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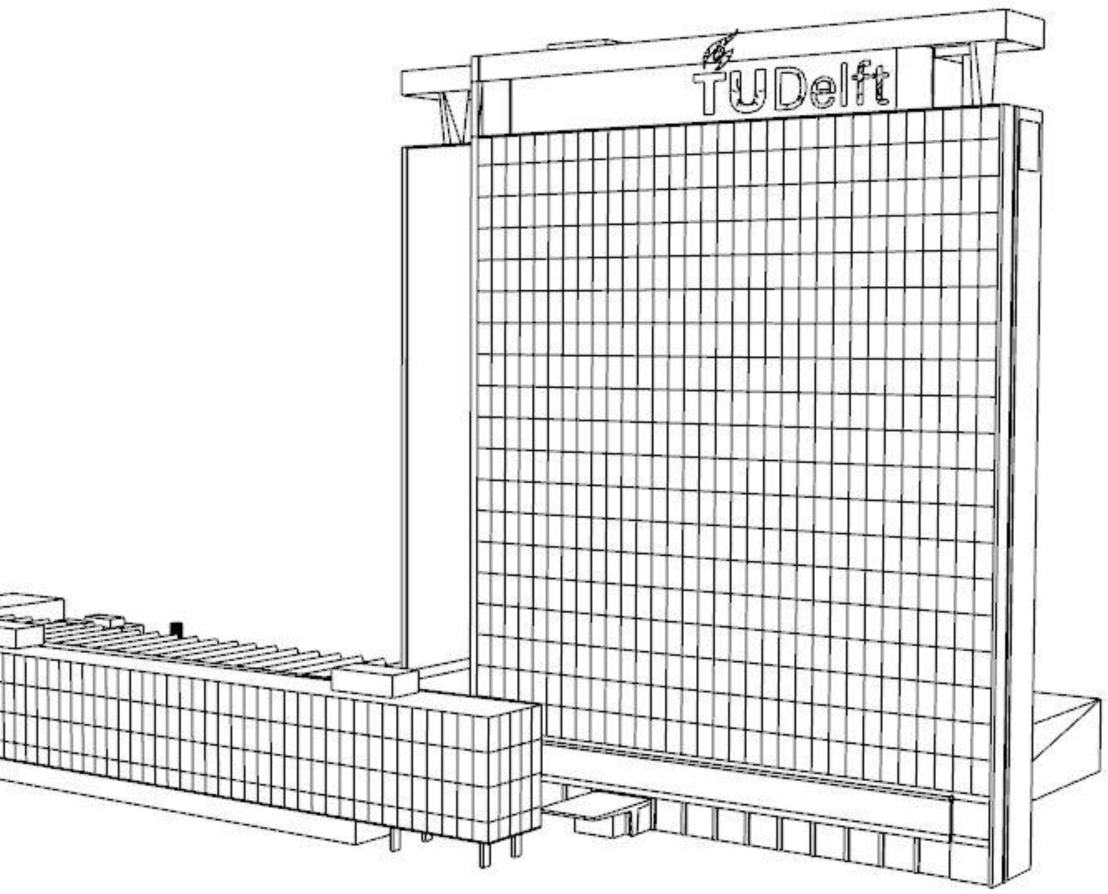

Cochleas: A methodology to convert an existing layout into a residential one

By

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Abstract

Usually in a renovation design process one of the first main tasks of the architect is to distribute effectively the program of requirements (spaces with their corresponding areas) in the building. To do so the architect inserts in the existing floorplan the spaces in the form of circles; the so called “bubble diagram”. The purpose of this project is to propose a methodology to wave proximity relationships with illuminance requirements.

The designer inserts existing geometry of the building in the software. An illuminance analysis of the room is performed so as to determine the ideal light locations for each room according to regulations. The user inserts the desired proximity and illuminance requirements of the rooms in the form of points and lines and prioritizes them. Given these inputs the goal is to place the rooms in positions that the objective function (potential energy) is minimized. The tool finds the optimal position of the rooms regarding proximity and illuminance requirements in the given boundaries without overlapping themselves by simulating it as a spring network and produces the bubble diagram. The diagram produced serves as the starting point for the designer to further develop the layout into a proper floorplan manually.

Keywords: layout, configuration, optimization, generative design, spring network, proximity, illuminance

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1 Introduction

1.1 Background & necessity

Residential design has always been one of the most favorite and popular design tasks for architects. And this is, in my opinion, because of the great importance of having a suitable home. Throughout the years residential design has been evolved in different ways all over the world. And it is or should be still evolving in respect to current situation and users' needs. But there was not always feasible to build a house from scratch. The idea of reusing an existing building is not new; on the contrary it has been introduced in multiple cases since ancient times [1]. Nowadays reuse still remains an important topic not only because of lack of free space, but also from an economical and sustainable point of view [2]. More and more architects explore ways of renovating the interior or even the exterior when repurposing a building [3]. While renovation of the exterior results in more specific solutions regarding mainly structural methods' applications, renovation of the interior belongs essentially to the architectural field. The present graduation research attempts to explore a systematic way of repurposing the interior of an existing building to a residence using computational tools.

1.2 Motivation

From an architectural point of view any renovation design is very interesting because of the extra challenge of the existing form of the building. From a societal point of view renovation projects entail also sustainability purposes. In European Union there are many countries that are facing a considerable housing problem such as the Netherlands [4]. In the Netherlands many expats are arriving every year, and there is not enough housing stock to accommodate everyone [5]. On the contrary, there is a significant amount of buildings that are currently not in use and were originally designed for non-residential purposes [6]. The goal of this graduation thesis is to contribute to the repurpose of this kind of buildings so as to restrict the magnitude of the housing problem.

1.3 Conventional methods

From relative research and personal experience it has been noticed that most renovation methods apply to very specific scenarios [7][8][9]. Each renovation project has a unique design solution that cannot be easily applied to other buildings. This happens probably because conventional approaches of renovation projects produce a limited amount of different results, mostly due to time restrictions the architect has to face. In this context computer science can be the keystone to base a kind of automated approach.

1.4 Knowledge gap

A field that belongs to computer science and is explored in the recent years in architecture and civil engineering is generative design[10]. An intuitive definition of generative design is described as an iterative design process where generation of form is based on algorithms [11][12]. Generative design applications in architecture are still emerging and that makes it difficult to find sufficient comprehensive academic literature [13]. Having that in mind any academic contribution to the topic is useful especially for future researches. This research aspires to contribute to this knowledge gap by proposing a systematic approach regarding layout design in renovation projects. In this way the housing problem not only in the Netherlands but also worldwide could be approached with the proposed general procedure.

1.5 Research objective

The broader objective of the present research is to contribute to the systematization of the renovation design process. A promising field for systematic approach seems to be generative design [14]. Given specific restrictions and guidelines it is possible to generate layouts according to the designer's wishes. The proposed approach is a systematic approach in which it is investigated until what point it is possible to automate a part of the design process (semi-automation for the moment) in primary design stage according to the user's wishes (manual input) in respect to rooms' connectivity (proximity of rooms) and illuminance requirements using computational methods. A more detailed description of the methodology proposed is presented in the Proposed methodology chapter.

Subgoals

1. To develop a method for finding an optimal position of the rooms in the layout in respect to their connectivity in primary stage of renovation design process.
2. To develop a method for finding an optimal position of the rooms in the layout in respect to illuminance requirements in primary stage of renovation design process.
3. To create a methodology that applies these two methods using computational tools.

1.6 Research question

The main research question of the graduation project can be formulated as: "To what extent is it possible to convert an existing layout into a residential one regarding proximity relationships and illuminance requirements using computational tools during primary design stages?".

Subquestions:

1. What method can be used to find the optimal position of the rooms in respect to their proximity relationships in primary stage of a renovation design process?
2. What method can be used to find the optimal position of the rooms with respect to their illuminance requirements in primary stage of a renovation design process?
3. How to combine daylight and proximity preferences in one layout design configuration?

4. Are existing plugins for Grasshopper useful for the thesis' purposes?

Design assignment

The main delivery assignment is the methodology for applying computational methods to convert an existing layout into a residential one regarding proximity and illuminance requirements during primary design stages. A basic case study will be used to demonstrate the process in a simpler form. To evaluate the methodology two more complex applications will be used to test the effectiveness of the tool. The tool is not expected to be fully automated but to serve as a guide that gives more freedom to the designer to customize the renovation design process according to his/her preferences. The tool development is explained in detail in the present report and the script of the tool will be added in the appendix so as to ensure transparency and reproducibility of the process.

1.7 Scope

As it can be seen in the Venn diagram depicted in figure 1 the main focus areas of the research are architecture (design criteria) and computational design (generative design). Climate design and physics are essential for simulating real world situation that are used in the tool, such as daylight and physics analysis.

Research scope includes:

- layout
- proximity
- illuminance
- optimization
- algorithmic design

Research scope does not include:

- facade
- structure
- ventilation / HVAC system
- odor/ thermal / light comfort
- furniture arrangement
- real estate
- fire safety
- local climate conditions
- thermal requirements
- other daylight requirements
- window to wall ratio
- BIM
- urban context
- furniture arrangement

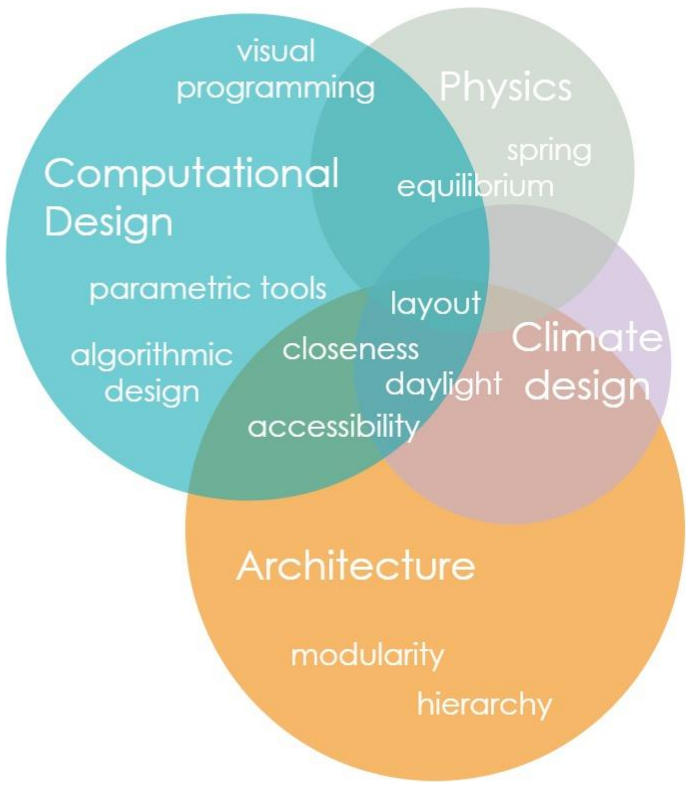


Figure 1: Research scope

1.8 Problem statement

Renovation of buildings is a topic that concerns many architects all over the world. Generative design seems a promising field to apply computational methods in the primary design renovation process. To do so the design task has to be translated in mathematical terms. The formulation of the part of the design process in a mathematical way constitutes the part that will be attempted to be automated. The approach constitutes basically the development of an algorithm whose parts are a combination of manual and automated subtasks. In some cases the manual work is legitimate as for example the inputs (building, program of requirements, desired proximity between rooms) and in others it is a limitation due to computational power or lack of advanced programming skills.

Usually in a renovation design process one of the first main tasks of the architect is to distribute effectively the program of requirements (spaces with their corresponding areas) in the building. To do so the architect inserts in the existing floorplan the spaces in the form of circles; the so called “bubble diagram”. A bubble diagram is a simple diagram of rooms shaped like circles whose purpose is to understand the relationship between rooms. The purpose of the tool is to wave the room relationships with the lux requirements. Apart from the question “what is the optimal room arrangement based on my desired relationships?” the tool assists the architect answer also the question “what is the optimal room arrangement based on the relationships and the illuminance requirements?”.

For this reason, a graph is used to express mathematically the problem. The vertices of the graph indicate the rooms’ positions, whereas the edges their connectivity. In the following figure:

- vertices as room centroids and edges as their proximity connections (in red).
- vertices as ideal illuminance position and edges as the connections with the room centroids (in green)
- vertices’ final position where both requirements are fulfilled as much as possible (in blue).

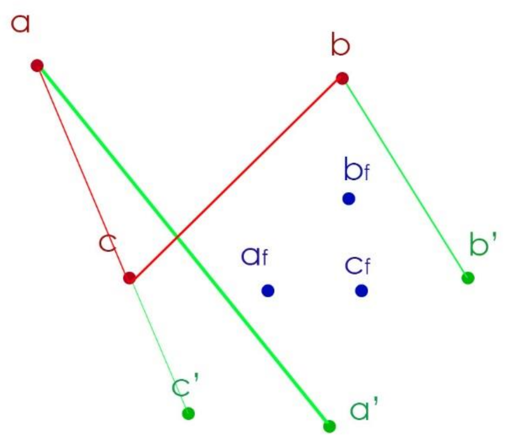


Figure 2: graph representing the problem in a simple form where a, b, c the initial room positions, a', b', c' the ideal illuminance positions and a_f , b_f , c_f the final room positions

The edges of the graph are weighted with a factor (0/0.5/1) so as to prioritize their importance, as it can be seen in the following tables:

	a	b	c
a	0	0	0.5
b	0	0	1
c	0.5	1	0

Figure 3: adjacency matrix for proximity connections

	a'	b'	c'
a	1	0	0
b	0	1	0
c	0	0	1

Figure 4: adjacency matrix for illuminance connections

The graph is simulated as a spring network, where the weight of the edges is expressed by stiffness.
The objective function is the minimization of elastic potential energy
$U = \frac{1}{2}k\, x^2$
where k stiffness is the constant
x position is the unknown/variable
constraints $x \geq 0$ and $k \geq 0.$
(The approach is presented more clearly in the following chapter.)

The major steps of the methodology are illustrated in the following figure. The designer inserts existing geometry of the building in the software (step 1). An illuminance analysis of the room is performed so as to determine the ideal light locations for each room according to regulations (step 2). The designer inserts the desired proximity and illuminance requirements of the rooms in the form of points and lines (step 3). Given these inputs it is desired to find a position for the rooms such that the objective functions is minimized. The tool finds the optimal position of the rooms regarding proximity and illuminance requirements in the given boundaries without overlapping themselves by simulating it as a spring system in the form of a bubble diagram (step 4). The configuration produced serves as the starting point for the designer to further develop the layout into a proper floorplan manually (step 5).

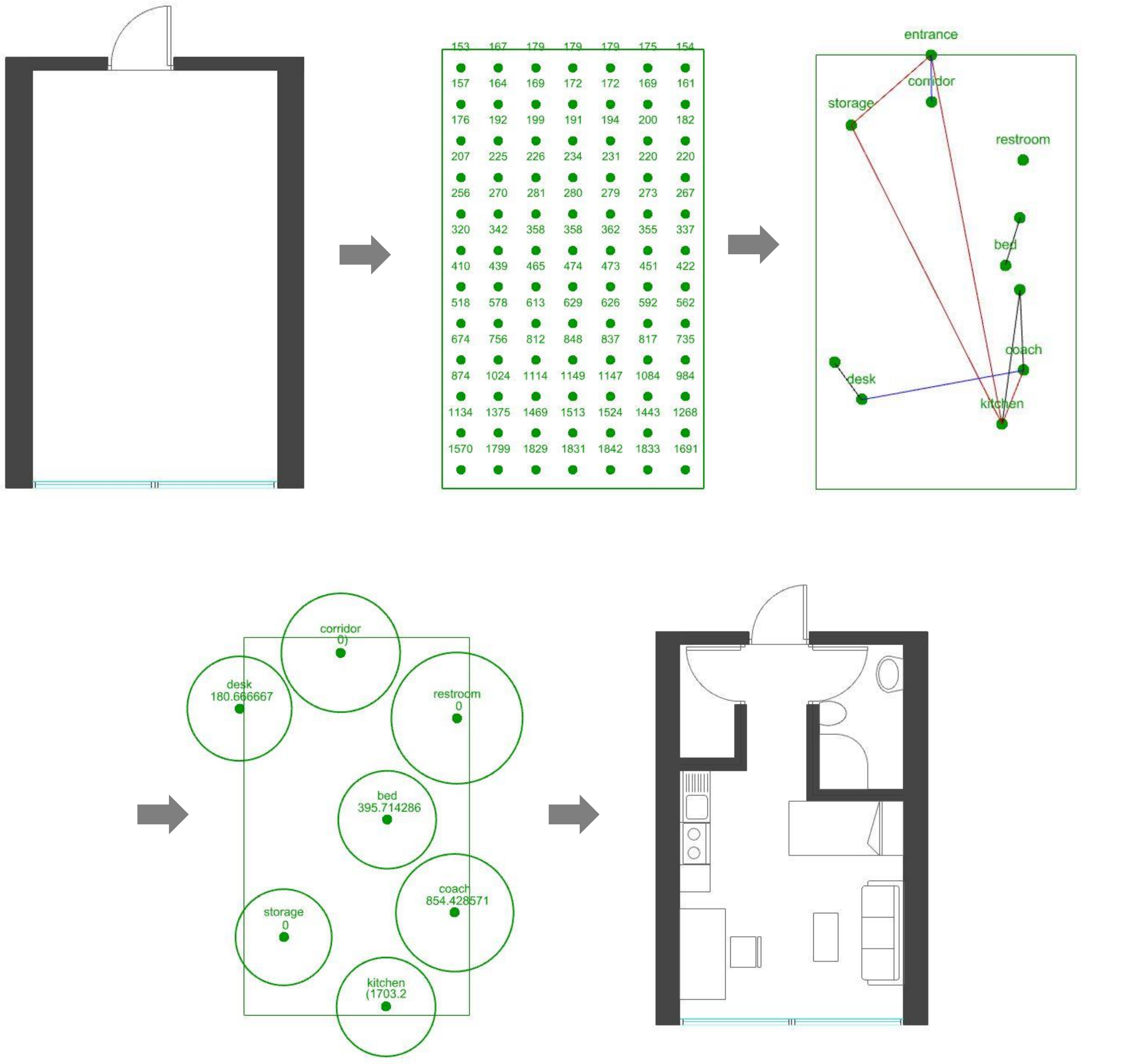


Figure 5: Problem statement Step 1: empty existing building, Step 2: calculate illuminance values of test points on grid Step 3: set room' centroids and their proximity requirements as line segments, Step 4: final configuration of rooms based on proximity and illuminance requirements set are shown as bubble diagram, Step 5: final layout based on the bubble diagram

1.9 Advantages

Some of the advantages of formulating the design problem as a mathematical problem are:

- Innovation

Contribution into filling the knowledge gap that exists in the computational literature.

- Complexity

A large complex building can be divided into smaller parts. Iterations of processes can be relatively easy to handle by computers once they are set in the correct procedure.

- Data structure

A lot of data can be stored in a mathematical way so that they can be accessed more easily (matrices).

- Time-saving

Once the workflow is set it will be much quicker to find the optimized layout for different specifications.

- Money-saving

As a result of time saving. [15]

1.10 Challenges

Challenges of formulating the design problem as a mathematical problem:

- Advanced mathematics

A Building Technology student does not have the necessary background knowledge to use advanced mathematics.

- Data oversimplification

Data simplification should not be too abstract to be realistic.

- Technicalities

The programming background level to tackle the topic fully computationally does not correspond to that of a Building Technology MSc student.

- Bugs

Debugging can be time-consuming and requires advanced programming skills.

1.11 Assumptions

This tool is intended to be used by architects, interior designers and students during the early design phases so as to have a quick intuition of how the arrangement of the rooms affects the user's movements (proximity) and visual comfort (illuminance). It is assumed that the user already knows the basic commands of Rhinoceros and Grasshopper software.

In order for the design assignment to be translated in a mathematical problem it is inevitable to simplify reality. This refers to simulations run by software that simulate approximately natural phenomena such as spring transformation, body collision, daylight, etc. Since the design is a renovation assignment there are some elements that are assumed to remain fixed and untouched. These elements are the building's core, rest bearing elements (structural walls, columns), HVAC system, etc. The whole façade is assumed to be from standard materials and any improvement falls out of the scope. Even windows are considered to have standard material properties that are used in daylight simulation but any improvement falls also out of the scope.

1.12 Limitations

In case the bubble diagram produced by the tool is not satisfactory the process has to be repeated from the beginning. Moreover, the tool considers a limited amount of design criteria (proximity and illuminance only), but the design criteria an architect takes into consideration are much more (e.g. privacy, safety, view, circulation, supervision). Also the tool ignores the existence of obstacles in the interior of the building (such as columns and walls). These have to be manually excluded from the area of interest or the user has to take it into account during the manual design development phase. Additionally, the tool is designed for 2D drawings only. The illuminance values in reality would be much more different since the illuminance analysis at first is made with open floor plan, which is usually not the case in the final floorplan.

1.13 Scientific and societal relevance

As far as society concerns, renovation was and still is an import design assignment, especially in countries where its available to build area is limited. Converting existing buildings into residences is a way to tackle the housing problem many people (locals and expats) from all over the world face. In a professional point of view, finding a way to systemize the renovation design process could have a great impact on the way architects would approach a renovation project since the very beginning. As soon as they have an initial design idea by following the suggested methodology it would be possible to insert the necessary data and produce the schematic residential layout based on the two –most important according to the author- design criteria: proximity and daylight. One of the main advantages of computational applications is that they can handle a respectable amount of data simultaneously. This means that many levels of complexity can be added to the tool and in that way help the architect find the optimum layout. This could speed up the design process and also produce non-conventional but still functional layouts.

The current graduation project is directly related to MSc Architecture, Urbanism and Building Sciences and the Building Technology track. Firstly, the computational methods proposed are intended to be applied in existing buildings, in real life scenarios, which is what architecture and building sciences is about. The case study selected empower the practicality and the usefulness of the tool and is itself a property of TU Delft (Faculty of electrical engineering, mathematics and computer science) . The intention to contribute in the systemization of the renovation design process is an architectural intention interwoven with sustainability, that is one of the main aspects of Building Technology track. Building Technology is also the field where architects are more oriented towards engineering. Mathematics and physics are some of the fundamental subjects of an engineer. Engineering is also about improving existing methods as well as inventing new ones. In this dissertation the innovation lies in developing a methodology on how to systemize a renovation design project using principles of computer science, mathematics and physics.

1.14 Research methodology

The first step in the graduation research is to formulate the research framework. In order to define the research objective a research of the relative background and the conventional methods of renovation design processes was conducted to spot the knowledge gap. After having set the research objective the research question and subquestions has to be defined in a more clear way.

The second step is to obtain the necessary theoretical background. This includes reading relative literature regarding generative design in layout applications, exploring existing commonly used parametric tools and finding a representative case study to apply the proposed methodology.

During the third step the specifications and assumptions are set so as to start the tool development. In the beginning the main skeleton of the tool is defined by relative research and it is fully developed when applied in the case study. By following the proposed methodology it is possible to produce and evaluate the outputs. If the result is not satisfactory the process has to be repeated but this time the chosen parameter should be shifted slightly to observe its impact. By repeating and improving the tool starts to take its final form.

In more detail, the tool is developed in five stages: the first stage starts with all necessary input set by the user, then an illuminance analysis is performed in order to obtain the lux values, afterwards the optimal configuration is found by performing dynamic relaxation. The configuration is later evaluated based on proximity and illuminance requirements set at the beginning. The output of the tool is a schematic layout (bubble diagram) indicating the ideal position of the rooms as well as their corresponding lux values.

The evaluation step is a test to check how the tool performs in larger and more complex cases. The last step includes the discussion upon the results, the conclusions drawn from the discussions and recommendations for improvement of the tool and further research.

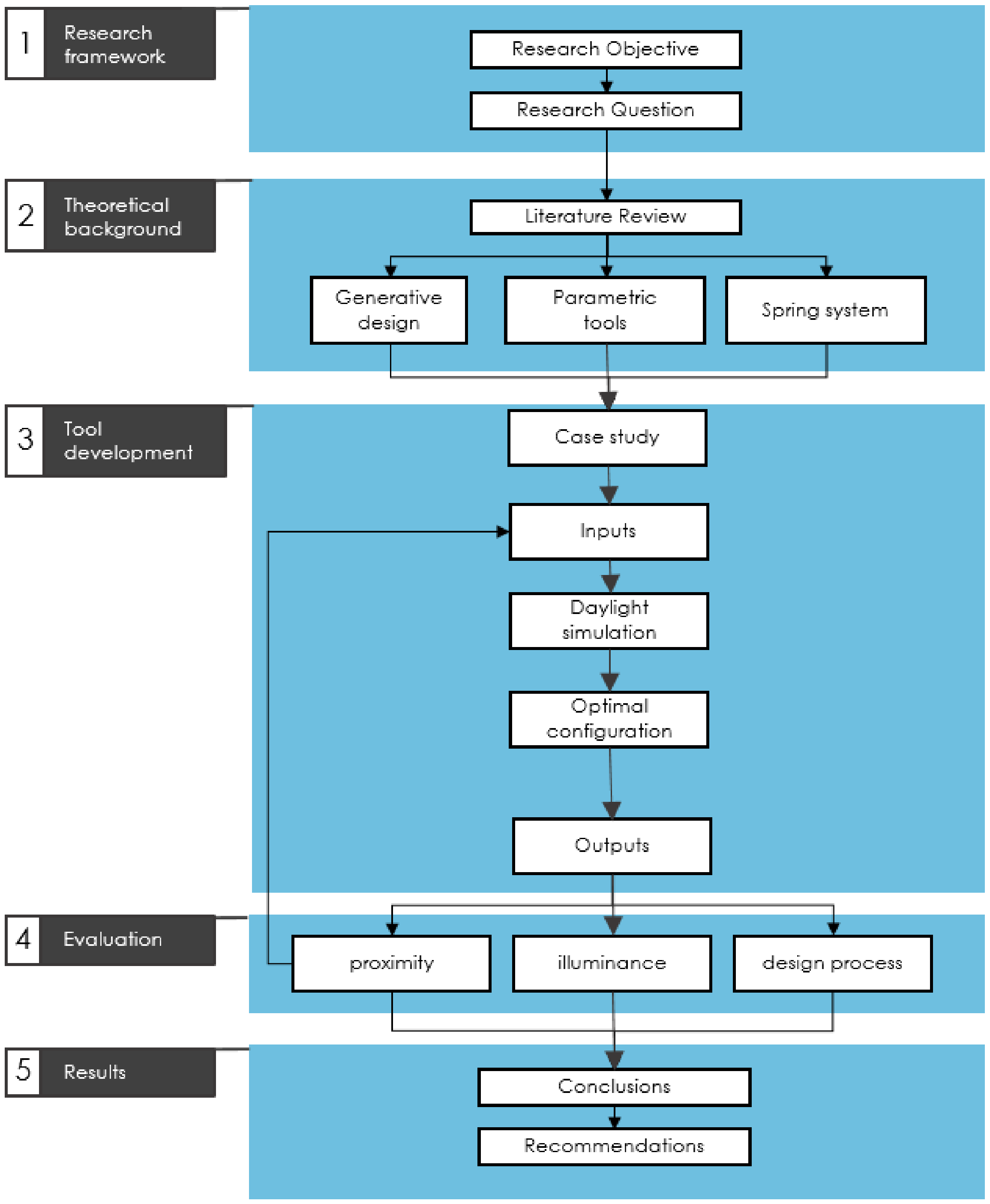


Figure 6: Research methodology workflow

1.15 Related tools

The following software applications are related to the scope of this research in that they provide various methods of modeling and processing data.
The main software to be used:

- Rhinoceros by Robert McNeel & Associates (CAD) [16] and
- Grasshopper by David Rutten, Robert McNeel & Associates (visual programming) [17]

The plug-ins for Grasshopper required are:

- KangarooPhysics & Kangaroo2 by Daniel Piker (physics simulation) [18]
- Honeybee & Ladybug by Mostapha Sadeghipour Roudsari (daylight simulation) [19]
- GH Python by Guilio Piacentino (IronPython included in GH) [20]
- GH CPython by Mahmoud Abdel Rahman (python scripting) [21].

1.16 Outline

The report begins with the introduction where a brief overview of the graduation research is presented. The next chapter Background knowledge aims at clarifying some of the methods and techniques used while developing the tool. The tool development is described in detail in chapter 3 Proposed methodology. As an example for demonstration purposes a representative case study (studio) is used, namely Case study I (EEMC). For evaluation purposes two more applications in the same building will be examined (shared apartment and common facilities). The results of the evaluation of the proposed methodology are presented in chapter 4 Evaluation. Afterwards, the main results of the research are discussed and the basic conclusions are drawn. The last chapter of the report contains the personal reflection of the author upon the graduation thesis based on the requirements set by the faculty. In short, the outline of the report look like this:

- Chapter 1: Introduction
- Chapter 2: Background knowledge
- Chapter 3: Proposed methodology
- Chapter 4: Evaluation
- Chapter 5: Conclusions
- Reflection

2

2 Background knowledge

2.1 Generative design

An intuitive definition of generative design can be described as "an iterative design process where generation of form is based on algorithms" [11][12]. The generative design process is defined by applying constraints, parameters and goals to a project and then exploring all possible design options through a series of iterations. A generative design software (such as Grasshopper) then applies computational algorithms, which generate the design according to the parameters set. Afterwards designers can select the outcome that best meets their needs [22]. The following figure shows the workflow of designing a product by using generative design process [23].

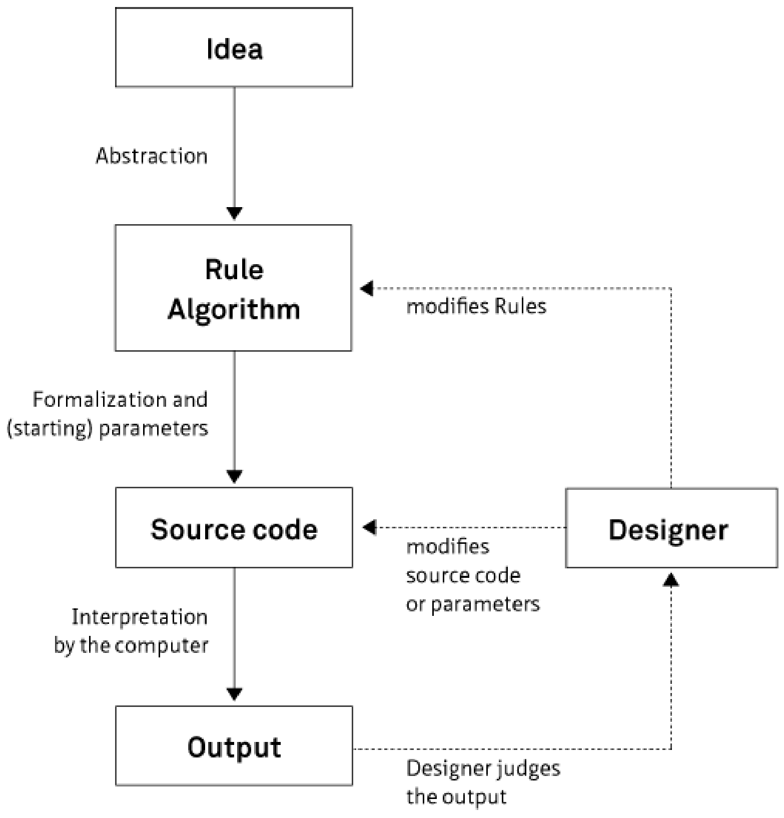

Idea
Abstraction
Rule Algorithm
modifies Rules
Formalization and (starting) parameters
Source code
Designer
modifies source code or parameters
Interpretation by the computer
Output
Designer judges the output

Figure 7: generative design flowchart by H. Bohnacker [23]

2.2 Gradient descent

"Gradient-based methods are iterative methods that extensively use the gradient information of the objective function during iterations." For the minimization of a function $f_{(x)}$, the method can be described as:

$$\mathbf{x}^{(n+1)} = \mathbf{x}^{(n)} + \alpha g(\nabla f, \mathbf{x}^{(n)}),$$

where *a* is the step size that can take different values,
g(∇f,x(n)) is a function of the gradient ∇*f* and the current location x(n).[24]

By using an algorithmic gradient based approach to automate a generative design process, the design outcome always goes towards the optimum solution.
"Gradient descent is the most common optimization algorithm in machine learning and deep learning. (Optimization refers to the task of minimizing/maximizing an objective function f(x) parameterized by x). In machine/deep learning terminology, it is the task of minimizing the cost/loss function J(w) parameterized by the model's parameters w ∈ R^d.) Gradient descent is a first-order optimization algorithm. This means it only takes into account the first derivative when performing the updates on the parameters. The gradient gives the direction of the steepest ascent. On each iteration, the parameters are updated in the opposite direction of the gradient of the objective function J(w). The size of the step we take on each iteration to reach the local minimum is determined by the learning rate a. Therefore, it is followed the direction of the slope downhill until a local minimum is reached."[25]

A pseudocode for a gradient descent algorithm look like this:
Let's say we want function J(x_1, x_2) to be minimized:

```
1. Start with some values for $x_1$, $x_2$ (eg $x_1$=0, $x_2$=0)
2. Keep changing $x_1$, $x_2$ to reduce J($x_1$, $x_2$)
3. Repeat until convergence:
   $x'_j$ = $x'_j$ - a ∂/∂xj J($x_1$, $x_2$)
where:
a the learning rate
∂/∂xj J($x_1$, $x_2$) the derivative
4. Until $x_j$ = $x_j$
```

Figure 7 shows the relationship of the cost and weight function regarding the derivative of function J, whereas the next one shows the result which is a local minimum [26].

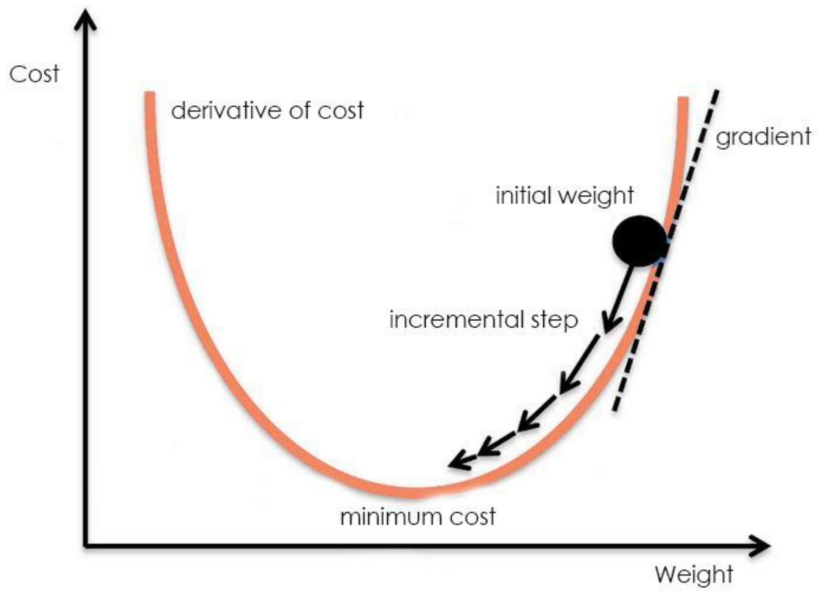


Figure 8: the graph of gradient descent algorithm in respect to cost and weight [26]

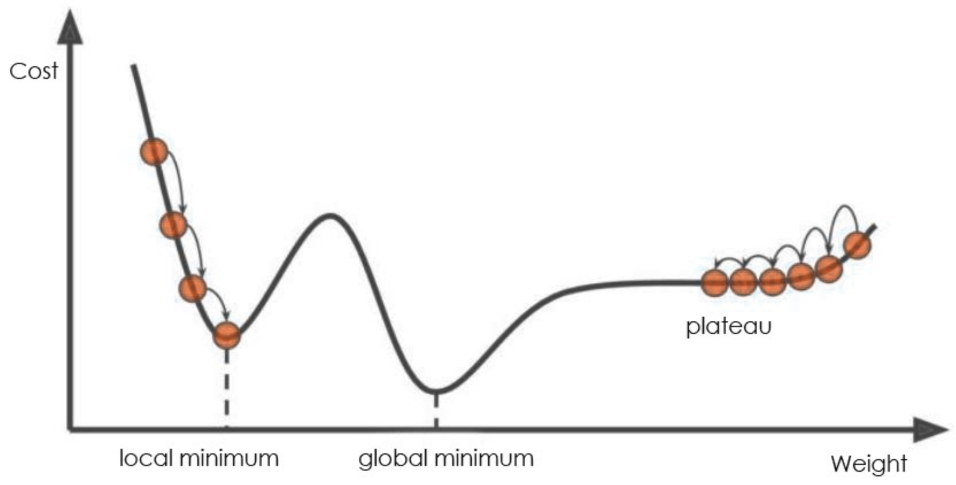


Figure 9: the three possible results of gradient descent: local minimum, global minimum and plateau [26]

So, in this project it is aimed to find a local minimum and the learning rate used (α) is small (0.1).

2.3 Newton's laws

The following equations of Newton are used in the proposed algorithm, so this section serves as a reminder.

First law: Inertia

$$\sum F = 0$$

Second law: Acceleration

$$F = m\,a$$

Third law: Action-Reaction

$$F_A = -F_B$$

Fourth law: Superposition

$$F_{(x_1+x_2)} = F_{x_1} + F_{x_2}$$

F: force
m: mass
k: spring constant
a: acceleration
x: displacement
[27]

2.4 Hooke's law

The algorithm proposed uses also Hooke's law, which states that " for relatively small deformations of an object, the displacement or size of the deformation is directly proportional to the deforming force. Under these conditions the object returns to its original shape and size upon removal of the force." [28]

$$F = k\ x$$

where F : force
k: stiffness
x: elongation

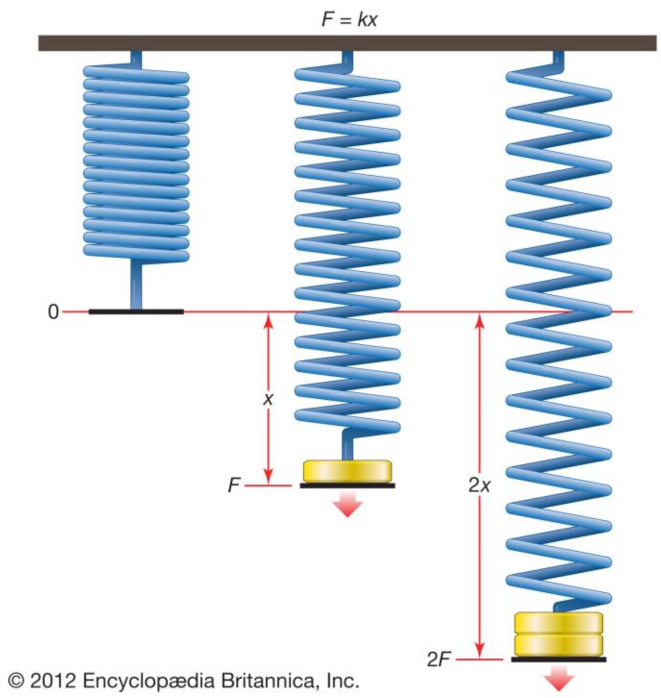


Figure 10: Schematic explanation of Hooke's law[28]

2.5 Elastic energy

The objective of the optimization is to minimize the elastic potential energy. It is reminded here that "elastic energy is energy stored as a result of applying a force to deform an elastic object. The energy is stored until the force is removed and the object springs back to its original shape, doing work in the process." [29]

$$U = \frac{1}{2} k\, d^2$$

$$U = \int_0^{L-L_0} k\, x\, dx = \frac{1}{2} k\, (L - L_0)^2$$

where U: elastic potential energy
L: final length
L_0: initial length
$\Delta x, dx, x$: elongation
k: stiffness

In the following diagram it can be noted that the area of the triangle formed by the blue line and x axis is the actually the work. [29]

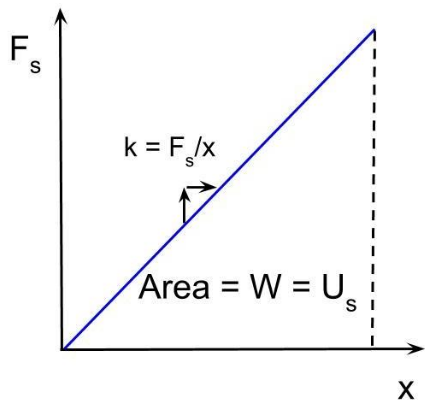
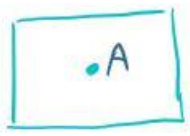


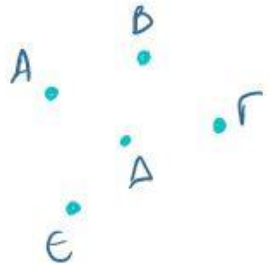
Figure 11: Force towards displacement diagram [29]

2.6 Spring network

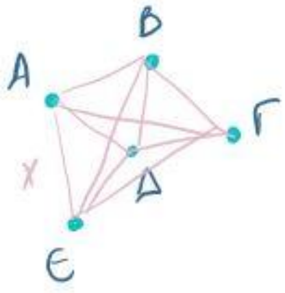
A graph with vertices and edges can be simulated as a spring network, a physical system drawn where the edges represent springs of given stiffness and length. In the case of this research the vertices can represent the centroids of the rooms (as points) and the springs the connections between them (as line segments). Assuming linear springs, where no energy is lost and no rotation, twisting or deformation is involved, the spring system can be considered as a system of linear equations or, equivalently, as an energy minimization problem (minimization of elastic potential energy).



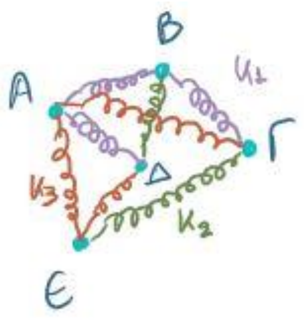
As input from the user inserts points that represents the position of the centroids of each room, e.g. point A.



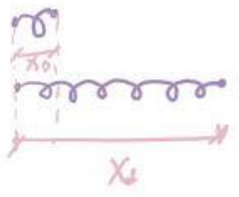
These points are placed in initial random positions inside the building's boundaries.



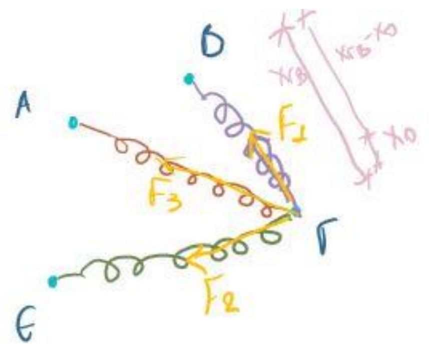
All points (vertices) are interconnected with straight line segments (edges) , from which it is derived their Euclidean distance x. The set of vertices and edges forms a graph.



Almost every pair of vertices is connected with an edge (fictitious mechanical spring) representing their type of connection. There are three types of connections expressing the hierarchy (strong, medium and weak) and thus three types of springs with different values of the spring constant k_1, k_2, k_3.

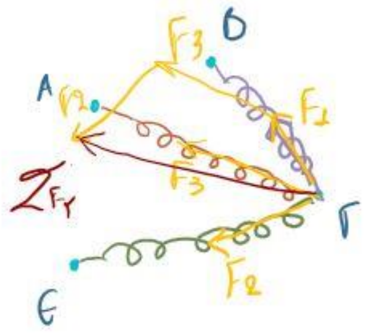


All springs have the same rest length x_0 = 0 m. All distances between centroids should be more than 0, so $x > x_0$. This means that once the springs are attached to the centroids all of them are under tension $x_1 > x_0$.



At point Γ external forces occur. These forces can be calculated by applying Hooke's law:

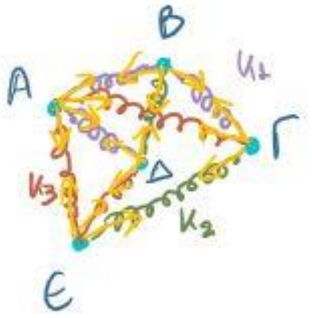
$F_1 = k_1\,(x_{ΓB} - x_0)$
$F_2 = k_2\,(x_{ΓE} - x_0)$
$F_3 = k_3\,(x_{ΓA} - x_0)$



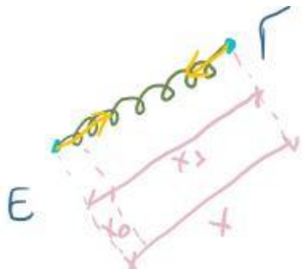
The resultant force at point Γ is vector sum of all forces acting upon it:

$\sum F_Γ = \vec{F}_1 + \vec{F}_2 + \vec{F}_3$

The resultant force can be calculated by using the polygon rule.



The same process is repeated for all points.

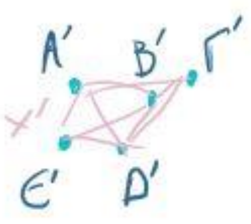


The elastic potential energy for one spring is:

$U_{EΓ} = \frac{1}{2}k_2(x - x_0)^2$

If n₁ the number of springs that have spring constant k₁ and x₁ their corresponding deformation, then the total elastic potential energy of the system *U_{tot}* can be calculated by:

$$\mathrm{U_{tot}} = \frac{1}{2}\mathrm{k_1(x_1 - x_0)^2} + \frac{1}{2}\mathrm{k_2(x_2 - x_0)^2} + \frac{1}{2}\mathrm{k_3(x_3 - x_0)^2}$$



By setting the springs free they tend to reach their original rest length, so they tend to approach each other because the rest length x_0 was set to be 0. The system will try to reach to an equilibrium where U_{tot} is minimum.

The objective is to find new positions of the points (A', B', Γ', Δ', E') that fulfill the proximity requirements. The objective in terms of physics could be expressed as to minimize the potential energy of the springs. A way to do so is by using gradient descent methods such as force directed graph drawing developed by P. Nourian and S. Azadi.

2.7 Force directed graph drawing

P. Nourian and S. Azadi. have proposed "a 'force-directed graph-drawing algorithm to draw a bubble diagram based on nodes, links, and the intended area for the nodes. This way, the designer does not need to manage to draw a neat diagram, as the system does it for them." [30] The pseudocode is presented below:

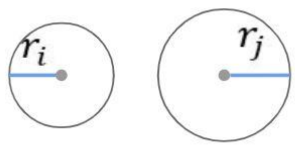
```
Input: the graph Γ (V, E), E = ($V_i$, $V_j$) if Vi is linked to $V_j$

Step 1: Compute **resulting forces**:
        Resulting_forces = ∑Attraction_forces(v) + ∑Repulsion_forces(v)
        υ = υ moved by Resulting_forces
Step 2: Recompute **Continuance_condition**:
        $\forall(i,j) \in E$, $x_{ij}$ ($R_i+R_j$) +- ErrorTollerance
Step 3: **Iteration_count** = iteration_count + 1
**Until** Continuance_condition=False or Iteration_count > Maximum_iterations

Output: a kissing-disk drawing of graph Γ

where
        Attraction_forces = AFij = ka Δxij
                ka = attraction strength factor,
                Δxij = Distance Vi to Vj - RestLength(i,j),
                RestLength(i,j) = Ri+Rj

        Repulsion_forces = $RF_{ij} = k_r / x_{ij}$ $\forall(i,j)$ if $x_{ij}$ < RestLength(i,j)
                $k_r$ = repulsion strength factor,
                $x_{ij}$ = Distance $V_i$ to $V_j$
                RestLength(i,j) = $R_i+R_j$
        [30]
```

Based on the above algorithm the approach proposed in this project is also a gradient descent based approach. It is a numerical method that attempts to minimize the potential energy of a spring network. The method $x^{(n+1)} = x^n + a\, g(\nabla f, x^n)$ of gradient descent in this case is:

$$v'_i = v_i + 0.1\, \Sigma F_{ij}$$

where $\Sigma F_{ij} = F_{ij} + R_{ij}$

In more detail, given a vertex v_i and v_j its neighbor vertex both representing the initial positions of two rooms.

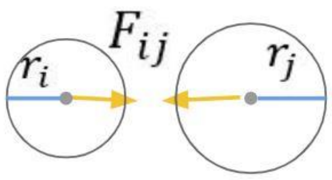


The areas of the rooms are represented with a circle with corresponding radii r_i, r_j and centers the vertices v_i, v_j respectively.

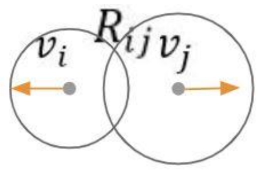
The line segment connecting the two vertices is called edge e_{ij}.

The edge has a specific stiffness value k_{ij}.

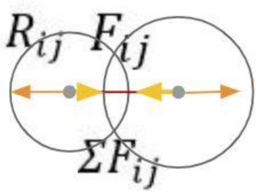
The edge has also a set length d_{ij} , the distance between the two vertices v_i, v_j that is calculated by: $d_{ij} = v_i - v_j$



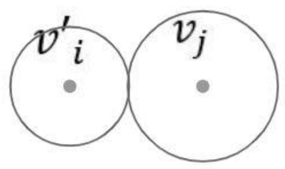
The proximity requirements of the rooms are expressed by an attractive force that tries to place the rooms closer with each other. The strength of the force is defined by the edge's stiffness and distance: $F_{ij} = k_{ij} * d_{ij}$



In case the distance between the vertices is smaller than the sum of their radii ($if\ d_{ij} < r_i + r_j$) then a repulsive force R_{ij} is added to avoid collision. This force acts in the opposite direction of the attractive one and is defined by another stiffness value k_r and the distance: $R_{ij} = -1 * k_r * d_{ij}$



The resultant force ΣF_{ij} is the algebraic sum of the forces acting on vertex v_i : $\sum F_{ij} = F_{ij} + R_{ij}$



After we have the direction of the resultant force $\sum F_{ij}$, the vertex v_i is moved slightly towards this direction to approach its neighbor vertex v_j , so: $v'_i = v_i + 0.1 * \sum F_{ij}$

The process is repeated for all vertices until the system is converged, where the distance between the vertices is as close as possible to the sum of their radii: $\frac{|d_{ij}|}{r_i + r_j} - 1 < 0.0001$ or the maximum number of allowed iterations is reached.

This method fulfills the proximity requirements of the rooms. In the same logic the illuminance requirements are expressed as proximity requirements (strong connections) between the room and its ideal position in the building regarding illuminance.

As seen in problem statement paragraph, the vertices of the graph indicate the rooms' positions, whereas the edges their connectivity. In the following figure:

- vertices as room centroids and edges as their proximity connections (in red).
- vertices as ideal illuminance position and edges as the connections with the room centroids (in green)
- vertices' final position where both requirements are fulfilled as much as possible (in blue).

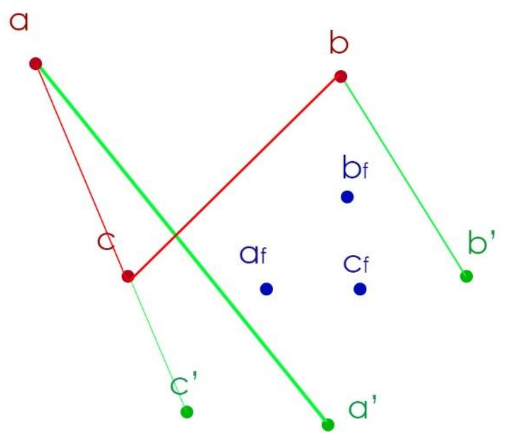


Figure 12: graph representing the problem in a simple form where a, b, c the initial room positions, a', b', c' the ideal illuminance positions and af , bf , cf the final room positions

In order to define the illuminance requirements an illuminance analysis is performed and a grid of test points (fixed locations) is created all over the buildings' surface (floor). The test points with the required illuminance value that is the closest to the initial room's position is selected (a', b', c') and an edge that connects them with the corresponding room is created (green line segments). The green edges that express the illuminance requirements are considered in the above mentioned algorithm in the same way as proximity connections.

Taking into consideration the above mentioned algorithm the resultant force is:

- for proximity:

$$\sum F_p = F_p + R_p$$
$$F_p = k_p * d_p$$
$$R_p = -1 * k_r * d_p$$

- for illuminance:

$$\sum F_i = F_i + R_i$$

$$F_i = k_i * d_i$$
$$R_i = -1 * k_r * d_i$$

- in total:

$$\sum F_t = F_p + R_p + F_i + R_i$$

After the direction of the resultant force $\sum F_t$ is known, each vertex is slightly moved towards this direction : $v'_i = v_i + 0.1 * \sum F_t$

The objective function is then: $U = \frac{1}{2} k_p \, d_p^{\ 2} + \frac{1}{2} k_i \, d_i^{\ 2}$

2.8 Kangaroo

The iterative process of the above algorithm is performed by Kangaroo engine, but ideally it should be developed in Python within Grasshopper. An attempt of developing it in Python can be found in appendix B; it was not completed due to time restrictions of the thesis.

Grasshopper is "a visual programming language and environment that runs within the Rhinoceros 3D CAD application" (by D. Rutten, Robert McNeel). [31] [17] Kangaroo is "a Live Physics engine for interactive simulation, form-finding, optimization and constraint solving developed by D. Piker. It is an add-on for Grasshopper/Rhino which embeds physical behaviour directly in the 3D modelling environment and allows user to interact with it 'live' as the simulation is running." [32]

Kangaroo is not open-source to be able to study how it works, but as the developer reveals "Kangaroo works by finding the total force vector F for each particle by:

- adding up all the different forces acting on it,
- using Newton's 2nd law to get the acceleration,
- and numerically integrating the resulting differential equation of motion over time to find new positions for all the particles." [33]

Moreover, "a point in Kangaroo reaches equilibrium when the weighted average of the move vectors from all goals acting on it is zero. The solver can also be seen as a minimization of the (weighted) sum of the squares of the distances from the rest positions for each goal acting on each point."[34]

2.9 Literature review

The topic of this thesis is relatively new so the most relevant existing literature are academic projects by individuals. The first three projects use parametric tools as the design environment, while the last two make use of graph theory in their approach. Graph theory is not the approach for this thesis but was used as an inspiration only (graph, adjacency matrix). The project closes to the approach proposed is "Architectural space planning using parametric modeling" by M. Elsayed where he also simulates the problem as a physical system. During the research some other projects developed by students were found but were not officially published and or well documented and therefore were not included in the review. The overall impression is that there are many gaps in relative literature and every attempt is beneficial.

Rapid Data Collection using Automated Model Generation and Performance Evaluation

The first part of the project is a proposal of a workflow for speeding up the collection of data from apartment floorplans. In the second part a tool for automated model generation and evaluation is suggested. The purpose of the tool is to find the relations between various design variables and selected performance criteria. Some of the design variables are: number of rooms, their relevant position, dimensions, walls, windows and some of the design criteria are: daylight (daylight factor), energy consumption (window layout, orientation), common quantities (total area, effective area, number of rooms, neighboring and interior walls). [35]

The software selected is Rhinoceros and Grasshopper and two main plugins used are Decoding Spaces Toolbox (for layout generation) and Diva (for energy simulation). [35]

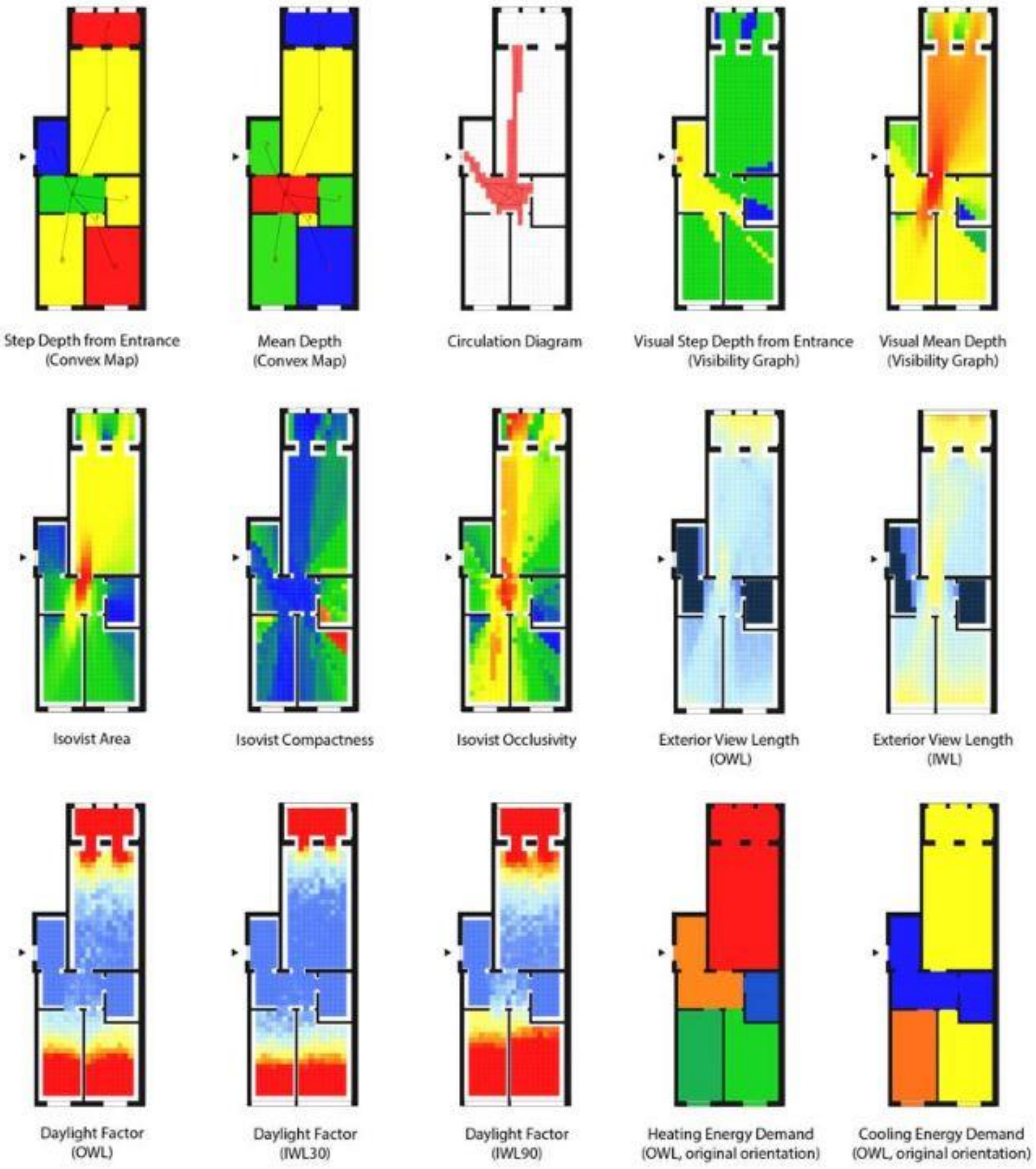

Step Depth from Entrance (Convex Map)
Mean Depth (Convex Map)
Circulation Diagram
Visual Step Depth from Entrance (Visibility Graph)
Visual Mean Depth (Visibility Graph)
Isovist Area
Isovist Compactness
Isovist Occlusivity
Exterior View Length (OWL)
Exterior View Length (IWL)
Daylight Factor (OWL)
Daylight Factor (IWL30)
Daylight Factor (IWL90)
Heating Energy Demand (OWL, original orientation)
Cooling Energy Demand (OWL, original orientation)

Figure 13: Different analysis diagrams for one apartment floor plan [34]

Computational Floorplan Synthesis

In this book the first chapters are dedicated to ALES projects, a general layout design system. Based on ALES the research project KREMLAS explored various methods for automatic floorplan generation. The methods explored to produce layouts were based on a) the principle of tight packing of geometric elements (dense packing), b) K-dimensional trees c) subdivision algorithms, d) voronoi diagram.

The two main requirements were a) the sizes of the desired rooms and b) their topological neighborhood relationships (which room should be next to which).

The proposed system generates automatically a geometrical solution and it can adapt the geometry to new requirements. Apart from that an additional study evolved the generation of a floorplan by dense packing with visibility evaluation. [36]

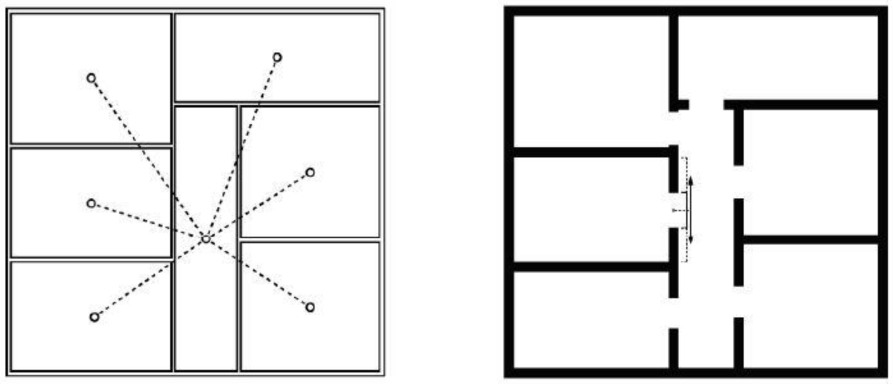


Figure 14: links of rooms with dense packing and respective door placement [35]

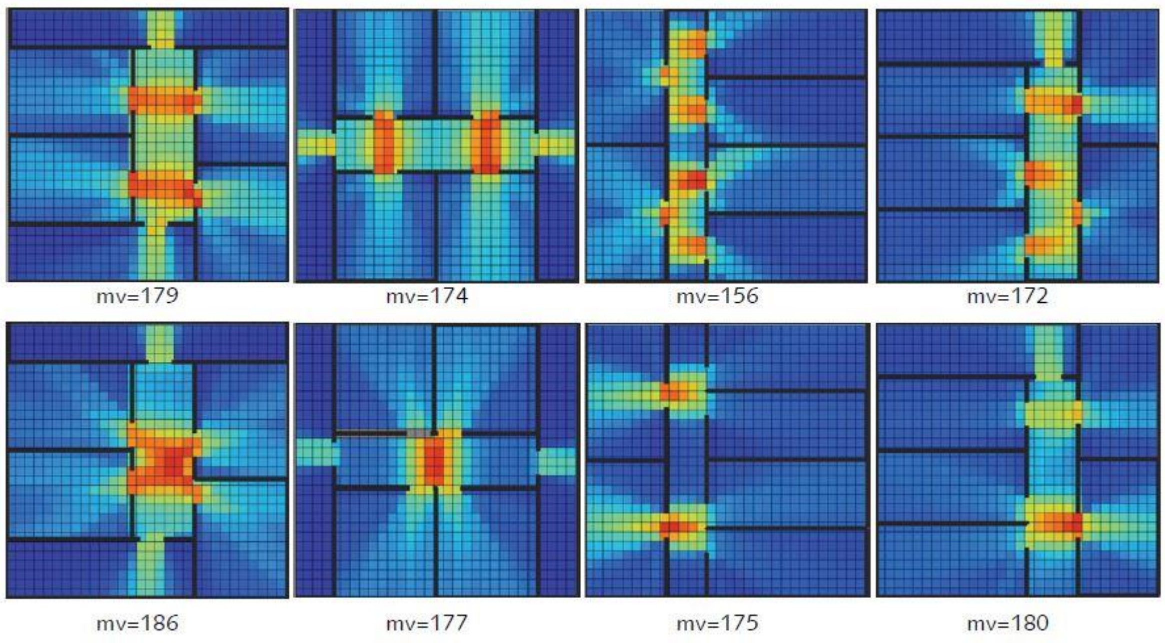


Figure 15: alterations of rooms' arrangement together with possible visibility offered by the doors [35]

Evolutionary parametric analysis for optimizing spatial adjacencies

This paper utilizes Grasshopper as a planning tool to graphically represent a 3-dimensional analysis of adjacency requirements in program and spaces. The purpose of this project is to investigate whether there are new ways to use evolutionary algorithms so as to optimize floorplan layouts. A tool developed in Grasshopper is proposed and it generates diagrammatic layouts based on given adjacency requirements. The inputs are simple geometry representing the building's rooms (perimeter, height, area). The proximity is determined by the distance between each origin point of the rooms. The optimization tool Galapagos tries to minimize this distance and produces the most suitable arrangement of the all volumes (rooms) set within the larger volume (building). [37]

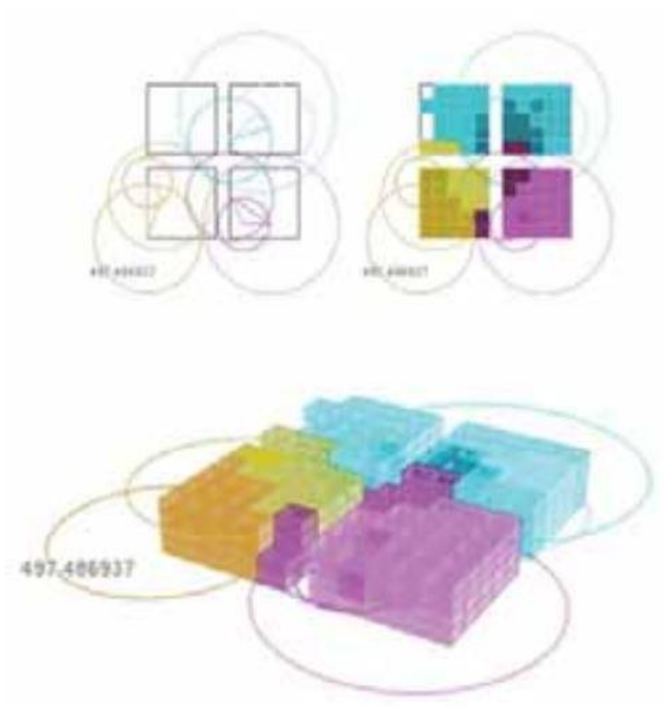


Figure 16: input: geometry as circles and height, output: pixelated, extruded and arranged volumes [36]

Architectural space planning using parametric modeling

This paper proposes an automatic multi-stories space planning tool. The investigated method uses two kids of physics simulation: a) mechanical springs and b) boxes collision so as to rearrange the position of the rooms (attraction to the vertical core). The main tools utilized are Grasshopper, Microsoft Excel (for the inputs) and Kangaroo (for physics simulations). Some of the inputs are number of spaces, spaces proximity, floor height. The output of the first simulation is the position of the spaces after the spring forces have been applied and of the second simulation is the compact rearrangement. [38]

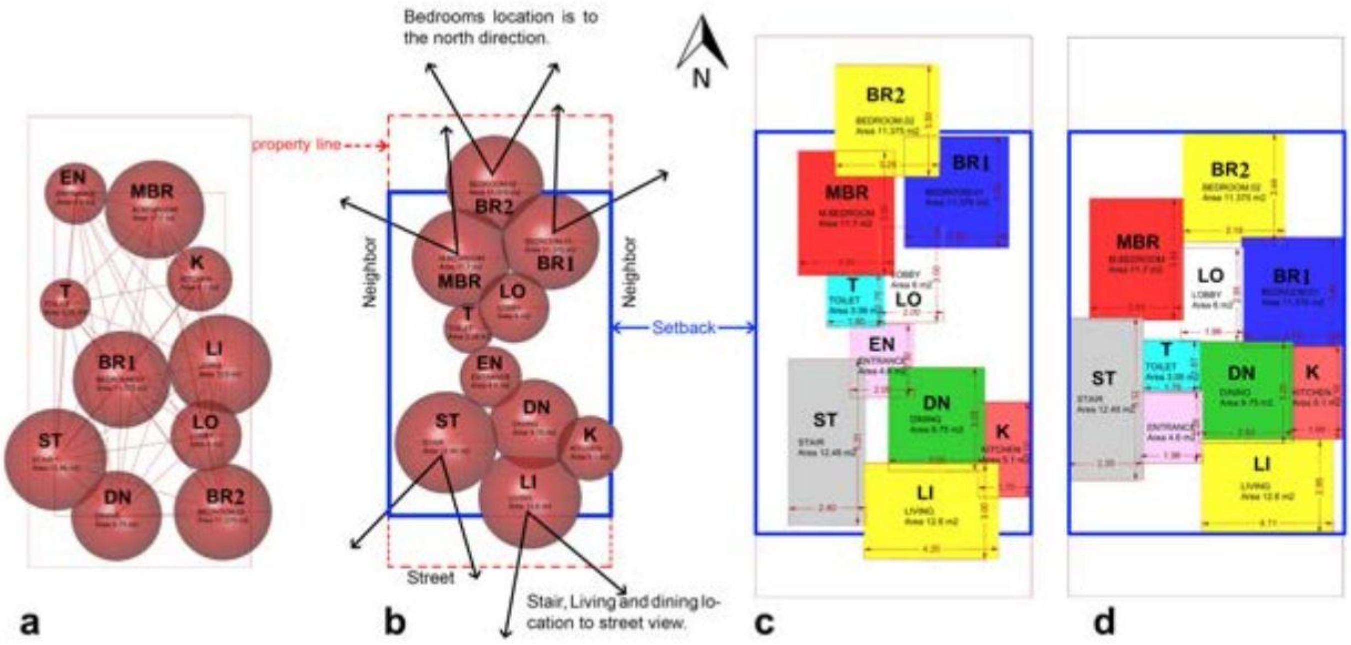
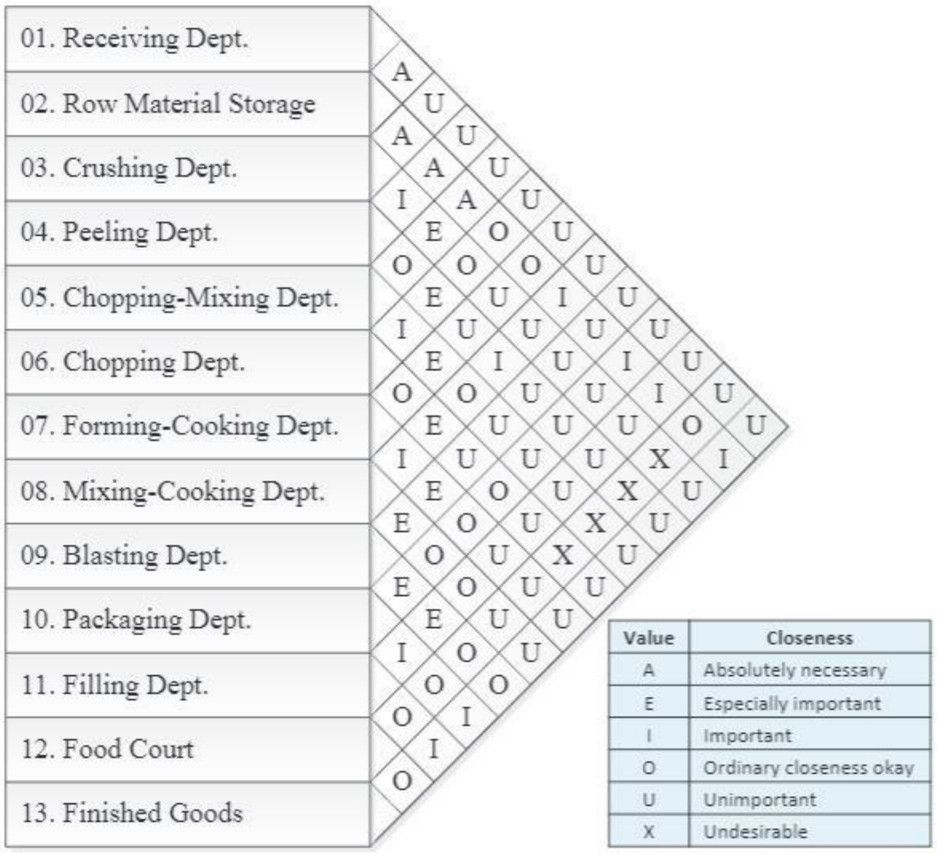

Bedrooms location is to the north direction.
N
property line
Neighbor
Neighbor
Setback
Street
Stair, Living and dining location to street view.
EN
MBR
K
T
BR1
LI
LO
ST
DN
BR2
a
b
c
d

Figure 17: The simulation process: a) The initial position of spaces showing volumes and springs action directions. b) Spaces behavior under spring forces. c) First simulation result. d) Second simulation result. [37]

Production layout optimization for small and medium scale food industry

This study aims to create a production layout for a food company using facility planning techniques. The first phase is the generation of layouts using two different types of construction techniques Systematic Layout Planning (an 11-step procedure) and Graph Based Theory (adjacency and design phase). The second phase is the calculation of the Efficiency Rate (sum of department adjacency score/sum of relationship score). The layout with the highest ER was selected and then improved using Pairwise Exchange Method.

The software used was MATLAB and the input was the order of the different departments in a spiral way, the number and size of the machines as well as the required area around them. The output was the improved order of the departments again in spiral way. [39]



Value	Closeness
A	Absolutely necessary
E	Especially important
I	Important
O	Ordinary closeness okay
U	Unimportant
X	Undesirable

Figure 18: Relationship chart [38]

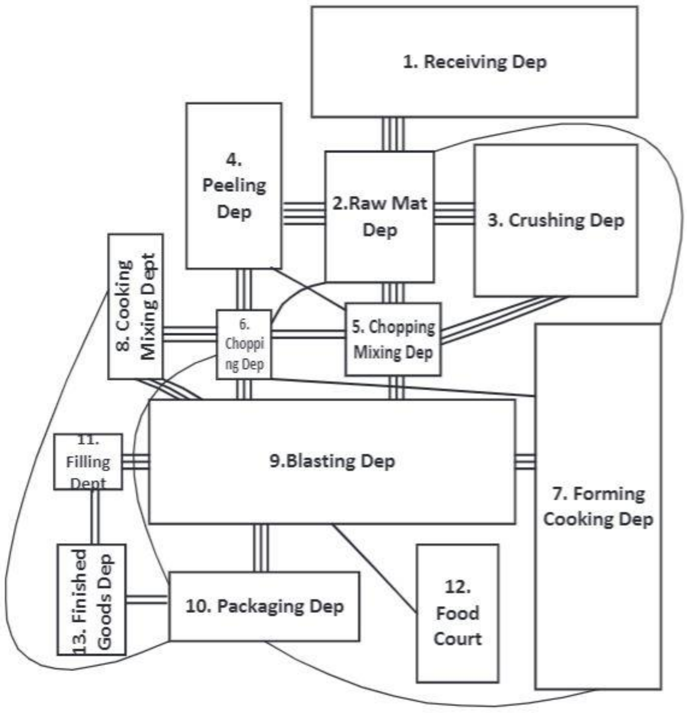


Figure 19: Space relationship [38]

Parallel planning: An experimental study in spectral graph matching

One project of this research is to design a prototype of a spatial configuration defined by a graph so that it can be applied to an existing configuration using spectral graph theory (for matching the two graphs).
Based on an existing spatial structure an adjacency graph is computed first. Next a bubble diagram shows the desired spatial configuration. Inexact Graph Matching is used to match the desired configuration with the existing one. The matching is improved by applying a hill climber algorithm resulting in the desired layout. The results show that in two from 30 cases a correct matching was found. (The tools used, inputs and outputs were not mentioned in this paper.) [40]

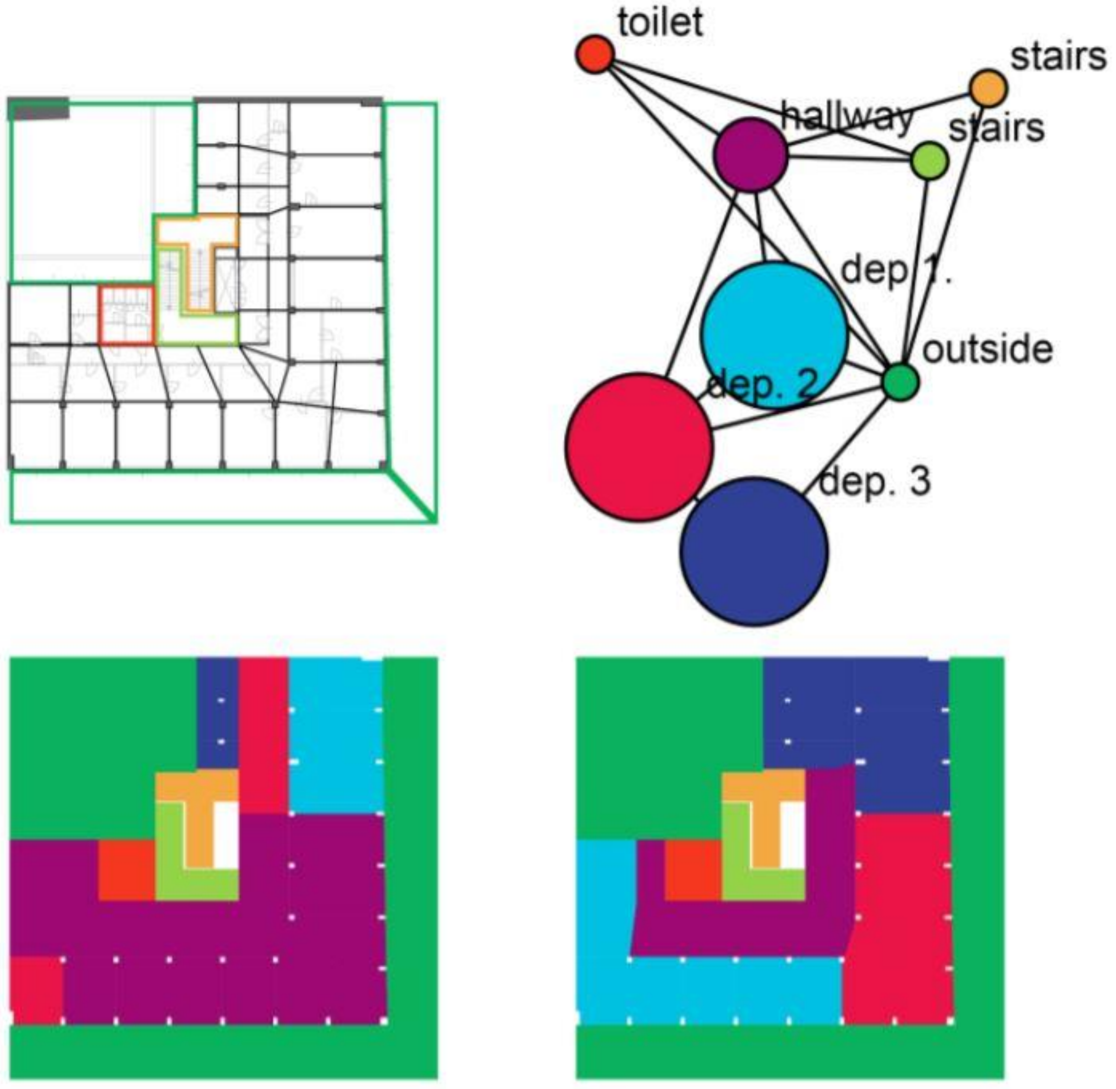


Figure 20: An existing floor plan with a spatial subdivision and pre-matches; Bubble diagram of functions (with relative sizes); The initial spectral matching (normalized-Laplacian matrix and UPGMC, Renormalized); Improved matching through a hill climber. [39]

3

3 Proposed methodology

3.1 Case study

As a case study that would be representative and useful for the application of the proposed methodology was selected the Faculty of Electrical Engineering, Mathematics and Computer Science (EEMC). It is a large building complex situated at the center of the T.U. Delft campus, in Mekelweg 4. The building was conceived from the start as the place that would host the department of Electrotechnical Engineering. Designed by G. Drexhage in 1959, it contains a 92-meter tall building that is a landmark for the entire city of Delft, rising higher than the church towers at the center of the city. Its construction started in 1962 and was finished only in 1972, spanning through an entire decade. EWI stands for Electro (electrical), Wiskunde (mathematics) and Informatica (computer science), the three studies that are located in the building. EEMC is considered to be the most recognizable faculty of TU Delft University, a tall monument with 23 floors.

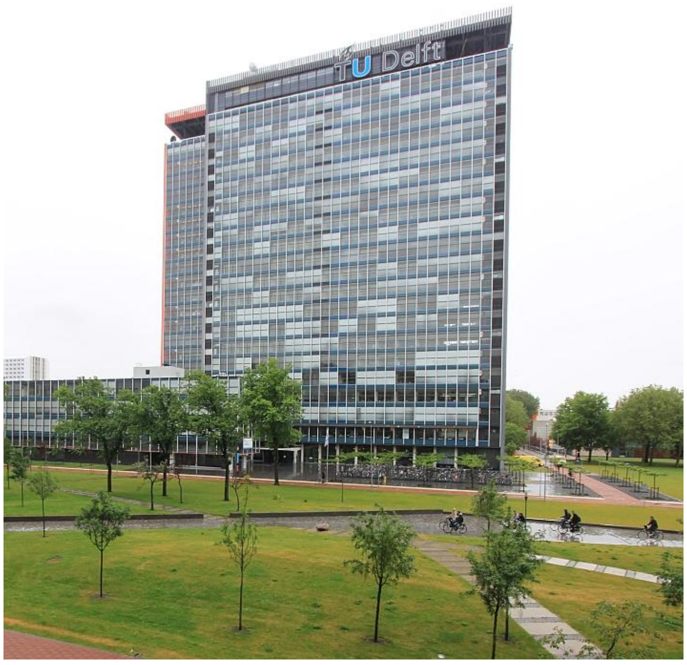


Figure 21: Photo of EEMC in Delft (from ground level) [52]

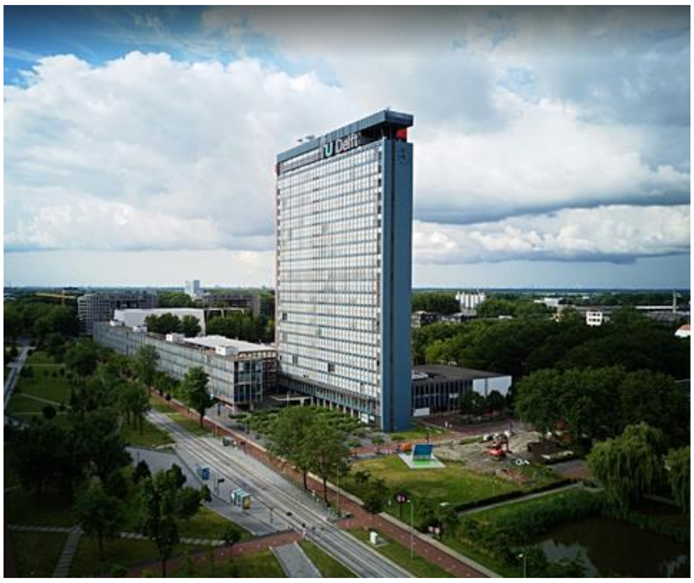


Figure 22: Photo of EEMC in Delft (aerial view) [41]

3.2 Context

The EWI building is currently considered a listed monument in the Delft landscape. But EWI is also well known for having very strong winds around it, generated by the shape of the building. [42] These functional problems arouse is a lot of discussion around whether it should be demolished or not. This year (2020) it is said that the facade has reached the end of its lifespan and therefore should be replaced. One of the proposals considered is to change also the functions of the complex. In this context, it could be transformed from the home of the electrical engineering faculty to a student center and accommodation [43]. Taking the above into account EEMC constitutes an ideal case study as it is a) a listed building (its cell should not be changed), b) it is already discussed to be transformed into student housing, c)it is located in Delft, that faces a shortage of residences in comparison to the high demand due to the University. A tool that converts an existing layout into a residential one (Cochleas) can be considered ideal to EEMC case.

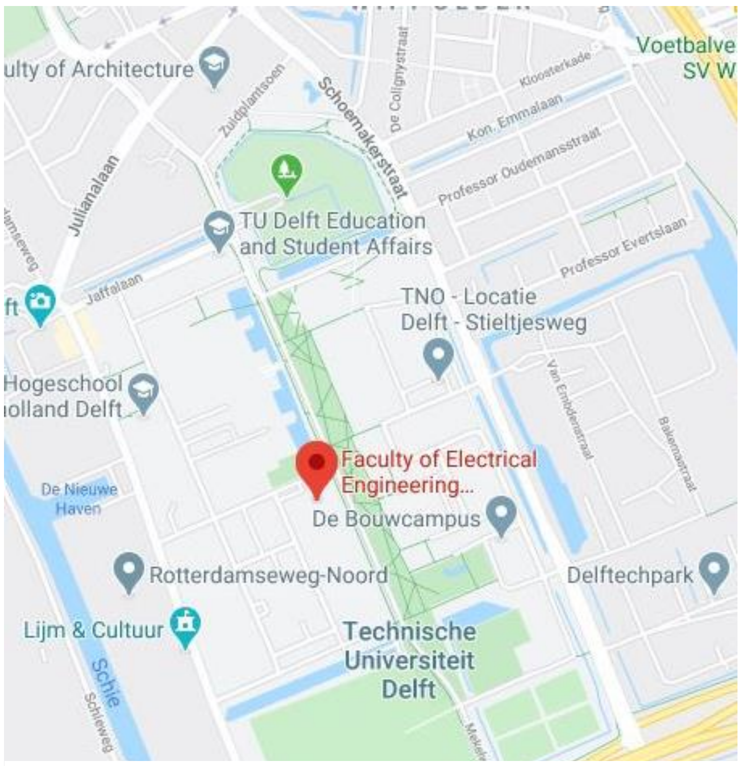


Figure 23: Screenshot from google maps indicating the location of EEMC [45]

Climate analysis

As it can be seen in the following figures, the central entrance of EEMC is at Northeast, the sun is at the southern side during summer months and the dominant wind blows towards Southwest.
[44]

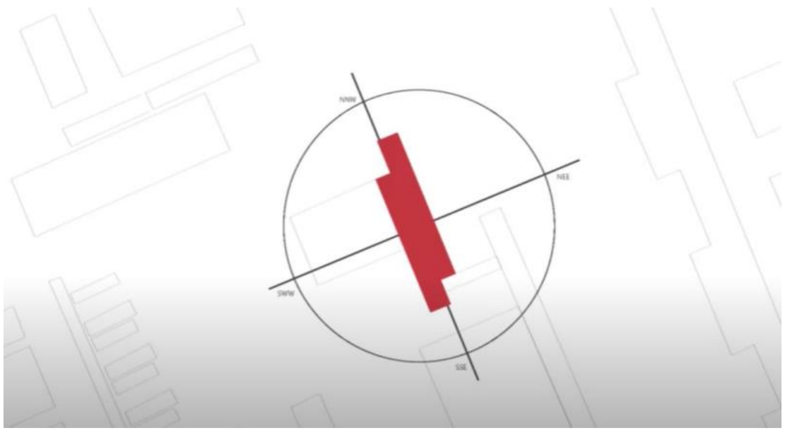


Figure 24: Orientation of EEMC [46]

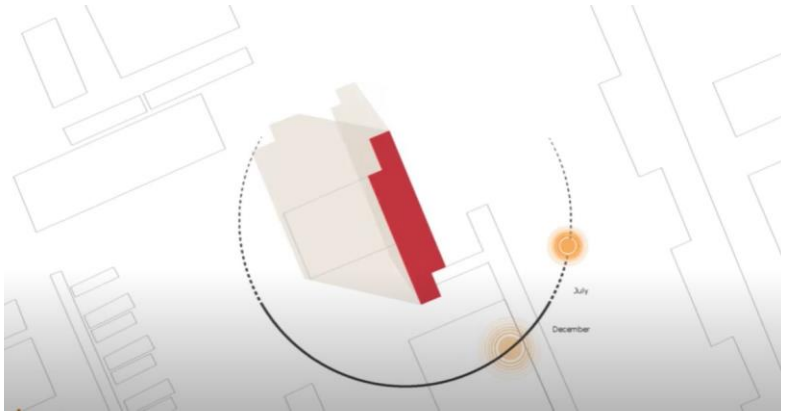


Figure 25: Direct sunlight analysis of EEMC for July [46]

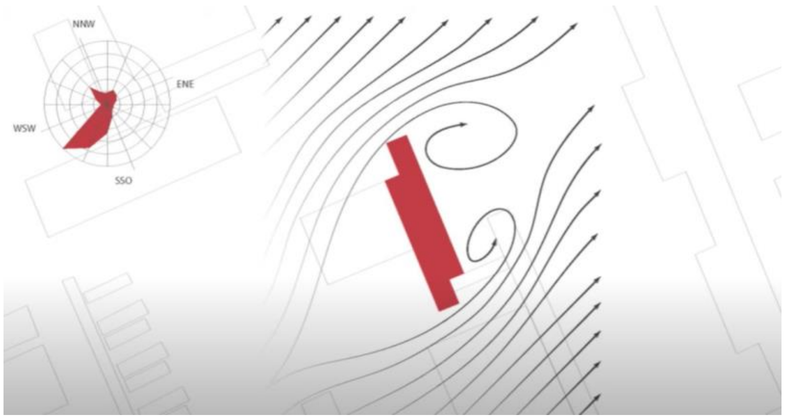


Figure 26: Dominant wind analysis for EEMC [46]

3.3 Existing floorplan

The ground floor of EEMC accommodates a reception, a meeting area, halls, lecture rooms and two large amphitheaters. The floorplan of the ground floor can be seen in the figure below: [45]

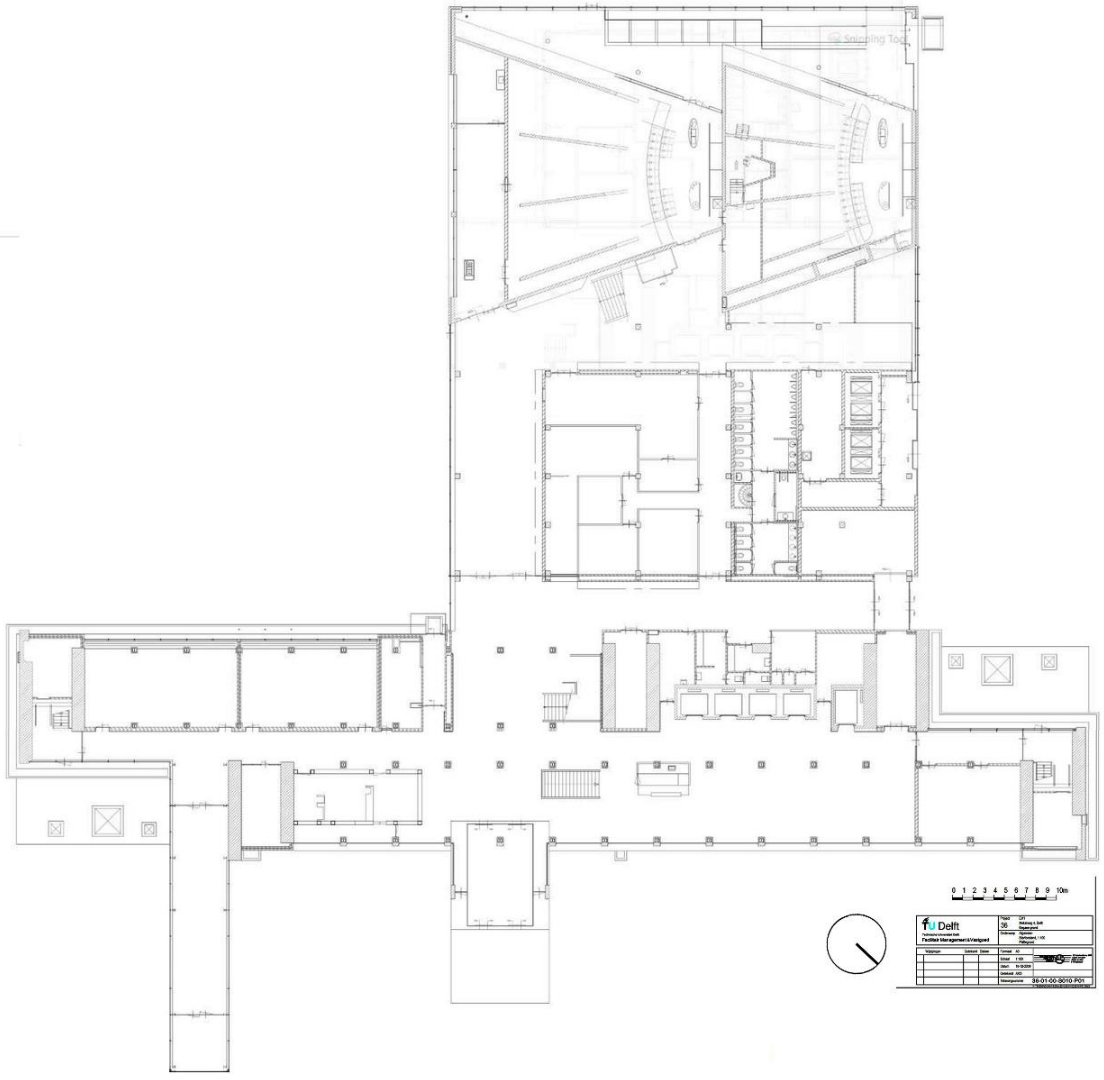


Figure 27: Ground floor layout of EEMC [45]

The tower

The main area selected to apply the proposed methodology is located at the tower, because the tower is the main concern of the TU Delft community and one of the most problematic elements. Moreover, since there was no access to the floorplans of the rest floors it is assumed that they are identical. The tool was applied also on the ground floor, because it includes and additional part apart from the tower.

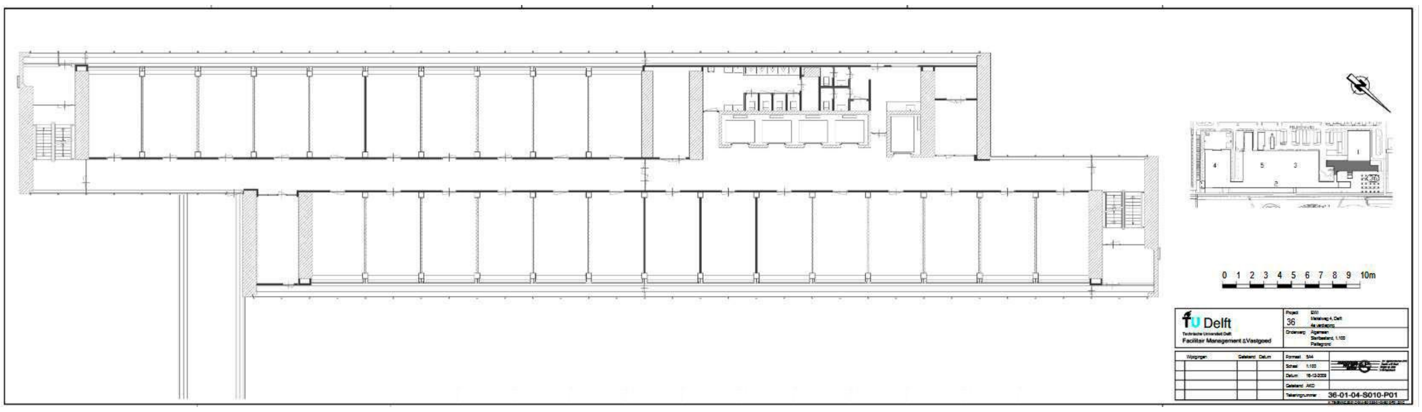


Figure 28: Layout of a typical floor of the tower of EEMC [45]

Interior

The EEMC complex accommodates three faculties: electrical engineering, mathematics and computer science. It includes eleven lecture rooms, workshops and laboratories. Most lecture room and halls are located at the ground floor whereas labs and offices are located at the upper floors. As for its basic structural system, it consists of concrete walls and steel columns. [44]

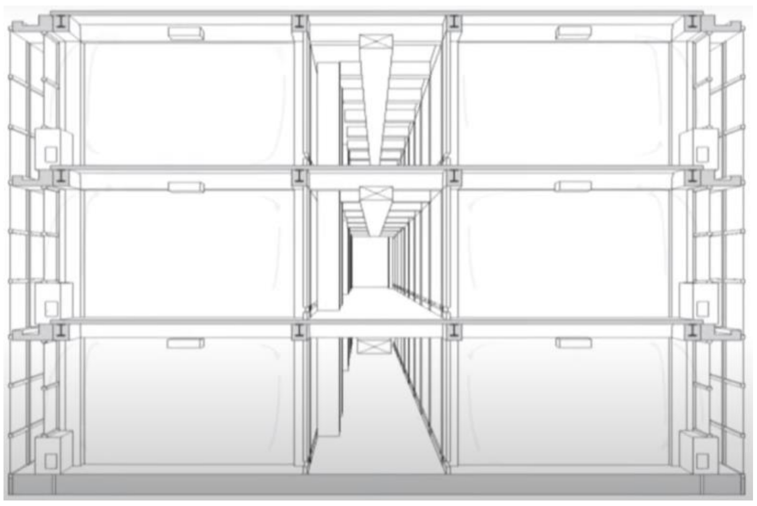


Figure 29: perspective view of the main corridor at the tower (existing situation) [44]

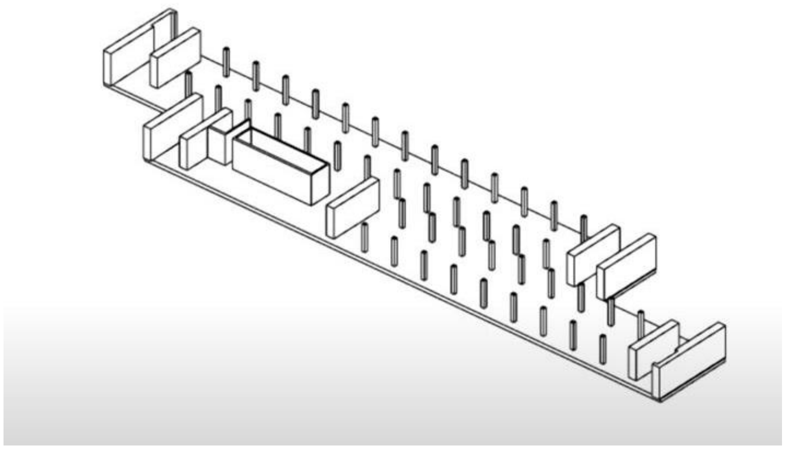


Figure 30: schematic representation of the structural system a typical tower's floor [46]

The following pictures give an idea of the existing situation in the interior of EEMC. [46]

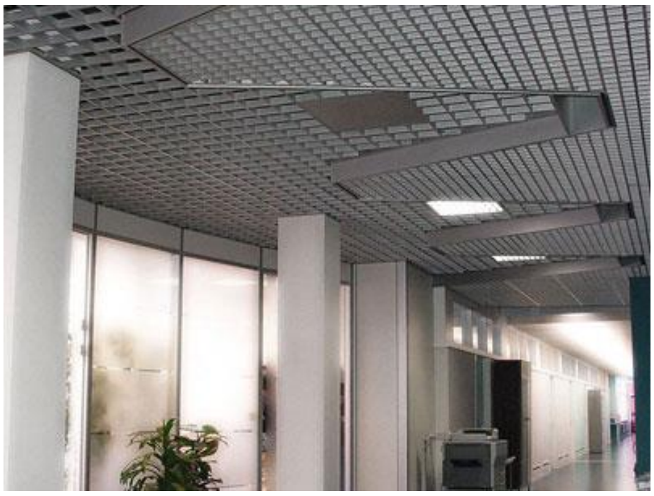


Figure 31: photo of the interior of the main corridor at the 21st floor [48]

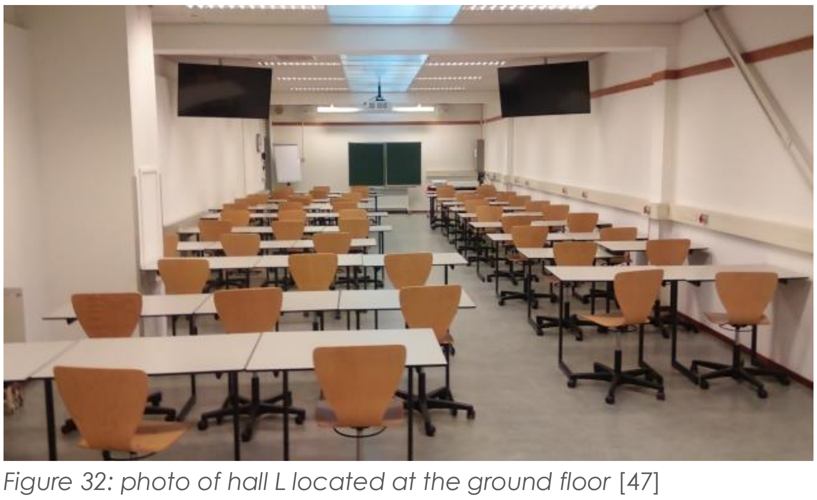
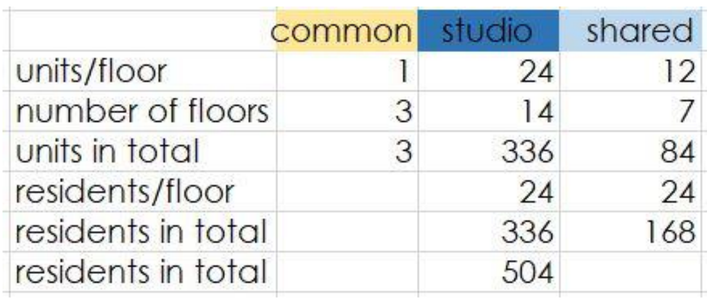


Figure 32: photo of hall L located at the ground floor [47]

3.4 Design assignment

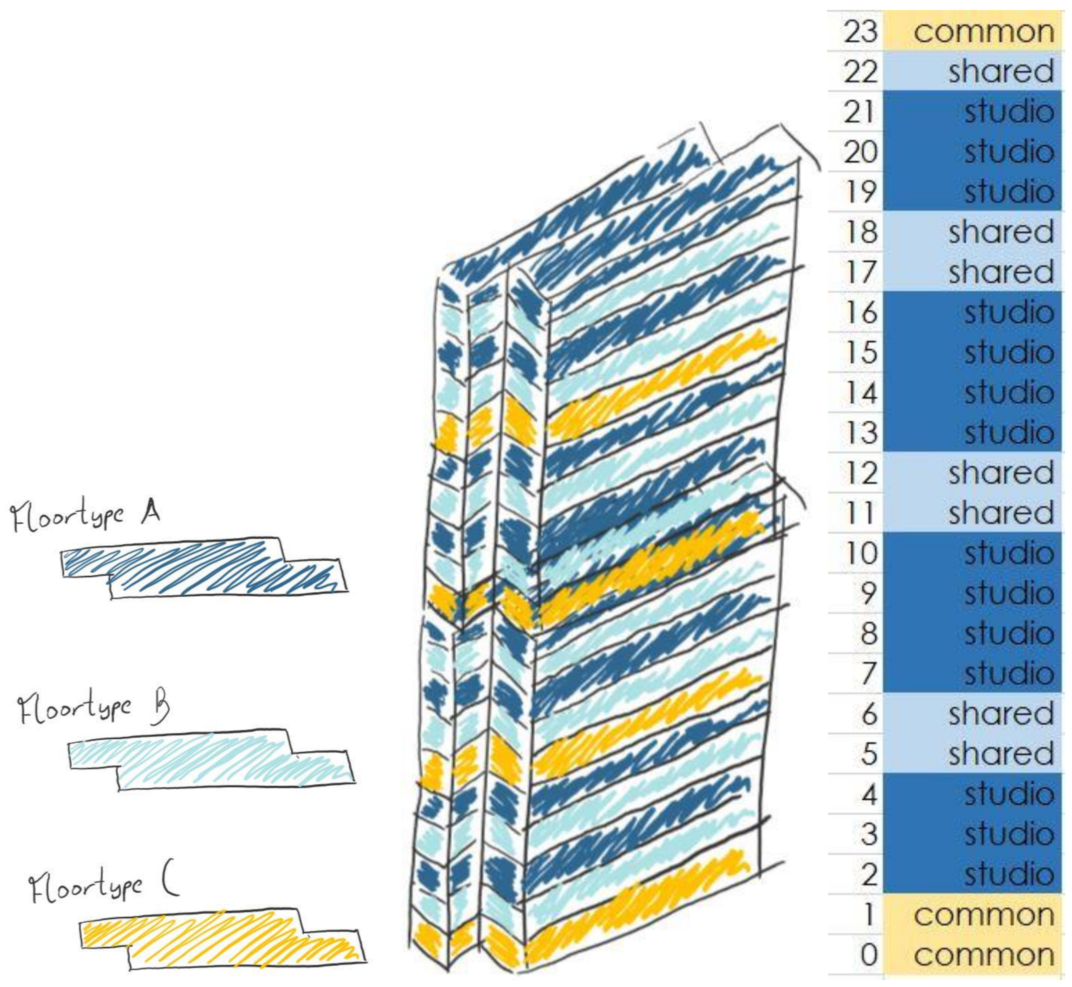
The hypothetical client of the design renovation assignment is supposed to be TU Delft because it is its property. For this thesis' purposes it is supposed that TU Delft wants to repurpose the building and convert it into student housing. The relevant authorities decide to create an architectural competition for this. An architecture office/ student wants to participate in the competition and decides to use Cochleas during the primary stages of the design so as to speed up the design process. For the purposes of this graduation topic the author acts as the architect participating in the competition and as the developer of Cochleas. The main requirement of the competition is to accommodate 500 students and cover 3000 m^2 of common facilities.

The EEMC building will be divided vertically regarding three floor types A,B and C.
Floortype A: studios
Floortype B: shared apartments
Floortype C: common facilities
Floortype D: ground floor



	common	studio	shared
units/floor	1	24	12
number of floors	3	14	7
units in total	3	336	84
residents/floor		24	24
residents in total		336	168
residents in total		504	

Figure 33: Table with units and residents numbers



23	common
22	shared
21	studio
20	studio
19	studio
18	shared
17	shared
16	studio
15	studio
14	studio
13	studio
12	shared
11	shared
10	studio
9	studio
8	studio
7	studio
6	shared
5	shared
4	studio
3	studio
2	studio
1	common
0	common

Figure 34: Vertical arrangements of uses

Floor area (in grey and pink): 1035 m^2
Two main parts to be rearranged (in pink): 746 m^2

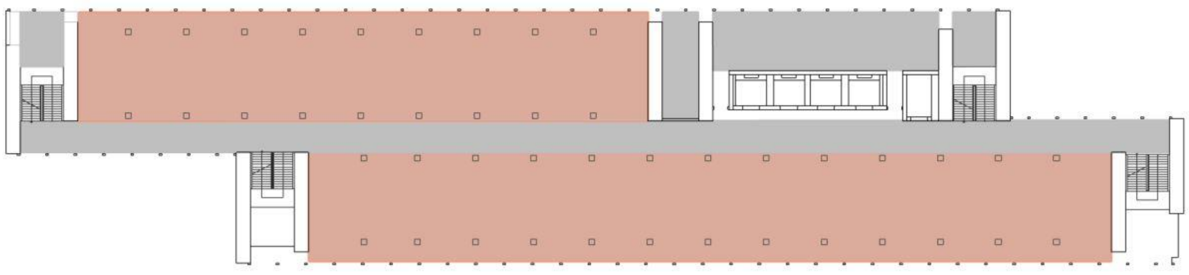


Figure 35: Area of interest (in pink) in a typical floor of the tower

3.5 Program of requirements

The area of application is expected to be converted into a studio apartment for one person. The total square footage was set to be 26 m^2, which is a relative typical size for studio apartments in the Netherlands. A usual program of requirements includes a patio, a kitchen, a living room, a bedroom, a restroom and, occasionally, a desk, a storage room and a closet. The following table shows the rooms set by the user together with their corresponding desired areas. The procedure of how the area values were calculated is shown in the next paragraph.

POR	area (m2)
kitchen	2
coach	3
bed	2
restroom	3.75
desk	2.25
storage	2
corridor	3
tot. used area	18
tot. available area	23

Figure 36: Program of requirements for unit A (studios)

POR	area (m2)
kitchen	2
living room	5
bedroom 1	7.5
bedroom 2	7.5
shower	2.25
WC	2.25
dining room	3
storage	2.25
hall	3
tot. used area	34.75
tot. available area	49

Figure 38: Program of requirements for unit B (shared apartments)

POR	area (m2)
kitchen	8.75
living room	100
leisure	48.5
study area	171
workout area	90
WC	8.25
dining room	12.5
laundry	14
storage	36
party area	56
corridor	73
tot. used area	545
tot. available area	858

Figure 37: Program of requirements for unit C (common facilities)

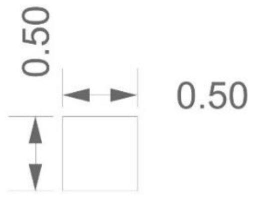
POR	area (m2)
reception	50
living room	125
hall	45
lecture room	190
restaurant	150
WC	40
café	95
storage	60
cinema	245
entrance	5
offices	180
tot. used area	1185
tot. available area	2960

Figure 39:Program of requirements for unit D (common facilities at ground floor)

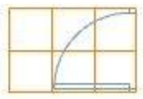
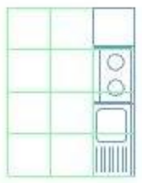
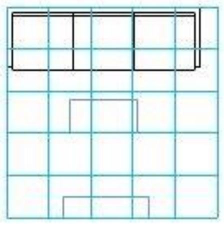
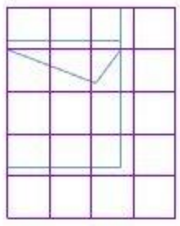
3.6 System of modules

In order to standardize interior configuration it was decided to use a modular system. The module was set to be a square of 0.50 x 0.50m. The square size makes it convenient to be multiplied in x and y direction and also it is in the allowable limits for an illuminance analysis according to NEN (see paragraph "Illuminance requirements"). The half a meter size is considered to be handy because the combination of two tiles (resulting in 1m width) can form a corridor, a door, or a window. The combination of four modules forms one square meter that is the typical unit of measuring area. The module is used to find the minimum area needed for each room by arranging the required furniture in relation to these modules. For defining an efficient required area of a room it was useful to first set the required area for each room and then add extra space for movement (such as corridors).

Module size:



For studios, different arrangements of furniture were made in Rhinoceros software always based on the modules. Below is presented a sample of the experimentations. The same method was applied for all units.

	patio	kitchen	living room	bedroom
no of 0.5x0.5 modules	6	12	25	20
m²	3 m²	6 m²	12.5m²	10 m²
congifuration 4				

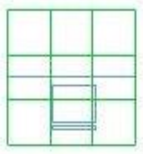
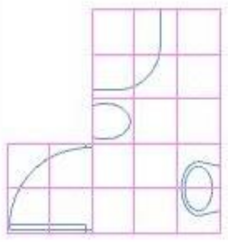
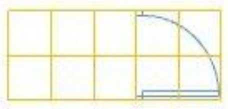
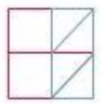
office	bathroom	storage	shelves
9	19	10	4
4.5 m²	9.5 m²	5 m²	2 m²
			

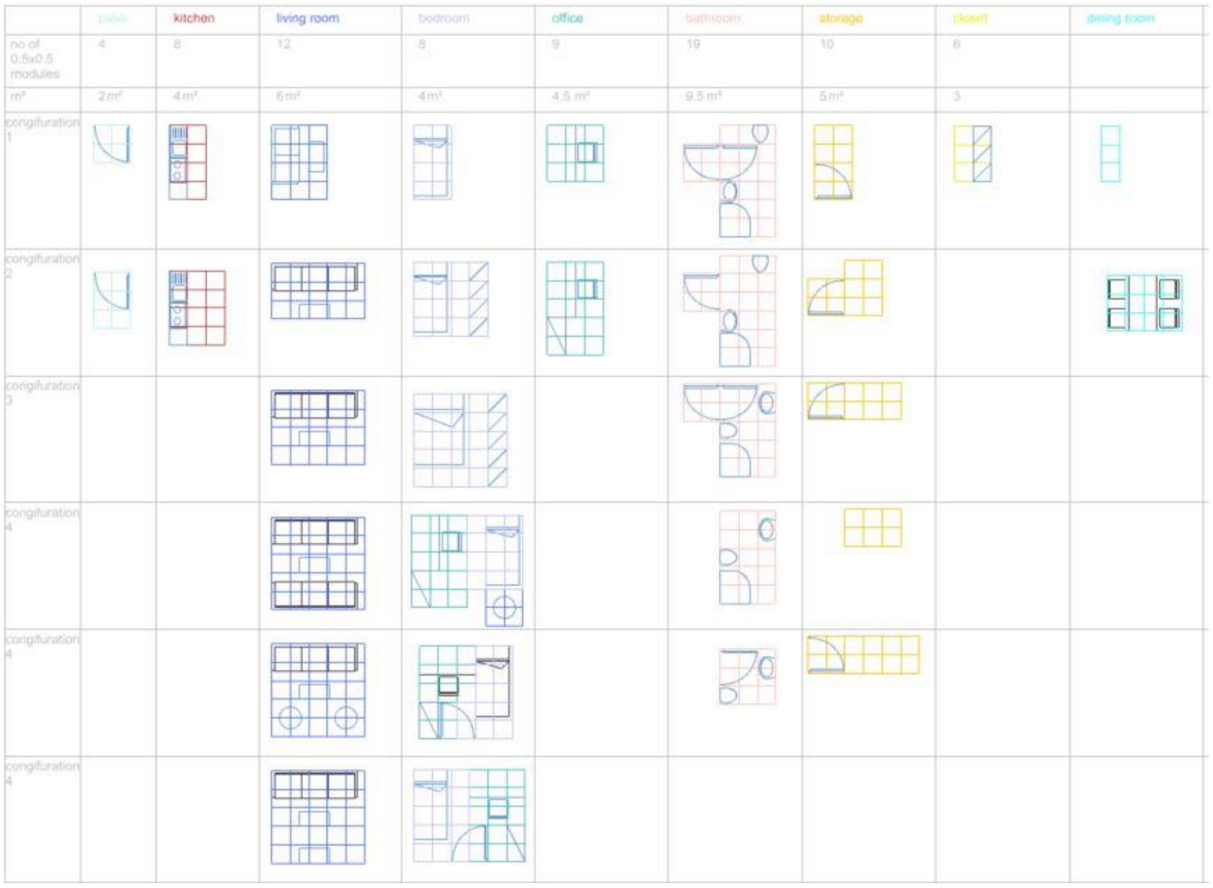
Figure 40: configuration exploration based on the modules and minimum furniture required per room for type A

The minimum square footage of rooms as wells as the correspondent number of modules 0.5x0.5m was calculated. Below it is presented an example for one studio of 26 m^2 (type A).

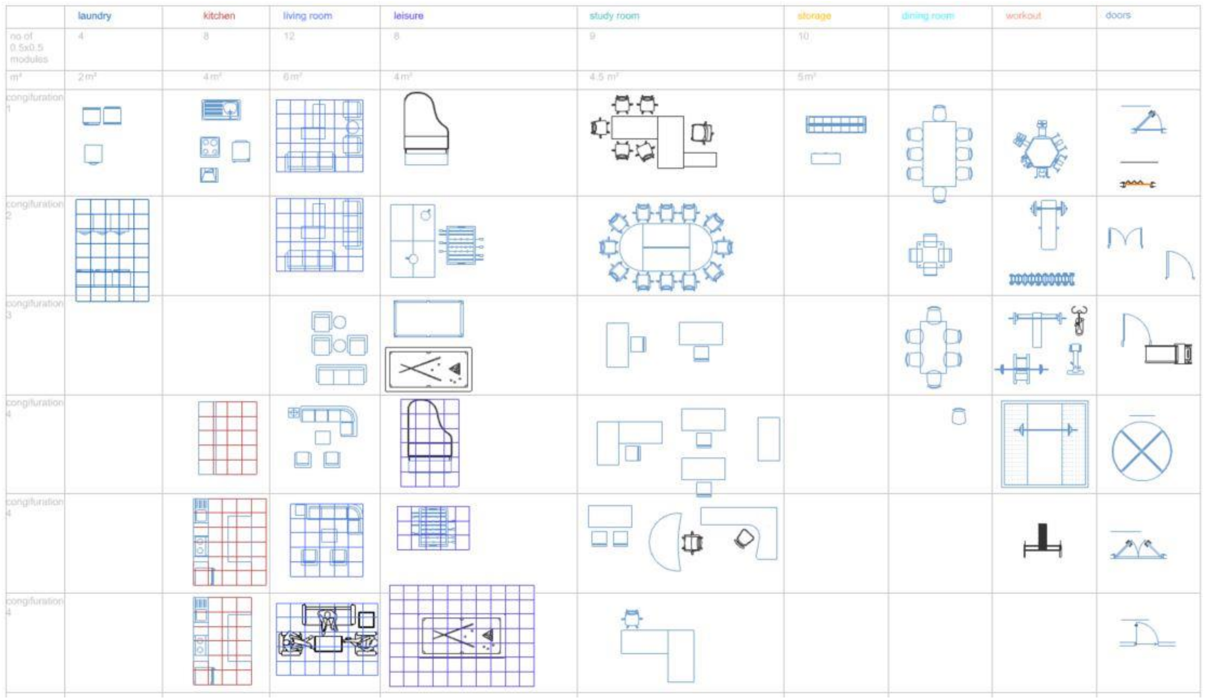
Patio	1,50 m^2	6 modules
Kitchen	3,00 m^2	12 modules
Living room	6,25 m^2	25 modules
Bedroom	5,00 m^2	20 modules
Restroom	4,75 m^2	19 modules
Desk	2,25 m^2	9 modules
Storage	2,50 m^2	10 modules
Closet	1,00 m^2	4 modules
Total	26,25 m^2	105 modules

An example of the experimentations regarding the furniture arrangement for housing and common facilities can be seen in the following pictures:

Configuration of modules for residents



Configuration of modules for common facilities

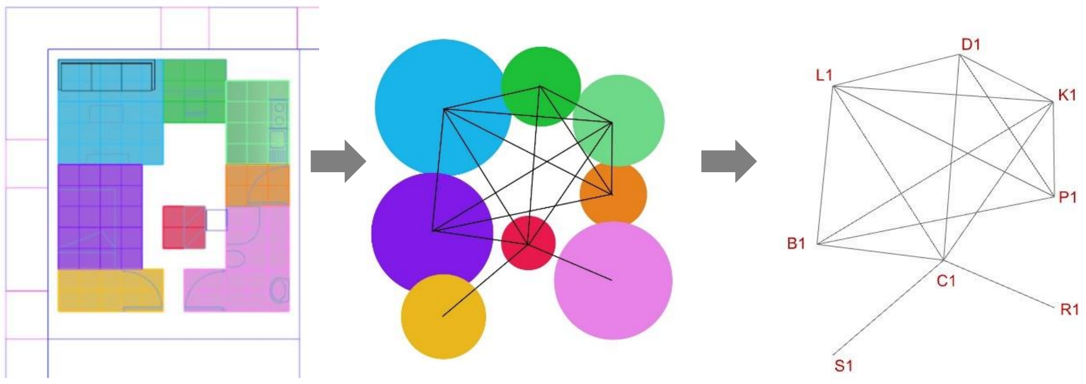


3.7 Bubble diagram

The main goal of Cochleas is to help the user design a rough bubble diagram. Each room can be represented as a circle (bubble). Each centroid is used as the center of the circle. The lines connecting the centroids represent the connections between the rooms. For the purposes of the graduation project the design criteria upon which the bubble diagram is drawn is proximity and illuminance. Proximity was selected as it reflects connections, movements of people and much more. Nevertheless, this is the most common reason to use a bubble diagram. Illuminance was selected as a form of indicating the daylight in the interior that is also very essential criterion for architectural layouts. Of course an architect takes into consideration many more criteria simultaneously such as view, routes, privacy, constructability, etc but it is not possible of course to substitute the role of the architect with just one tool. Under this spectrum the two most important criteria were decided to be proximity and illuminance.

Levels of abstraction:

schematic layout => bubble diagram => graph

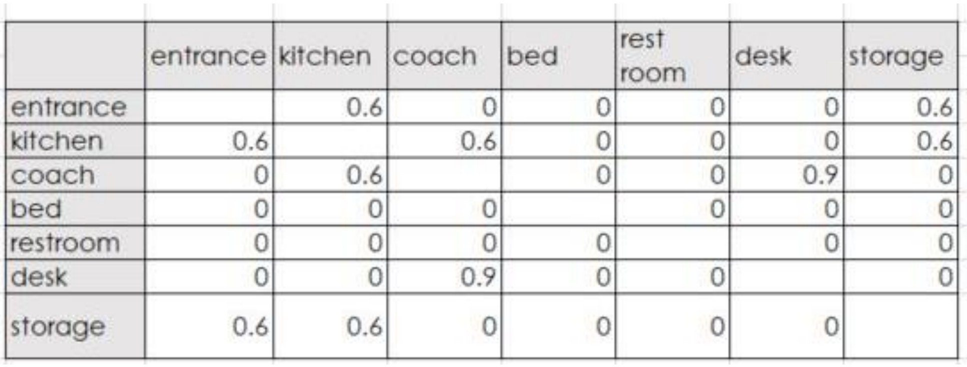


In this thesis the opposite process is attempted, meaning from an abstract topology such as the graph, to find a bubble diagram and then to form a layout.

3.8 Proximity requirements

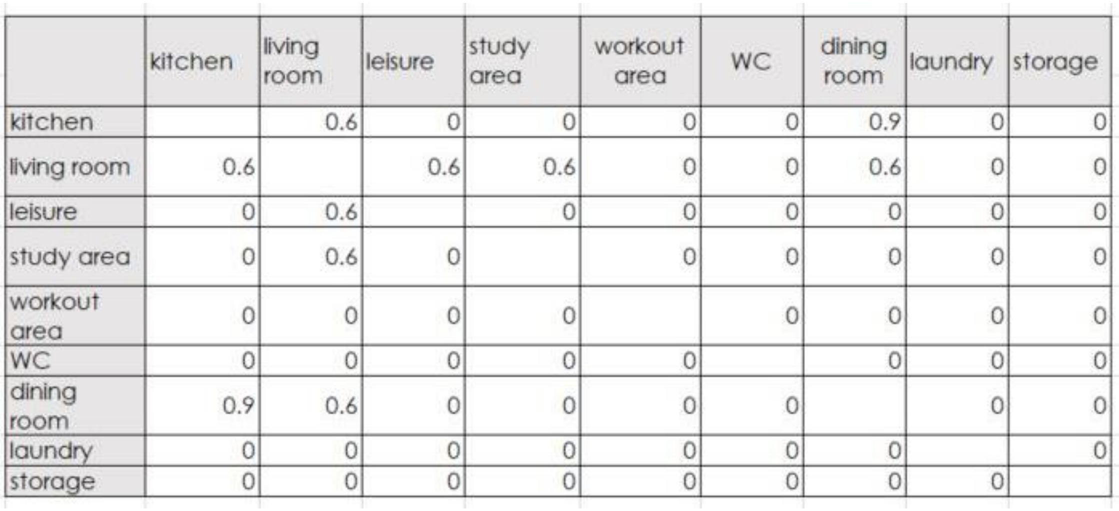
In order to construct the bubble diagram the REL-chart has to be decided first. The REL-chart is actually a chart that indicated the relationship (proximity) of one room to another. A new REL-chart has to be made for each unit (studio, shared apartment, common facilities). Below are presented the REL-charts for each unit (A, B, C, D).

REL-chart



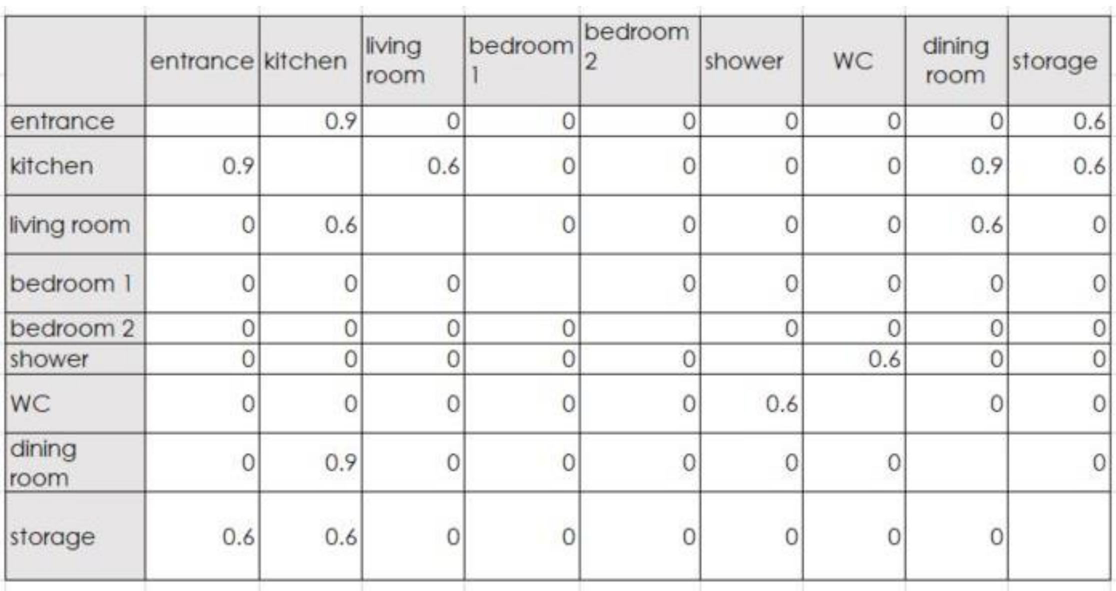
	entrance	kitchen	coach	bed	rest room	desk	storage
entrance		0.6	0	0	0	0	0.6
kitchen	0.6		0.6	0	0	0	0.6
coach	0	0.6		0	0	0.9	0
bed	0	0	0		0	0	0
restroom	0	0	0	0		0	0
desk	0	0	0.9	0	0		0
storage	0.6	0.6	0	0	0	0	

Figure 41: REL-chart for studios (type A)



	kitchen	living room	leisure	study area	workout area	WC	dining room	laundry	storage
kitchen		0.6	0	0	0	0	0.9	0	0
living room	0.6		0.6	0.6	0	0	0.6	0	0
leisure	0	0.6		0	0	0	0	0	0
study area	0	0.6	0		0	0	0	0	0
workout area	0	0	0	0		0	0	0	0
WC	0	0	0	0	0		0	0	0
dining room	0.9	0.6	0	0	0	0		0	0
laundry	0	0	0	0	0	0	0		0
storage	0	0	0	0	0	0	0	0	

Figure 42: REL-chart for shared apartments (type B)



	entrance	kitchen	living room	bedroom 1	bedroom 2	shower	WC	dining room	storage
entrance		0.9	0	0	0	0	0	0	0.6
kitchen	0.9		0.6	0	0	0	0	0.9	0.6
living room	0	0.6		0	0	0	0	0.6	0
bedroom 1	0	0	0		0	0	0	0	0
bedroom 2	0	0	0	0		0	0	0	0
shower	0	0	0	0	0		0.6	0	0
WC	0	0	0	0	0	0.6		0	0
dining room	0	0.9	0	0	0	0	0		0
storage	0.6	0.6	0	0	0	0	0	0	

Figure 43: REL-chart for common facilities (type C)

	reception	living room	hall	lecture room	restaurant	WC	café	storage	cinema	entrance	offices
reception		0	0	0	0	0	0	0	0	0.9	0
living room	0		0.3	0	0	0	0	0	0	0.6	0.6
hall	0	0.3		0	0.6	0	0.6	0	0	0.9	0
lecture room	0	0	0		0	0	0	0	0	0	0
restaurant	0	0	0.6	0		0	0.9	0	0	0	0
WC	0	0	0	0	0		0	0	0	0	0
café	0	0	0.6	0	0.9	0		0	0	0	0
storage	0	0	0	0	0	0	0		0	0	0
cinema	0	0	0	0	0	0	0.3	0		0	0
entrance	0.9	0.6	0.9	0	0	0	0	0	0		0.6
offices	0	0.6	0	0	0	0	0	0	0	0.6	

Figure 44: REL-chart for common facilities at ground floor (type D)

3.9 Illuminance requirements

Daylight can contribute significantly to the lighting needs of any type of building. The evaluation of daylight provision should make account of the availability of daylight at the site in addition to accounting for the properties of the space (e.g. external obstruction, glazing transmittance, thickness of walls, internal partition and surface reflectance, furniture, etc).

Criteria for daylight provision
A space is considered to provide adequate daylight if a target illuminance level is achieved across a fraction of the reference plane within a space for at least half of the daylight hours. The reference plane of the space is located 0,85 m above the floor. Values for target illuminances, minimum target illuminances and fractions of reference plane are given in Table A.1.

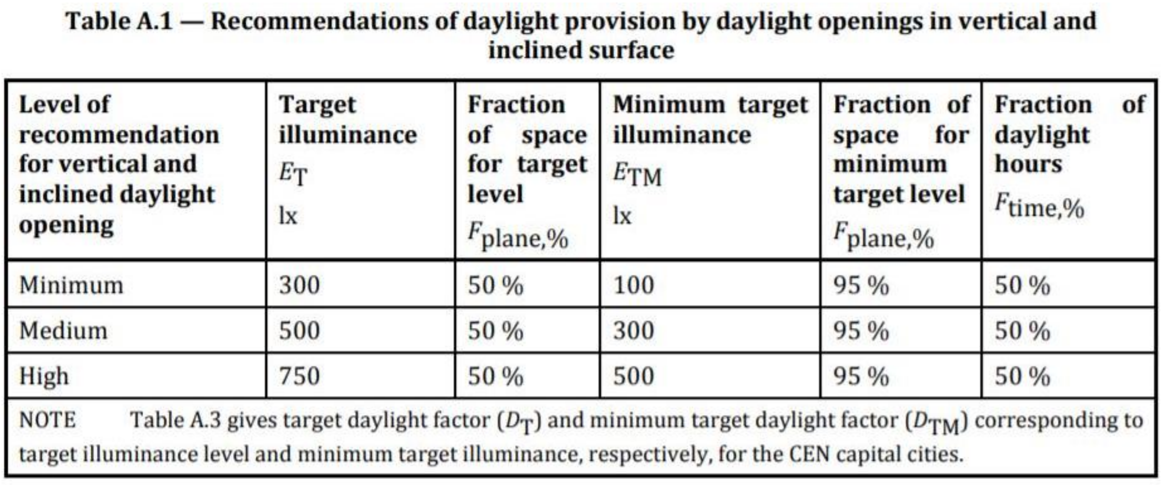


Table A.1 — Recommendations of daylight provision by daylight openings in vertical and inclined surface

Level of recommendation for vertical and inclined daylight opening	Target illuminance E_T lx	Fraction of space for target level $F_{plane,\%}$	Minimum target illuminance E_{TM} lx	Fraction of space for minimum target level $F_{plane,\%}$	Fraction of daylight hours $F_{time,\%}$
Minimum	300	50 %	100	95 %	50 %
Medium	500	50 %	300	95 %	50 %
High	750	50 %	500	95 %	50 %
NOTE Table A.3 gives target daylight factor (D_T) and minimum target daylight factor (D_{TM}) corresponding to target illuminance level and minimum target illuminance, respectively, for the CEN capital cities.					

Figure 45: Recommendations of daylight provision [50]

Daylight Provision Calculation Methods
The following methods to assess daylight provision to the interior, using validated software, are possible:

Method 1: Calculation method using daylight factors on the reference plane.
Method 2: Calculation method of illuminance levels on the reference plane using climatic data for the given site and an adequate time step.

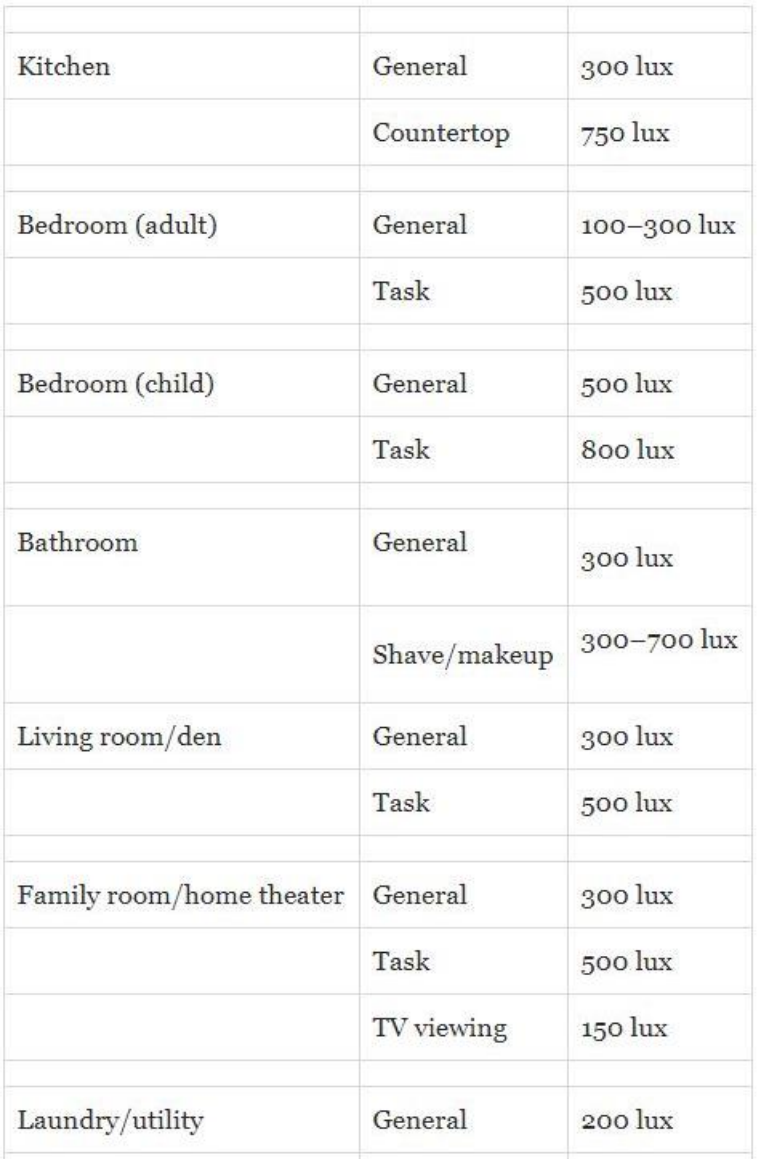
Calculation method using illuminance level (method 2)
Method 2 was selected as the calculation method to be performed in this project. This method requires the use of a detailed daylight calculation method where hourly internal daylight illuminance values for a typical year are computed using hourly sky and sun conditions derived from climate data appropriate to the site. This calculation method determines daylight provision directly from simulated illuminance values on the reference plane.

Calculation grids
To determine target values of illuminances and daylight factors, it is necessary to perform calculations over the entire reference plane, located 0,85 m above the floor of the area to which they apply. The points at which calculations should be carried out are defined in Formula (B.1). Grid cells approximating to a square are preferred, the ratio of length to width of a grid cell shall be kept between 0,5 and 2. The maximum grid size shall be:

$$p = 0{,}5 \times 5^{\log_{10}(d)} \quad \text{(B.1)}$$

[48]

Other guidelines regarding minimum recommended lighting levels for residential spaces are presented below [49]:



Kitchen	General	300 lux
	Countertop	750 lux
Bedroom (adult)	General	100–300 lux
	Task	500 lux
Bedroom (child)	General	500 lux
	Task	800 lux
Bathroom	General	300 lux
	Shave/makeup	300–700 lux
Living room/den	General	300 lux
	Task	500 lux
Family room/home theater	General	300 lux
	Task	500 lux
	TV viewing	150 lux
Laundry/utility	General	200 lux

Figure 46: Minimum recommended lighting levels for residential spaces [49]

After taking into consideration the above mentioned guidelines it was decided to categorize the illuminance requirements into three main categories. The illuminance requirements for the three units were formed as followed:

Illuminance categories:

	Illuminance weight factors	min lux	target lux
Cat. 1	low illuminance	100	300
Cat. 2	medium illuminance	300	500
Cat. 3	high illuminance	500	750

Figure 47: illuminance categories with their respective minimum and target lux values

Below are presented the categorization of rooms for each type:

Room	category
kitchen	2
coach	2
bed	2
restroom	1
desk	3
storage	1

Figure 48: illuminance requirements for studios

Room	category
kitchen	2
living room	2
bedroom 1	3
bedroom 2	3
shower	1
WC	1
dining room	2
storage	1

Figure 49: illuminance requirements for shared apartments

Room	category
kitchen	2
living room	2
leisure	2
study area	3
workout area	2
WC	1
dining room	2
laundry	1
storage	1

Figure 50: illuminance requirements for common facilities

Room	category
reception	2
living room	2
hall	1
lecture room	3
restaurant	3
WC	1
café	3
storage	1
cinema	1
entrance	1
offices	3

Figure 51: illuminance requirements for common facilities at ground floor

Daylight simulation

For daylight simulation the plugins Honeybee and Ladybug (both developed by M. Roudsari) are recommended to be used because they communicate smoothly Grasshopper, are producing reliable results and are popular among architects. In particular, Honeybee and Ladybug are Python librariesy to create, run and visualize the results of daylight (RADIANCE) and weather files (EnergyPlus) respectively [50].

3.10 Tool development

Overview

The designer inserts existing geometry of the building and desired proximity and illuminance requirements of the rooms. The tool finds the optimal position of the rooms regarding proximity and illuminance requirements in the given boundaries. The configuration produced serves as the starting point for the designer to further develop the layout into a proper floorplan. In the next pages each milestone is presented in more detail. In short the tool development stages are:

1. Inputs
2. Daylight simulation
3. Optimal configuration
4. Overlap
5. Outputs

The tool comprises of many components that made urgent to implement organisation rules (chapters, groups, colour coding). There is colour coding for the input, data, processes and output and extensive use of groups and notes throughout the Grasshopper script so as to make it more clear to the user. All screenshots from the final Grasshopper script are attached in the appendix. In the report only some examples are presented whenever it is useful to visualize a process. In order to present the tool as clear as possible the smallest application (unit A) is presented in detail in the following paragraphs. For the rest units only the initial and final stages are presented .

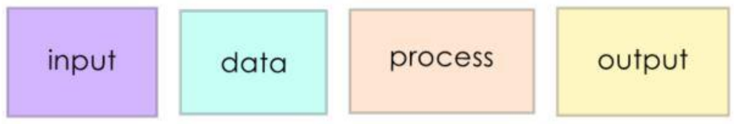


Figure 52: colour coding rule

A flowchart of the tool is presented below:

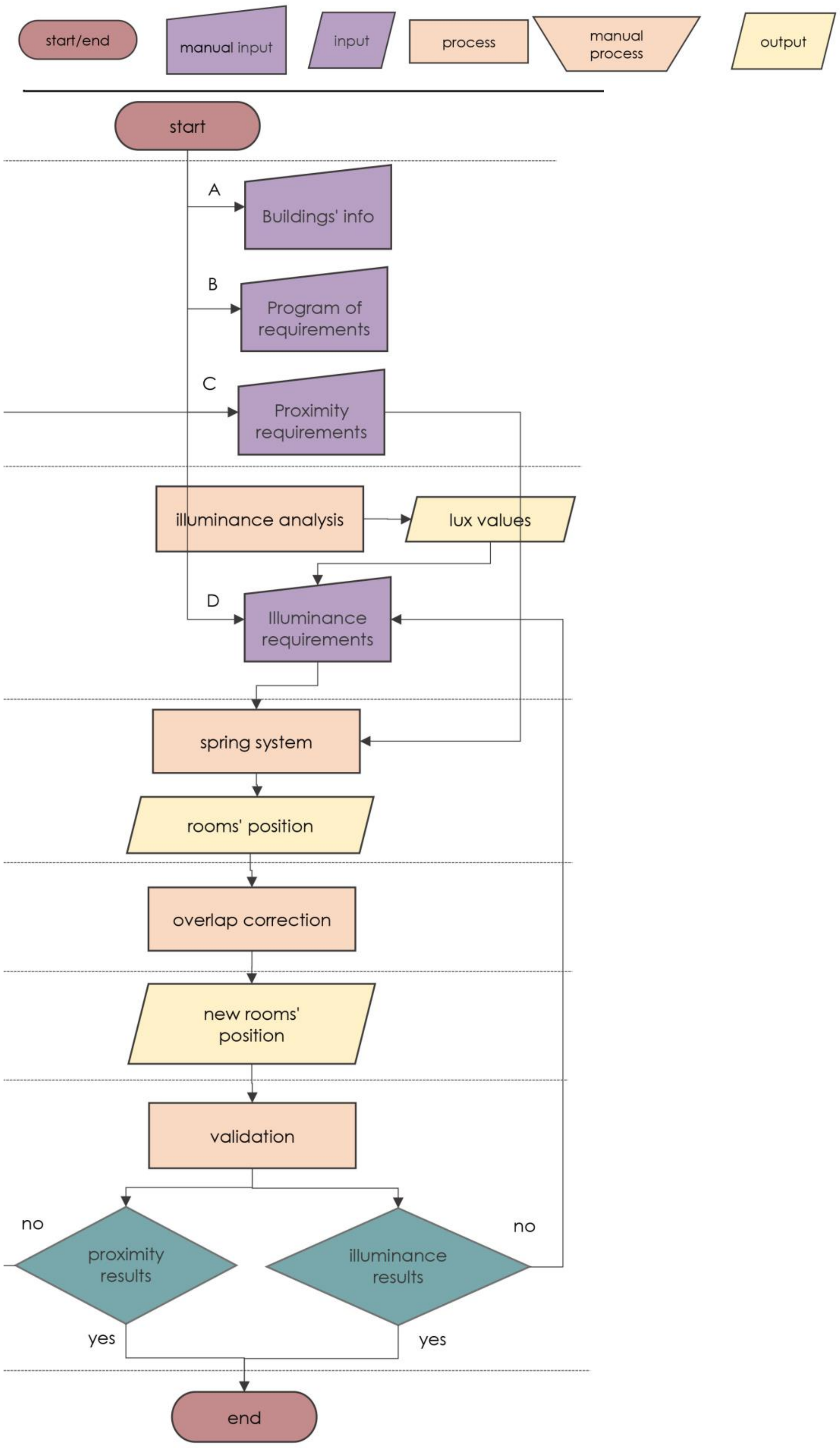


Figure 53: Flowchart of the tool

Script overview:

1. INPUTS
    - Program of requirements
        - Room centroids
        - Room areas
    - Building's info
    - Proximity requirements
        - Proximity connections
        - Proximity categorization
    - Illuminance requirements
        - Illuminance categories
        - Illuminance connections

2. DAYLIGHT SIMULATION
    - 1 Create apartment box
    - 2 Create zone masses
    - 3 Add glazing
    - 4 Generate test points on grid
    - 5 Generate climate-based sky
    - 6 Grid-based simulation recipe
    - 7 Daylight simulation
    - 8 Legend customization
    - 9 Recolour mesh
    - 10 Save analysis' files

3. OPTIMAL CONFIGURATION
    - Proximity
    - Illuminance
    - Kangaroo engine
    - Trails of moving points
    - Overlap correction
        - Circle collision
        - Trails of moved circles

4. OUTPUTS
    - Bubble diagram with lux values

5. CALCULATIONS
    - Geometry related calculations
        - Set room dimensions
        - Circles with predefined areas
        - Middle point of curve
        - Surface from curve
    - Mathematical calculations
        - Radius calculation

        - Round number to floor
        - Mean of a number
        - List length

6. EVALUATION
    - Proximity results
    - Illuminance results
        - Rooms to be checked
        - Test points included in circle
        - Finding the index
        - Put items in list

3.10.1 Inputs

The user has to insert some inputs into the Grasshopper script. A handy way to do it is by referencing geometry created in Rhinoceros environment in Grasshopper. These inputs are:

Program of requirements

- rooms' centroids
- rooms' areas

Buildings' info

- windows' position
- entrance's position
- apartment boundaries
- orientation
- location
- apartment's height
- windows' surfaces and position

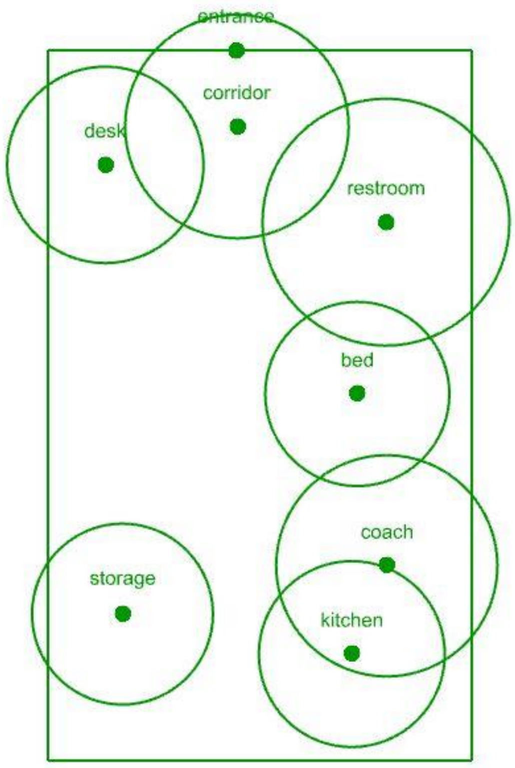
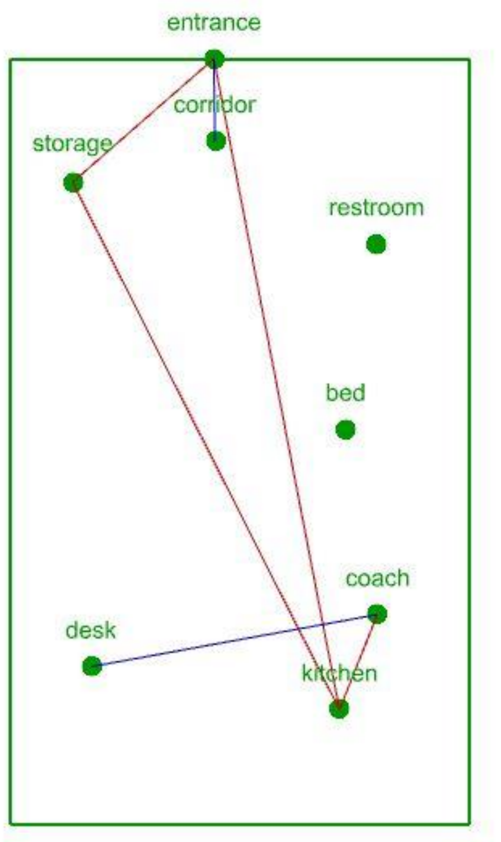


Figure 54: some of the inputs as seen in grasshopper (entrance position, boundary, rooms' centroids)

Proximity requirements

The creation and categorization of the connections between the rooms are set in the script. As for the creation, the connectivity of the rooms is represented as lines that connect all centroids of the rooms. However, it is up to the user to decide which connections will belong to each category (hierarchy). In particular, there are three types of connections: strong connections, medium connections and weak connections with the corresponding proximity factor (weight).

The desired proximity between rooms is expressed as lines (euclidean distances) that connect the points (centroids). The creation of the lines are pre-set in the Grasshopper script. However, the user can modify (add/delete) connections.



Node 1	Node 2	Connection
Coach	Desk	strong
Kitchen	Entrance	medium
Storage	Entrane	medium
Kitchen	Storage	medium
Kitchen	Coach	medium
Entrance	Corridor	strong
Kitchen	Coach	medium

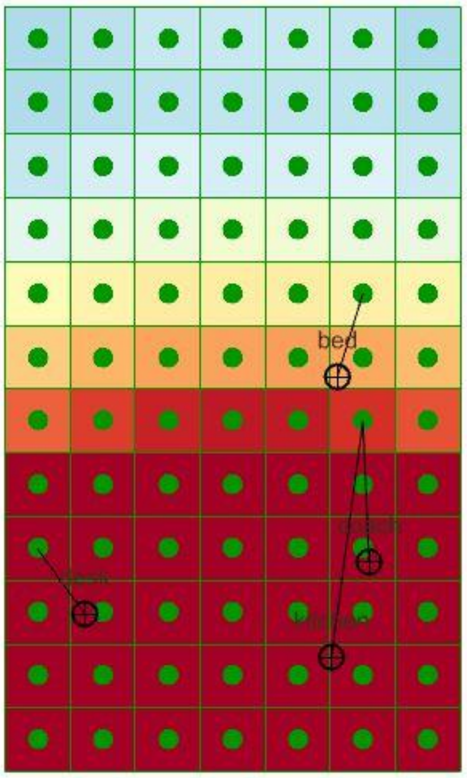
Figure 55: proximity requirements (strong connections in blue, medium connections in red)

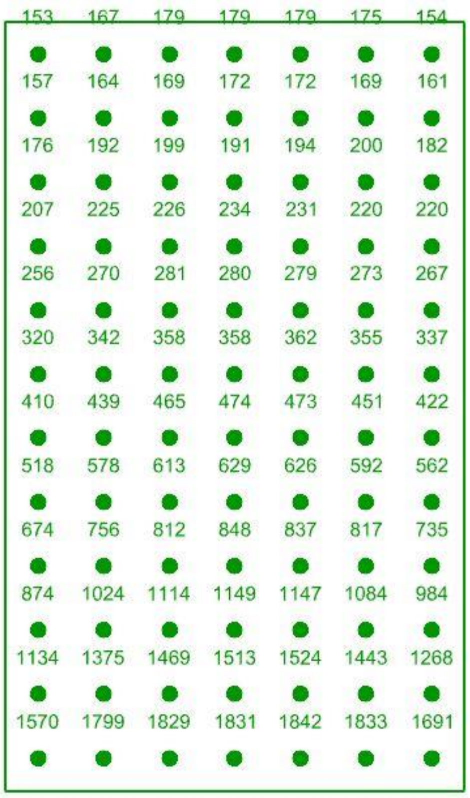
Category	Prox. factor	Connection type
0	0.0	No
1	0.3	Weak
2	0.6	Medium
3	0.9	Strong

Figure 56: Hierarchy of proximity connections

Illuminance requirements

In order to design the illuminance requirements first the illuminance analysis has to be performed so as to obtain the illuminance values for the floor surface. A grid of 0.50x0.50m is made and in the center of each square a test point is created. The analysis is presented in more detail in the next paragraph. Each room has to be in certain illuminance limits according to regulations. To fulfill this requirement the test point that belongs to the desired category and is the closest to the room is selected. Then the same principle is used and a connection(line) is drawn from the room centroid to the closest point of the test point with the desired illuminance value.





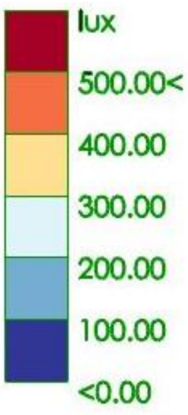


Figure 57: legend of the illuminance analysis

Figure 58: all test point with their corresponding lux values

Figure 59: points in black: centroids of rooms, points in green: test points, lines: illuminance connections

	Illuminance weight factors	min lux	target lux
Cat. 1	low illuminance	100	300
Cat. 2	medium illuminance	300	500
Cat. 3	high illuminance	500	750

Figure 60: illuminance categories with their respective minimum and target lux values

3.10.2 Daylight simulation

For daylight analysis the plugins for Grasshopper called "Honeybee" and "Ladybug" are required. The two plugins work together and can be used to perform daylight simulation analysis. In order for them to run 3D geometry is needed. After preparing the geometry to be tested considering the z axis, setting the windows' size, location and orientation all necessary inputs are ready to be fed to the definition. In more detail, the inputs are:

- The boundary geometry of the tested rooms (as breps)
- The window surfaces (on the breps' surfaces)
- The north vector
- The EPW file of the city

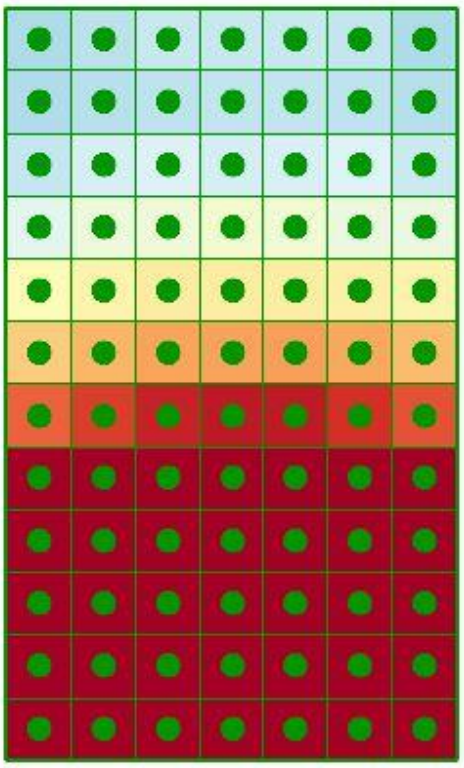
The definition consists of 10 steps (the last three of them are optional). To begin with, the tested rooms have to be transformed into zones. Then the zones are connected to glazing and both are passed to a grid component to create the test points based on the grid. This component is also connected to a ladybug component that receives the location and the orientation of the building, as well as the duration of the analysis. The next step is to plug the necessary data to the daylight analysis engine. The daylight analysis gives as outputs a coloured grid as a mesh together with the corresponding legend, and the illuminance level of every zone.

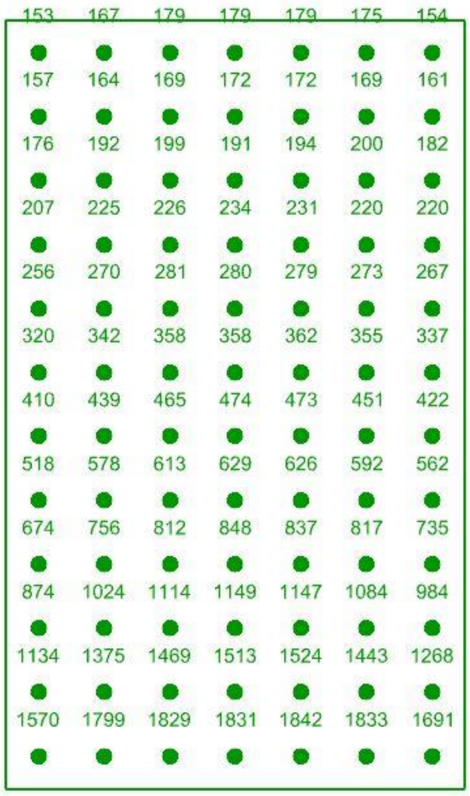
The Honeybee definition consists of 10 steps

1. Create apartment box
2. Convert geometry to Honeybee zone
3. Add custom windows
4. Generate test points
5. Set location, orientation, date and time
6. Prepare the grid based simulation
7. Run the analysis
8. Customize legend (optional)
9. Visualize the results (optional)
10. Save analysis files (optional)

From the daylight analysis the outputs are:

- a colored grid as a mesh
- the corresponding legend
- the test points of the grid
- the illuminance values of the test points in lux





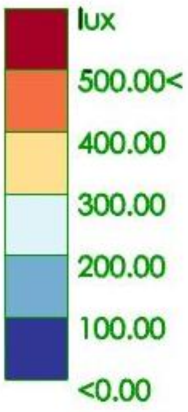


Figure 61: colored mesh result of illuminance analysis

Figure 62: all test point with their corresponding lux values

3.10.3 Optimal configuration

A simulation engine for Grasshopper called KangarooPhysics is required to perform the physics simulation. In the newest version of Grasshopper KangarooPhysics is already built in. This engine has its own components that perform certain tasks. In order for the engine (Kangaroo solver) to work all components have to be plugged in the solver. As inputs to the components are given:

- All connections (both proximity and illuminance connections in the form of lines)
- All room centroids (in the form of points)
- All anchor points

A live physics engine for Grasshopper called Kangaroo is required. The algorithm presented in paragraph "Force directed graph drawing" explains the iterative process that this engine performs, but it does not add any repulsion forces. This engine has its own components and in order for the engine to work all components have to be plugged in the solver. The Kangaroo components used are:

- Springs

  Springs represent the connections between the rooms and are categorized according to which type of connection correspond to. This component simulates Hooke's law. The spring has the same length as the line that connects the rooms' centroids. Its rest length is zero. Its stiffness value is analogous with the type of connection; strong connections correspond to smaller stiffness value whereas medium connections to larger. The values used are:

  Rest length = 0
  Damping constant = 10
  No elasticity
  Stiffness values are set according to connection types, so:
  Strong connection = 0.9
  Medium connection = 0.6
  Weak connection = 0.3

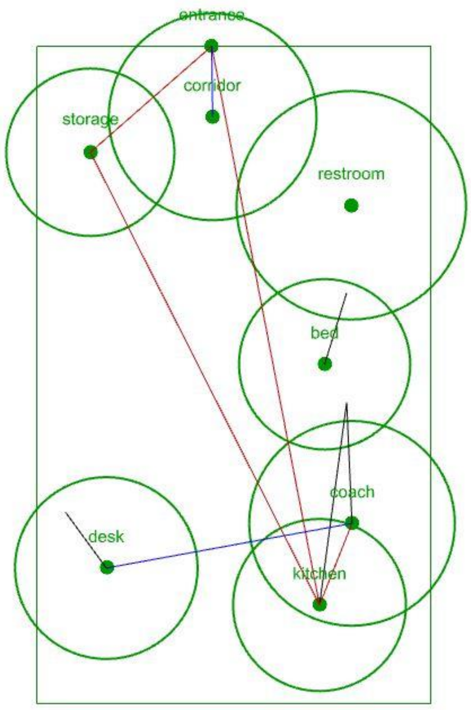
- Anchor points

  Anchor points are the points that should not be moved from their original position (usually entrance and test points). Entrance is assumed to remain fixed throughout the renovation process. Its position plays another significant role; it is the reference point for the layout arrangement.

  Outputs:
- centroids' positions at equilibrium state
- kinetic energy before and after the release

Before the simulation starts, the total potential elastic energy of the system is calculated by the solver. After the simulation the total kinetic energy is set to zero, where the system reaches equilibrium and the solver produces the new centroids' positions.

After the physics analysis is performed the output is the relaxed (moved) points (rooms' centroids) and the total kinetic energy. While running the analysis all intermediate points' position until reaching their final position are recorded. This produces the trails of the points. Trails are worth noting because they give an intuition of how the forces interfere with each other and also indicate in a clearer way the initial and final points' positions.



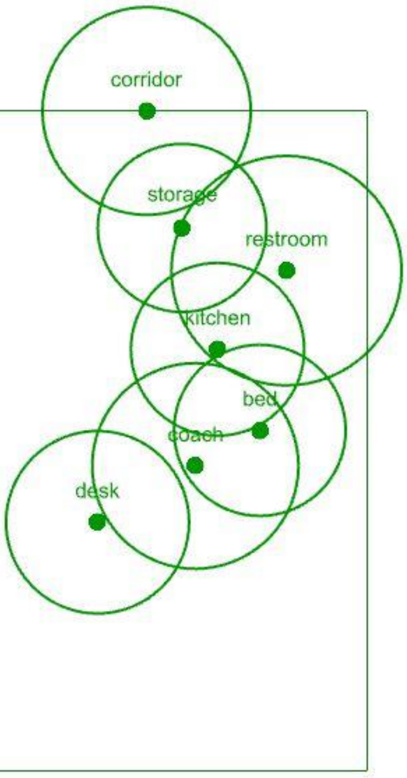


Figure 63: system's input

Figure 64: system's output

Overlap correction

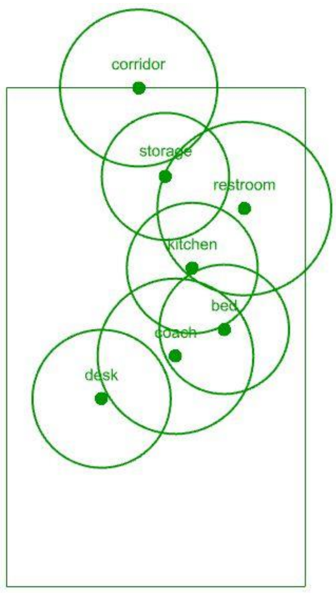
As mentioned before, the physics simulation part produces as output new positions of the rooms' centroids. But the centroids are placed too close to one another (due to small rest length value). This has as a result the circles created to overlap with each other and with the boundary as well. One strategy to fix this is to use the Curve collide component of Kangaroo2. The collision definition rearranges the centroids' position until there is no more collision by moving them in a straight line as it can be seen in the pictures below.

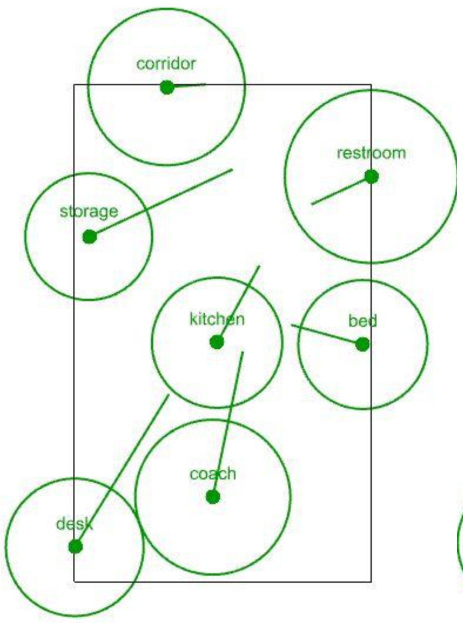
The inputs are:

- the relaxed points from physics simulation,
- the circles drawn around these points and
- the perimeter of the apartment.

The outputs are:

- The not overlapping circles
- Their centers





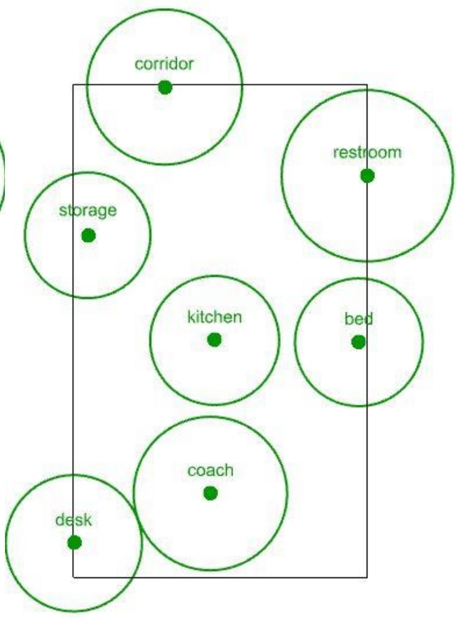


Figure 65: System's output

Figure 66: New positions of points

Figure 67: Move points with curve collide component of Kangaroo2

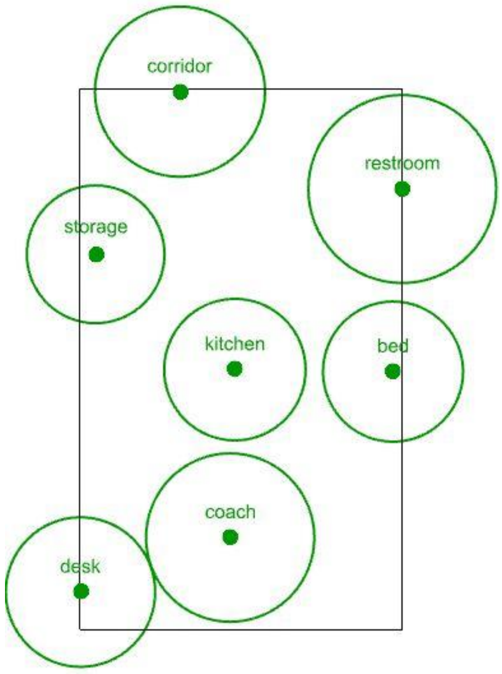
However this definition is not able to keep always all circles inside the apartment's boundaries. The overlap issue with circles could be avoided if instead of Kangaroo it was used the custom script in python described in "force directed graph drawing". That script takes into consideration the distance between the points and if it is less than the sum of their radii it creates a repulsion force. With the same logic the overlap issue with the boundary could be dealt by creating an additional connection. The closest point between the boundary and each centroid would be selected and in each iteration it would be checked whether this distance is smaller than the radius of the room or not. If so, an extra repulsion force would be created to avoid overlap with the boundary.

3.10.4 Outputs

The objective of the tool is to find suitable positions for the rooms so as to fulfill their proximity and illuminance requirements set by the user. The form of the output was selected to be a bubble diagram, because it is usual and convenient for architects to use during the early design stages. So, the output of Cochleas is a bubble diagram that includes:

- rooms' positions
- rooms' tags
- bubble diagram with circles' center being the centroid and its area to be the required area

It is also possible to include the illuminance value of each room. The way it is calculated is described in detail in "Evaluation" chapter.



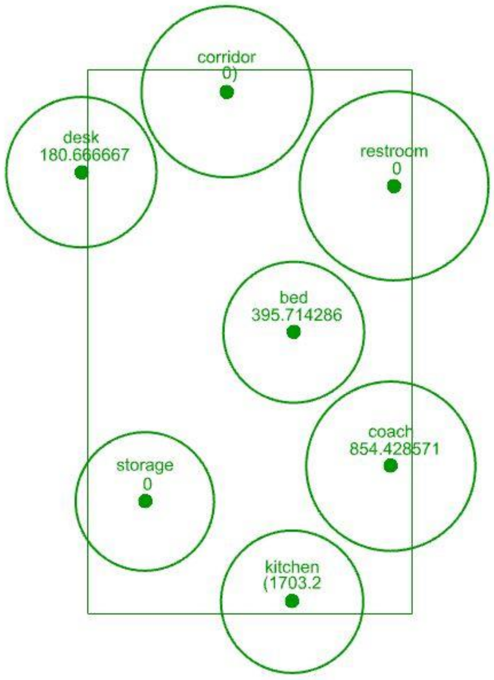


Figure 68: Final bubble diagram with tags

Figure 69: Final bubble diagram with tags and lux values

3.10.5 Calculations

From the inputs inserted it is essential to execute some calculations in order to obtain data that will be used in other definitions of the script. Components of Grasshopper are used to execute calculations. In simple mathematical calculations GhPython component is used. The input data are pre-connected. The output data are used as inputs in other definitions throughout the script. These calculations can be divided into two categories geometry-related and plain mathematical ones:

Geometry-related calculations

- Set room dimensions (convert a circular area to a rectangular one with the same square footage)
- Create surface from a curve
- Create circles with predefined area
- Find the middle point of a curve

Mathematical calculations

- Calculate radius from fixed area
- Round a number to floor
- Find the length of a list
- Calculate the mean number

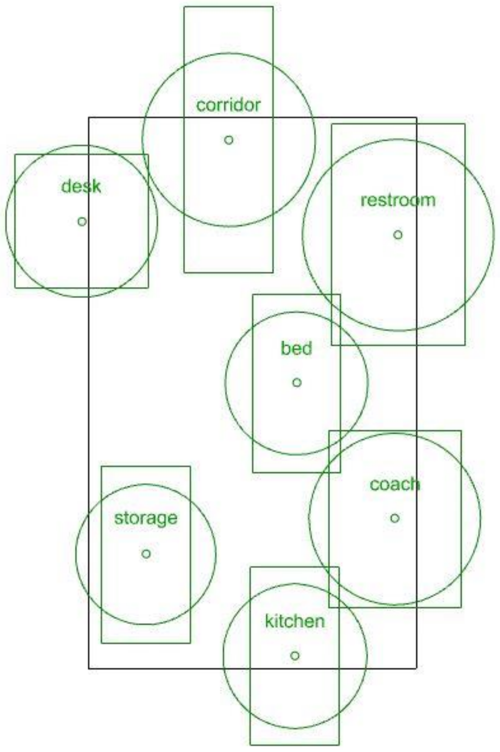


Figure 70: set room dimensions definition's output

3.11 Layout development

From bubble diagram to layout

In order to design a proper layout based on the bubble diagram produced by the tool the following 7-steps algorithm was developed and executed manually in Rhinoceros software:

1. The starting point is the bubble diagram (this is the output of the tool)
2. Then the bubbles (circles) are converted into rectangles. To set dimensions with the same area a definition called “Set room dimensions” was developed and can be found in appendix A.
3. Next step is to add existing external elements such as walls, main entrance and windows.
4. Some of the rooms require walls (eg restroom) and other do not (eg corridor). In this step it is determined which rooms require what amount of walls (0-4).
5. Afterwards the rooms with largest number of rooms (4) are move towards the inner corners of the boundary, so as to cast as much less shadow as possible to the rest rooms.
6. The rest rooms are placed beneath the closed rooms (rooms with 4 walls)
7. Last step is to add furniture. As discussed in paragraph “System of modules” a series of experiments were made for each unit based on a system of a square model of 0.50x0.50m.

Unit A – studio for one student

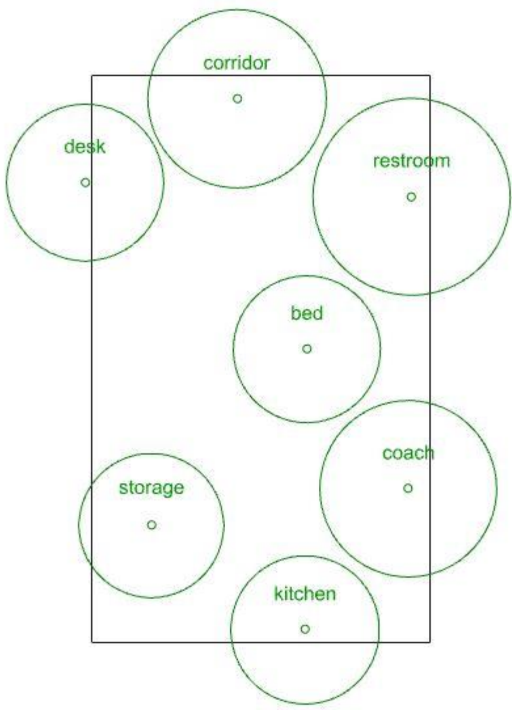


Figure 71: Step 1 - Bubble diagram (output of tool)

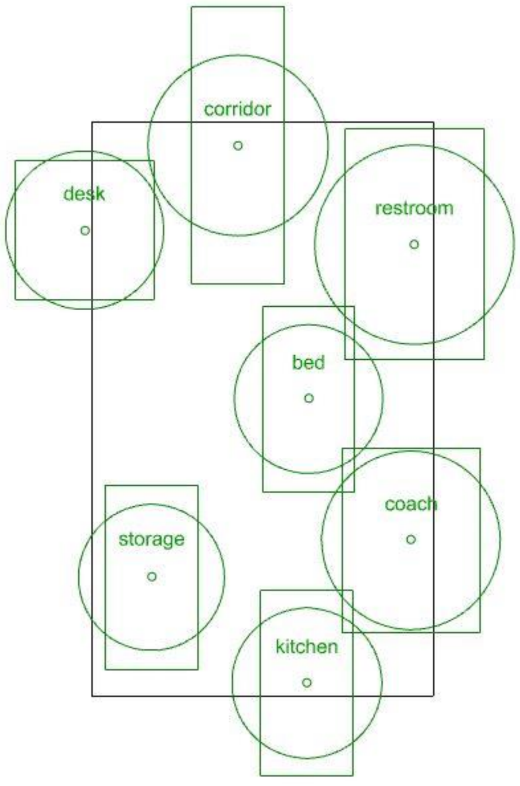


Figure 72: Step 2 - Convert bubbles to rectangles with the same area and set rooms' dimensions

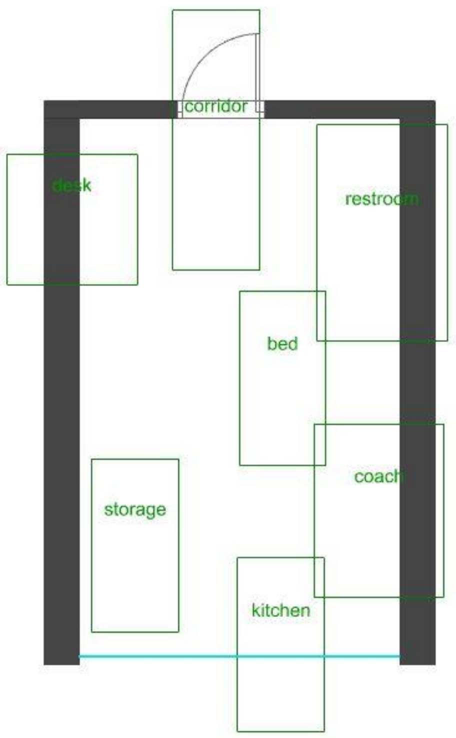


Figure 73: Step 3 - Add exterior elements (walls, entrance, windows)

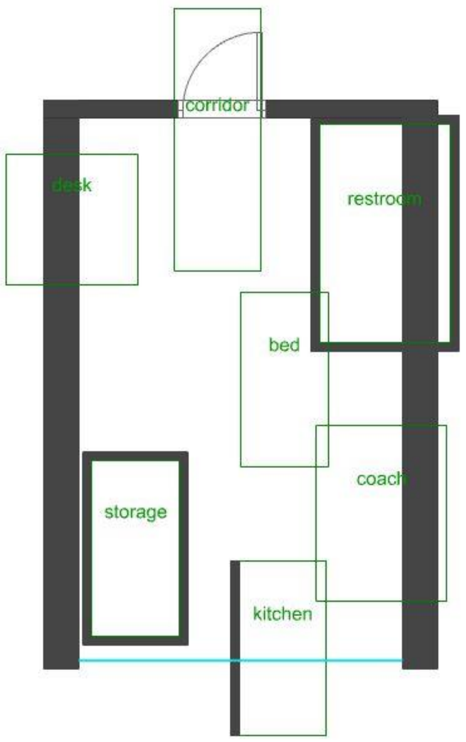


Figure 74: Step 4 - add necessary interior walls of the rooms

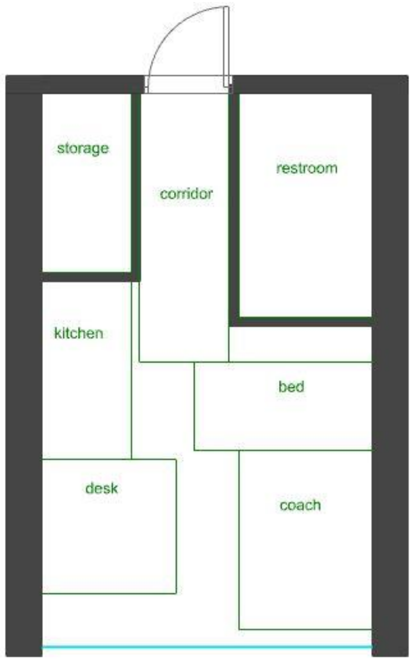


Figure 76: Step 5& 6 - Move rooms with 4 walls towards the inner corners of the boundaries so as not to cast much shadow to the rest rooms. Rest rooms are placed beneath them

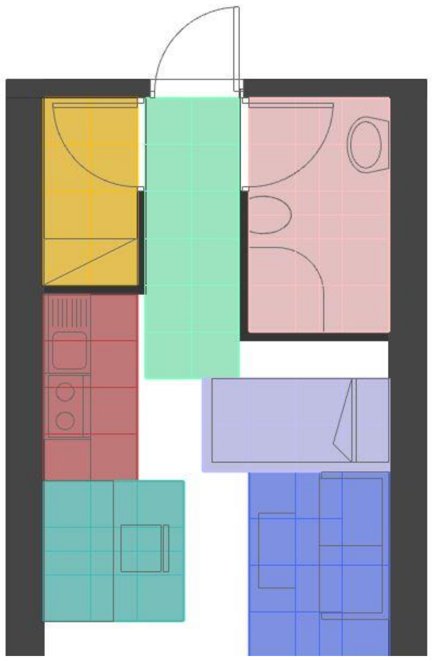


Figure 75: Step 7 - Add furniture. The furniture configuration emerged after a series of experimentations based on the system of modules with typical furniture (see paragraph System of modules)

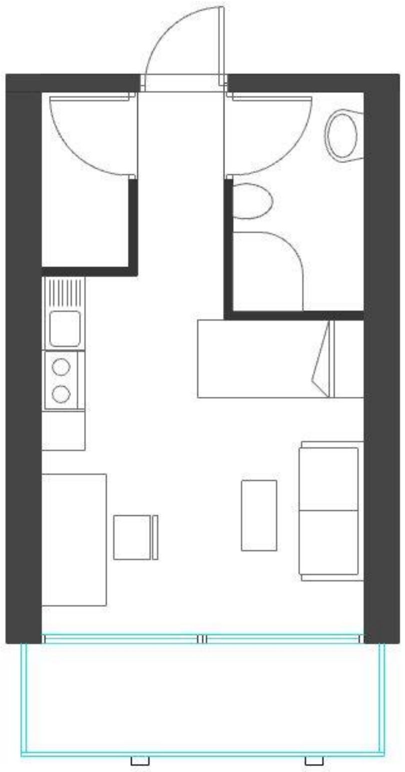


Figure 77: Final layout of unit A (studio for student) with recommended furniture arrangement and balcony

The same process was repeated for the rest unit types. Below are present the first and final stages only:

Unit B – shared apartment for two people

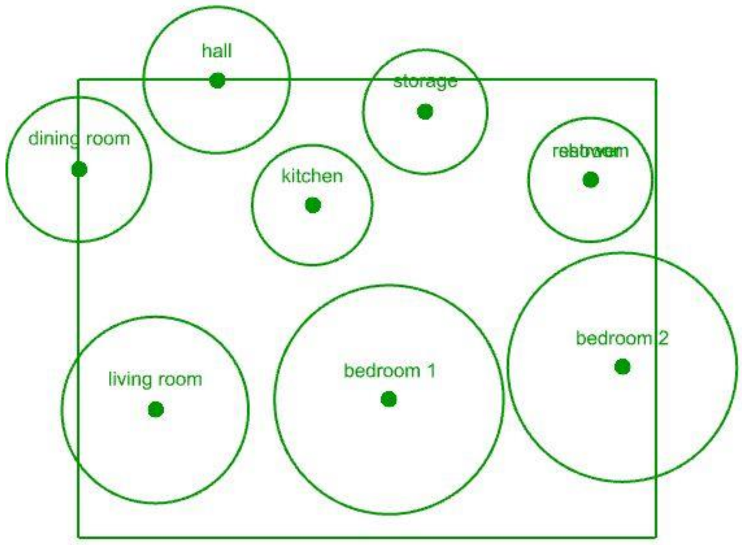


Figure 78: Unit B - Bubble diagram

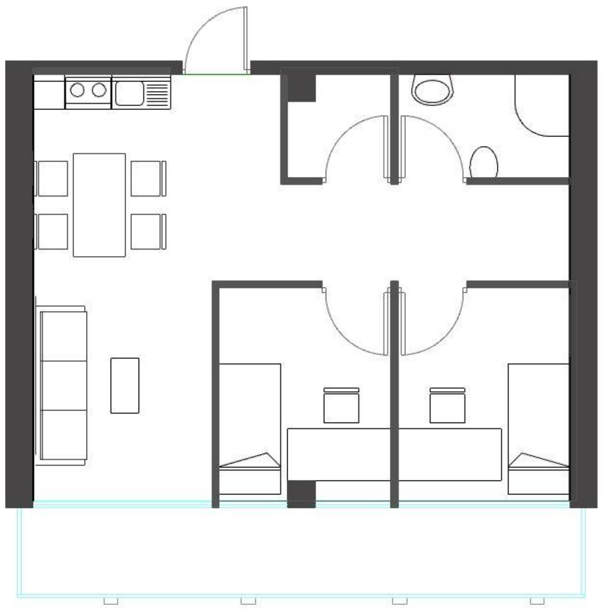


Figure 79: Unit B - Final layout

Unit C – common facilities for student housing

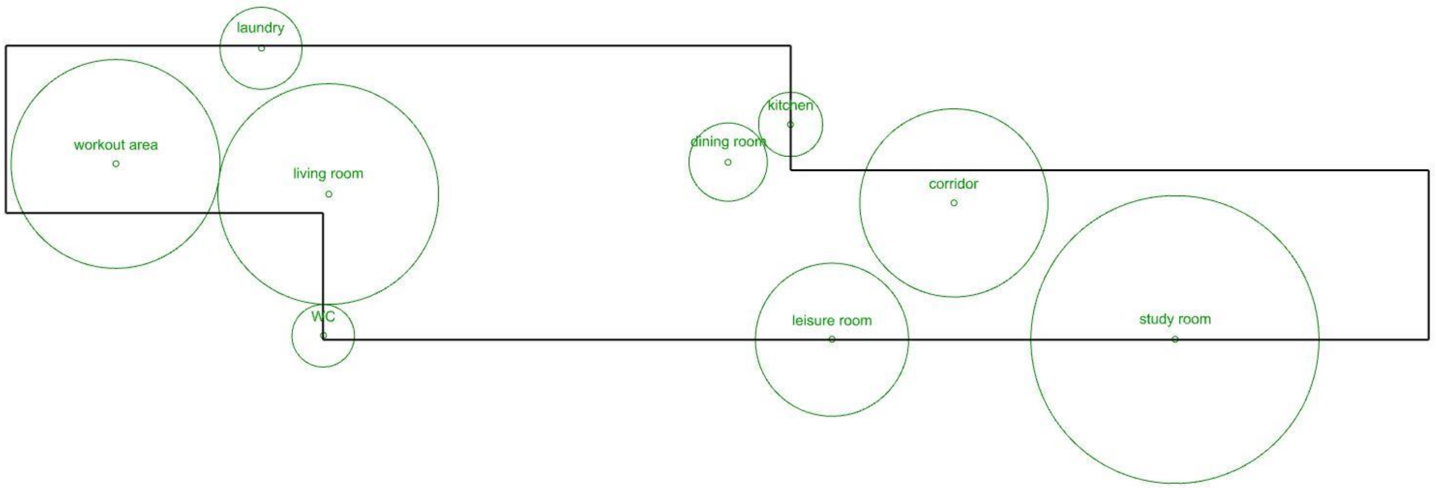


Figure 80: Unit C - Bubble diagram

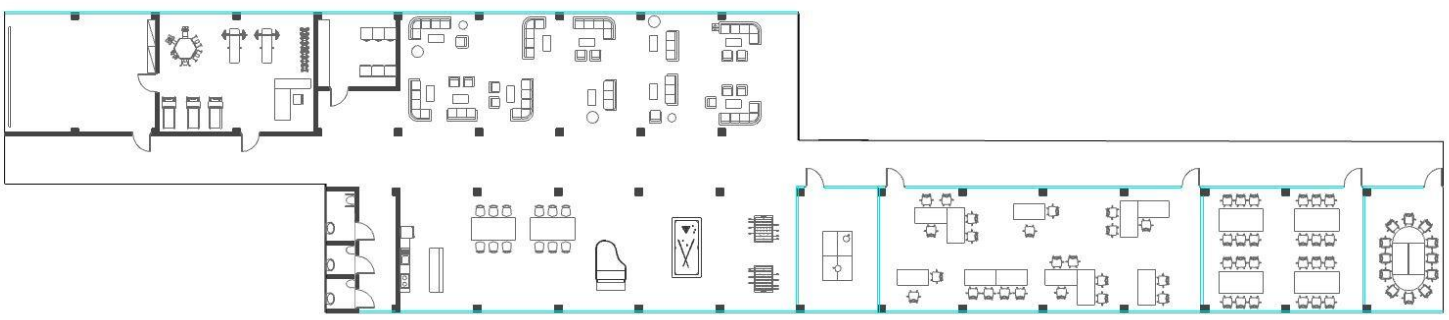


Figure 81: Unit C - Final layout

Unit D – common facilities for student housing at ground floor

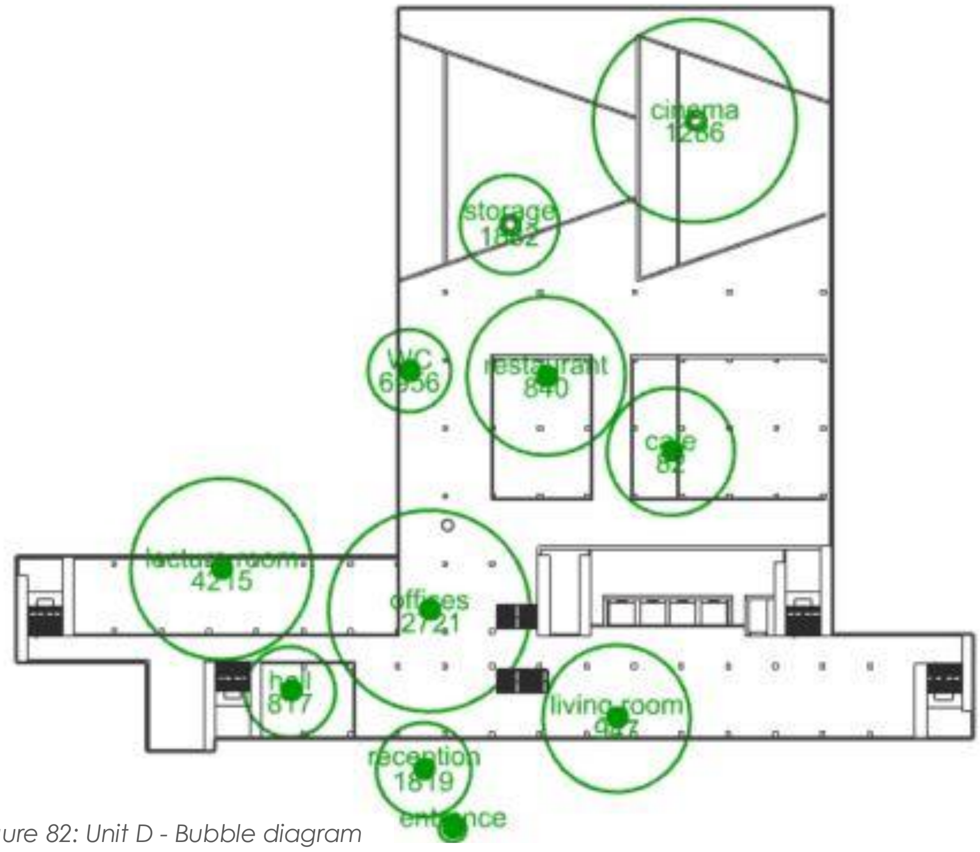


Figure 82: Unit D - Bubble diagram

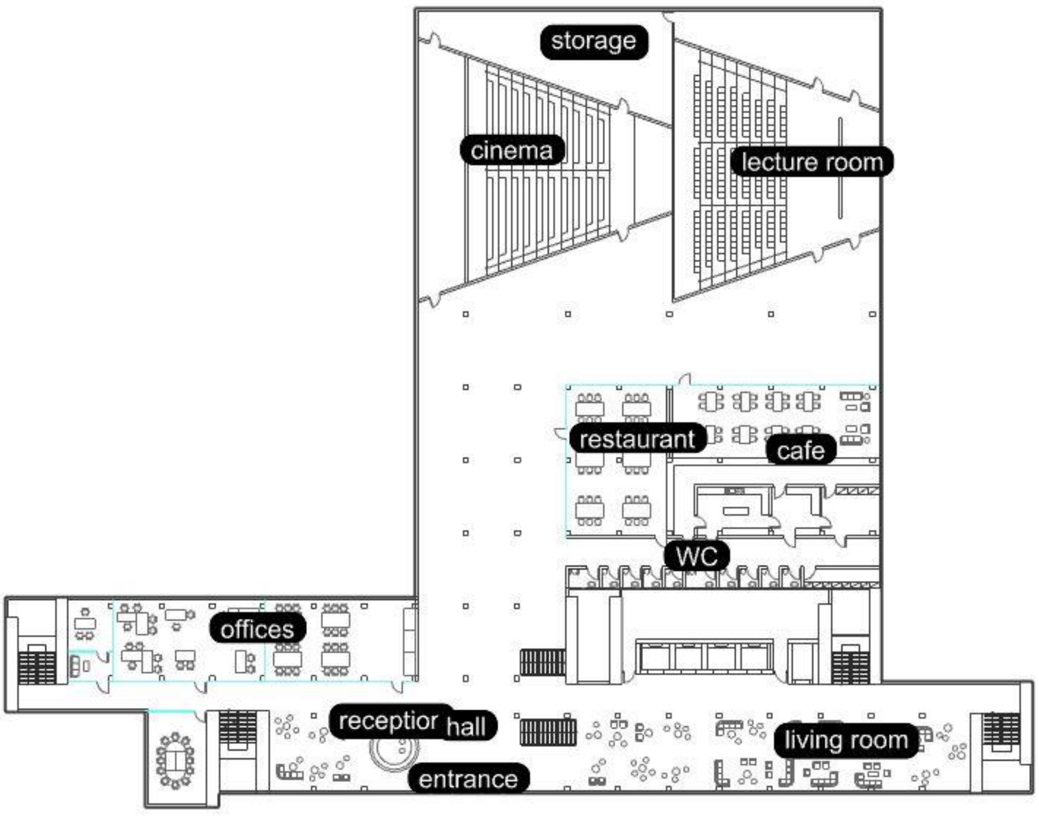
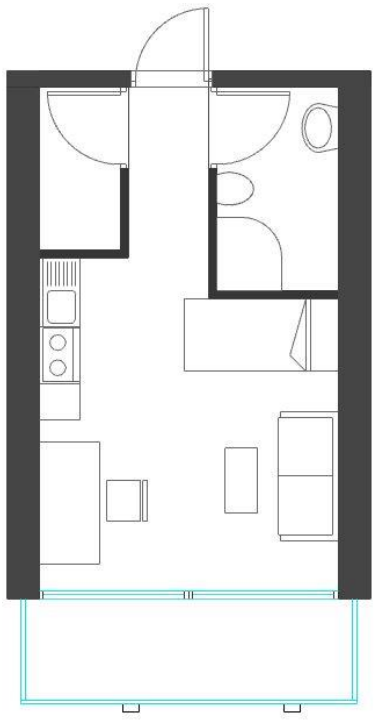


Figure 83: Unit D - Final layout

3.12 Design proposal

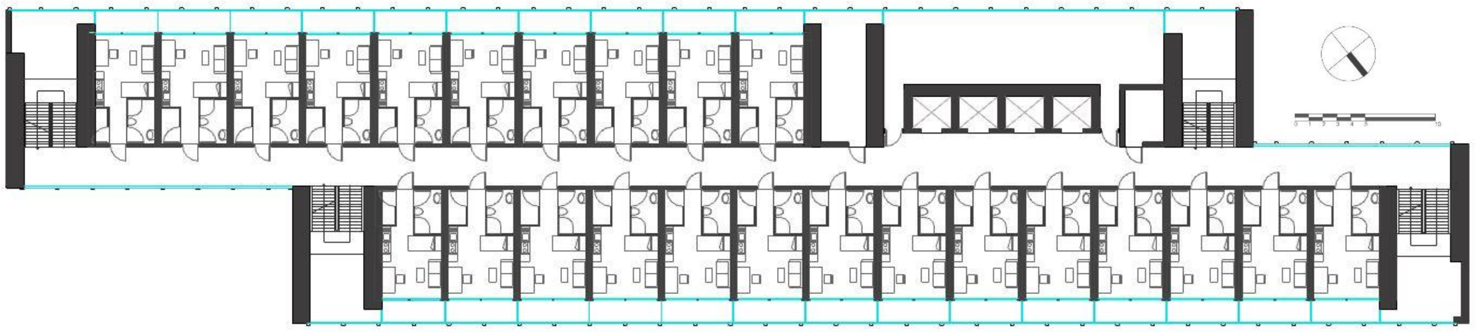
Below are presented the final floorplans for each type A, B, C and D. Units A and B are multiplied throughout the floor, whereas units C and D consist one floor anyways.

Unit A

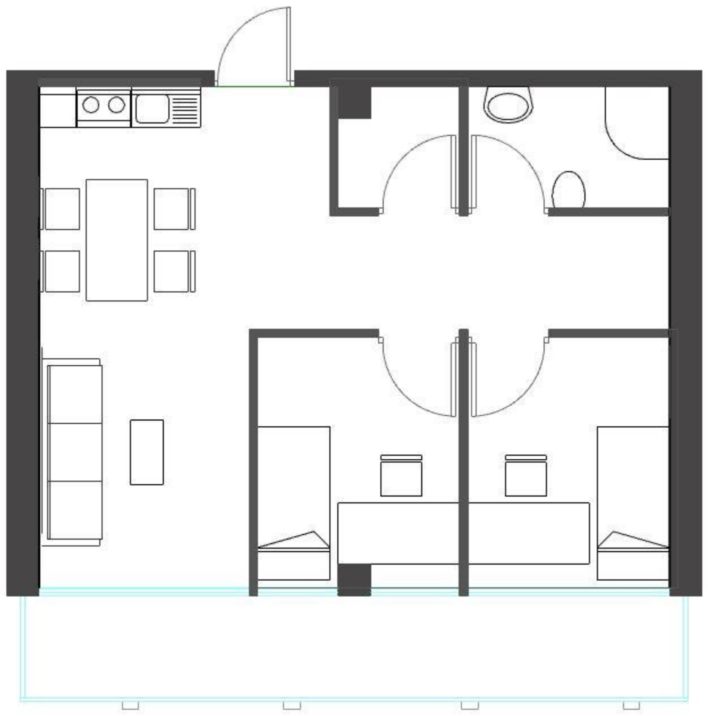


Studio for one person 23 m^2
24 studios per floor

Floortype A

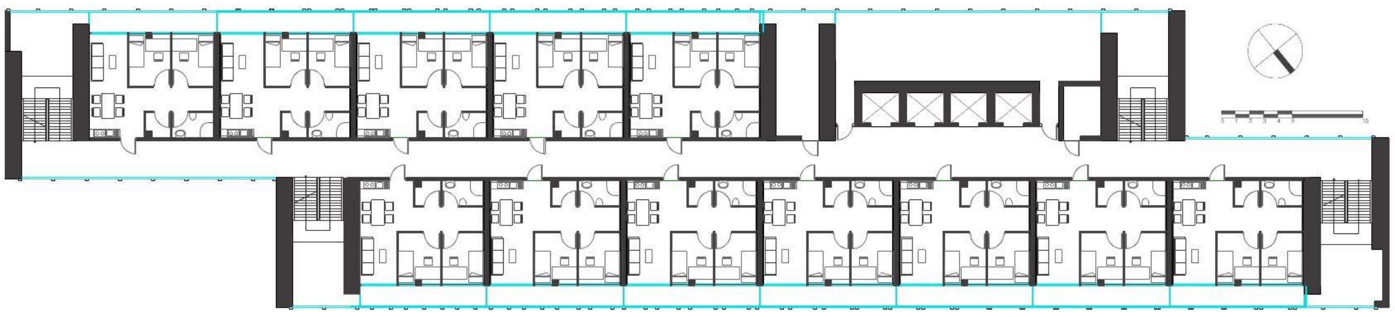


Unit B

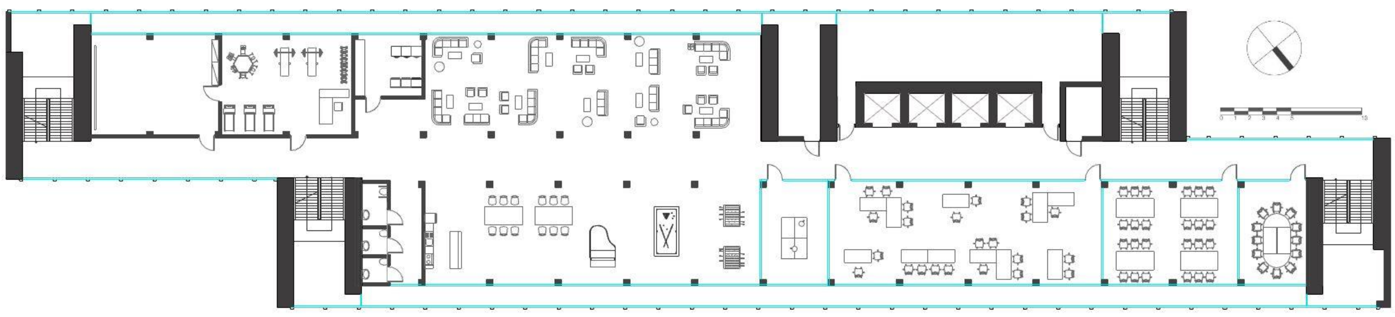


Shared apartment for two people 49 m^2
12 apartments per floor

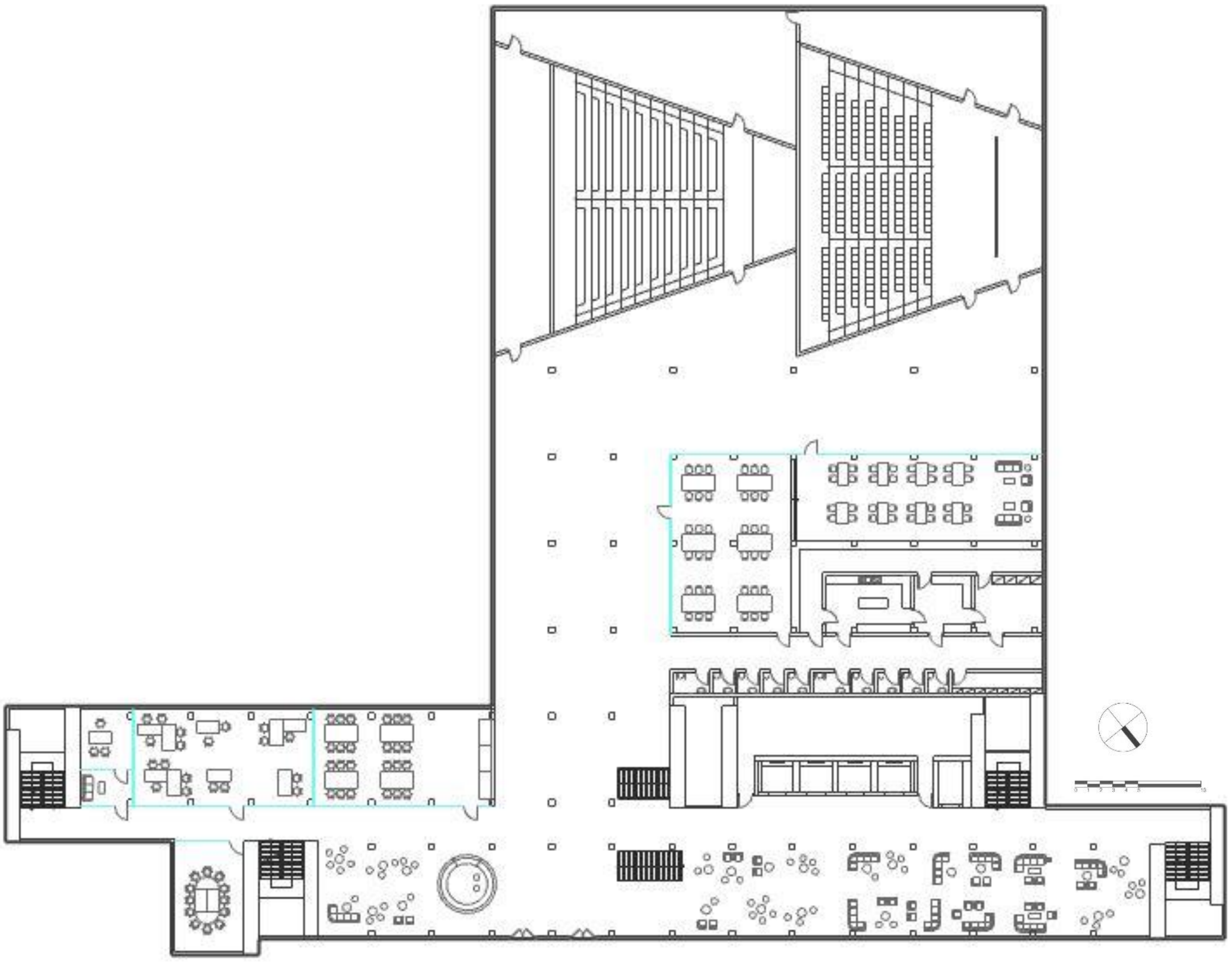
Floortype B



Floortype C



Floortype D



4

4 Evaluation

Evaluation is a critical part of this research, since these kind of tools are relative new to architectural workflow and are still under development. For this reason, any contribution is welcome. The evaluation concerns the evaluation of the tool (computational part) as well as the evaluation of the design development (manual part).

4.1 Evaluation of the tool

In order to validate the results (both for proximity and illuminance) two checks can be carried out using Grasshopper. The first one checks whether the proximity requirements set at the beginning are met, meaning if the rooms with strong connections are placed very close to each other and with medium connections are placed relatively close, etc. The second check calculates the mean illuminance of each room and informs the user about the result (if it matches with the illuminance category requested). In this way the user can easily assess whether the illuminance requirements of each room are met or not. In case one or more requirements are not met the user has to adjust the requirements set in the inputs section. A good idea would be to check also if the requirements set are reasonable. In any case the results are indicative so the user should evaluate himself/herself whether any modifications are needed.

Proximity check

In order to check whether the proximity requirements are met the distance between the points is calculated first. Then the sum of the corresponding radii is calculated. Afterwards, a tolerance factor is created for the three different proximity connection types (strong, medium, weak). The definition checks if the ratio of the distance to the sum of the radii is smaller than the tolerance factor. If it is then the proximity requirement is met. The detailed definitions are presented in appendix A.

- Distance calculation d_{ij} and sum of radii calculation $r_i + r_j$
- Ratio calculation $\frac{d_{ij}}{r_i + r_j}$
- Ratio check

$$\frac{|d_{ij}|}{r_i + r_j} < t \quad , for\ t = 1.5$$

Below some recommendations for the tolerance factor are presented:

Category	Prox. factor	Connection	Tolerance
1	0.3	Weak	4* t
2	0.6	Medium	2 * t
3	0.9	Strong	t

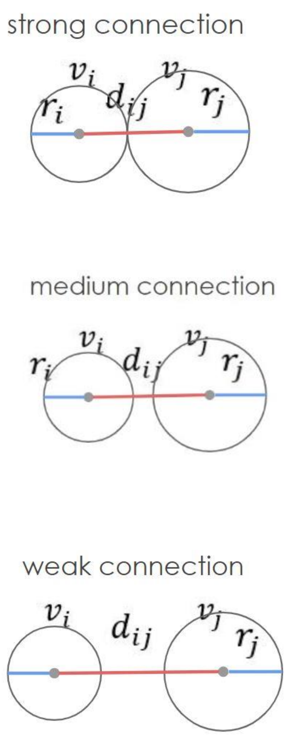


Figure 84: relationship between distance and radii according to different proximity connection types

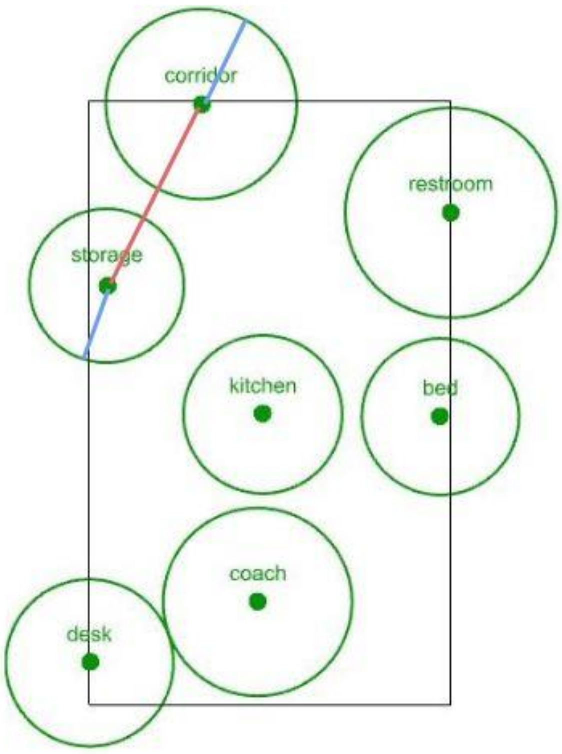


Figure 85: calculate distance between centroids and check them according to the sm of their radii

Illuminance check

A way to check whether the rooms are placed in positions that fulfill the illuminance requirements is by finding which test points are included in each circle and then calculate the mean illuminance value of these points. The detailed definitions can be found in appendix A. An overview of the definition is presented below:

- First decide which rooms need to be checked
- Find which test points are included in the circle
- Find the index of these test points
- Calculate the mean value in lux of the test points included

$$mean = \frac{\sum lux}{n}$$

- Put all lux values in a list (display bubble diagram with illuminance values)

Below the illuminance categories as set in “Illuminance requirements” paragraph are presented:

Category	Min lux	Max lux
1	100	300
2	300	500
3	500	max

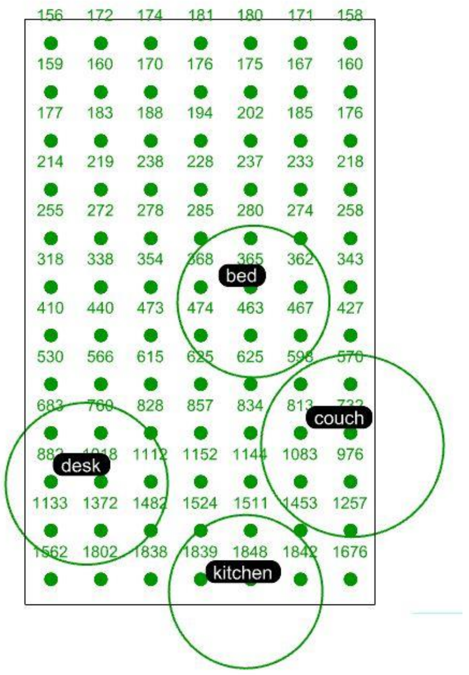


Figure 87: all test points with their corresponding illuminance values in lux

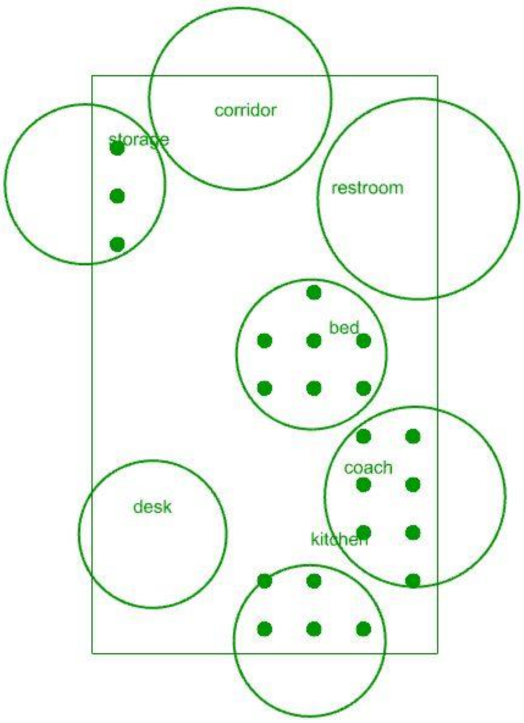


Figure 86: test points included in circles

4.2 Evaluation of the design development

Comparison with conventional method

In the following figure P. MacLeamy compares a preferred design process (in his case an integrated) with a conventional one through the design stages. For the purposes of this thesis the preferred integrated design process is a computational process that integrates proximity and daylight criteria. As we can see in the figure the design stages that require more effort are the three first ones. In particular, schematic design and design development require the highest effort and the cost of any changes is smaller in comparison to conventional design process. In this dissertation the schematic design was managed to be developed computationally, whereas the design development phase was developed manually. By following the computational approach the hardest part is done early, when the cost of modifications is low and all rest phases require less effort, since most decisions were made from the beginning. [51]

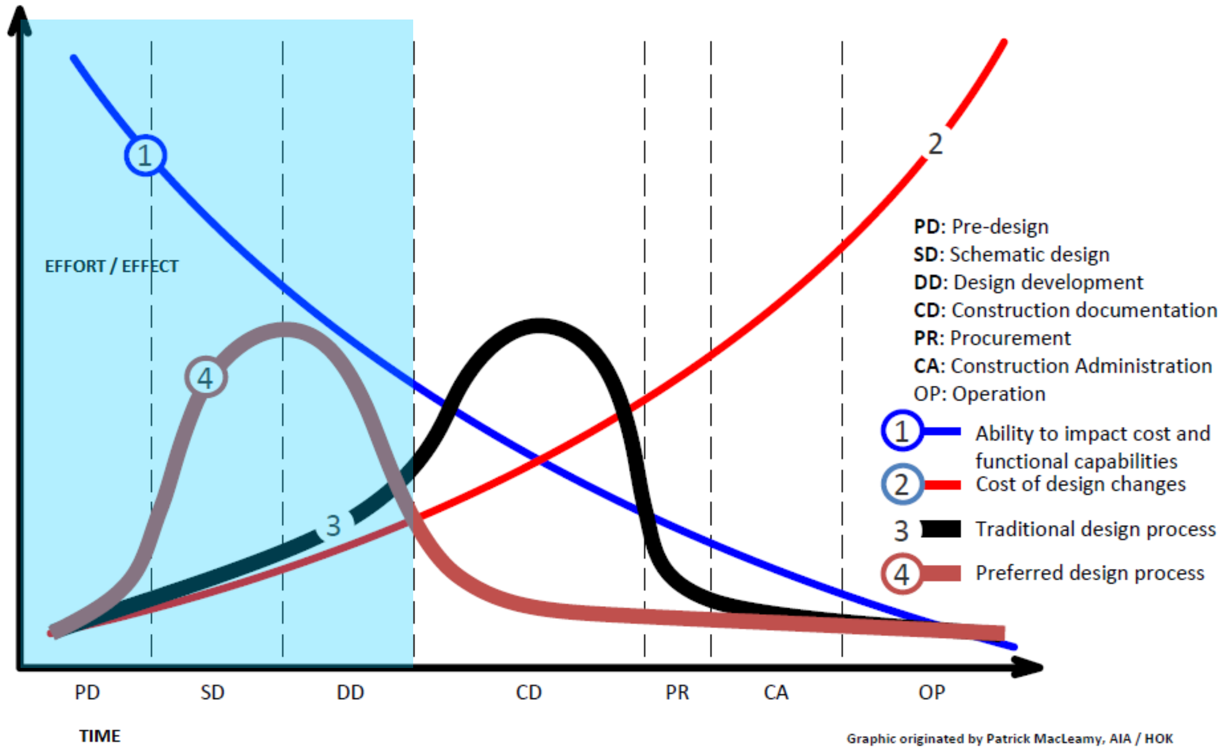


Figure 88: Patrick MacLeamy curve [51]

The phases that were included in this project were:

Pre-design (inputs)

- building's info
- rooms
- areas

Schematic design (bubble diagram)

- proximity requirements
- illuminance requirements
- prioritization of connections
- rooms' positions based on requirements

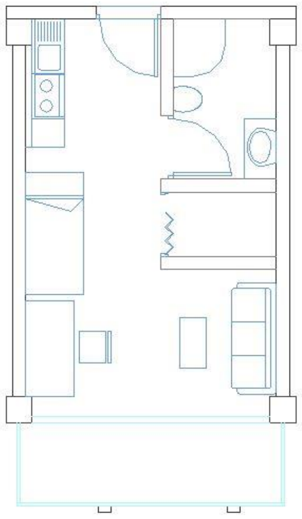
Design development (layout)

- interior walls
- rooms' dimensions
- furniture

Before developing the tool the layouts for floortypes A, B and C were made without using Cochleas at all. It is interesting to make a comparison between the completely manual layouts and the ones generated with Cochleas in respect to proximity and illuminance. As far as time and effort concerns it took almost 8 hours (one working day) to complete a floorplan following the conventional design method taught in architecture school, whereas it took 3 hours only to complete the same floorplan when following Cochleas. The reasons behind it is that the script in Grasshopper is structured clear enough so as to allow modifications easily and also the user has to make clear decisions such as proximity connections between rooms at the very beginning. This reduces the range of options that usually the architect spends much time experimenting with. As for the bubble diagram itself, the one produced manually is slightly better, but the one produced by the tool is very similar when rational inputs used. The final design result, the layout, is clearly of a higher quality when designed manually, which makes absolute sense since the architect takes many more than two design criteria into consideration (even subconsciously). The table below shows the result from the comparison made between conventional and proposed methodology in this thesis:

criteria	conventional	proposed
time effort		3x less
decision making		prioritization
bubble diagram	slightly better	
layout	better	

Unit A



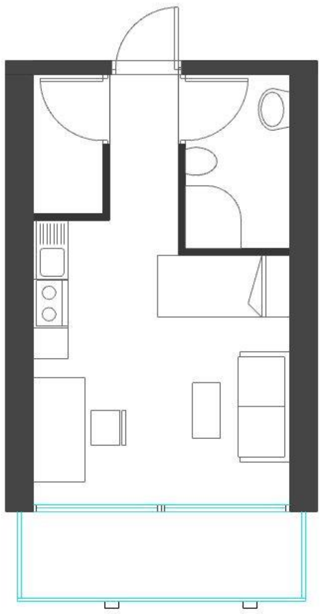
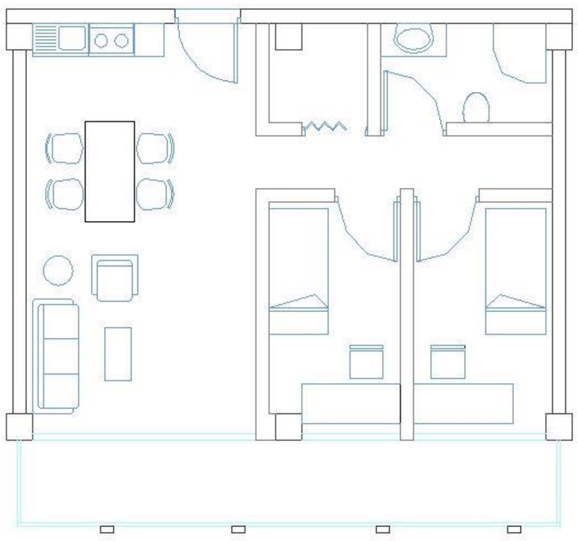


Figure 89: Layout of unit A designed completely manually

Figure 90: Layout of unit A designed partly computationally

Unit B



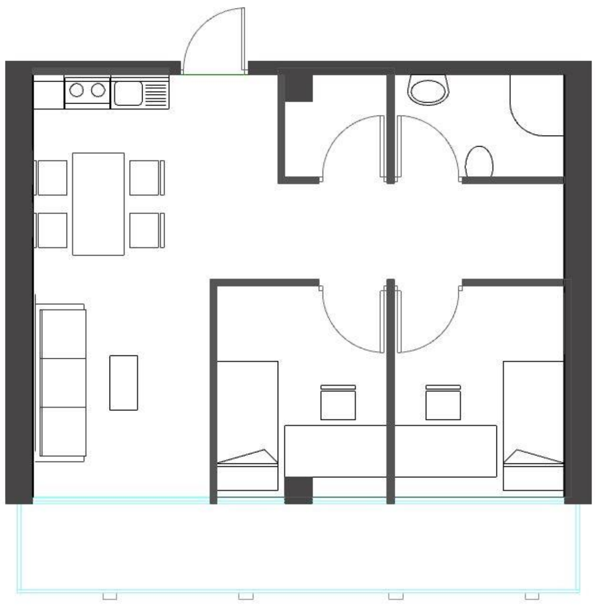


Figure 91: Layout of unit B designed completely manually

Figure 92: Layout of unit B designed partly computationally

Floortype C

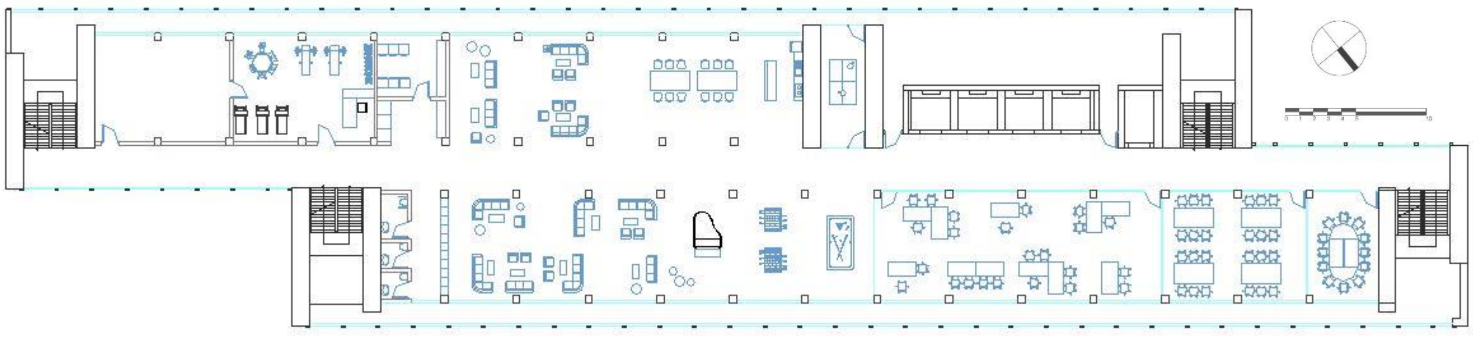


Figure 94: Layout of unit C designed completely manually

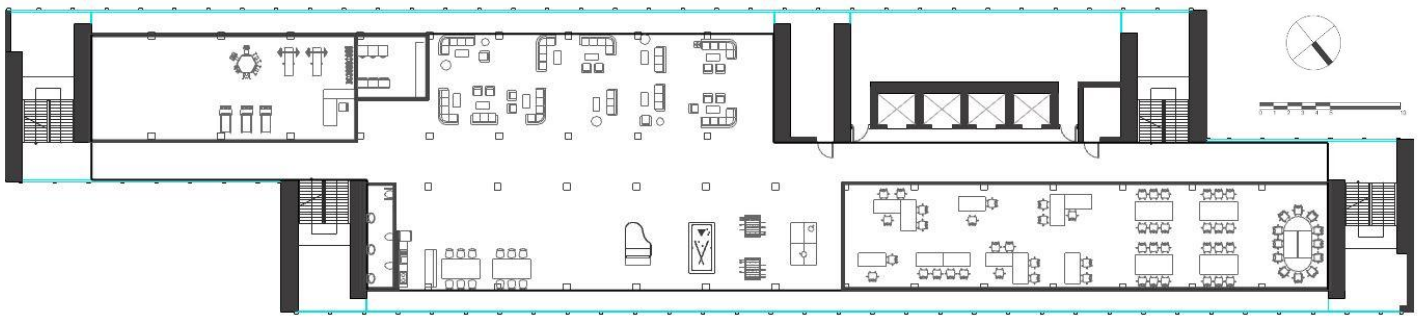


Figure 93: Layout of unit C designed partly computationally

5

5 Conclusions

In order for the tool to be useful to architects it has to be assured that it can be easily understood and customized by them. Customizability and repeatability conclusions are presented below:

Customizability
One of the main reasons why Grasshopper was chosen as the environment to apply the methodology is because it was designed to build generative algorithms. Every numerical input is inserted in the form of sliders so that the user can quickly customize the values. By designing parametrically all changes in values and geometry can be done much quicker than using conventional design software (such as Rhinoceros alone).

Repeatability
This research is documented in detail in the present report so that it can be repeated and improved by future researchers. The full Grasshopper script is presented in appendix A. The tool includes explanatory tags so as to guide the user through it.

By evaluating the tool (see chapter 4 "Evaluation") it can be concluded that the proposed tool succeeds to do what it is asked; to produce the optimal configuration regarding proximity and illuminance results. The framework used, spring network simulation, was successful since the proximity and illuminance checks within the tool are performing as expected in most cases.

Optimal configuration regarding proximity & illuminance
The spring system approach proved to be successful for dealing with connectivity requirements. The hierarchy of requirements can be expressed by using different stiffness values and in this way allow the user to have more control over the resulting bubble diagram. Illuminance requirements can be translated into proximity requirements if rooms are connected with points on the floor that have the ideal illuminance values. The tool handled both requirements as expected.

Computational tools
Existing computational tools (Rhinoceros, Grasshopper and their plugins) are very useful for architects because they are relatively easy to grasp and intuitive. An architect with minimum knowledge of mathematics and physics could understand every step of the process. The computation time of calculations is very low, since no weird geometry is involved and the illuminance analysis is performed for one day of the year only. However existing plugins for Grasshopper, such as KangarooPhysics, have limited capacities and the user cannot have a full control over the procedures, as it happened with the spring system. In this spectrum it is best to design the definition from scratch in a programming language (such as the force directed graph drawing algorithm).

Converting an existing layout into a residential one

The extent to which it is possible to convert an existing layout into a residential one depends on the level of complexity desired. From this research it is clear that a residential layout requires way more than two design criteria (proximity and illuminance in this case). In order to design a bubble diagram that can be transformed into a proper layout more parameters have to be taken into consideration (privacy, safety, view, noise, circulation). The resulting bubble diagram can be used as guidelines for the designer to design a high-quality layout. The bubble diagram consists a very important step for interior space planning.

Further recommendations

The tool has a strong potential to include more climate aspects to the optimization such as thermal, noise, drift, etc. The same framework could be used and these extra requirements could be added as extra connections (springs). Apart from this, it could be applied not only for residences, but also in other uses such as offices, shops. An attempt is made in this thesis in units C and D that accommodate communal facilities. Moreover, the tool could take into consideration z axis and apply it in two-stories apartments. An interesting experiment would be to use the tool to design a layout from scratch (instead of repurposing an existing one) or try irregular shapes as building's boundaries and/ or as proposed rooms' geometry. It can be definitely improved as far as computational efficiency concerns by automating manual tasks (during design process) and by structuring the script better (avoiding loops and unnecessary commands). The environment chosen for application (Grasshopper) was not the best one, since it still a project under development, it is limited in capabilities and it not open source. Therefore, coding in a programming language (such as python) would be much more suitable for this project. Hence this is the area to further improve. So next step until graduation is to translate as many grasshopper nodes as possible to python nodes. The ultimate goal would be to bypass Kangaroo completely and perform dynamic relaxation with python instead.

Reflection

The ultimate goal of the research is to explore ways of how to rationalize and formulate mathematically a configurational design problem. This design problem refers to how to arrange a residential program into an existing building not only in terms of available space but also in relation to two design criteria: proximity and illuminance.

The initial approach aimed to formulate the problem as abstract as possible using mathematical procedures. The procedure that seemed the most promising was to understand what spectral graph theory is and how it is possible to formulate the above mentioned configurational problem by using principles of graph theory. In a later stage these principles could be (ideally) written in a programming language (such as Python or C#) but this was not feasible in this case because of lack of programming skills from the author. So the most feasible scenario seemed to be to try implementing the graph theory principles needed into the workflow of Grasshopper environment. However, the initial approach was abandoned after the second presentation (P2) because it was realized that it was not possible for the author to gain knowledge in advanced mathematics topics of discrete mathematics (spectral graph theory, topology) and rest topics relative to calculus and linear algebra needed in such a short period of time so as to develop a methodology on how to apply these methods to the design assignment. Under these circumstances the approach of a fully automated methodology - although well-grounded and challenging - would be way beyond the MSc graduation thesis purposes of a Building Technology student.

The next step was to find another approach to achieve the ultimate goal of the research. According to research methodology set at the beginning of the research, stages 1 (research framework) and 2 (theoretical background) had to be repeated. After completing the new literature review, generative design using existing computational tools seemed to be the most promising approach. The visual programming environment for this purpose was chosen to be Grasshopper, because of its popularity among the architectural community and its ability to support generative algorithms. The proposed approach is a systematic approach in which it is investigated until what point it is possible to automate a part of the design process in primary design stage according to the user's wishes (manual input) in respect to rooms' connectivity (proximity of rooms) and daylight criteria (illuminance) using computational methods.

The research methodology was set at the very beginning of the research (P1) and was followed until the completion of the research. It can be summarized in the following stages:

- Research framework
- Theoretical background
- Tool development

- Evaluation
- Conclusions

The first two steps were repeated after P2 retake and resulted in the new approach which is dynamic relaxation. During the tool development phase the specifications and assumptions were set so as to structure the tool. In the beginning, the main skeleton of the tool was defined by relative research, but it was not fully developed until it was applied in the case study. By following the proposed methodology it was possible to produce and evaluate the outputs. If the result was not satisfactory the process was repeated but this time the chosen parameters were adjusted to see which parameter had the greatest impact. By trials and relative research in literature the tool started to take its final form. The evaluation step was necessary so as to check how the tool performs in future applications. The last step includes the discussion upon the results, the conclusions drawn from the discussions and recommendations for the tool's improvement.

As far as society concerns, renovation was and still is an import design assignment, especially in countries where its available to build area is limited. Converting existing buildings into residences is a way to tackle the housing problem many people (locals and expats) from all over the world face. In a professional point of view, finding a way to systemize the renovation design process could have a great impact on the way architects would approach a renovation project since the very beginning. As soon as they have an initial design idea by following the suggested methodology it would be possible to insert the necessary data and produce the schematic residential layout based on the two –most important according to the author- design criteria: proximity and daylight. One of the main advantages of computational applications is that they can handle a respectable amount of data simultaneously. This means that many levels of complexity can be added to the tool and in that way help the architect find the optimum layout. This could speed up the design process and also produce non-conventional but still functional layouts.

The current graduation project is directly related to MSc Architecture, Urbanism and Building Sciences and the Building Technology track. Firstly, the computational methods proposed are intended to be applied in existing buildings, in real life scenarios, which is what architecture and building sciences is about. The case studies selected empower the practicality and the usefulness of the tool. The intention to contribute to systemize the renovation design process is an architectural intention interwoven with sustainability, that is one of the main aspects of Building Technology. Building Technology is also the field where architects are more oriented towards engineering. Mathematics and physics is some of the fundamental subjects of an engineer. Engineering is also about improving existing methods as well as inventing new ones. In this dissertation the innovation lies in developing a methodology on how to systemize a renovation design project using principles of computer science, mathematics and physics.

The peculiarity of this graduation topic, as well as most topics of generative design, is that the methodology followed during the research is in fact the research product. In this report is presented not only the final methodology that led to the desired results, but also the process of exploration; all trials and the logic behind them. This is also the main teaching objective of this research: to learn from successes as well as from failures.

To sum up, the proposed tool succeeds to do what it is asked for; namely to produce the optimal configuration regarding proximity and illuminance results. The framework used, dynamic relaxation was successful as my main mentor predicted. The tool has a lot of potential to be enlarged and include more climate aspects to the optimization such as thermal, noise, drift, etc. The same framework could be used and add these requirements as extra connections (springs). However, the environment chosen (Grasshopper) was not the ideal choice, because it still a project under development, is limited in capabilities and it not open source. Therefore, coding in a programming language (such as Python) would be the ideal environment for this project.

List of figures

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Appendices

Appendix A: Grasshopper script

For documentation purposes the Grasshopper script developed is presented in this appendix with screenshots. To make things more clear the colour coding rule and the overview of the script is presented below:

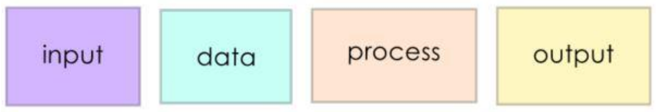


Figure 95: colour coding rule

Script overview:

7. INPUTS
    - Program of requirements
        - Room centroids
        - Room areas
    - Building's info
    - Proximity requirements
        - Proximity connections
        - Proximity categorization
    - Illuminance requirements
        - Illuminance categories
        - Illuminance connections

8. DAYLIGHT SIMULATION
    - 1 Create apartment box
    - 2 Create zone masses
    - 3 Add glazing
    - 4 Generate test points on grid
    - 5 Generate climate-based sky
    - 6 Grid-based simulation recipe
    - 7 Daylight simulation
    - 8 Legend customization
    - 9 Recolour mesh
    - 10 Save analysis' files

9. OPTIMAL CONFIGURATION
    - Proximity
    - Illuminance
    - Kangaroo engine
    - Trails of moving points
    - Overlap correction
        - Circle collision

    - Trails of moved circles

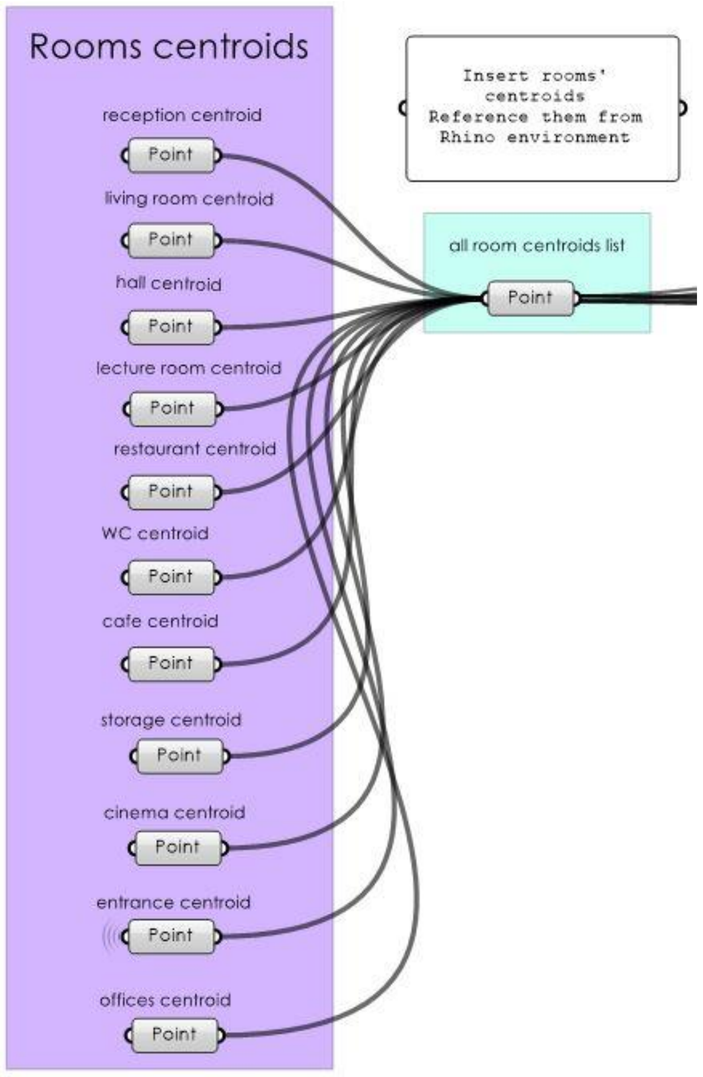
10. OUTPUTS
    - Bubble diagram with lux values

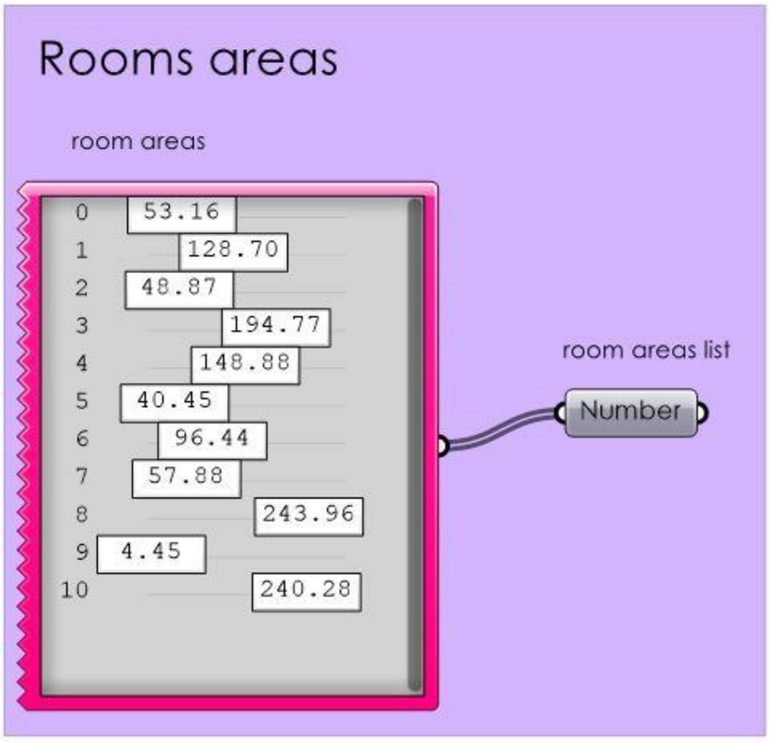
11. CALCULATIONS
    - Geometry related calculations
        - Set room dimensions
        - Circles with predefined areas
        - Middle point of curve
        - Surface from curve
    - Mathematical calculations
        - Radius calculation
        - Round number to floor
        - Mean of a number
        - List length

12. EVALUATION
    - Proximity results
    - Illuminance results
        - Rooms to be checked
        - Test points included in circle
        - Finding the index
        - Put items in list

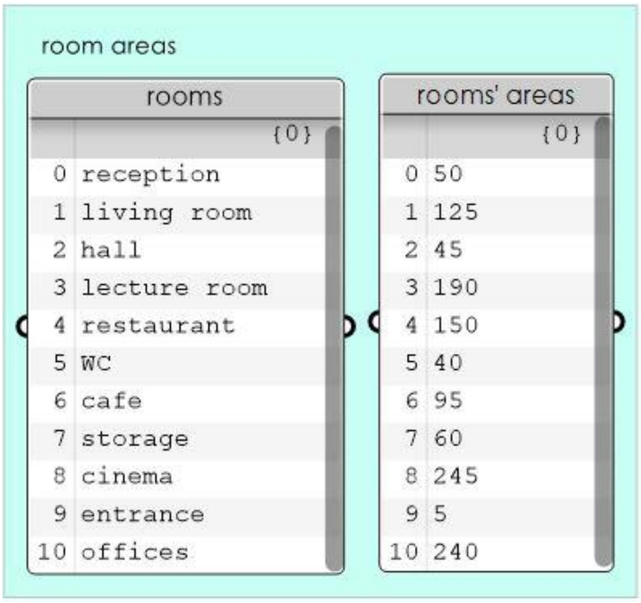
1. INPUTS

Program of requirements



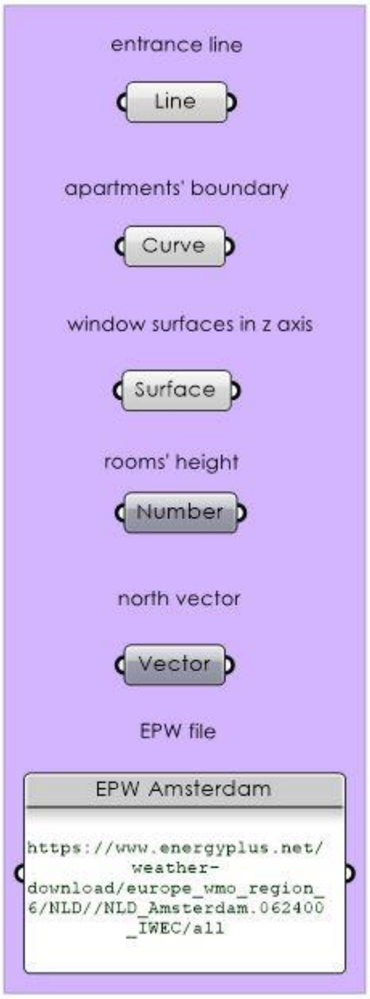


0	53.16
1	128.70
2	48.87
3	194.77
4	148.88
5	40.45
6	96.44
7	57.88
8	243.96
9	4.45
10	240.28



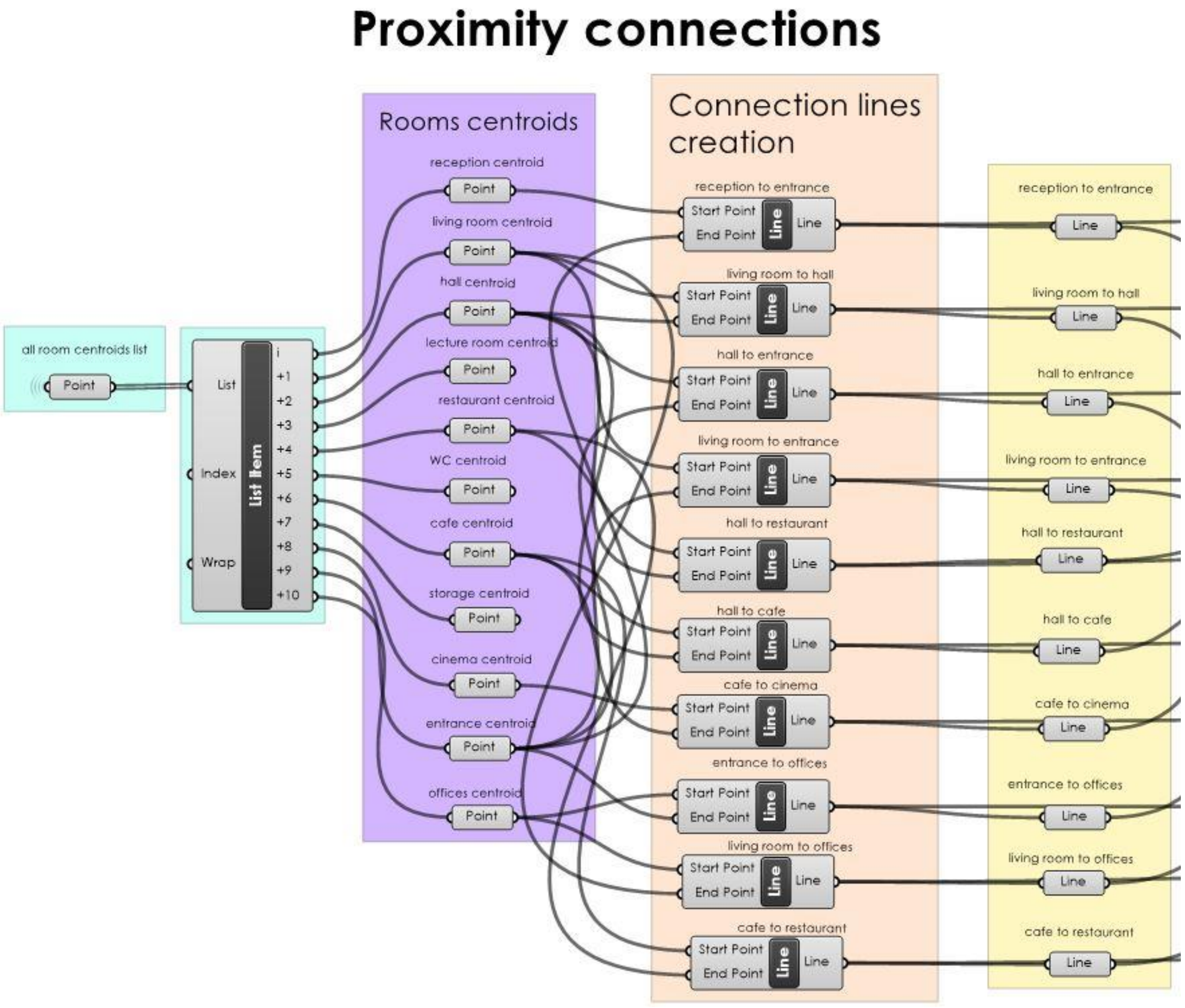
	rooms {0}	rooms' areas {0}
0	reception	50
1	living room	125
2	hall	45
3	lecture room	190
4	restaurant	150
5	WC	40
6	cafe	95
7	storage	60
8	cinema	245
9	entrance	5
10	offices	240

Building's info

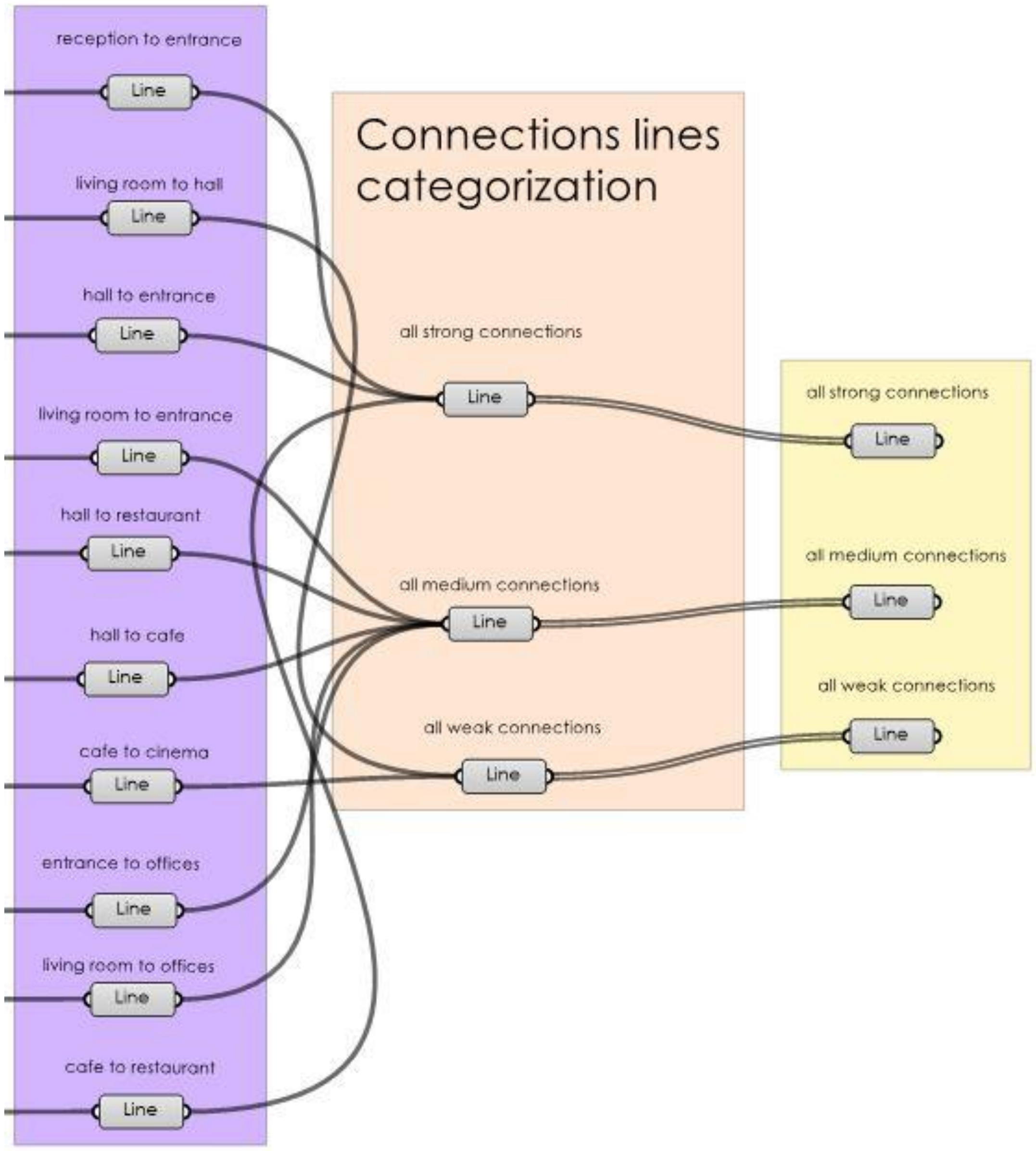


```
https://www.energyplus.net/
weather-
download/europe_wmo_region_
6/NLD//NLD_Amsterdam.062400
_IWEC/all
```

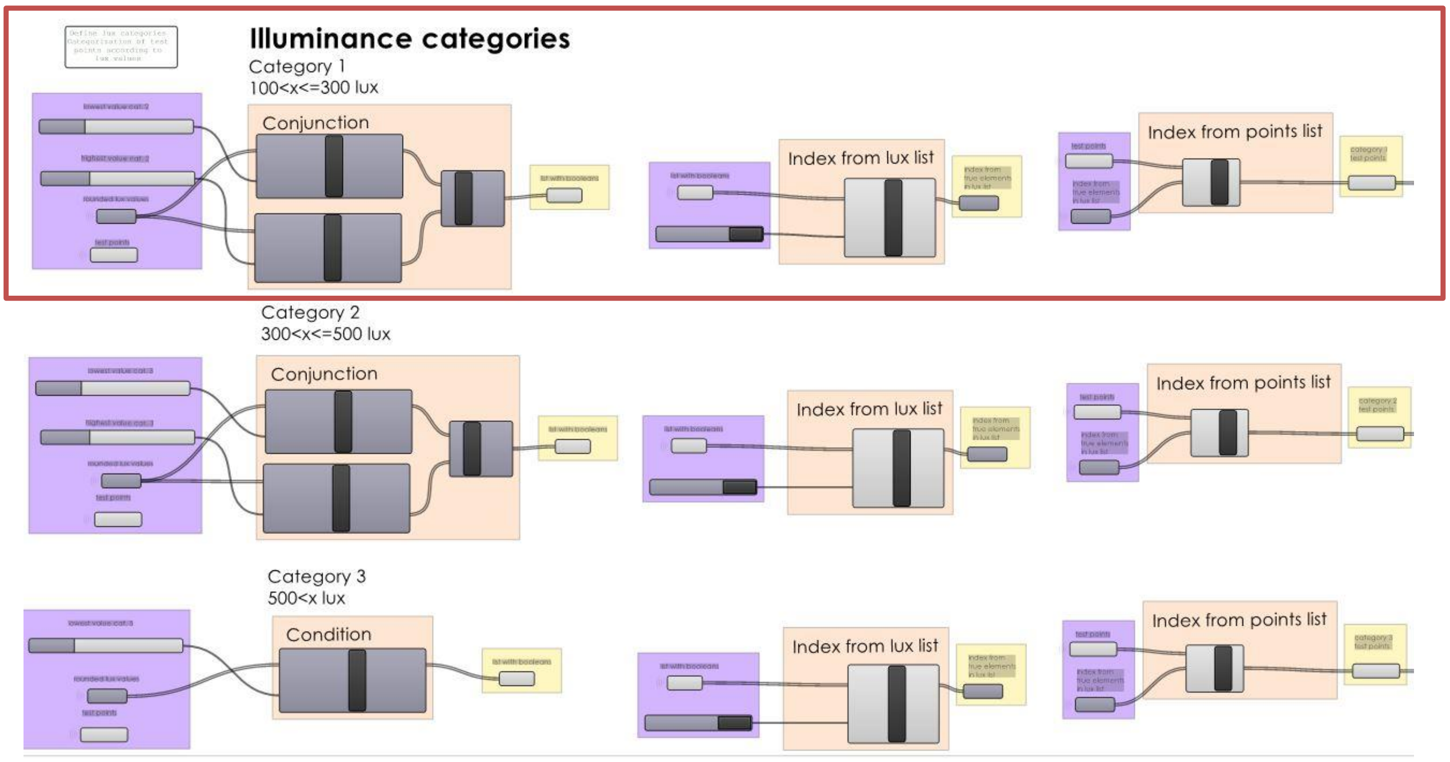
Proximity requirements

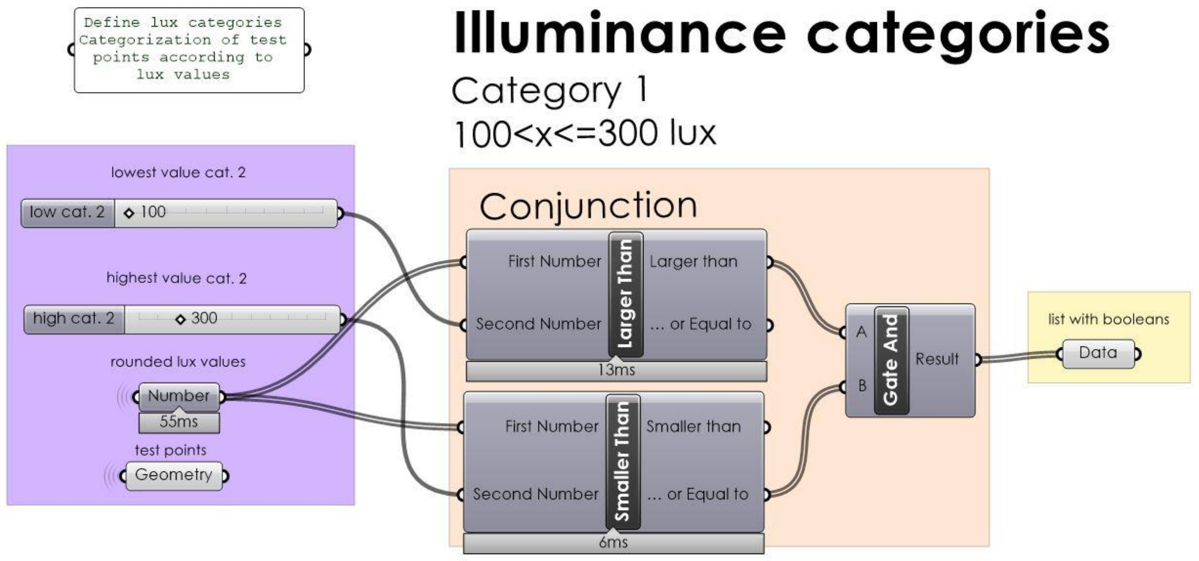


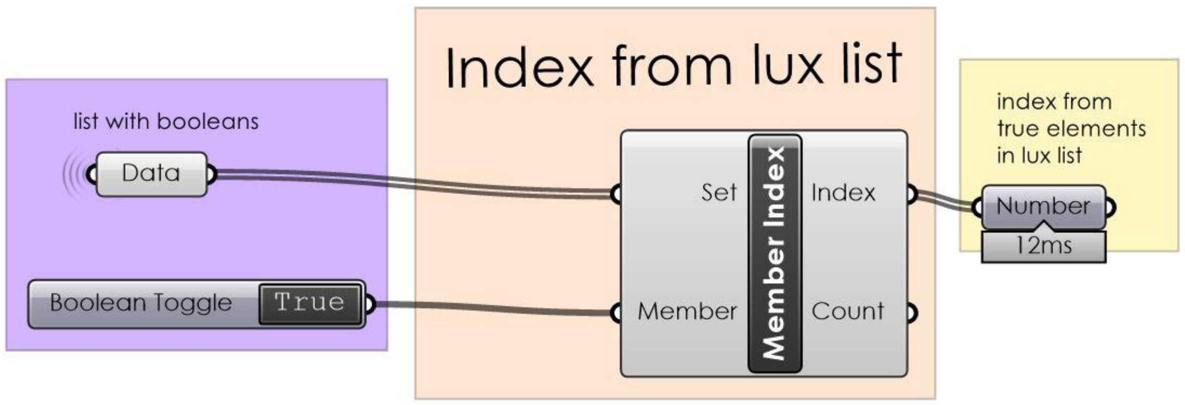
Proximity categories

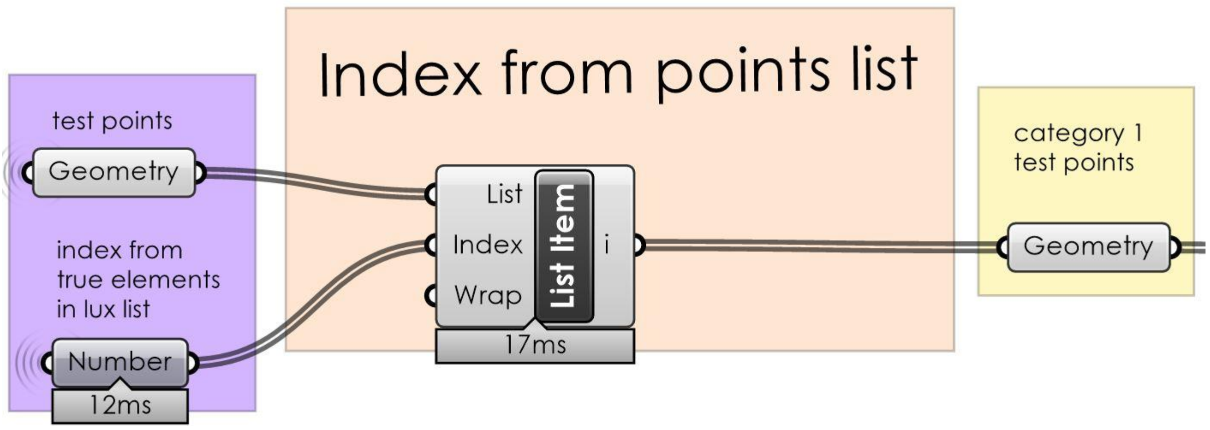


Illuminance requirements



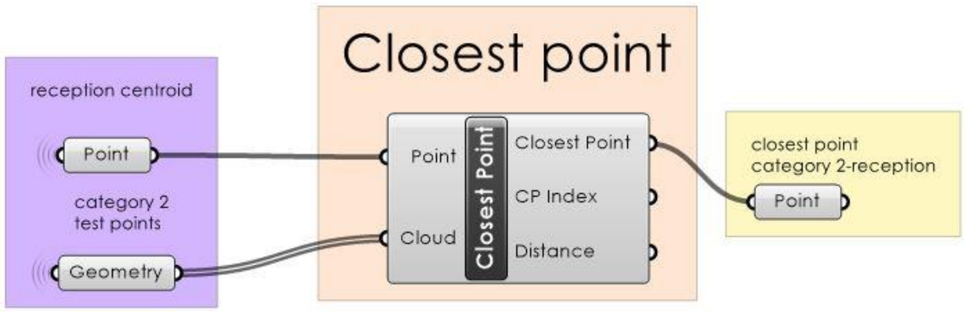


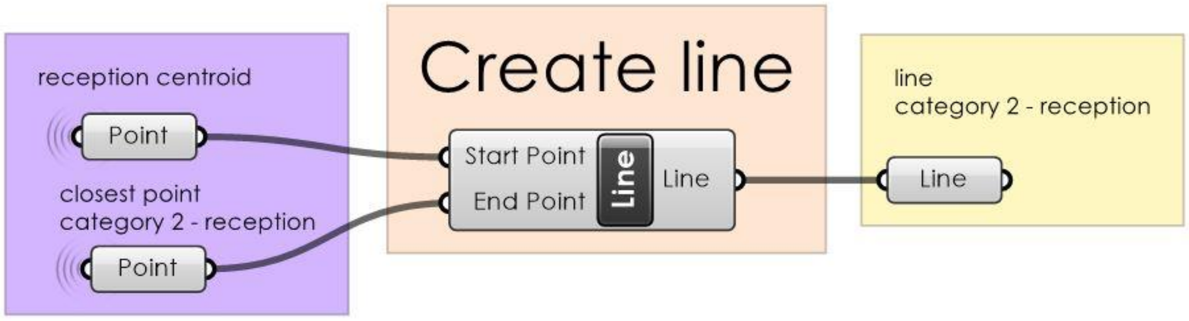




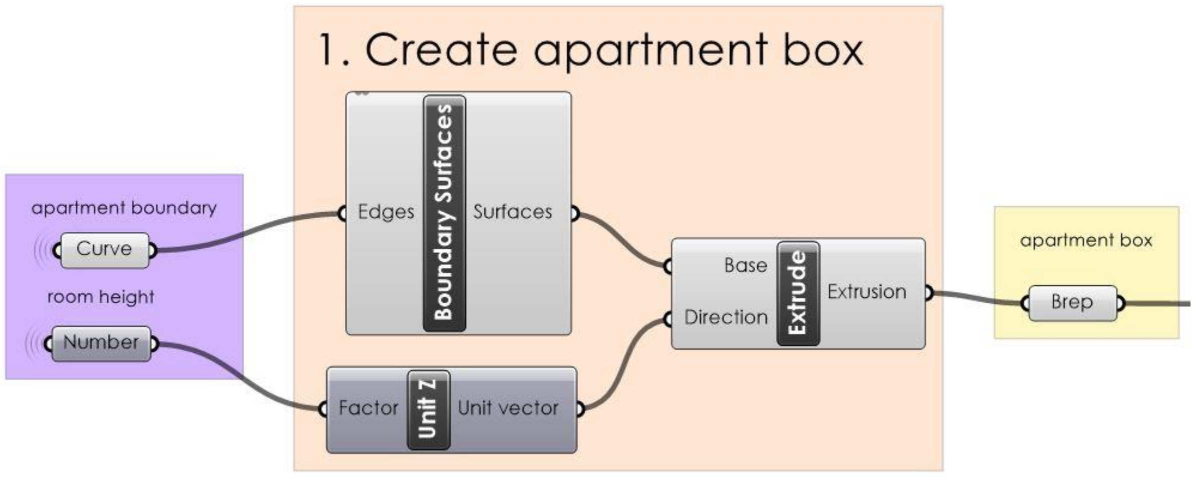
Illuminance connections

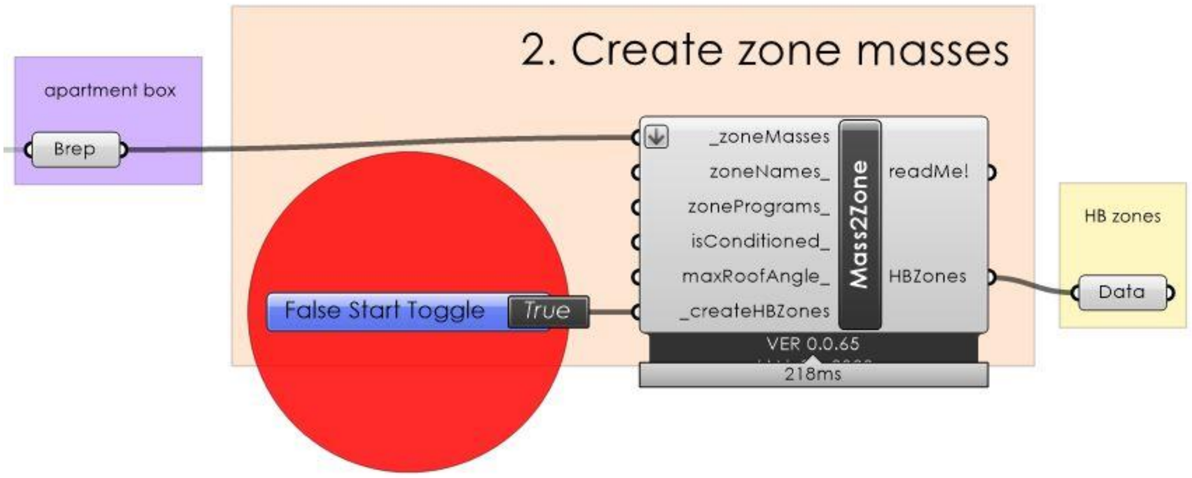
Assign centroids to lux categories

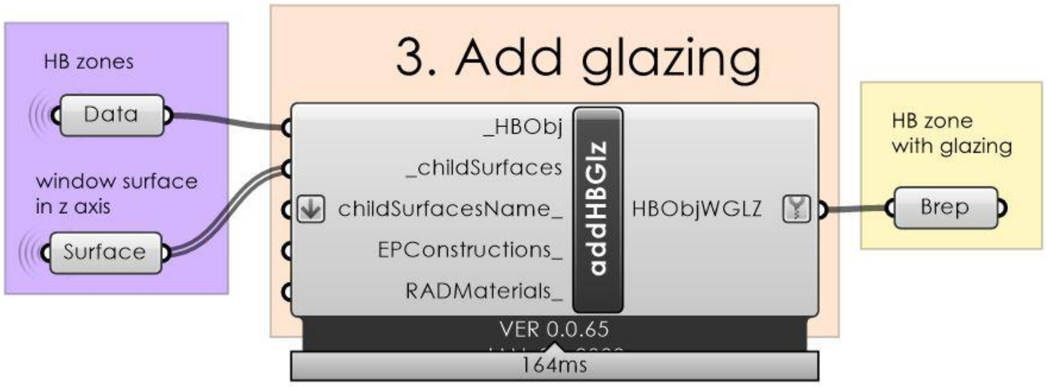


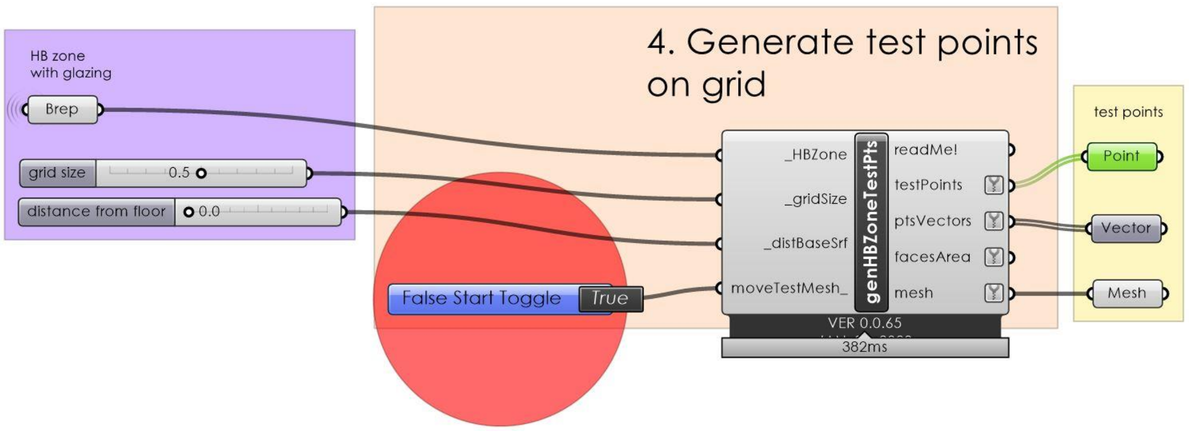


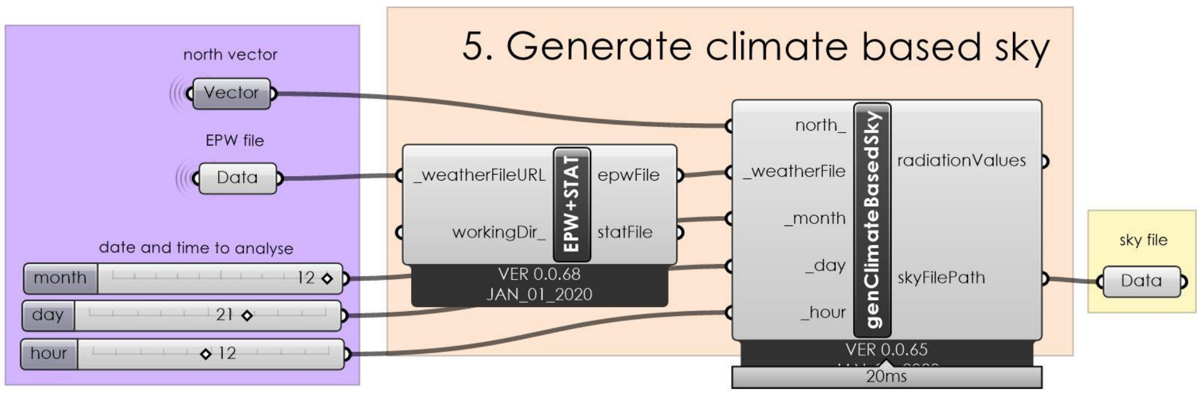
2. DAYLIGHT SIMULATION

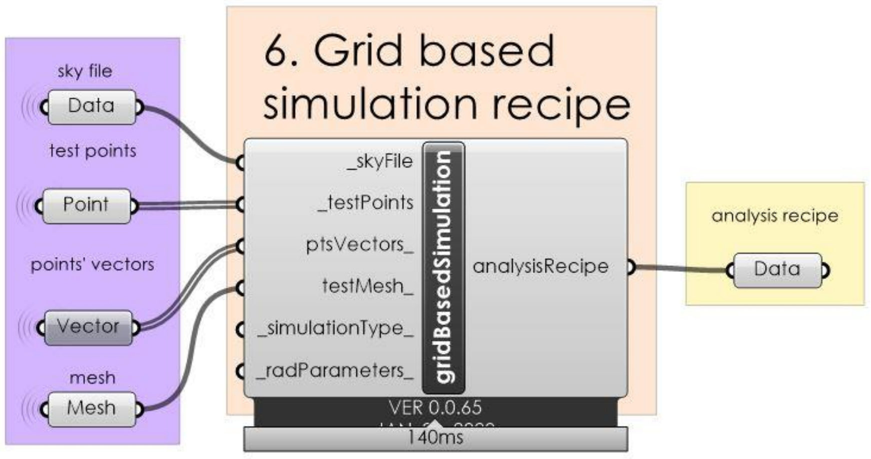


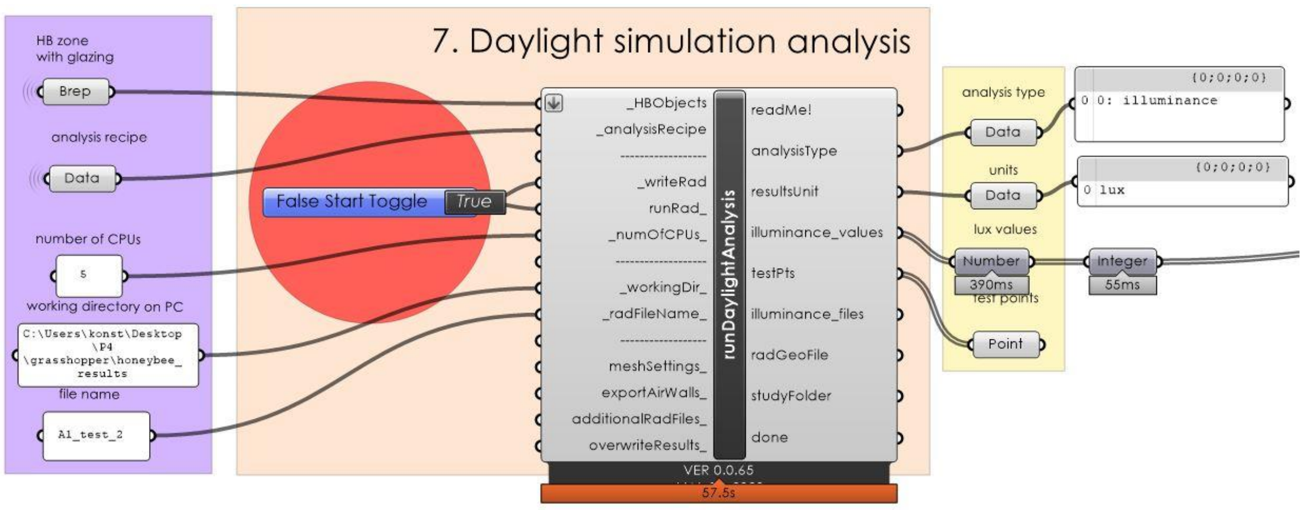


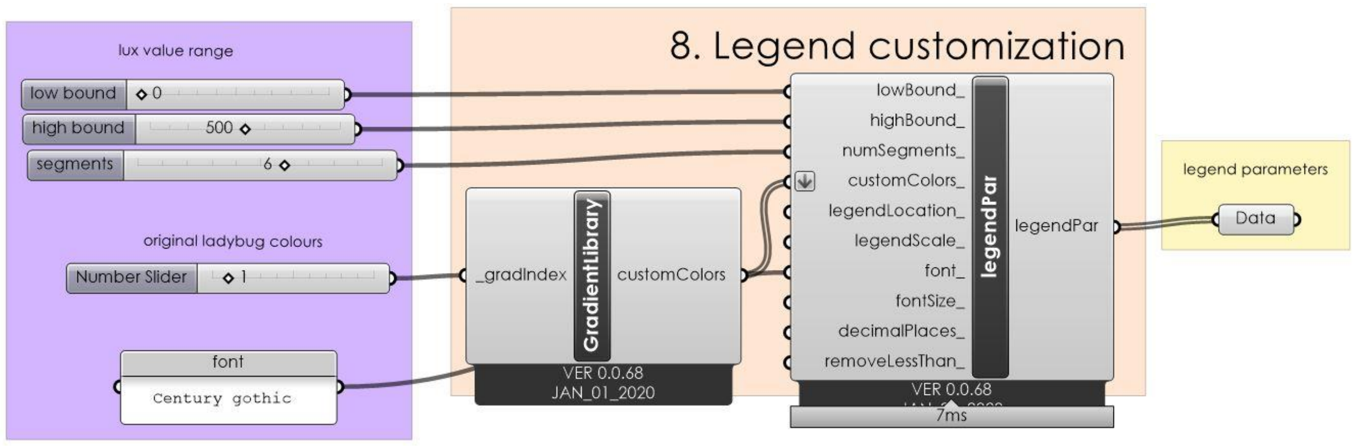


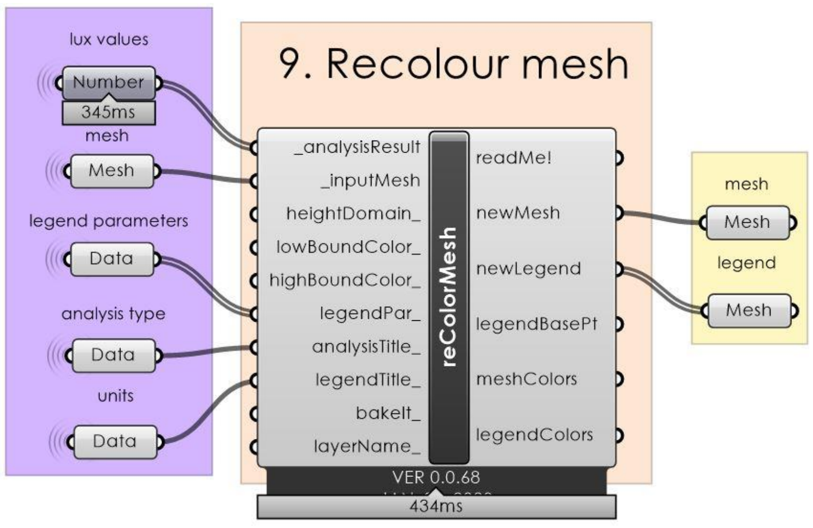

4. Generate test points on grid
HB zone with glazing
Brep
grid size 0.5
distance from floor 0.0
False Start Toggle True
_HBZone
_gridSize
_distBaseSrf
moveTestMesh_
genHBZoneTestPts
readMe!
testPoints
ptsVectors
facesArea
mesh
VER 0.0.65
382ms
test points
Point
Vector
Mesh

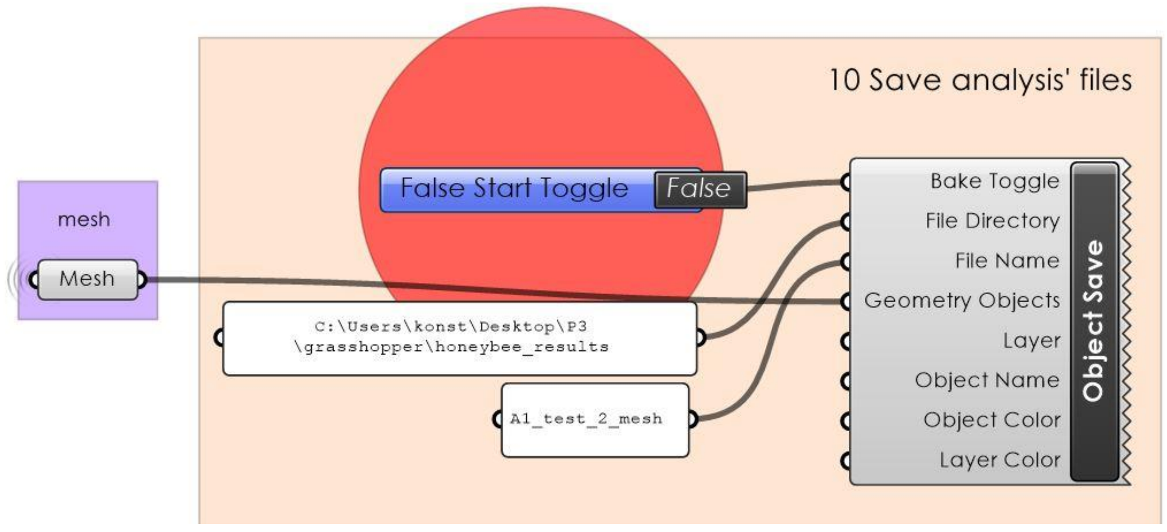

5. Generate climate based sky
north vector
Vector
EPW file
Data
date and time to analyse
month 12
day 21
hour 12
_weatherFileURL
workingDir_
EPW+STAT
epwFile
statFile
VER 0.0.68
JAN_01_2020
north_
_weatherFile
_month
_day
_hour
genClimateBasedSky
radiationValues
skyFilePath
VER 0.0.65
20ms
sky file
Data


6. Grid based simulation recipe
sky file
Data
test points
Point
points' vectors
Vector
mesh
Mesh
_skyFile
_testPoints
ptsVectors_
testMesh_
simulationType
radParameters
gridBasedSimulation
analysisRecipe
VER 0.0.65
140ms
analysis recipe
Data


7. Daylight simulation analysis
HB zone with glazing
Brep
analysis recipe
Data
number of CPUs
5
working directory on PC
C:\Users\konst\Desktop\P4\grasshopper\honeybee_results
file name
A1_test_2
False Start Toggle True
_HBObjects
_analysisRecipe
_writeRad
runRad_
numOfCPUs
workingDir
radFileName
meshSettings_
exportAirWalls_
additionalRadFiles_
overwriteResults_
runDaylightAnalysis
readMe!
analysisType
resultsUnit
illuminance_values
testPts
illuminance_files
radGeoFile
studyFolder
done
VER 0.0.65
57.5s
analysis type
Data
{0;0;0;0}
0 0: illuminance
units
Data
{0;0;0;0}
0 lux
lux values
Number
390ms
Integer
55ms
test points
Point

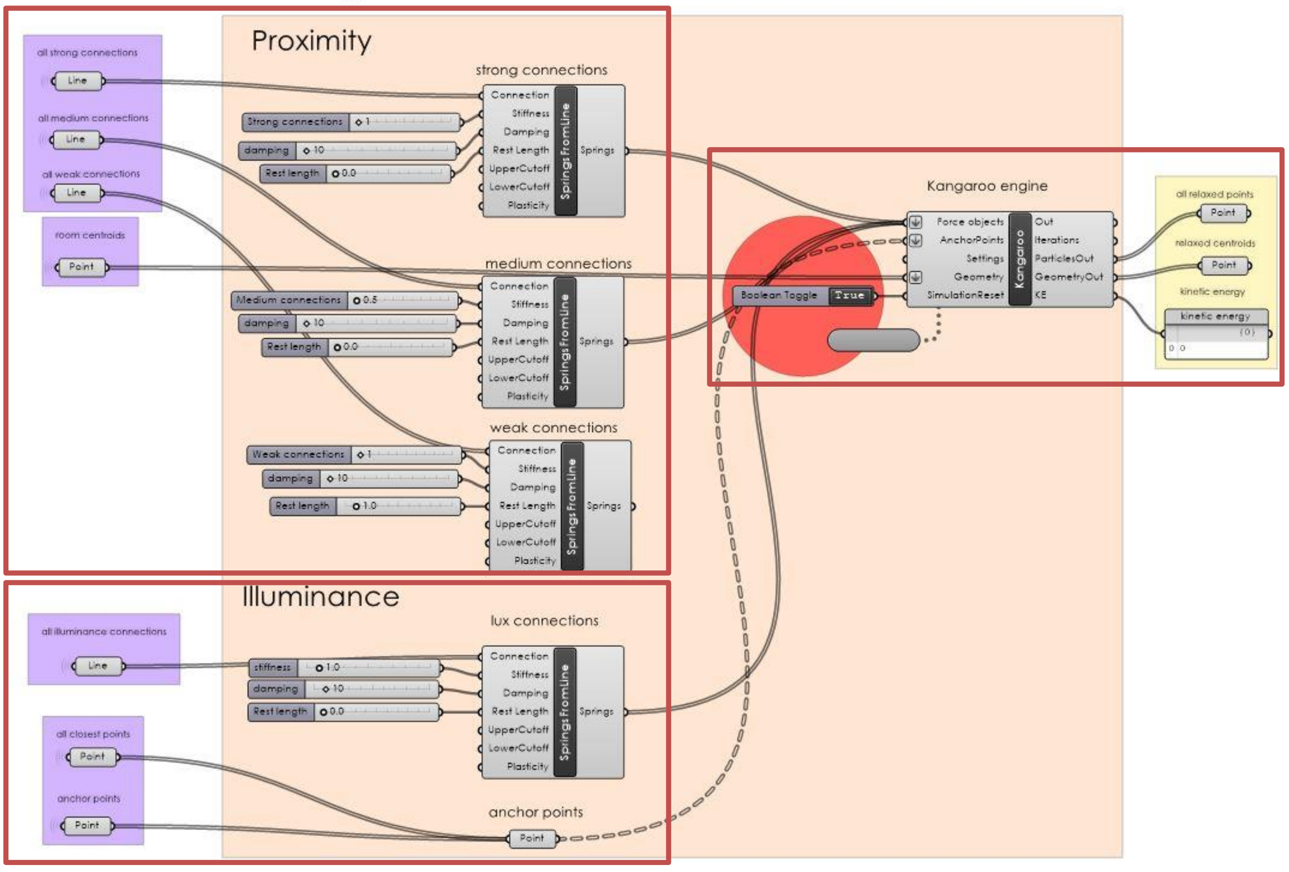

8. Legend customization
lux value range
low bound 0
high bound 500
segments 6
original ladybug colours
Number Slider 1
font
Century gothic
_gradIndex
GradientLibrary
customColors
VER 0.0.68
JAN_01_2020
lowBound_
highBound_
numSegments_
customColors_
legendLocation_
legendScale_
font_
fontSize_
decimalPlaces_
removeLessThan_
legendPar
legendPar
VER 0.0.68
7ms
legend parameters
Data


9. Recolour mesh
lux values
Number
345ms
mesh
Mesh
legend parameters
Data
analysis type
Data
units
Data
_analysisResult
_inputMesh
heightDomain_
lowBoundColor_
highBoundColor_
legendPar_
analysisTitle_
legendTitle_
bakeIt_
layerName_
reColorMesh
readMe!
newMesh
newLegend
legendBasePt
meshColors
legendColors
VER 0.0.68
434ms
mesh
Mesh
legend
Mesh


10 Save analysis' files
mesh
Mesh
False Start Toggle
False
C:\Users\konst\Desktop\P3
\grasshopper\honeybee_results
A1_test_2_mesh
Bake Toggle
File Directory
File Name
Geometry Objects
Layer
Object Name
Object Color
Layer Color
Object Save

3. OPTIMAL CONFIGURATION

Spring network



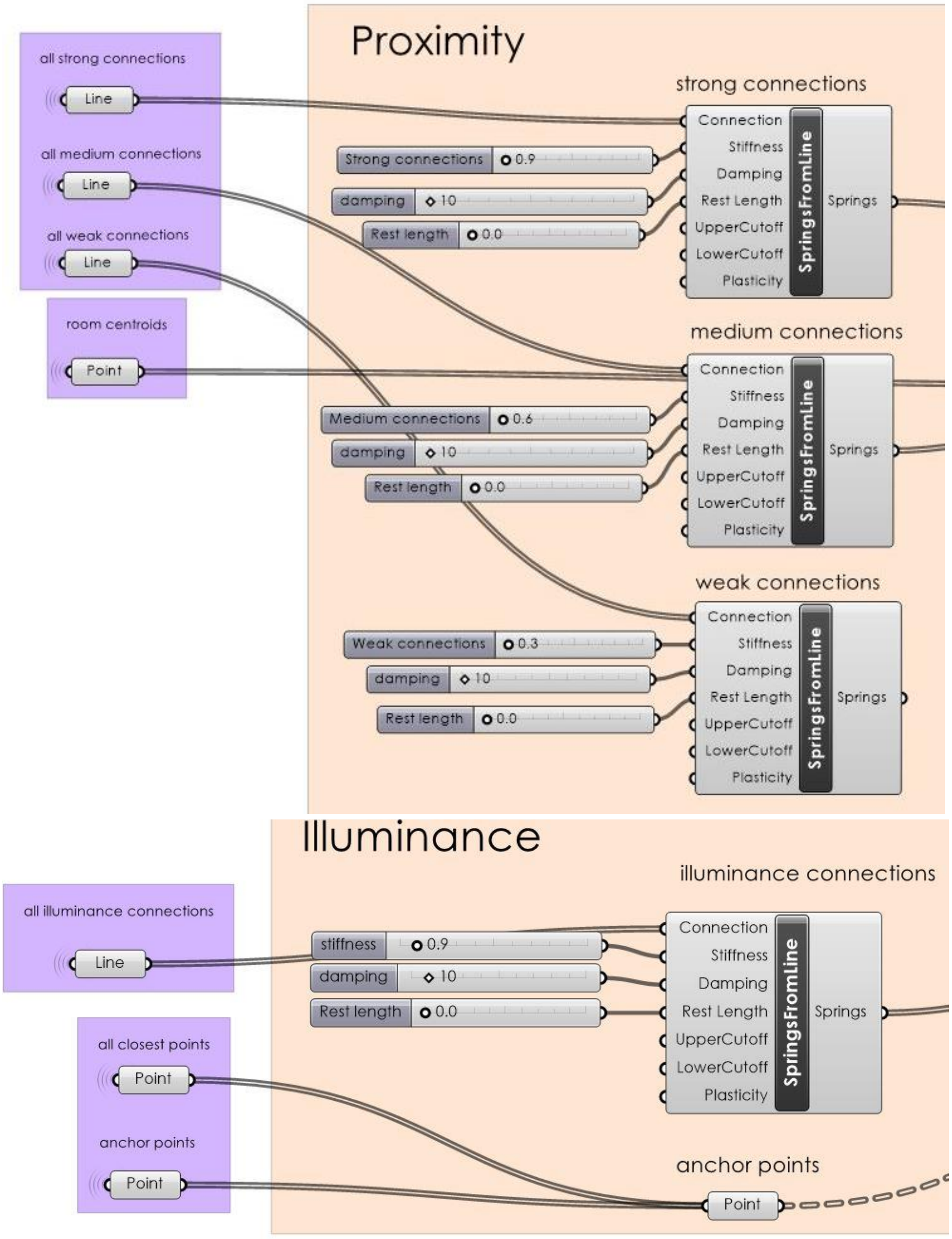
Strong connections 1
damping 10
Rest length 0.0

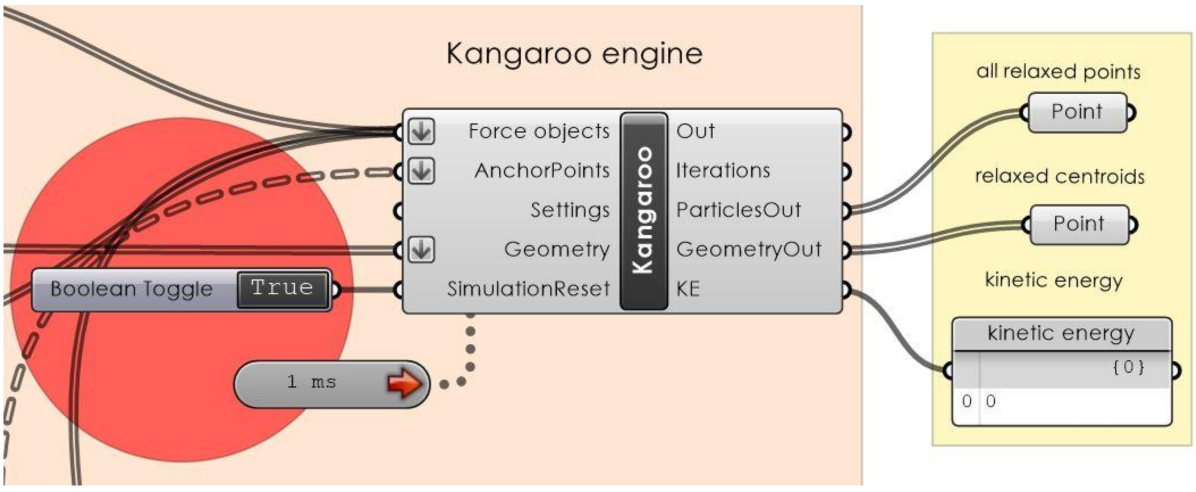
Medium connections 0.5
damping 10
Rest length 0.0

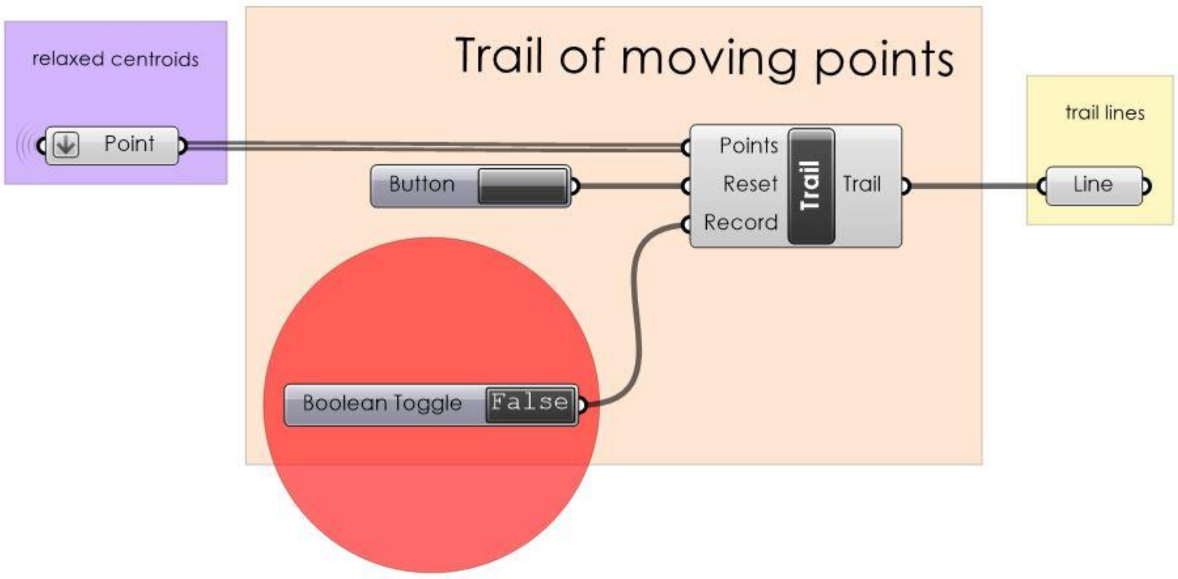
Weak connections 1
damping 10
Rest length 1.0

stiffness 1.0
damping 10
Rest length 0.0

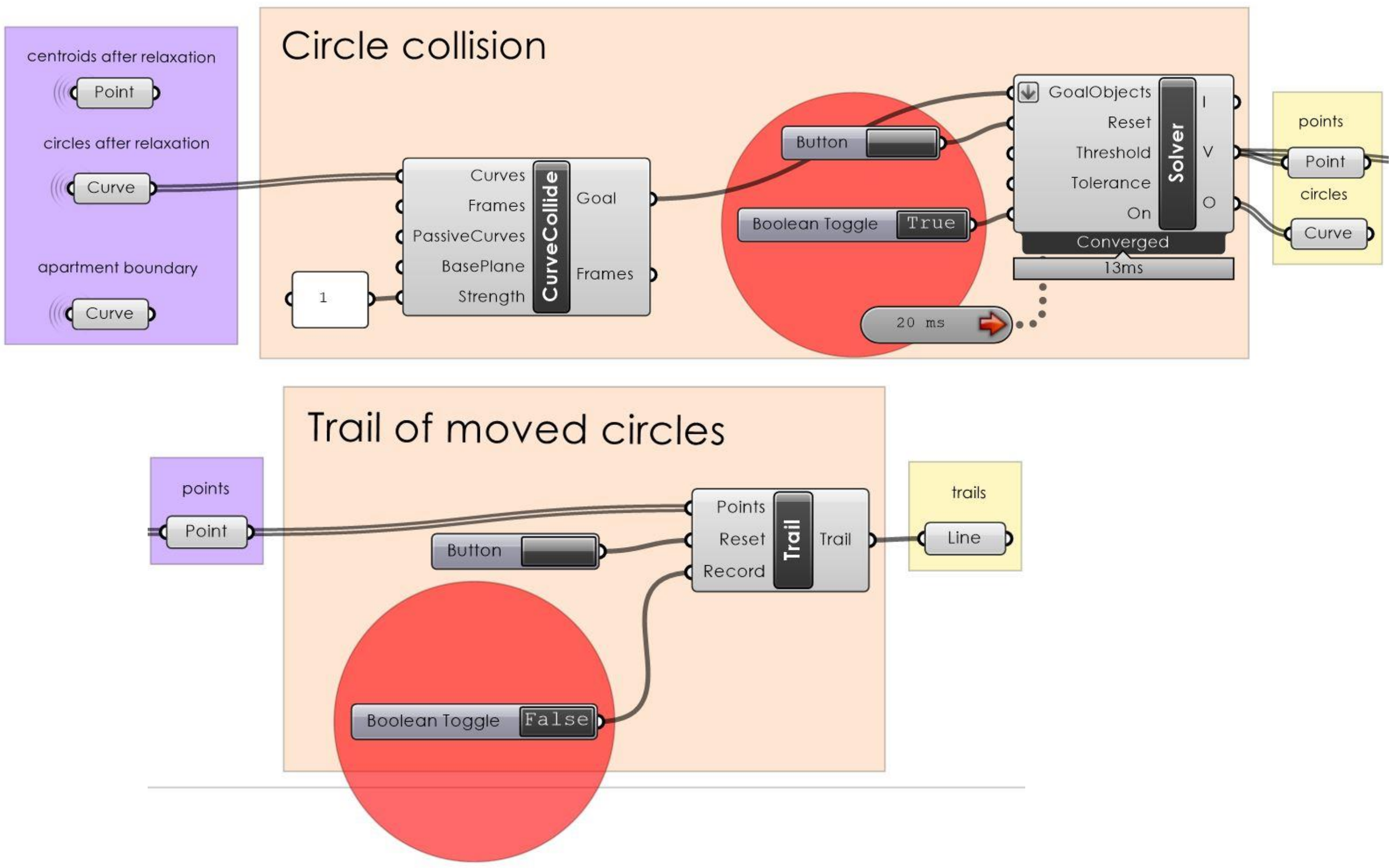
Boolean Toggle True


Proximity
all strong connections
Line
all medium connections
Line
all weak connections
Line
room centroids
Point
strong connections
Strong connections 0.9
damping 10
Rest length 0.0
Connection
Stiffness
Damping
Rest Length
UpperCutoff
LowerCutoff
Plasticity
SpringsFromLine
Springs
medium connections
Medium connections 0.6
damping 10
Rest length 0.0
weak connections
Weak connections 0.3
damping 10
Rest length 0.0
Illuminance
illuminance connections
all illuminance connections
Line
stiffness 0.9
damping 10
Rest length 0.0
all closest points
Point
anchor points
Point
anchor points
Point

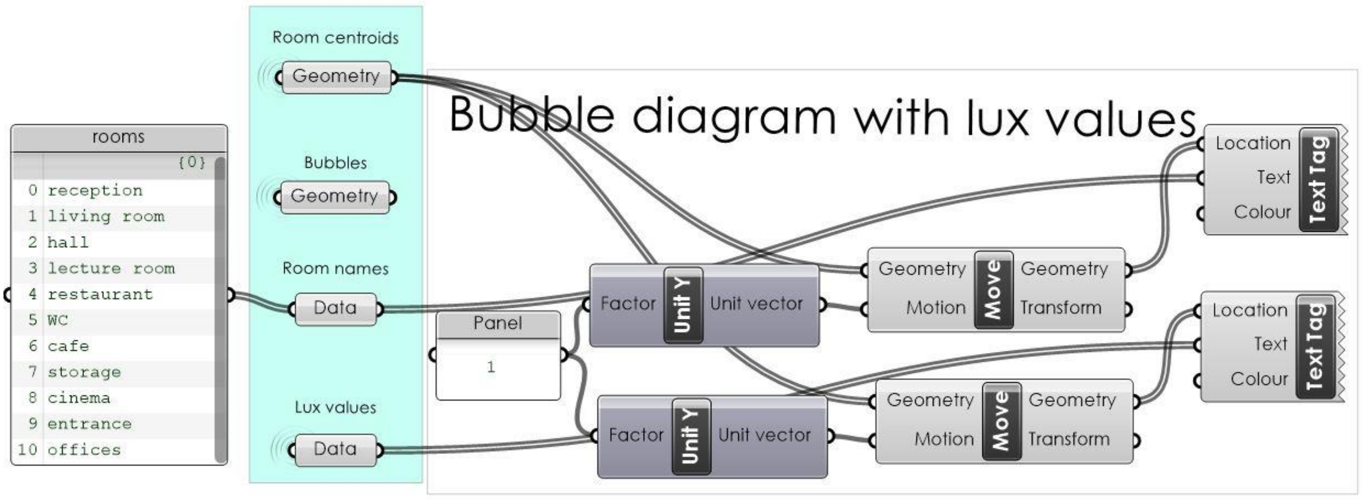

Kangaroo engine
Force objects
AnchorPoints
Settings
Geometry
SimulationReset
Kangaroo
Out
Iterations
ParticlesOut
GeometryOut
KE
Boolean Toggle
True
1 ms
all relaxed points
Point
relaxed centroids
Point
kinetic energy
kinetic energy
{0}
0 0


relaxed centroids
Point
Trail of moving points
Points
Reset
Record
Trail
Trail
Button
Boolean Toggle
False
trail lines
Line

Overlap correction

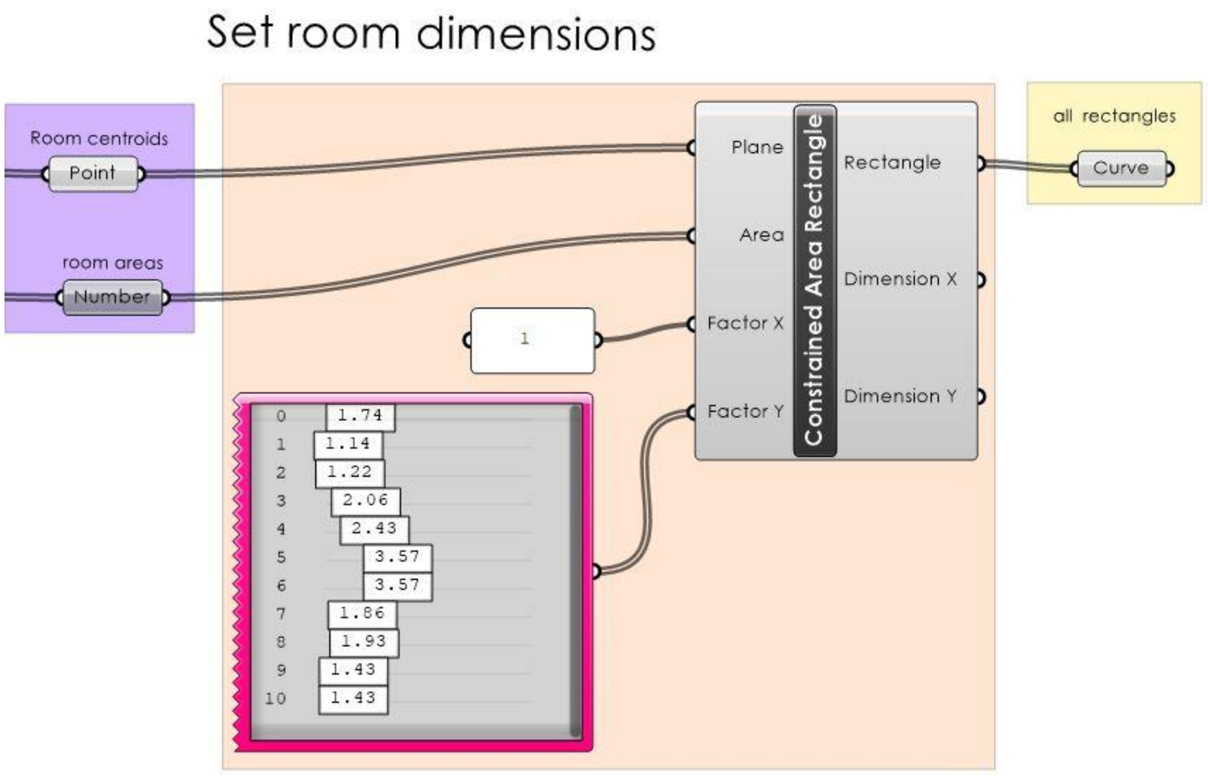


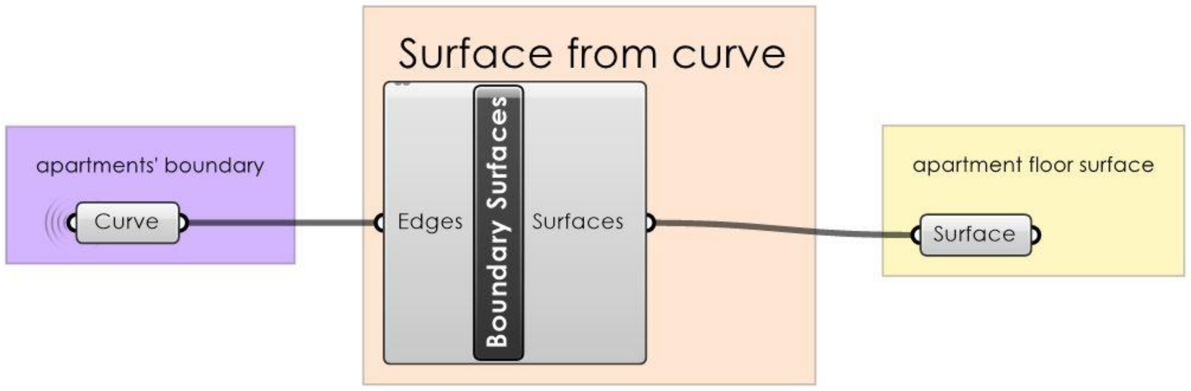
4. OUTPUTS

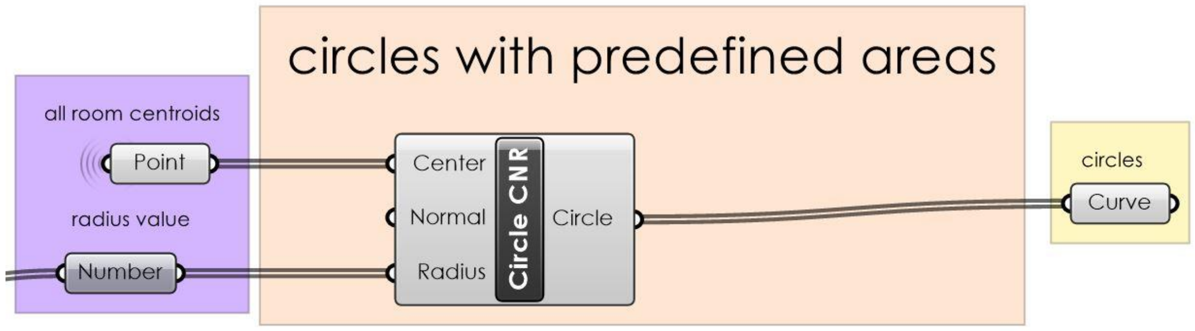


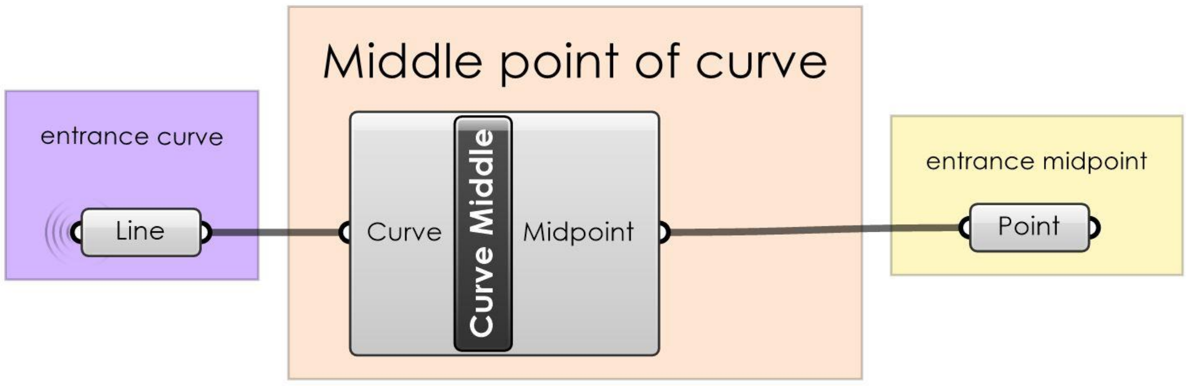
5. CALCULATIONS

Geometry related calculations

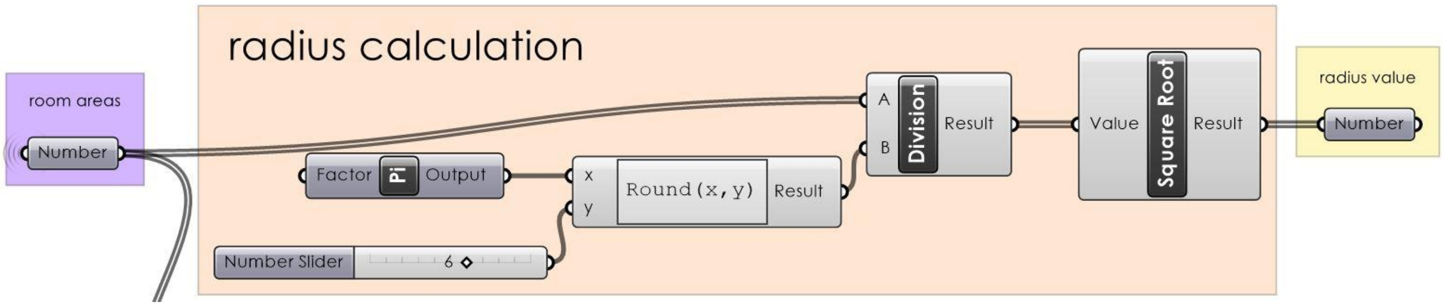



Surface from curve
apartments' boundary
Curve
Edges
Boundary Surfaces
Surfaces
apartment floor surface
Surface

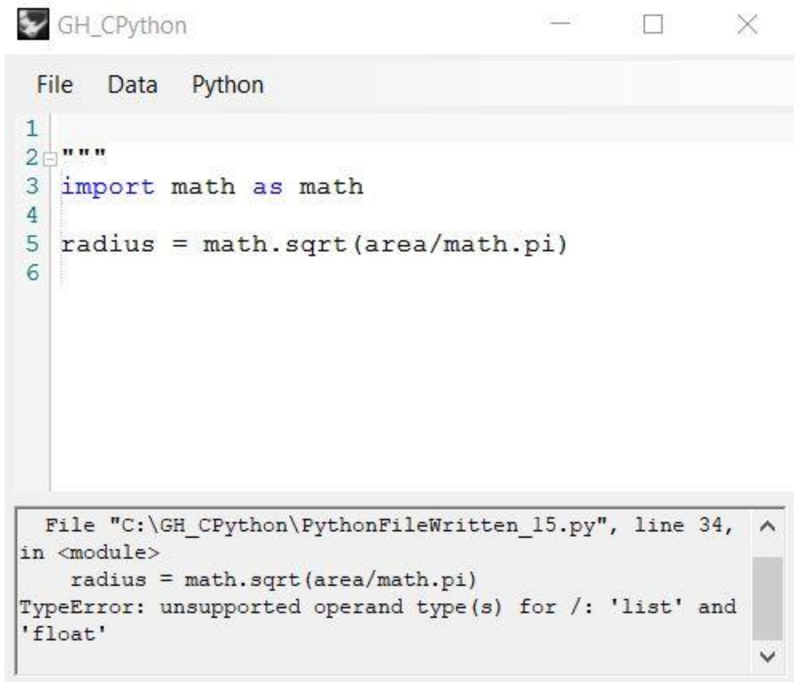

circles with predefined areas
all room centroids
Point
radius value
Number
Center
Normal
Radius
Circle CNR
Circle
circles
Curve


Middle point of curve
entrance curve
Line
Curve
Curve Middle
Midpoint
entrance midpoint
Point

Mathematical calculations



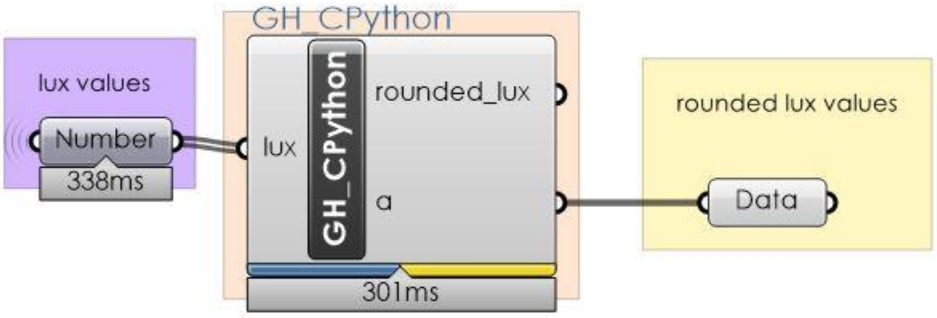
2nd way in python (not working)

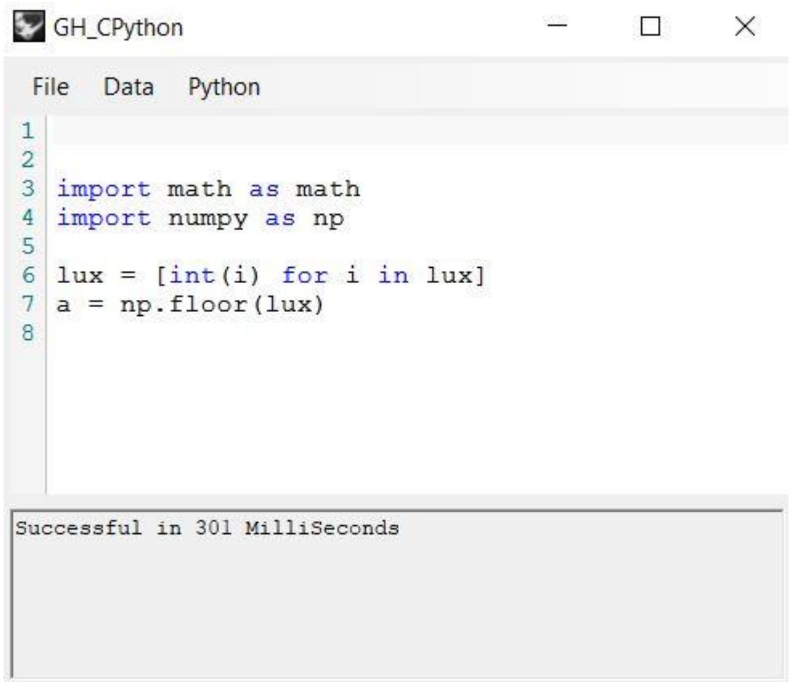


```
"""
import math as math

radius = math.sqrt(area/math.pi)

```

```
  File "C:\GH_CPython\PythonFileWritten_15.py", line 34,
in <module>
    radius = math.sqrt(area/math.pi)
TypeError: unsupported operand type(s) for /: 'list' and
'float'
```

Round number to floor

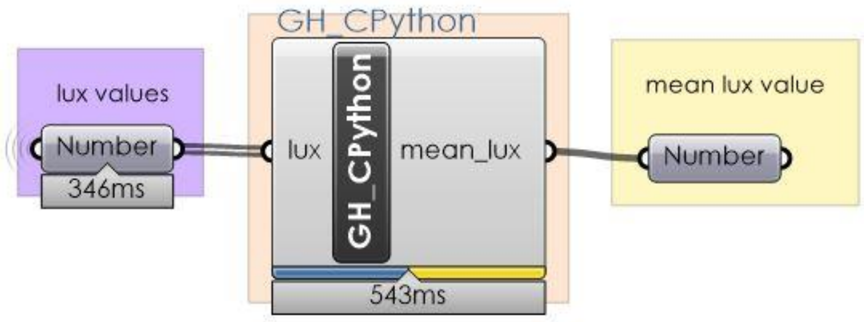


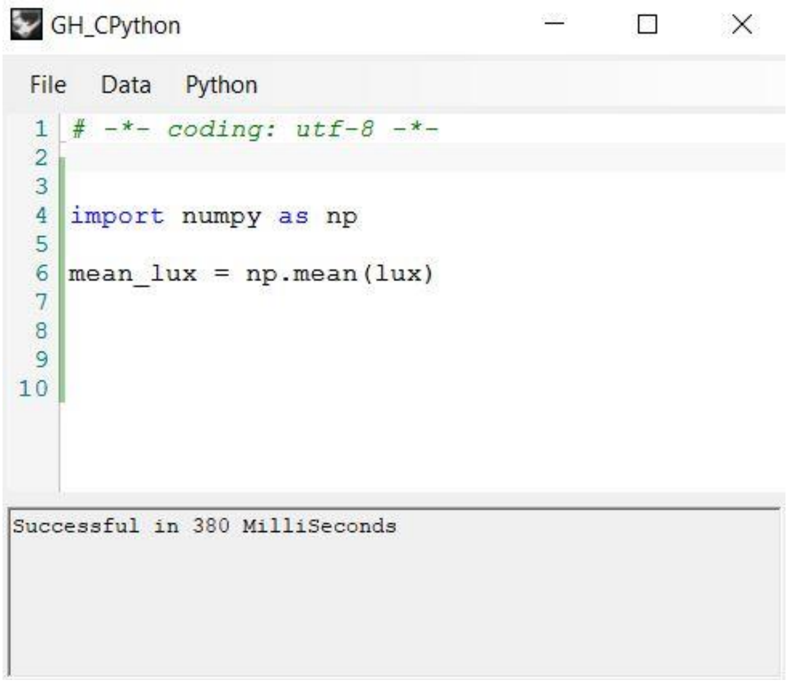


```


import math as math
import numpy as np

lux = [int(i) for i in lux]
a = np.floor(lux)

```

```
Successful in 301 MilliSeconds
```

Mean of a number

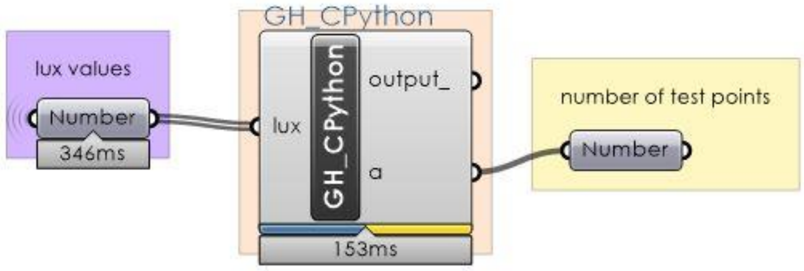


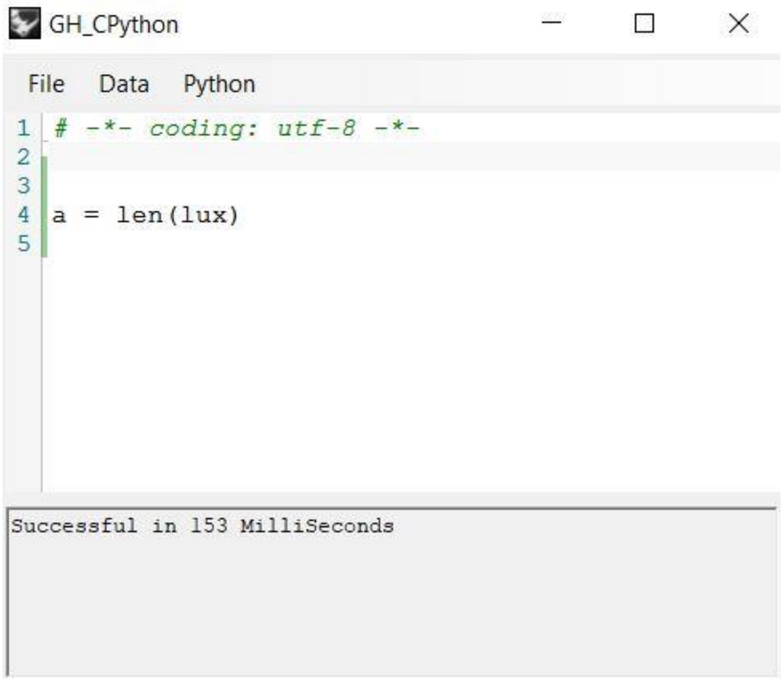


```
# -*- coding: utf-8 -*-


import numpy as np

mean_lux = np.mean(lux)
```

```
Successful in 380 MilliSeconds
```

List length



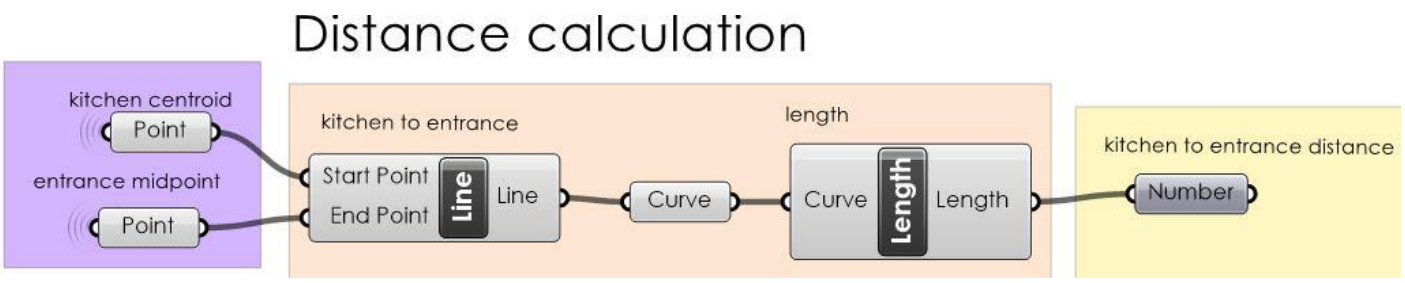


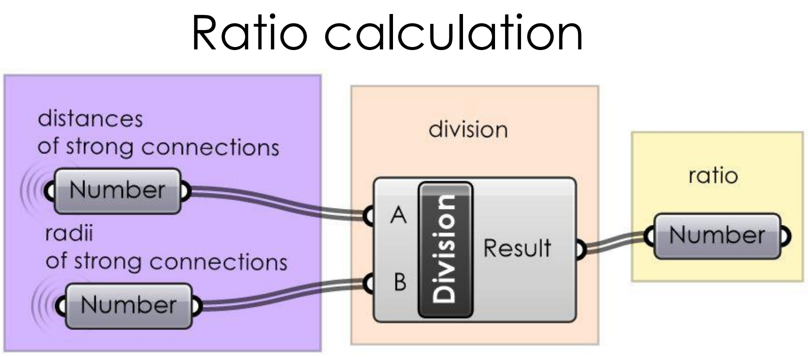
```
# -*- coding: utf-8 -*-


a = len(lux)

```

```
Successful in 153 MilliSeconds
```

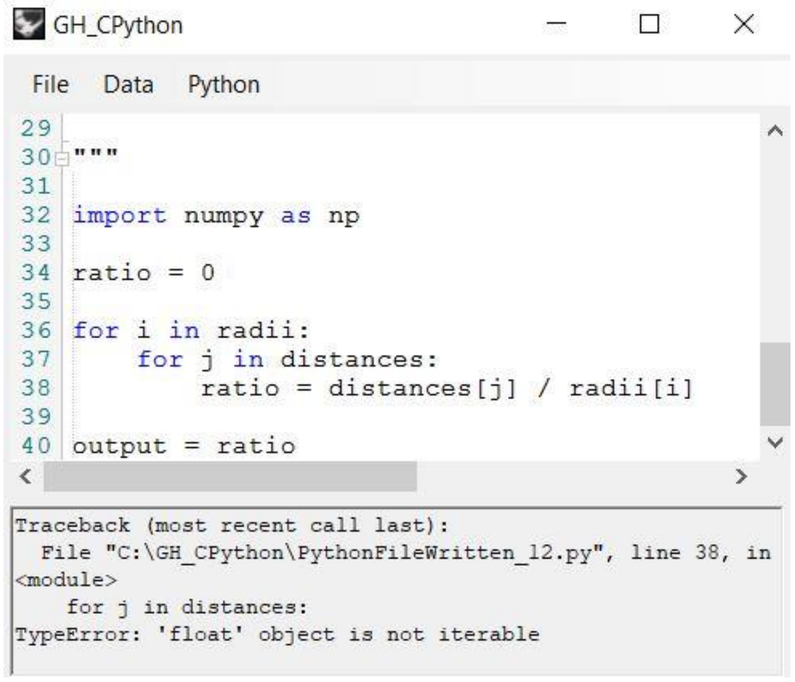
6. EVALUATION

Proximity results





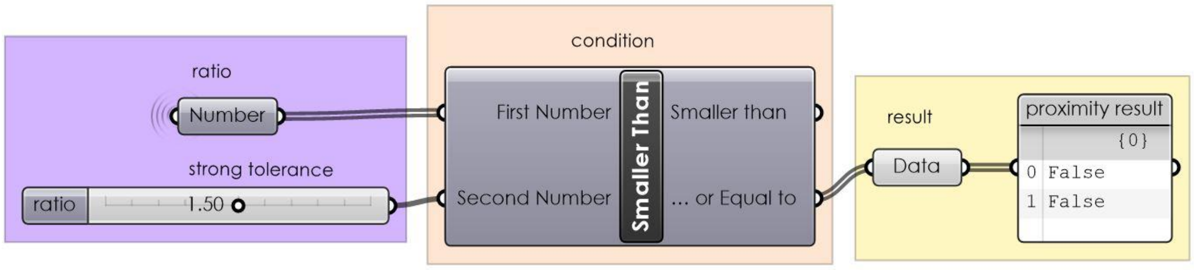
2nd way in python (not working)



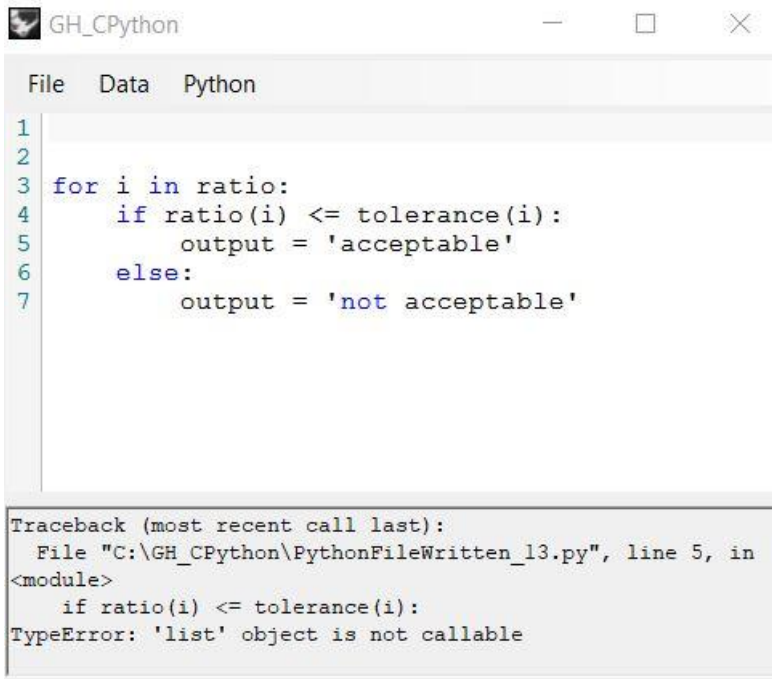
```
"""

import numpy as np

ratio = 0

for i in radii:
    for j in distances:
        ratio = distances[j] / radii[i]

output = ratio
```

```
Traceback (most recent call last):
  File "C:\GH_CPython\PythonFileWritten_12.py", line 38, in
<module>
    for j in distances:
TypeError: 'float' object is not iterable
```

Ratio check



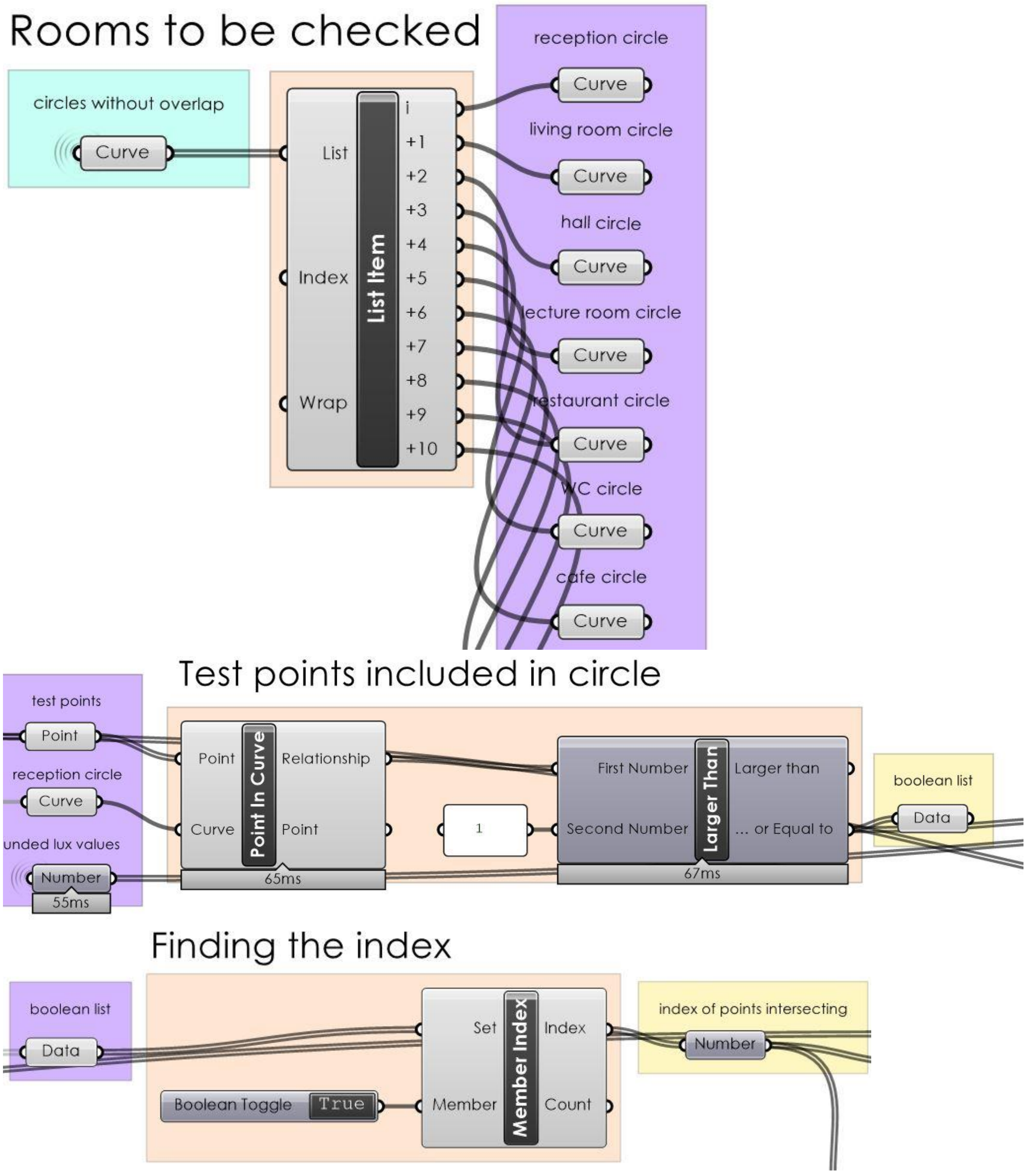
2nd way in python (not working)



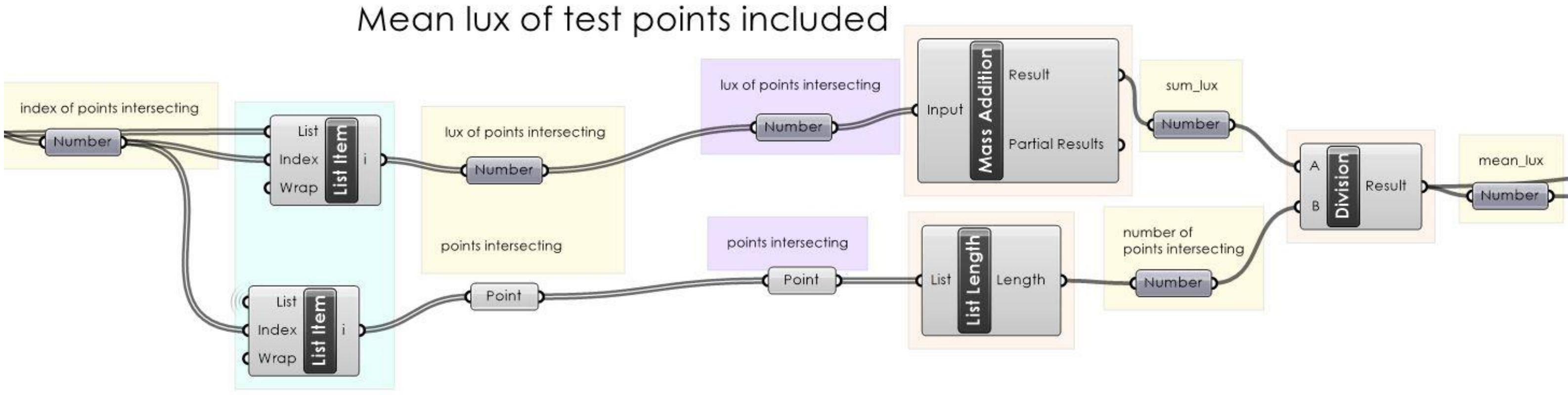
```


for i in ratio:
    if ratio(i) <= tolerance(i):
        output = 'acceptable'
    else:
        output = 'not acceptable'
```

```
Traceback (most recent call last):
  File "C:\GH_CPython\PythonFileWritten_13.py", line 5, in
<module>
    if ratio(i) <= tolerance(i):
TypeError: 'list' object is not callable
```

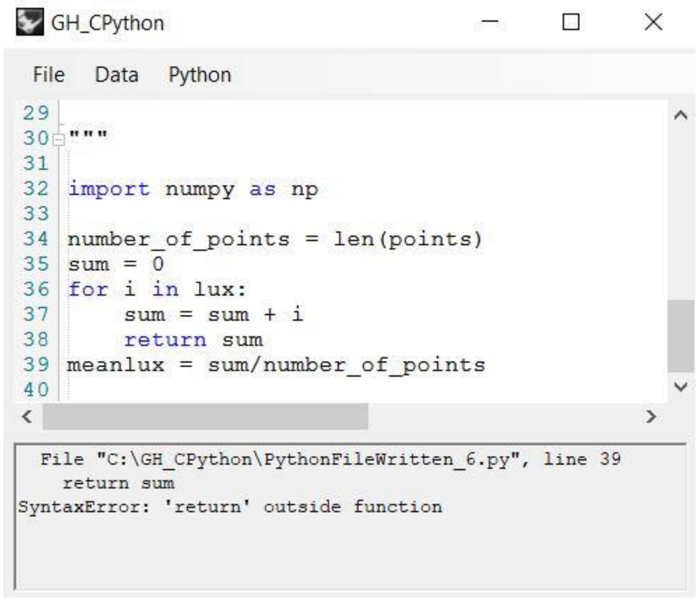
Illuminance results



Mean lux of test points included

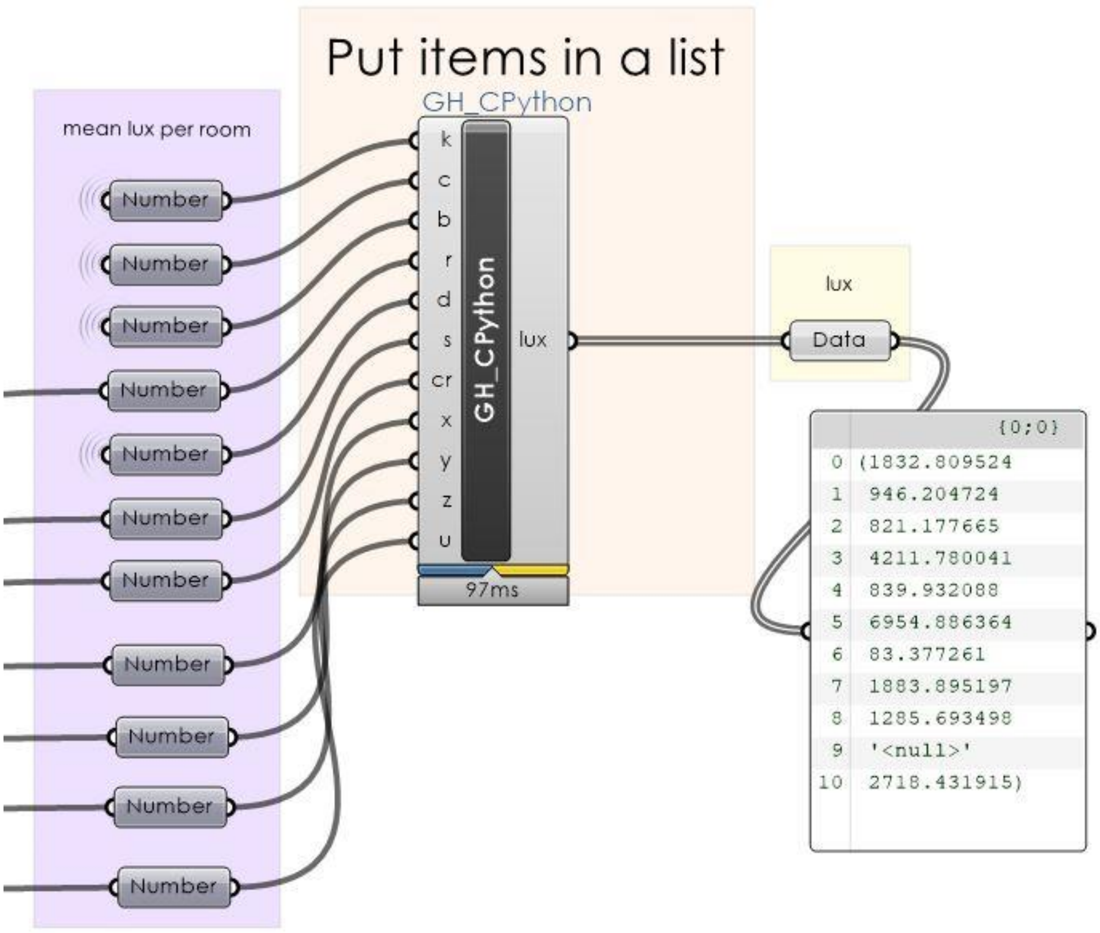


2nd way in python (not working)



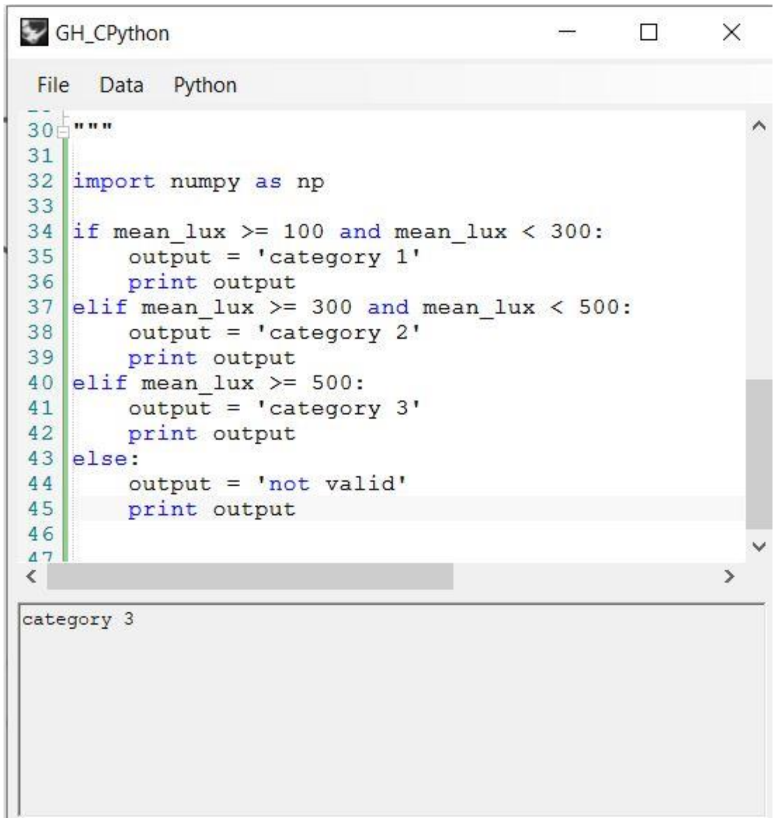
```
"""

import numpy as np

number_of_points = len(points)
sum = 0
for i in lux:
    sum = sum + i
    return sum
meanlux = sum/number_of_points

```

```
  File "C:\GH_CPython\PythonFileWritten_6.py", line 39
    return sum
SyntaxError: 'return' outside function
```



```
{0;0}
0  (1832.809524
1   946.204724
2   821.177665
3   4211.780041
4   839.932088
5   6954.886364
6   83.377261
7   1883.895197
8   1285.693498
9   '<null>'
10  2718.431915)
```

2nd way in python (not working)



```
"""

import numpy as np

if mean_lux >= 100 and mean_lux < 300:
    output = 'category 1'
    print output
elif mean_lux >= 300 and mean_lux < 500:
    output = 'category 2'
    print output
elif mean_lux >= 500:
    output = 'category 3'
    print output
else:
    output = 'not valid'
    print output
```

```
category 3
```

Appendix B: Pseudocode in Python

With the valuable help of my mentor ir. P. Nourian, the pseudocode of the iterative process could be structured like this:

```
Epsilon=0.00001
repulsionStiffness=1
continuance_condition=True
iterationCount=0
While (continuance_condition=true 'and' iteration_count<max_iteration):
•   for i in range(0,n):
    o   if not i is in fixedVertexIndices:
        ▪   sumAttractionForces=rg.Vector3d(0,0,0)
        ▪   sumRepulsionForces=rg.Vector3d(0,0,0)
        ▪   for j in range(0,n):
        ▪   edgeKey=(i, j)
            ➢   (length, stiffness, force, r_i, r_j,v_i,v_j)=edges[edgeKey]
            ➢   v_i=vertices[i]
            ➢   v_j=vertices[j]
            ➢   d_ij=v_j-v_i
            ➢   r_i=radii[i]
            ➢   r_j=radii[j]
            ➢   k_ij=K[i,j]
            ➢   f_ij=k_ij*d_ij
            ➢   converged=((abs(d_ij.length/(r_i+r_j) -1))<epsilon)
            ➢   continuance_condition= continuance_condition and !converged
            ➢   sumAttractionForces=force+sumAttractionForces
            ➢   if (length<(r_i+r_j)):
                ....1.   repulsionForce=-1*length*repulsionStiffness
                ....2.   sumRepulsionForces= sumRepulsionForces+repulsionForce
            ➢   resultantForce = sumAttractionForces+ sumRepulsionForces
        ▪   vertex=vertices[i] vertex=vertex+0.1* resultantForce

iterationCount=ierationCount+1
```