain their semantical representations that allows them to be evaluated by evaluation tools such as daylight availability and envelope radiation as shown in the results of the demonstration.

The demonstration has shown that it is possible to create a generative process by using parametric modelling techniques to transform a 2D polygon into 3D developments with numerous variants. The variants too are evaluated without any semantical mismatch with the evaluation tools, proving that the generative process has been successful.

Chapter 6

6 Conclusion

6.1 Summary of main contribution

The main contributions of this research are as follows:

- ***Problem identification:*** The lack of use of 3D models in developing high-dense, mixed use developments has been identified as the primary problem (Chapter 1, Section 1.2.1) in the research. In addition, the lack of use of 3D design variants to thoroughly explore scenario planning analysis has been identified as the secondary problem (Chapter 1, Section 1.2.2) as well.

    - In establishing the need for the use of 3D models to evaluate high-dense, mixed-use development, the research substantiates with further background research through the analysis of the "plot-ratio problem". Using evaluation techniques of continuous daylight availability (cDA), spatial daylight availability (sDA), urban heat island (UHI) and solar envelope radiation to evaluate 3D models of high-dense, mixed use developments (Chapter 2, Section 2.5 and 2.6), the background research attempts to answer the question of "to which degree of plot ratio is the use of 3D models in high-dense, mixed-use development necessary?".

    - The background research concludes that it is necessary to use 3D models when developers work at higher densities. In the case of evaluation techniques such as continuous daylight availability and solar envelope radiation, the use of 3D models is required when developers work at plot ratio of 3.0 and 1.0 respectively (Chapter 2, Section 2.5 and 2.6).

    - The research also identified the secondary problem of requiring numerous 3D design variants to thoroughly explore planning scenario. In (1) Chapter 3, Section 3.4.2, "Choosing between variants" and (2) Chapter 5, Section 5.3.3, "Variants evaluated by external 3D tools", the research respectively explains and demonstrates the need of generating numerous 3D design variants, which would then be evaluated, subsequently resulting in design variants with varying performance scores. These performance scores are then analyzed using statistical techniques such as pareto ranking or linear regressions to allow developers to choose between the different variants. The research demonstrates and concludes in these chapters on the importance and need for developers to thoroughly explore any given planning scenario to carefully identify desirable, high performing variants for further development.

- ***Research proposition:*** In order to overcome the research problem, a research design workflow, ***function distribution design (FDD) workflow,*** which comprise of (A) a five-design-steps workflow, (B) a computational architecture and (C) a prototype has been proposed (see Chapter 3, Section 3.1.1):

- In (A) five-design-steps workflow: (1) develop scenario, (2) codify scenario, (3) generate variants, (4) analyze variants and (5) detail design workflow explicitly prescribes the way of designing a type of product, in this research, defining a scenario planning procedure for using parametric modeling techniques to generate and evaluate numerous 3D variants in a very specific order (Section 3.1.2).

- In (B) computational architecture, an implementation plan using parametric modelling techniques is presented. The system uses a set of constraints (development and building regulations) as part of the generative techniques in the parametric modeling (Section 3.1.2).

- In (C) prototype, a demonstration is presented on how to encode a design scenario, that generates numerous 3D design variants that strictly adhere to constraints in the form of local development, building, fire-safety, traffic and environmental regulations. A set of generative steps of general pathway is presented as a set of solution to address the primary and secondary research problems. Consequently, eight 3D design variants were generated from the generative steps and are evaluated using three evaluation techniques of (1) financial viability through return-on-investment (ROI) analysis, (2) Continuous Daylight Autonomy (cDA) analysis and (3) Solar Envelope Radiation analysis. Finally, the evaluation performance were graphically plotted onto a chart where further statistical tests can be conducted. This therefore allow the developer team to comprehend and understand the performance of different 3D design variants in a meaningful way (see Chapter 5, Section 5.3).

- ***Constraint satisfaction*** (development, building, fire safety, traffic and environmental regulation adherence) (see Chapter 4, Section 4.2.1):

  - The research strictly adheres to the voluminous amount of development, building, fire safety, traffic and environmental regulation and codes as mandated by the local authorities. These codes and regulation strictly constraint the parametric model developed in the demonstration (Chapter 5).

  - The research has to satisfy the land development and functional landuse control by the Urban Redevelopment Authority (URA), satisfy the construction scheme (concrete development) by the Building and Construction Authority (BCA), satisfy the fire safety code and allowable maximum travel distance by Singapore Civil Defense Force (SCDF), satisfy the noise control issues of developing a bus interchange by the National Environment Agency (NEA) and satisfy the safety, practical and functional development of the bus interchange by the Land Transport Authority (LTA) (see Chapter 4, Section 4.2.1).

- ***Controlled Variability***: The research identified controlled variability as a key factor in the performance of the generated 3D design variants (see Chapter 3, Section 3.2.1):
    - The generation of variants in terms of design variability should not be overly restricted nor should it be unrestricted and too constrained. This variability problem requires striking a balance between an approach to generate variants that are neither too restrictive nor unrestrictive.
    - When the design variability is highly unrestricted, the output may be too unpredictable/ chaotic and risks not being a sensible/ acceptable variant. In addition, it may become problematic for the evaluation process or it may not be meaningfully compared to one another.
    - When the design variability is overly restricted, the output may risk excluding the best possible designs.
- ***Enhancement of 3D design variants generation:*** The research enhances the generation of high-dense, mixed-use development in an automated manner (see Chapter 1, Section 1.6.1):
    - The development of high-dense, mixed-use development is a very complex and difficult problem. It takes a significant amount of time to develop a high-dense, mixed-use development by hand. The problem compounds further when numerous variants must be developed and yet strictly adhere to the voluminous amount of development, building and fire safety regulations. While it may take a significant amount of time to develop a high-density, mixed-use development by hand, it can also take more time to develop a parametric model of a high-density, mixed use development. Only when numerous variants must be developed does it make sense to invest first in the development of a parametric model (see Chapter 1, Section 1.6.1).
    - Thus, this research contributes by facilitating the generation of numerous variants of high-dense, mixed-use development in an automated manner, thereby allowing developer to focus more on the different variant types that are generated that they would like to explore and evaluate, rather than spend time hand making each variant (see Chapter 1, Section 1.6.1).
- ***Enhancement of scenario planning approach:*** The research enhances the scenario planning approach with computational support through a synergistic way (see Chapter 1, Section 1.6.2):
    - tasks that require predominantly creative and subjective judgment are handled by the developer team,

- tasks which are less creative and subjective such as creating the parametric model is delegated to the parametric modelling team under the guidance of the developer team

- while tasks which are predominantly repetitive and objective can be assigned to the computer.

- Thus, this process benefits and encourages exploration, experimentation and innovation in the planning process amongst the developer team.

6.2 Conclusion

In conclusion, the research achieves both its primary and secondary research objectives (see Chapter 5, Section 5.3, Implementation) to be able to generate 3D models from a 2D site plan as well as to generate and evaluate numerous variants to any given scenario (see Chapter 5, Section 5.2, Generative Steps).

Through the demonstration (Chapter 4 and 5), the research also achieves the initial hypothesis of this research to computationally support the scenario planning method to explore high-dense, mixed-use developments in an automated manner, so that scenarios can be thoroughly explored in the search space and evaluated by developers, in a more systematic way.

But one of the most interesting and useful aspect of this approach, as illustrated by the demonstration, is the fact that this approach allows unexpected or unthought of design variants that still satisfies the constraints and regulations. By allowing these unexpected or unthought of variants to be generated by the tool, the research hopes that more innovation to be achieve when developers experiment and explore through this tool. This aspect is valuable to the developer team to generate innovative solutions that still adhere to the constraints of the development.

6.3 Future Work

A future work is to expand this set of approach much higher up on the planning scale. Presently, this research is conducted on the Site Plan Scale, and with its successful proof-of-concept through the demonstration, the research hopes to conduct a similar research on the Neighbourhood or District Planning Scale to benefit planners to evaluate their 2D plans.

7 Bibliography

7.1 Scenario Planning Bibliography

Drummond, William., & Herndon, Joshua., Mixed0Use Development in Theory and Practice: Learning from Atlanta's Mixed Experiences,May 2011.

Kenneth E. Corey, Mark Wilson, Urban and Regional technology Planning: Planning Practice in the Global Knowledge Economy, Routledge, 2006.

Gert de Roo and Geoff Porter, Fuzzy Planning: The role of actors in a fuzzy governance environment, Ashgate, 2007).

Bartholomew, Keith., Integrating Land Use Issues into Transportation Planning: Scenario Planning, Summary Report, Federal Highway Administration, 2005.

Doug Walker and Tom Daniels, The planners guide to CommunityViz, The essential tool for a new generation of planning, American Planning Association Planners Press, 2011

Dana Mietzner and Guido Reger, Advantages and disadvantages of scenario approaches for strategic foresight, International Journal of Technology Intelligence and Planning, Vol.1 No. 2, 2005.

7.2 **Mixed-Use Development Bibliography**

Niemira, M.P. The Concept and Drivers of Mixed-use Development: Insights from a Cross-Organizational Membership Survey. Research Review. 4(1):53-56. 2007

Schwanke, D., Phillips, P., et al. Mixed-Use Development Handbook, Second Edition. Washington, D.C., ULI – The Urban Land Institute. (2003)

Rabianski, J., and Clements, J. Mixed-Use Development: A Review of Professional Literature. The National Association of Industrial and Office Properties research Foundation.

Chua, Victor. ESRI International User Conference, San Diego, USA. 2014.

7.3 **Daylight-Availability Bibliography**

Arvo, James. 1986, Backward Ray Tracing, SIGGRAPH Volume 12.

Compagnon, Raphael. 2004, Solar and Daylight Availability in the Urban Fabric, Energy and Buildings 36, pp 321-328

Haberl, J, Kota, Sandeep. 2007, Historical Survey of Daylighting Calculations Methods and Their Use in Energy Performance Simulations, Ninth International Conference for Enhanced Building Operations.

Mardaljevic, John. 2006, Chapter 6, Daylight Simulation, pp 341-388

Ng, Edward and Chan, T.Y 2003, 21st eCAADe Education and Research in Computer Aided Architectural Design in Europe.

Reinhart, Christopher., Dogan, Timur. and Michalatos, Panagiatos. 2012, Urban Daylight Simulation. Calculating the Daylit Area of Urban Designs, Fifth National Conference of IBPSA-USA.

Robinson, Darren. Stone, A. 2005, A Simplified Radiosity Algorithm for General Urban Radiation Exchange, Building Services, Engineering Residential Technology, 26, 4 pp 271-284

Ward, G. Nov 1991, RADIANCE Manual, Lighting Systems Research Group, Lawrence Berkeley Laboratory, pp8-68

Wittkopf, Stephen and Sukardi, Jenny. 2011, Solar fractions for Urban Planning in Singapore, 49th AuSES Annual Conference

7.4 **Network Analysis Bibliography**

Gil, Jorge , Stutz, Chris and Chiaradia, Alain. 2007, Confeego: Tool Set for Spatial Configuration Studies

Hillier, Bill & Hanson, Julienne 1984 The Social Logic of Space Cambridge

Hillier, Bill et al 1987, Syntactic Analysis of Settlements, Architecture & Comportement, Vol.3, No.3, pp 217-231

Hillier, Bill et al 1993, Natural Movement, Environment and Planning B, Vol.20, pp 29-66

Wiener, J.M., Gerald, F., Rossmanith, N., Reichelt, A.,& Bulthoff, H. H. 2007, "Isovist analysis captures properties of space relevant for locomotion and experience", Perception, Vol. 36, pp. 1066-1083

Turner, A (2009) The role of angularity in route choice: an analysis of motorcycle courier GPS traces. In: Stewart Hornsby, K and Claramunt, C. and Denis, M. and Ligozat, G., (eds) Spatial Information Theory. Lecture Notes in Computer Science: Theoretical Computer Science and General Issues (5756)., Springer Verlag, Berlin/ Heidelberg, Germany, pp.489-504

Turner, Alasdair and Penn, Alan (2002). Encoding Natural Movement as an Agent Base System: An Investigation into Human Pedestrian Behavior in the Built Environment. Environment and Planning B: Planning and Design, 29. pp. 473-490

Turner, Alasdair and Doxa, Maria and O'Sullivan, David and Penn, Alan (2001) From isovists to visibility graphs: a methodology for the analysis of architectural space. Environment and Planning B: Planning and Design, 28 (1). pp. 103-121

Zimring, C. & Dalton, R. C. 2003, Linking Objective Measures of Space to Cognition and Action, Environment and Behaviour, Vol. 35, No. 1, pp. 3-16.

Turner, A (2010). Introduction to UCL Depthmap 10, Lecture Notes in Network Analysis, University College of London.

Klarqvist Bjorn, 1993. A Space Syntax Glossary, Nordisk Arkitekturforskning 1993 : 2 pp 11-12

Klarqvist Bjorn, 1991. Manual for rumslig analys av stader och byggnader, SACTHR, Stadsbyggnad, CTH, Goteborg

Peponis, John 1989, A Theme Issue on Space Syntax, Ekistics, Vol.56, No 334/335

7.5 Walkability Bibliography

Zoning for Mixed Uses, Making Great Communities Happen, PAS QuickNotes No.6, American Planing Association 2006

S. Grignaffini, S. Cappellanti, A. Cefalo, 2008 Visualizing sustainability in urban conditions", *WIT Transactions on Ecology and the Environment*, Vol. 1, pp. 253-262

Todd Littman 2004, Economic Value of Walkability, *Transportation Research Board of the National Academies*, Vol. 1828.

Bill Hillier and Chris Stutz 2005, New Methods in Space Syntax, Urban Morphology, Urban Design, Issue 93

Lopez, Russel P. and H. Patricia Hynes , 2006 Obesity, physical activity, and the urban environment: public health research needs. Environmental Health: A Global Access

7.6 Market Driven (Construction Prices and Costs) Bibliography

Langdon & Seah Singapore Pte Ltd, Construction Cost Handbook, Singapore 2014.

7.7 Generative Techniques Bibliography

Handbook of Algorithm for Physical Design Automation, Taylor and Francis Group, 2008.

8 Annex A

8.1 Generative Techniques

8.1.1 Overview of Generative Techniques

There are four main approaches in generative techniques: (1) parametric approach, (2) combinatorial approach, (3) substitution approach and the (4) agent approach.

Table 8-1 Generative Techniques

Generative techniques						
(A) parametric approach		(B) combinatorial approach		(C) substitution approach		(D) agent approach
variational based parametric technique	history based parametric technique	template based combinatorial technique	algebra based combinatorial technique	shape based substitution technique	grid based substitution technique	

• In parametric approach, forms are generated through varying a number of parameters. However, in history based parametric technique, varying the parameters in a sequential procedure generates a different form output than the variational based parametric technique. However, the latter generates a form without making reference to the sequence of modeling operations.

• In combinatorial approach, forms are generated through the combination of predefined elements. In the template based combinatorial technique, a template is defined to organize which elements can be inserted while in the algebra based combinatorial technique, a collection of element types are defined together with a collection of operators to modify these elements.

• In the substitution approach, initial seeds forms are iteratively substituted, partly or in whole, with new parts through the use of rules. In shape based substitution technique, geometry of the individual shape are iteratively substituted producing complex geometrical output, Examples include L-systems, fractals, shape grammars. On the other hand, grid based substitution technique, a grid is defined and substitutions are performed in this grid, and an example is the cellular automata.

• In agent approach, autonomous agents are encoded with stochastic actions, interactions and behavior with a view to assess their effects on the system as a whole.

8.2 Consideration of Generative Techniques used in this Research

8.2.1 Introduction

There are a wide range of established generative techniques that can generate 3D models that offer different spectrum of variability. However, the consideration of any generative technique must be based in satisfying the modeling needs of this research.

In summary, the 3D modeling needs of the research need to be accommodate these criteria:

- (1) offer controlled variability
- (2) ensure that numerous constraints are strictly adhered to
- (3) generate three building structural systems (modular grids) representing the three different functions (production, commercial and residential functions).

(1) generative technique that accommodates controlled variability
The different generative techniques offer different spectrum of variability. In particular, the shape based substitution techniques (substitution approach) tend to result in models that have a wide variability. This is undesirable as the technique may generate 3D models that are too chaotic, or models that are difficult to be evaluated, or models that may not be representative of reality. Parametric modelling approaches allow some degree of variability while not be too chaotic unlike the rule based approaches.

(2) ensure that numerous constraints are strictly adhered to
For the model to be useful to the developers, the generative techniques need to be able to ensure that multiple constraints that represents development, building and fire safety regulations must be strictly adhered to. Constraints such as building setbacks, structural construction schemes, permissible building height, fire escape distance, etc, cannot be violated to ensure that the computational models are an accurate representation of developments that can be realized. Parametric modelling approaches, unlike rule-based approaches allow constraints to be satisfied easily.

(3) generate three building structural systems (modular grids) representing the three different functions (production, commercial and residential functions).

The three structural grid systems represent the structural requirements for the three different functions in the development, ie, the production, commercial and residential functions. The parametric modelling technique allows a control over standardized and modular coordination of structural systems.

Thus, in satisfying the modeling needs of this research, the parametric modelling technique is used.

8.2.2 Advantages of Parametric Modelling over other Rule-Based Approaches

(1) Ease of use by non programming planners

Parametric modelling as opposed to rule-based modelling allow a faster and easier way to generate computer programs (define form generating procedures) as a majority of practicing developers tend to be non-programmers.

- A large number of parametric modelling programs are written in visual languages. This is in contrast to rule-based modelling, where a large number of the programs require textual languages. Thus non programming planners only have to manipulate graphical elements rather than by entering text.

    ◦ **Eliminate syntax error**
    Defining form generating procedures by using graphical elements eliminate syntax errors commonly experienced on textual languages programs.

    ◦ **Eliminate the need to use complex rules**
    In rule based approaches, developers must learn complex rules to generate complex 3D models. In contrast, parametric modelling allows quicker feedback and a more intuitive 'cause and effect' while working on the 3D model, through visual graphical elements that defines the form generation procedure.

    ◦ **Ease of setting up an iterative design process**
    With the ease of creating computer programs, non programming developers can quickly set up an iterative design process, thereby allowing larger numbers of design possibilities to be explored. This is difficult in rule based approaches as this requires more programming skills

(2) Ease of encoding constraints

Parametric modelling allows a much easier approach to encode constraints. There are two types of constraints (1) geometrical constraints and (2) dimensional constraints which can be encoded into parametric modelling:

- **Geometrical constraints**
Geometric constraints control the relationship of objects with respect to each other. In this type of constraint, changes made to objects can adjust other objects automatically, allowing the user to experiment and explore different designs when making changes. Changes in the geometrical constraints, changes *only one or some* of the objects on the design.

    ◦ **Quick application of geometric constraints to objects**
    In parametric modelling, it is relatively easy to apply geometric constraints between objects. This allows changes to the object to effect adjustments on other objects. However, in rule based approaches, this may be quite a difficult task.

    ◦ **Allow multiple geometric constraints to objects gradually through the project**
    In parametric modelling, users can begin working in an unconstrained state and define multiple geometric constraints to objects to reach either an under-constrained

or fully-constrained state. This is quite different in rule based approaches where constraints have to be defined during the initial stages of creating the design rules.

◦ **More expressive to allow computational definition in the form of formulas and equations**
In parametric modelling, geometrical constraints can be expressed as a set of formula or equations. This is fairly difficult to achieve in rule based approaches.

• Dimensional constraints
Dimensional constraints control the proportions and values of a design, such as the distance, length, angle, radius values of objects. Changes in the dimensional constraints, changes *all* of the geometrical constraints on the design.

◦ **Guarantees that multiple development or building regulations encoded as dimensional constraints are strictly adhered to**
A useful aspect of this dimensional constraint is that users can encode multiple dimensional constraints of development and buildings regulations by local authorities such as the building setbacks, structural construction schemes, permissible building height, etc easily. In contrast, it would be very difficult to encode multiple dimensional constraints to rule based approaches as the final outcome generated from rule based approaches may violate these dimensional constraints. Parametric modelling, however, guarantees that these dimensional constraints are never a broken in the first place, generating outcomes that are rule-compliant.

◦ **More expressive to allow computational definition in the form of formulas and equations**
Parametric modelling allows dimensional constraints to be expressed in the form as a set of formula or equations. Again, this is difficult to achieve in rule based approaches.

(3) Controlled variability

The generation of variants in terms of design variability should not be overly restricted nor should it be unrestricted and too constrained. This is known as the variability problem. This variability problem requires striking a balance between an approach to generate variants that are neither too restrictive nor unrestrictive.

• Unrestricted variability
When the design variability is highly unrestricted, the output may be too unpredictable/ chaotic and risks not being a sensible/ acceptable variant. In addition, it may become problematic for the evaluation process or it may not be meaningfully compared to one another.

◦ Numerous rule based approaches (such as shape grammar) have unrestricted variability that describes designs that are too chaotic. These chaotic designs are far too difficult and complex to be evaluated during the evaluation stages.

• Too restricted variability
When the design variability is overly restricted, the output may risk excluding the best possible designs.

Thus, for this investigation, using a grid-based method within parametric modelling allows a certain level of controlled variability that is not unrestricted or overly restricted, or controlled variability.

(4) High level semantics concept requirement for evaluation

The design variants generated from the generative steps would be required to be evaluated by evaluation and simulation tools. The evaluation tools used in the evaluation stage uses high-level semantic concepts to describe an urban design, such as building façades, roofs, streets, courtyards, podiums, towers, windows, walls, rooms, etc. Hence it is critical that the generative process generate 3D models that are of the same level for the ease of interpretation of the evaluation results. The generated models must be specified as complex representations at the high-level semantic concepts.

- **Numerous rule based approaches uses low-level geometric primitives**
  Many rule based approaches (such as shape grammar) describes designs using low-level geometric primitives. Thus, this forms a mismatch in evaluation requirements and attempting to infer high-level semantic constructs from low-level geometric primitives is far too complex.

- **Parametric modelling matches the requirement of using high level semantic conceptual requirements for evaluation tasks**
  Parametric models, allow the generation of 3D models that can be specified as complex representations at the high-level semantic concept to describe an urban design. Thus, there is a match in the evaluation requirements and evaluating parametric models can be a fairly straightforward process.

Therefore, parametric modelling offers that matching high level semantics conceptual requirement for the evaluation tasks.

8.2.3 Disadvantages of Parametric Modelling over other Rule-Based Approaches

The disadvantages_of parametric modelling over other rule-based approaches are:

(1) Difficulty in iteration procedure (recursive and looping)
However, parametric modelling has certain weaknesses that limit their usability. This primarily involves parametric modelling being weak in executing iterations (recursive and looping) commands to build complex models. Rule based approaches allows the iteration process to be executed in an easier manner:

> **• No explicit iteration node or limitations to list-based iterations**
> Many parametric parametric modelling tools do not have an explicit iteration node (for recursive or looping commands) or only have a limited list-based iteration command. The user has to 'workaround' by constructing nodes over lists and tree data structures. This can be too complex, even for a simple recursive loop and often causing a difficulty in understanding the network, especially for debugging purposes.
>
> **• Node-based iteration found only on a few parametric modelling tools**
> The more powerful node based iteration is presently available on a limited number of parametric modelling tool. Hence users are required to learn these tools should they require to define their parametric models in a complex iteration. Node based iterations are more powerful in the aspect of being able to be understood quickly by the user, allow more expressions to define more complex models, and allow both forward and reverse-order modelling methods. (Janssen, Patrick and Kian Wee, Chen, CAAD Futures, 2011).

• **Many rule based approach allow iterations (recursive looping) easily**
In contrast to parametric modelling, the rule based approach does very well when it comes to recursive looping. For example, the Chinese ice-ray lattice design (Stiny 1977), demonstrates how by using five rules to a problem, the rules are repeated again and again in a similar way until certain conditions are met to recursively generate the Chinese ice-ray lattice pattern design.

8.3 **Evaluation Techniques**

8.3.1 Urban Heat Island (UHI) Analysis Technique

The evaluation tool used for the evaluation of urban heat island (UHI), is the STEVE tool. In the STEVE tool, the method used for the evaluation of the 3D model is through the placement of 25 sensors point spaced at 5 metres away from each other. The sensor points are placed 1.6metres above the ground level,and they give five different readings: Tmax, Tmin, Tavg, Tavg-day and Tavg-night. These five readings are taken at all of the 25 sensor points and are given an average to summarise the performance of the development. The sensor points are also placed on the roads as well as the plot sites to detect any thermal difference between the developments.

Fig. 8-1 25 Sensor Points for each Plot ratio development