INTELLIGENT DESIGN OBJECTS APPLIED TO THE SPATIAL ALLOCATION PROBLEM

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JAVIER I. ZARATIEGUI FERNANDEZ

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ABSTRACT

INTELLIGENT DESIGN OBJECTS APPLIED TO THE SPATIAL ALLOCATION PROBLEM.

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This thesis approaches the spatial allocation problem as a multi-objective optimization problem. It proposes the use of Intelligent Design Objects (IDO) model to help designers with this task. Solutions are generated and evaluated, according the user defined criteria. Iterative improvement is proposed as a help to visualize candidate solutions and conceive the desired spatial relations. By defining the criteria and rating it numerically, both designer and client are able compare the solutions obtained. The use of fuzzy logic is implemented to address soft concepts as part of the architectural design process. New relations are defined until a good solution is found. The implementation is evaluated via two case studies: layout organization of sets of rectangles (two dimensions) and TUDelft graduation project for the American Embassy in The Hague (three dimensions).

Keywords: Spatial allocation, Intelligent Design Objects, Building layout, Optimization, Multi-objective, Genetic algorithm, Fuzzy logic.

ÖZ

MEKANSAL KURGU PROBLEMİNE AKILLI TASARIM OBJELERİ UYGULAMASI

Zaratiegui Fernández, Javier Ignacio
Yüksek Lisans, Mimarlıkta Sayısal Tasarım ve Üretim Teknolojileri
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Bu tez, mekan kurgusu problemine çoklu optimizasyon problemi olarak yaklaşmaktadır. Tez, bu iş için tasarımcılara yardımcı olmak amacıyla Akıllı Tasarım Objeleri (Intelligent Design Objects- IDO) modelini kullanmaktadır. Çözümler, kullanıcıların belirlediği kriterlere bağlı olarak üretilmekte ve değerlendirilmektedir. Yinelemeli geliştirme(iterative improvement), olası çözümlerin görselleştirilmesi ve istenilen mekânsal ilişkilerin kavranması için önerilmiştir. Hem tasarımcı hem de müşteri, kriterlerin tanımlanması ve derecelendirilmesi ile çözümleri kıyaslayabilmektedir. Bulanık mantığın (fuzzy logic) kullanımı, öznel ve ölçülemeyen kavramların mimari tasarım sürecinin bir parçası olarak adreslenmesi için uygulanmıştır. Yeni ilişkiler iyi bir çözüm bulunana dek tanımlanmaktadır. Uygulama, iki örnek çalışma ile değerlendirilmiştir: dikdörtgen kümelerinin plan organizasyonu (2 boyutlu) ve Lahey'de bulunan Amerikan Büyükelçiliği için TU Delft mezuniyet projesi (üç boyutlu).

Anahtar kelimeler: Mekân kurgusu, Akıllı Tasarım Objeleri, Plan Organizasyonu, Optimizasyon, Çok amaçlı, Genetik algoritma, Bulanık mantık

A mis padres,

César y Lourdes,

y mi hermana

Lidia,

con todo mi amor.

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CHAPTER 1

INTRODUCTION

In this thesis the spatial allocation problem is considered as a multi-optimization problem. The model used is the Intelligent Design Objects. It is proposed as a design tool and not as an automatization of the task. By studying and defining the formulation of the problem and visualizing some result, the designer can adapt it to his/her specific scenario and, gradually, build up the program relations.

The first chapter is an introduction to the spatial allocation problem. The second chapter exposes a perspective of previous approaches to the matter as well as their implementation in other industries, such as microchip and gaming industries.

The model used is explained in the third chapter: the tools used, the workflow and the use of optimization and genetic algorithms. Chapter four describes the mathematical formulation: the parameter definition, criterion definition and the implementation of fuzzy logic. The fifth chapter includes examples to evaluate the results and concludes with the application to a case study: the graduation project at TUDelft.

Finally, conclusions about the research and suggestions for further studies are presented.

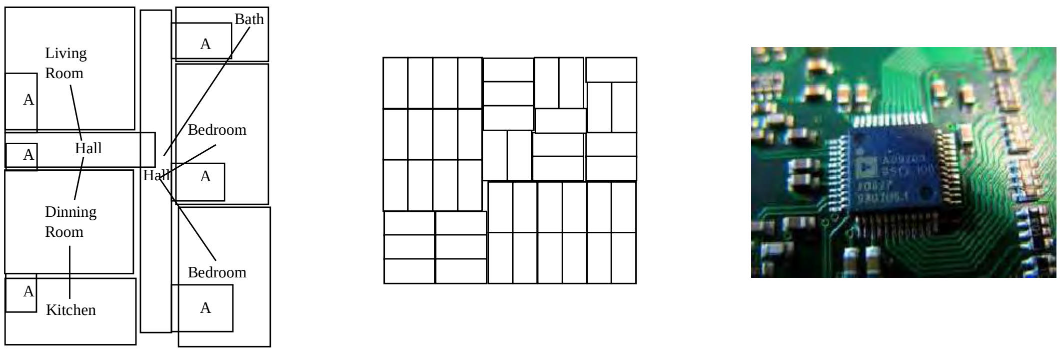
A building layout plan is the representation of the configuration and arrangement of different spatial elements in a building. Topological relations as alignment and adjacency; geometric properties such as shape, dimension and rotation are the main concerns in spatial synthesis (Eastman, 1973). It is one of the most difficult problems in architectural design as it has a significant impact on their function and accessibility.

A common workflow in architectural practice begins with refining the client´s requirements into an architectural program with diagrammatic representation of the rooms and connections (concept design process). In a later stage the program is used to generate floor plans. During this process, the architect reformulates the program as the importance of new relations are revealed, or the number of rooms redefined. The architect/s would study some of the outcomes and chose or propose to the client which one is the best. Due to the high number of possible combinations, the use of computers is advised for this operation. The task stands as an optimization problem, understood as the procedure or procedures used to make a system or design as effective or functional as possible.

As an example, for a family house building layout, the rooms are the elements to be arranged; the sizes and positions of each of them are parameters that will generate different solutions. Each outcome solution has different properties (dimensions, proportions, orientation, etc.) and there has to be some criteria and/or goals to compare them to be able to decide which one is better. Crisp goals (clearly measurable) are defined such as adjacencies, distances, total area, solar gain, etc. Fuzzy logic is introduced to address other concepts that are difficult to measure. For example, the concept of “big room”. This is referred as fuzzy because the exact value when a room is or is not considered “big” is not clear, it is subjective to the user. The implementation of these fuzzy concepts into the spatial allocation problem brings more design freedom in opposite to most of the previous researches on the topic whose formulations limit it.

It is likely that some of the goals introduced are conflicting and, as the value of one grows, the value of the other decreases. In the example, the bigger solar gain would come if the rooms are separated and a larger surface perimeter is presented to receive the sun but, at the same time, it results in larger walking distances among the rooms, ending up in a non-functional solution. Therefore, the search aims for a solution where all the objectives are in some degree satisfied.

Many researches have addressed the spatial allocation problem for building layouts and for other industries. However, their application is usually limited by the rigidity of their formulations. Some limit themselves to a certain type of building (residential), and their results cannot be extrapolated to other types. Others introduce the cost function of the overall solution and aim to minimize it. This is desirable in certain scenarios, but does not satisfy other architectural needs. The desired program relations in architecture are not a priori known, and are also different from project to project. Therefore the application of these researches in the field of Architecture has been limited, while micro-chip industry or pallet loading have successfully implemented them.



Apartment layout   Pallet loading   Microchip design

Fig. 1 From left to right: Apartment layout (Michalek et al. 2002), pallet loading (Morabito & Morales 1998), and microchip design (image by Uwe Hermann).

In this thesis the aim is to approach the spatial allocation problem through performance based design. The use of the cost function to compare different solutions is very limited. Instead, the user is intended to define the criteria for every specific scenario. Besides, the desired relations among the departments is not known and it is a process subject to changes. Questioning and formulating these relations is an important part of the design process. While previous methods take for granted that the relations are known, in this research it is part of the department parameter definition. As such, it is meant to be adapted and refined throughout the design process. Therefore, it is needed a tool that allows user customization.

The method adopted is called Intelligent Design Objects (IDO). IDO (Bittermann 2009) consists in generation of possible solutions, their evaluation regarding previously defined criteria, and generation of new solutions that improve the previous solutions (with the use of genetic algorithms).

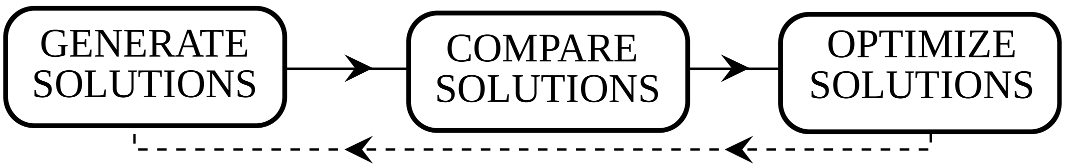


Fig. 2 Intelligent Design Objects scheme. Drawn by the author.

Multiple criteria instead a single criterion enables enhanced architectural outcomes. Likewise, both crisp and fuzzy goals are included as part of this multi-objective optimization. The use of fuzzy goals or objectives is included to echo the process taken in architectural design, especially in the early stage, but is not exclusive to this field. In the case of previous methods, each department area is fixed to a certain value, in most cases, or to a range of values. Fuzzy logic is included to extend the exploration of more solutions. For example, in a residential project the living room is desired to be "big". With other methods, the area value would be fix to 25 sq. m. or to a range of values from 20 to 30 sq. m. This excludes the consideration of solutions in which the living room is larger or smaller and, as such, it is a limitation. On the contrary, defining the abstract concept of “big” as a function allows a much wider solution exploration.

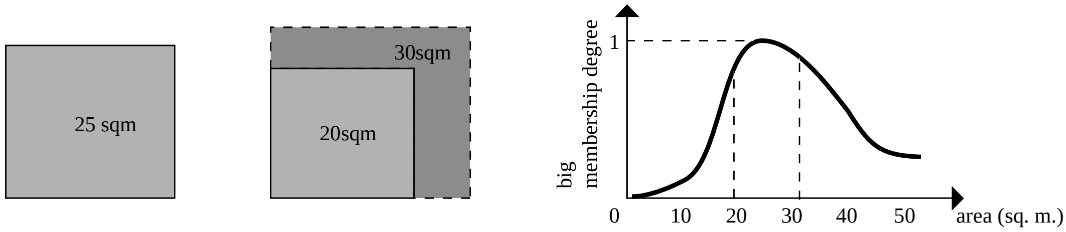


Fig. 3 From left to right: Fixed area value; range; fuzzy logic big membership function. Drawn by the author.

Defining this function is also part of the project analysis and reflects the designer intentions in a clear way and/or addresses the client wishes.

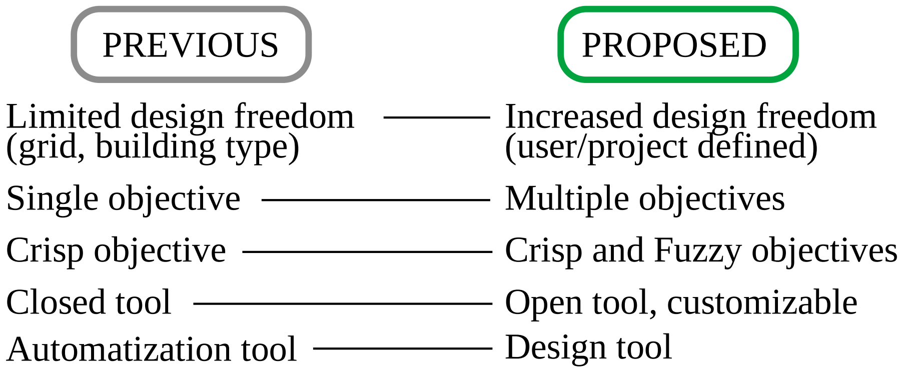


Fig. 4 Comparison between previous researches and this thesis proposal. Drawn by the author.

The increased freedom is reflected in an increase of the number of possible solutions. In order to deal with this high number of solutions a heuristic strategy is used, such as evolutionary algorithms. The encyclopedia Britannica defines heuristic “as relating to exploratory problem-solving techniques that utilize self-educating techniques (as the evaluation of feedback) to improve performance”. Also notice that the outcome with such method is not guaranteed to be optimal but, since it is unfeasible to analyze every possible solution, the aim is to find satisfactory solutions for the problem.

Within the scope of this thesis some examples will be studied and the graduation project for TUDelft will be used as a case for the evaluation of the model. This model, IDO, is suitable to be used for different building types and/or different problems than the spatial allocation, while the problem formulation and the criteria are user defined for each particular scenario.

CHAPTER 2

LITERATURE REVIEW

The use of a tool, any tool, in the design process seeks to enhance the quality of the design. In the case of computer tools, productivity, efficiency, precision, etc., but are not admissible if they restrain design freedom. Many studies have been carried out about the spatial allocation problem, and applied successfully in some fields, such as microchip industry. The microchip industry strived for a solution for chip layout design that minimize wiring costs, and researches like Khokhani & Patel (1977) were implemented effectively.

In many cases, researchers evaluated their software with architectural exercises. Liggett´s (1980) application to a hospital department organization, and coming studies seemed to open the path to practitioners. However, the limited design freedom (based in cellular module grid, for example), and/or the difficulty of the implementation (complex travel cost matrixes) have kept architects away from using these methods.

In the coming chapter, a review of previous researches is presented.

Table 1 Computing approaches used for space allocation.

YEAR	AUTHOR	TOOL	METHOD	APPLICATION
1964	Bufa and Armor	CRAFT	distance matrix, pair-wise exchange	hypothetical
1967	Evans and Sheedof	CORELAP	distance matrix, pair-wise exchange	hypothetical
1971	March and Steadman		network graph	hypothetical
1971	Grason		graph theory	rectangular disection
1975	Handel and Weinzapfel	IMAGE	random number generators	hypothetical
1976	Gross		spatial intensity based on solid boundaries	hypothetical
1980	Liggett and Mitchell		implicit enumeration	19 activities hospital
1981	Galle	FLOP 1	exhaustive enumeration	arrangements of rectangles in a plane
1984	Hillier and Hanson		space syntax	pedestrian movement
1985	Gero	EDGE	combinatorial optimization	office four floor building; Liggett´s hospital example;
1987	Shaviv		point-area model	3 floor school
1991	Baykan, Can A.	WRIGHT	constrained direct search	kitchen plan
1996	Scheithauer		heuristics	pallet loading
1997	Gross	CO-DRAW	co-relational modelling language	hypothetical
1998	Morabito et al.		recursive procedure	pallet loading
2001	Parish and Muller		L-systems	city street map
2002	Ebert et al.		procedural methods	textures
2002	Michalek et a..		simulated annealing and genetic algorithms	apartment complex building
2003	Greuter et al.		random generated polygons	city map
2003	Wonka et al.		bayesian network	one and two floor housing
2006	Martin, J.		procedural algorithm	residential interiors
2007	Doulgerakis, A.		genetic programming	3D building
2008	Indraprastha and Shinozaki		wall enclosure level analysis	Falling Water. Vitra firestation
2008	Caldas, L.	GENE-ARCH	genetic algorithm	Alvaro Siza building and urban and housing Islamic context
2009	Hyeyoung et al.		space syntax	indoor spatial analysis
2010	Hua, H. and Ting-Li Jia	FLOATTING BUBBLE	agent-based	two storey museum
2010	Hatice and Eldemir	SFLG	spiral facility layout	Craft improvement
2010	Doran and Parberry		agent-based	landscape generations
2011	Togelius		cellular automata	cave layouts
2013	Nourian et al.	SYNTACTIC DESIGN	space syntax and fuzzy modeling	residential interiors

2.1 Literature

The assignment of architectural discrete space elements in the plane to their locations is known as the spatial allocation problem. The relationships between the space elements include topology and geometry. Determining these relations make the design process complicated due to its combinatory nature. The use of computers was instated for automating this task. Automated spatial allocation aimed to assist architects during the conceptual design process. Since 1960 many soft tools have been developed for finding automated solutions for this problem.

The first attempts focused on producing arrangements of rectangles in a plane, or on the allocation of grid cells. Armor and Buffa were the first in 1964 to formulate the layout problem as a quadratic assignment problem. They considered the cost between departments to be the criterion to minimize. For that, they developed Computerized Relative Allocation of Facilities Technique (CRAFT). Probably their work was influenced by Eldars and Whitehead´s study, on the same year, on the pedestrian movement in a hospital (which turned to be 23%).

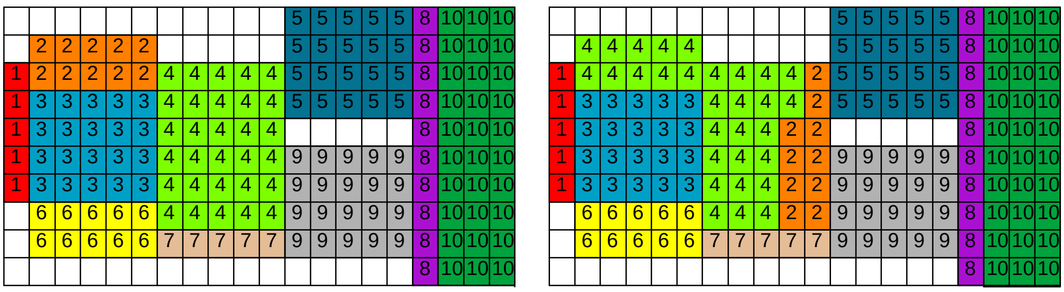


Fig. 5 CRAFT (Armor and Buffa, 1964). Initial layout (left); Iteration between departments 2 and 4(right). Drawn by the author using Paul A. Jensen (2004) Facility Layout Demo based on CRAFT.

The limits of the CRAFT were extended (Hatice & Eldemir 2010) SFLA, or Spiral Facility Layout Generation and Improvement Algorithm. The aim is to gather the most frequently used spaces at the center, as it will minimize the distance between them.

Later, Lee & Moore (1967) and Evans and Seehof (1972) developed Computerized Relationship Layout Planning (CORELAP) and Automated Layout Design Program (ALDEP) respectively, based on the importance of a set of pairwise evaluations of the closeness of two activities, rating them in 6 stages: Absolute essential, essential, important, ordinary, unimportant and undesirable.

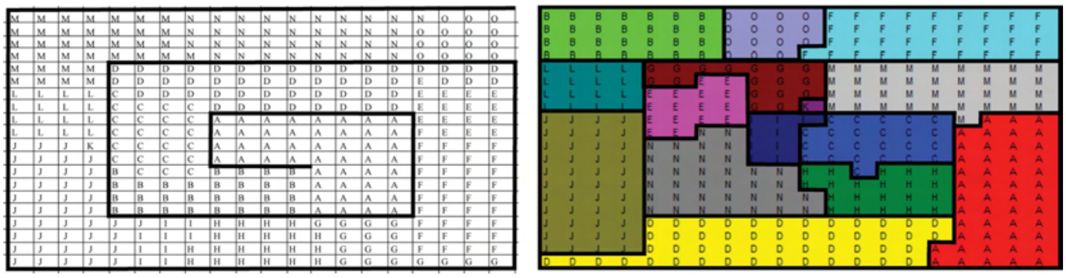


Fig. 6 SFLA Initial Layout (left); Final Layout (right). Hatice & Eldemir, 2010.

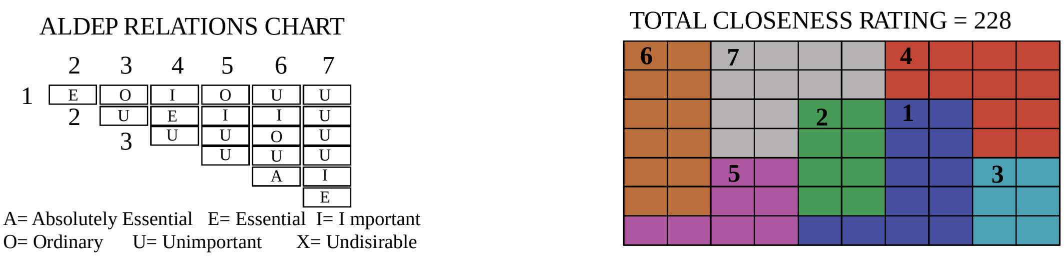


Fig. 7 ALDEP. 6 stage rating (left); outcome (right). Evans & Seehof 1972

These algorithms focus on the transportation cost function as the combination of flow, distance and unit cost. It is useful for organizing a production factory, defining the machinery tools as the departments, the moving cost and the flow chart. Its limitation is that it assumes that move costs are linearly related to the length of the move and that are independent of the department.

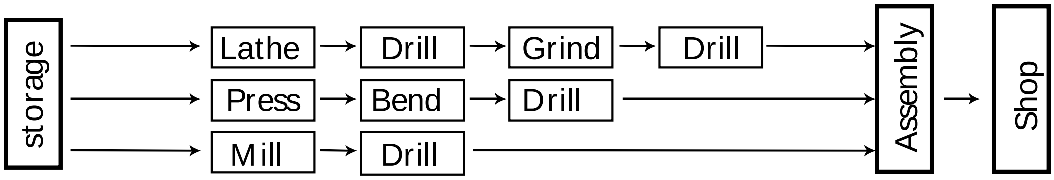


Fig. 8 Minimize cost distance to improve a factory. Drawn by the author.

Handel and Weinzapfel (1975) developed a three dimensional layout planning named IMAGE, in which a set of rectangular volumes represented the building functions. These volumes are defined by a set of dimension, position, and rotation. A set of constraints such as alignment, proximity and circulation form the constraints and the objective is to satisfy all of them.

Approaches that attempt to enumerate all possible arrangements with a specified number of rooms (Galle 1981), face the problem that increasing the number of elements (rooms) grows the possible arrangements exponentially, making this approach very limited. Others attempted to find "a good" arrangement using greedy local search over possible partitions of a regular grid (Shaviv & Gali 1986).

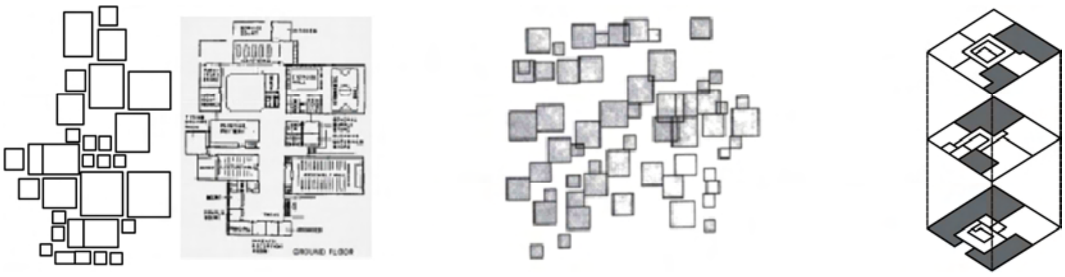


Fig. 9 From left to right: Shaviv & Gali, 1974; IMAGE, Handel & Weinzapfel, 1975 ; RENDER3, Hokoda, 1982.

Other studies continued investigating the spatial allocation problem, such as Liggett (1980), Hokoda (1982), Akin (1992), Yoon and Coyne (1992). It is seen that three major issues common to all of them arose:

The complexity of the problem (due to its non-linearity).

How to control the possible combinations.

How to evaluate the solutions.

The first one is inherent of the problem. It is referred as non-linear because the output is not directly proportional to the input.

Different algorithms deal with the control and evaluation of this problem in different ways. Liggett assigns the size of the space elements to modules. The assignment strategy is the multi-stage that includes floor, zone and block to locate the modules, and the largest spaces are placed first.

Jo & Gero 1985 implemented in C language the Evolutionary Design based on Genetic Evolution system (EDGE). They evaluated its performance by solving the same space layout attempted by Liggett in 1985.

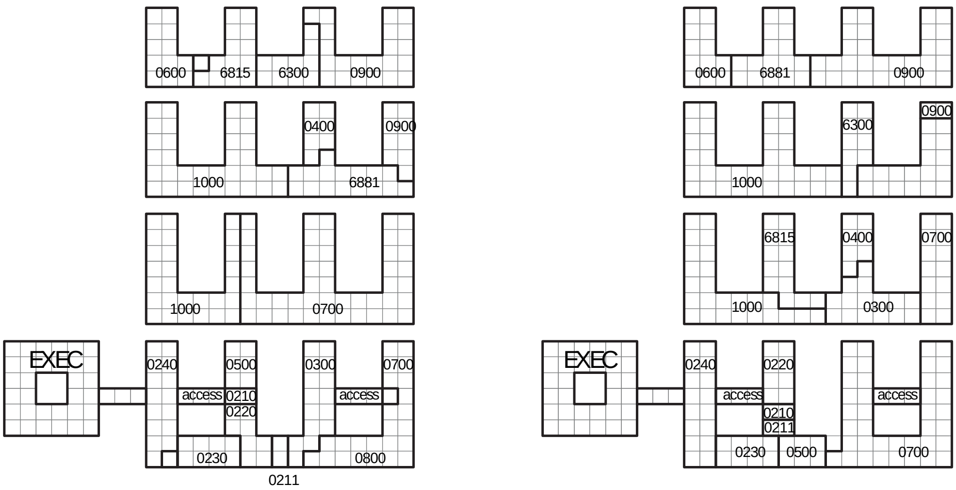


Fig. 10 EDGE. Solution after 500 generations (left). Solution evolved using Liggett´s as the initial population (right) Jo &Gero 2006.

It considers a set of 21 office departments to be placed in a building with 4 floors, divided into 17 zones. Their results indicate their strategy is less dependent on the initial population than Liggett´s and finds solutions closer to the global optimum.

Other strategies are constructive placement and pair-wise improvement. Graves & Whinston (1970) developed the constructive placement. It is a strategy of n-stage decision process, and locates activities one by one starting with an empty set. The next element is chosen based on the objective function. Then pair-wise change is used. It evaluates possible changes between pairs of activities and makes the exchange if it improves the value of the criterion for the highest value. The solution obtained is very dependent on the initial solution.

The change is applied on pairs of neighboring units, and not possible on units over 3 or more even it may produce a better solution. For example if the units consist of “0 1 1 0” and the objective is to locate the same kind of units together, the solution may never get “0 0 1 1” or “1 1 0 0” because it will not accept any change that would make the performance decrease immediately compared to the previous state. This is a limitation of the pair-wise method to find an optimal solution because even a decrease in performance in one pair exchange could lead to an improvement by the next exchange.

Recent studies have pointed out the suitability of data driven approach. Following Koller and Friedman (2009) probabilistic models, P. Merrell, E. Schkufka and V. Koltun (2010) structured relationships among features in architectural programs. They used Bayesian network to represent probability distribution over the space. For example, a kitchen is more likely to be adjacent to a living room than to a bedroom; three bedrooms increase the need of a second bathroom. These relations are often implicit in architect´s expertise but not clearly represented with ad-hoc optimization approaches. In Merrell et al., they encoded 120 architectural programs of residential layouts to train the Bayesian network. Their data is highly structured based on global (total area and footprint) and per room basis.

To convert the graph into a building layout, the metropolis algorithm is used. Metropolis-Hasting algorithm is a Markov chain Monte Carlo to obtain a randomly distribution when direct sample is difficult. As Sullivan & Beichl state (2000, p.69) “Monte Carlo is a last resort, to be used only when no exact analytic method or even finite numerical algorithm is available”.

Very large scale integration layouts (VSLI) and their trained Bayesian network took an average of 35 seconds to generate a layout. But many factors were not taken into account (such as climate, views, site, client desires, curved spaces…).

Feature	Domain
Total Square Footage	Z
Footprint	Z × Z
Room	{bed, bath, … }
Per-room Area	Z
Per-room Aspect Ratio	Z × Z
Room to Room Adjacency	{true, false }
Room to Room Adjacency Type	{open-wall, door }

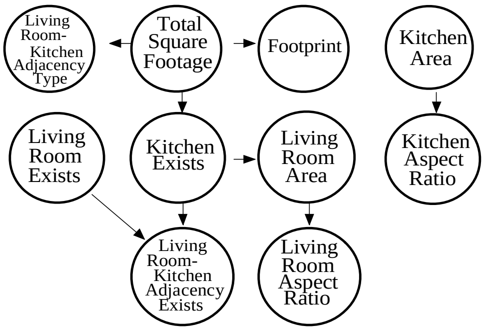


Fig. 11 Bayesian network. Merrel et. al., 2010.

2.2 Selection criteria

To evaluate the performance of each solution for privacy-publicity or inclusivity-exclusivity analysis Arabacioglu (2009) uses fuzzy inference and isovists. It is an attempt to quantify architectural space, since the distance objects and visibility provides different experience.

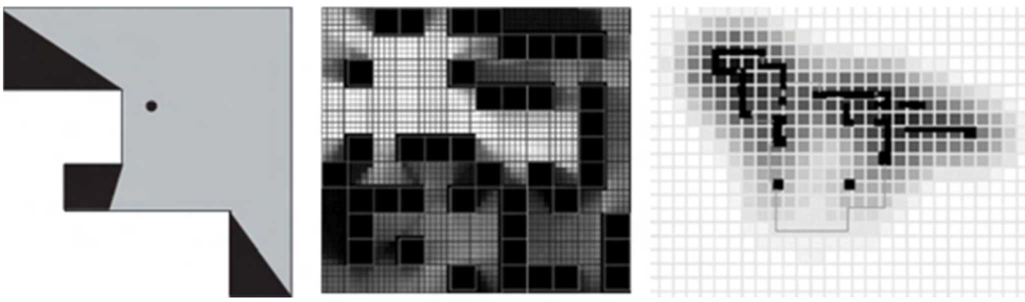


Fig. 12 Isovists, depth map tool and Falling water stress intensity analysis. Arabacioglu, B.C., 2009.

Indraprastha & Shinozakim (2008) study the experience of an architectural space as a product of out movement and perception, or as a result from the arrangement of its boundary elements. They refer to Gross (1997) and measure the level of spatial intensity based on number of solid boundaries. According to them each enclosed space is classified by the number of adjacent walls.

Their study consists in calculating enclosed spaces and axial lines to establish the enclosed spaces relative to a circulation space, and the determination of subdivided enclosed spaces using territorial lines. The main limitation of their model is to try to measure spatial intensity as a human experience but leaving the material properties like texture of opacity out of the model.

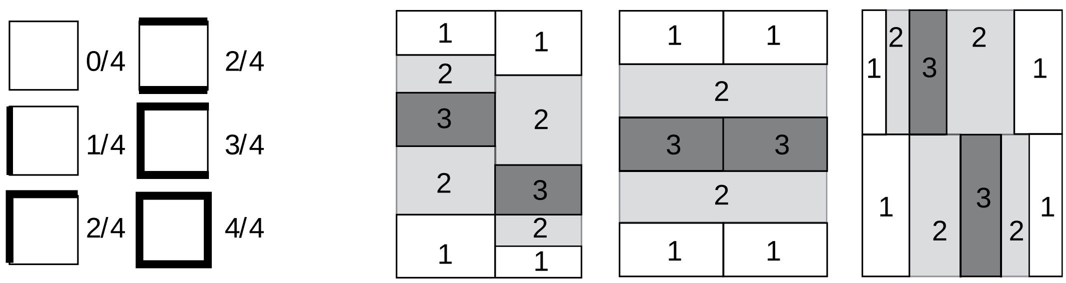


Fig. 13 Enclosure Level Given by the Different Compositions of Surrounding Walls based on Gross´s model (left); Enclosed space subdivision (right). Indrapastha & Shinozakim 2008.

Accessibility has been applied to urban problems. For large buildings, the interspatial accessibility among the parts is taken into account for evacuation planning, for example. Accessibility refers to the relative nearness from one place to another. It has been used mainly in 2D for urban cases but, in a building, those relations are 3D. Space syntax has been used to study the connectivity of architectural spaces. It has been applied in the attempt to model pedestrian movements to compute the network connectivity of the built environment.

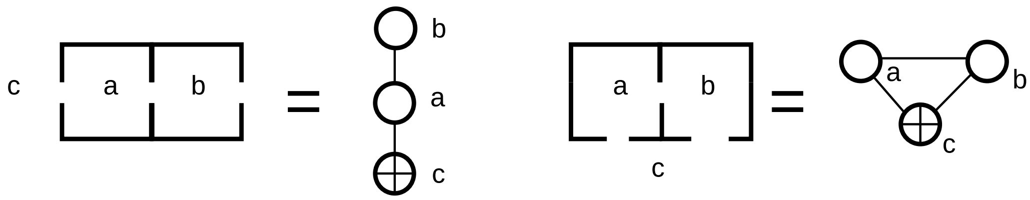


Fig. 14 Decoding configurations. Hillier & Hanson 1984.

Hyeyoung Kim, Chuilmin Jun, Yongjoo Cho and Geunhan Kim (2008) already reflect the main drawback of this approach: the difficulty of computing the costs taken in movement among spaces, like turns or floor transfers. They used the shortest path algorithm by Dijkstra, 1959, composed of node selection operation and distance update but they conclude that the depth of the linear space is not applicable to indoor spaces so they added penalties for turns and movement between floors (and called it "impedance").

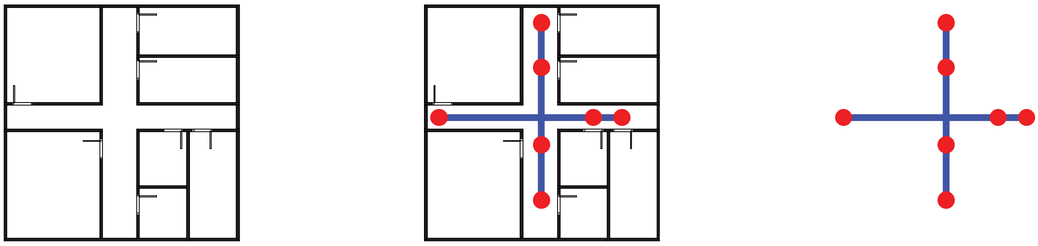


Fig. 15 Constructing a network. Kim, H., et. al., 2008.

Recent studies (Doulgerakis 2007), propose genetic programming (GP) instead genetic algorithms. The restriction of GAs is their fixed genotype length. GP is based on the idea that the structure of the attributes and their magnitude for the optimal solution are part of the answer and not on the question. Doulgerakis considers the layout problem as a program induction problem. The genotypes are expressed as tree-like recursive structures. The end nodes are spaces with two variables (width and height) and the intermediate nodes are transformation operations (move forward, rotate ad scale). That strategy, as he noted, led to a confusing process where separation and overlapping was difficult to avoid, and more inefficient when the outline of the site is given.

2.3 Other applications of the spatial allocation problem.

Microchip industry has successfully used iterative algorithms in their designs. Khokhani & Patel (1977) presented the benefits on the chip layout problem. The constructive methods obtain the initial solutions and the wirability evaluation and the wire length are used as constraint and criterion, respectively.

Maps generation is another interesting approach. Useful for creating terrains, the particle deposition algorithm drops particles at random locations. These particles move down till they reach other particle or the ground. Heights are adjusted or randomly determined. Same approach could be used for a layout configuration, although it may need other rules to bring significant architectural results.

Using multiple software agents (Doran & Parberry 2010) implement five agents with specific tasks to generate a landscape. The way they conceive their agents to create flat areas, mountains of paths could also be helpful when searching for a 3D building layout. But, for now, these approaches are more used by gaming industries than architecture firms due to the difficulty of the evaluation of the results.

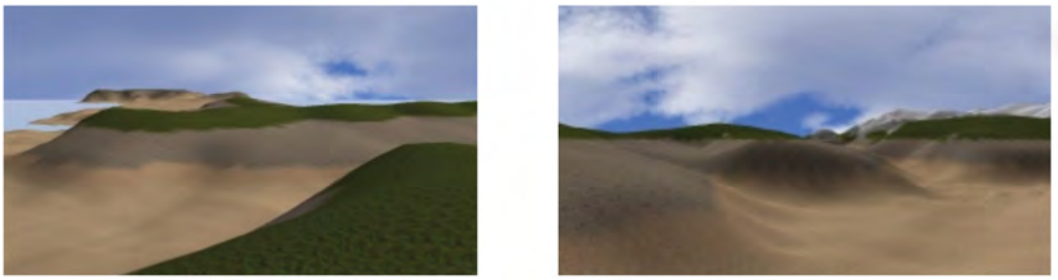


Fig. 16 Agent based landscape generations. Doran & Parberry 2010.

An algorithm with low computational cost allowing real time generations: cellular automaton. It is a collection of cells on a grid that evolves with a set of rules based on the neighboring cells. It has been used by Stanle, Yannakakis & Togelius (2010), to generate cave or dungeon layouts. After it runs the cave is evaluated to determine it if is acceptable or not. If some of the cells do not connect to the initial grid, the closest two are joined by a tunnel. At last, inconsistencies are removed or smoothing is performed.

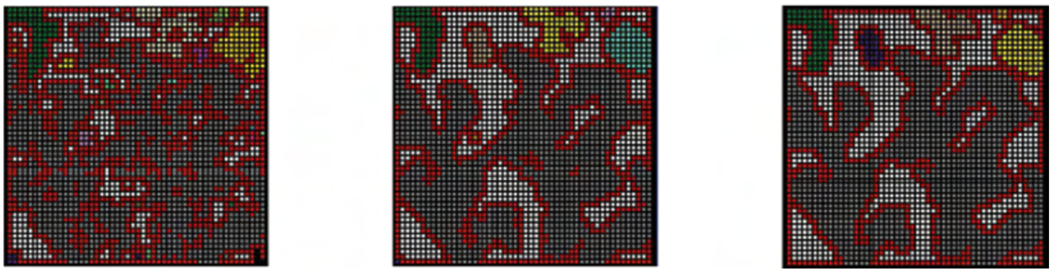


Fig. 17 Cellular automata cave layouts. Togelius, J. et al., 2010.

The increase in video games realism, has led to better real time buildings generations. Togelius et al., generate complete maps using a search-based procedural content generation (SBPCG). This algorithm does not only accept or reject a candidate: it grades the solution by assigning a numerical value.

The Rectangle Pallet loading consists in finding a pattern to pack small rectangles in a larger rectangle, so that the area used is maximized (Scheithauer & Sommerweiß 1996). Pieces of different height are combined, resulting in a three dimensional problem.

Fig. 18 Pallet loading. Scheithauer & Sommerweiß 1996.

As it is exemplified, spatial allocation problem has been applied successfully in many fields such as microchip manufacturing, pallet loading or factory tool disposition. Architectural problem solving, understood as the search and selection of solution alternatives during sketch design phase, still remains more to researchers than to practitioners (Galle 1981). The compromise in formulations needed to overcome the difficulty of the problem, in computation costs, result in many tools that claim partial good results but lack of design freedom. Some constrain themselves to grids (Armor & Buffa, Liggett & Mitchell, Gero, etc.) others to specific architectural types (Wonka et al.) and, in general, the departments are set as modules or rectangles. The difficulty of the architectural problem relies both on defining the relations and on the goal definition. The architect does not know a priori what are the relations among the departments neither what is the importance of every goal. Maximizing the used area (as in pallet loading) is certainly an architectural objective, but it is not the only one. In fact, the complexity of architectural design requires the consideration of multiple objectives.

In this thesis, since the relations are not defined, the computer is used as a design tool and not as an automated tool. The emphasis is put on the search of a basic layout that will be later modified and refined into a building layout. The use of rectangular shape pursues a reduction of computational costs, since it is up to the user modifying the solution into irregular shapes to his/her will. The computer produces some initial solutions in relation with the first set of inputs, and new relations come to the designer's mind, who redefines the inputs and runs the process again till a satisfying solution is found. In constructive approaches, the departments are added one by one, in relation to the previous state. In this thesis an iterative approach is pursued as the relations are not a priori established. By visualizing new solutions, new relations and/or their relative importance come out. However, to assure design freedom, the spatial allocation problem has to be formulated in a flexible manner, able to respond to different project scenarios. This is explained in the upcoming chapters.

CHAPTER 3

MODEL

In the previous chapter an overview of previous researches was presented. Their formulations, in most of them, differ and it is not possible to compare their results. Some of them have been successfully applied in other fields, such as pallet loading and microchip design, but the architecture scene is still reluctant to their usefulness.

In this thesis, the Intelligent Design Objects (IDO) model is presented as an aid in the design of different scenarios. An individual formulation is required for every case, which allows the user to embed his/her criteria and the singularities of each project. Finally, the user evaluation determines whether the solutions achieved are satisfactory or if it is needed a change in the problem formulation (parameters, criterion or both). In this chapter, this model is explained and the mathematical formulations are disclosed in the next one.

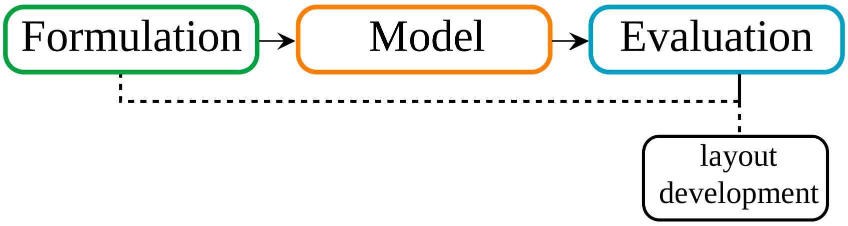


Fig. 19 Workflow: Formulation, Model and Evaluation. Drawn by author.

3.1 Approach

In this thesis the project is treated as a space allocation design problem. The computer is used to help the designer to define the different relations among the departments of the program proposed. Visual feedback is provided to guide the designer. Since these relations are not a priori established, the author does not aim to achieve the automatization of the task. Instead, a progressive refinement of these parameters and relations is carried out. The custom based formulations allow design freedom and flexibility to be applied to different projects. The number of criteria affects critically to the computation required to find optimum solutions. Once more, it is subject to the user the number of criterion to be considered, and their relative importance.

As seen before, the three main issues are:

The complexity of the problem (due to its non-linearity).

How to control the possible combinations.

How to evaluate the solutions.

To cope with these three topics, the Intelligent Design Objects methods (IDO) is used (Bittermann 2009). IDO consists of three steps: the first is the generation of possible solutions. The second is performance analysis. A set of criteria is defined to compare the outcome of the generations. Finally, an optimization process to obtain better solutions, with the use of genetic algorithms is presented.

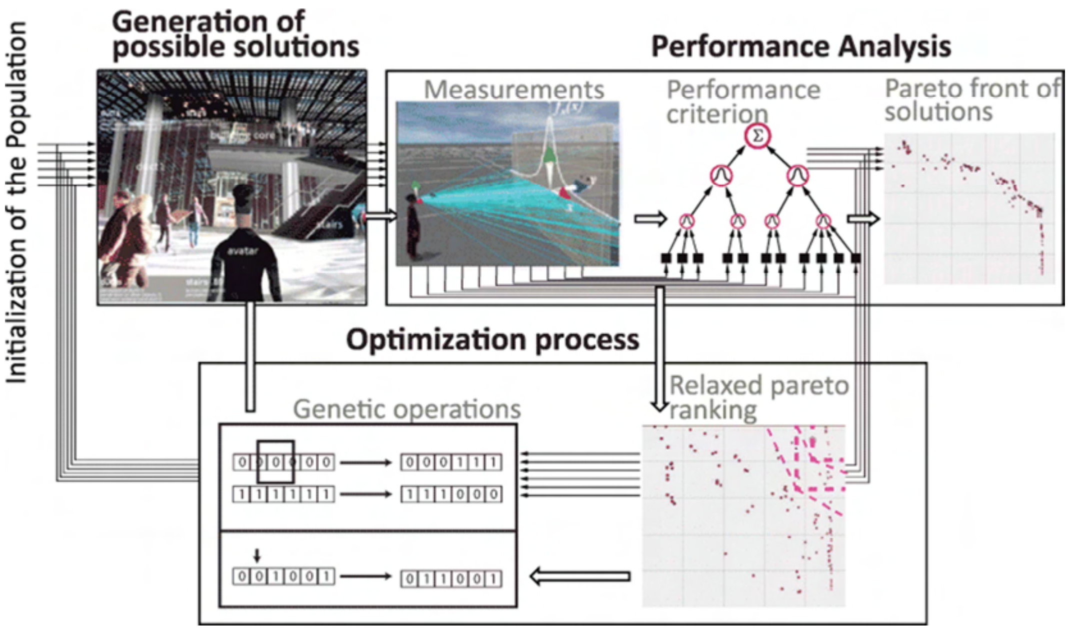


Fig. 20 IDO. Generation, performance analysis and optimization. Bittermann 2009.

3.2 Tools

For this research a student license from TUDelft for a modelling software was used. The program is called “Rhinoceros”, and the version used was 5.0, service release 5. A demo version is available at their website (http://www.rhinocd.com).

The parametric plugin for this software, “Grasshopper” (available at http://grasshopper3d.com), and a pre-released for testing version of “TO&I Lotus” was used. TO&I Lotus is a multi-objective evolutionary algorithm, based on adaptive, relaxed Pareto front formation developed by Professor O. Ciftcioglu and Dr. M.S. Bittermann at the Chair of Design Informatics (TO&I) of Delft University of Technology, combined with the Non-dominated Sorting Genetic Algorithm NSGA-II developed by Professor K. Deb at the Department of Mechanical Engineering of Indian Institute of Technology Kanpur (IITK). The component was programmed by MSc I. Chatzikonstantinou & Dr. M.S. Bittermann (Ciftcioglu & Bittermann 2009, Deb et al. 2000). Due to incompatibilities with TO&I Lotus, the version of Grasshopper used is September 28th 2012, build number 0.9.0014.

Fig. 21 Tools used (Left to right): Rhinoceros 5.0, sr5, Grasshopper 0.9.0014, TO&I Lotus.

The decision of a graphic interface over a programming language was to obtain visual outcome and interaction with the user. In the scenarios that the plugin performance was critical, other available plugins were tested: David Rutten's "Galapagos"; Simon Flöry's "Goat 2.0"; and Vierlinger & Zimmel's "Octopus 0.1"). Galapagos and Goat are single objective while Octopus is multi-objective. However, the number of parameters that TO&I Lotus is able to cope with is, at the moment this research was performed, much larger than in Octopus.

Fig. 22 Other optimization tools available for Grasshopper.

3.3 Workflow

In the following figure, three sets of actions are presented. The first one is referred as "formulation" and it is user defined and specific for every particular project. The second one is the model used, IDO. The last one is a personal evaluation of the outcome that leads to a reformulation of the problem, or to the layout development.

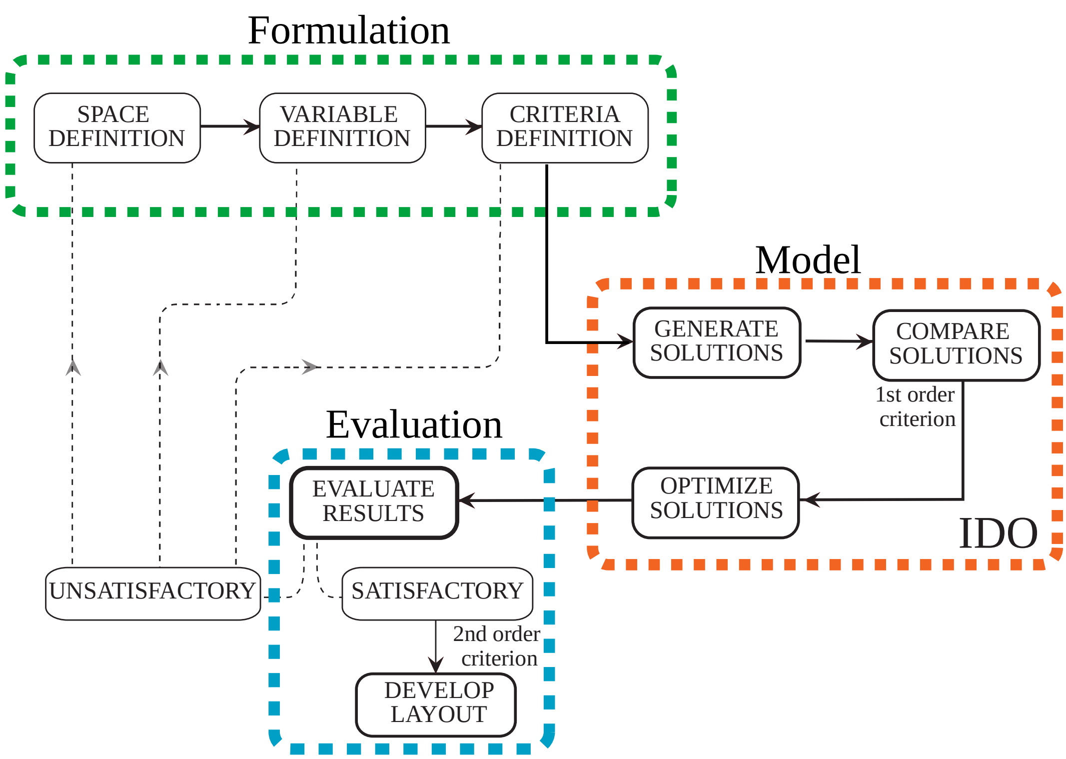


Fig. 23 Workflow chart. Drawn by the author.

These sets are performed in a loop sequence, because the relations and proportions of the departments are not pre-defined, until a satisfactory solution is found. As explained before, this method does not seek for the optimal solution (since the number of possibilities is high), but to provide satisfactory ones.

3.4 Optimization

The spatial allocation problem is treated as an optimization problem in this thesis.

In particular, the selection of the best set of positions and dimensions for a group of departments regarding the criteria defined. It is possible to combine these criteria into a single objective (also called as cost function) by combining with weights their relative importance, to minimize or maximize. The limitation of the single objective approach is that it requires fixing the weights in the objective function, while before finding optimal solutions it is unknown what the trade-offs are that characterize the problem.

For a multi-objective optimization problem, there is not a unique solution that optimizes each objective at once. This is due to the conflicting nature of some objectives. For example, in case that the smallest boundary that contains all the elements is required and, at the same time, the intersection of the elements is to be minimized. The smallest boundary optimum would intersect all of the elements, so the goal is to search where both criteria are satisfied. Particularly, the purpose is to search for non-dominated solutions. A solution is non-dominated if there is no other solution that performs better in every aspect. If analyzed the performance of a large number of design options in the objective function space for evaluation, the outer boundary of this collection of points defines the borderline limit beyond which the design cannot be further improved. When compared to any other solution, a non-dominated solution is superior for at least one criterion. This is referred as Pareto optimal solution. The group of Pareto optimal solutions is called Pareto frontier, or Pareto front.

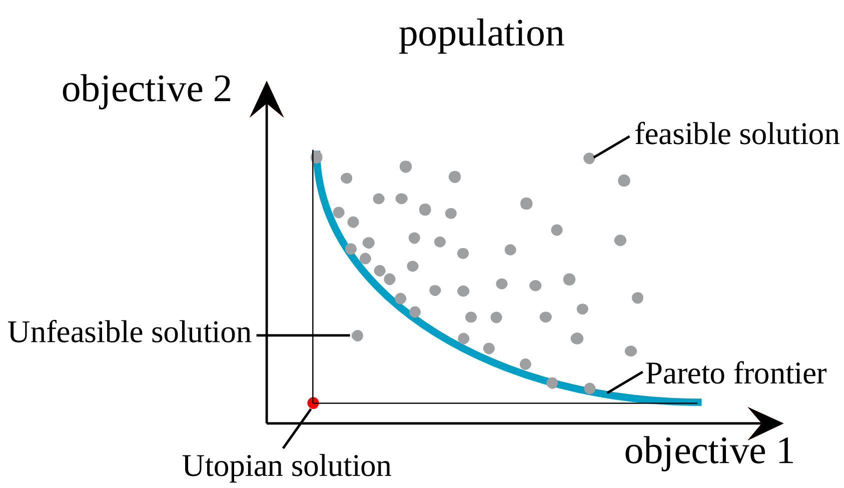


Fig. 24 Pareto front.

Without additional subjective preference information, all Pareto optimal solutions are considered equally good. By using this method the solutions concerning several goals are investigated without combining them beforehand.

3.5 Genetic algorithm

In the spatial allocation problem, the combination of possibilities is very high. It is not feasible to investigate all of them. Approaches like Galle (1981), who enumerated exhaustively all the possible solutions, are not useful.

For example, in a design with 10 departments, 4 variables each, and 10 possible states the amount of combinations is 10^{40}. Considering that a computer takes a single cycle to process the performance of one of those combinations and that the processor has a frequency of 10 GHz, it would take 10^{30} seconds to analyze all the solutions, which is millions of years.

To deal with this high number of combinations the method used in this thesis is the evolutionary search. It explores the possible solutions starting with a set of random ones and next states are determined by probability distribution, belonging to the stochastic methods. It relates to the combination of genetic material of species. The genetic material of the resulting individual matches the best of the parents or even outperforms it. This principle is used in evolutionary computation and it is known as genetic algorithm (GA).

A set of candidate solutions is referred as population. In this research, a solution consists of a set of positions and sizes of the departments. A population is a set of solutions.

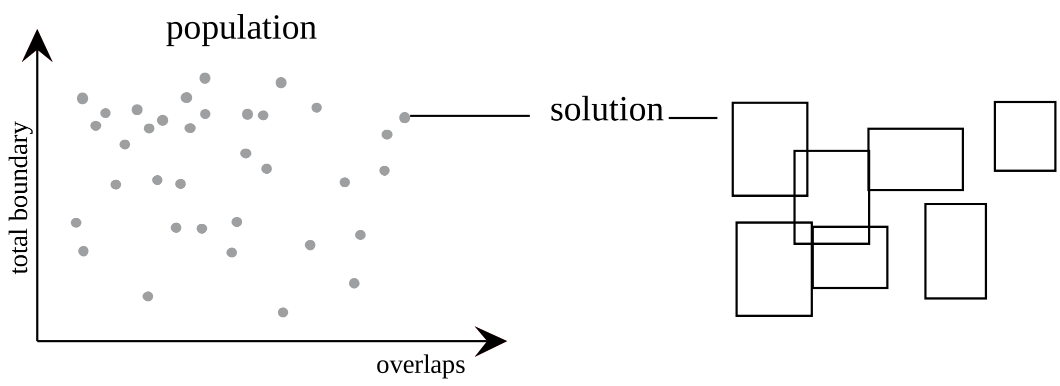


Fig. 25 Solution and population. Drawn by the author.

The first population is the outcome of random values of the parameters defined. Solutions from the first population are taken to form a new population. This is motivated by the aiming to improve features of the new population. The selection is according to the fitness or suitability to provide more probability to reproduce. This is determined by the performance of the solutions for the criteria defined. According to their fitness, the chromosomes are given a chance to survive to the next generation. This is called reproduction. Then it is repeated for a number of populations or till a “best solution” is achieved. But in order to increase the performance some operations are taken. In this thesis the operators of GA used are crossover and mutation.

The solutions of a population are coded into binary strings, or chromosomes. The first step is called selection which takes the fittest chromosomes. Crossover selects genes from parents and creates a new child (called offspring). It chooses randomly a point and copies the string before the point from the first parent and everything after from the second. The objective of the crossover is to maintain features of the parent solution and explore different places in the search space. After mutation is performed mutation is done to prevent from local optimum solutions. Mutation changes randomly a few bits from 0 to 1 or from 1 to 0.

Crossover			**Mutation**	
Chromosome 1	11011	00100110110	Original offspring 1	1101111000011110
Chromosome 2	11010	11000011110	Original offspring 2	1101100100110110
Offspring 1	11011	11000011110	Mutated offspring 1	1100111000011110
Offspring 2	11010	00100110110	Mutated offspring 2	1101101100110100

Fig. 26 GA operators: crossover and mutation. Drawn by the author.

A layout solution is a set of departments. These departments are defined by the starting point, area and the dimension of one of their sides. These values are coded into a binary string. With the use of the crossover operator, part of that string will be maintained in the next generation. In figure 27, the first two chromosomes are combined to generate the third solution.

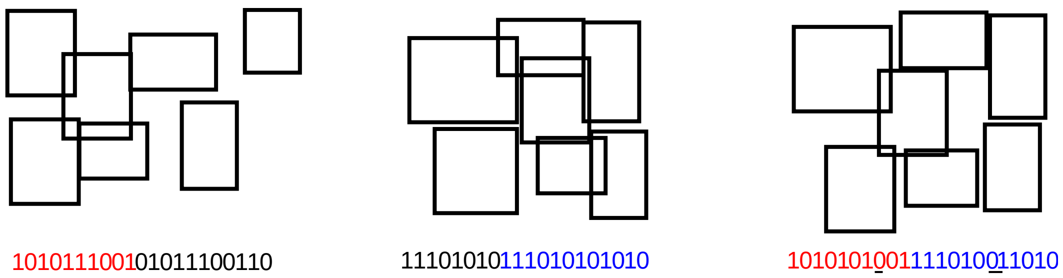


Fig. 27 Example of crossover (red and blue) and mutation (underlined). Drawn by the author.

For the author, the previous researches presented significant limitations that prevent architects to take advantage of them. The first limitation is regarding the number of criterion. Cost function optimization is useful in some fields, and it is also beneficial in certain architectural cases, although it is not sufficient to express the complexity of architectural design. Therefore, multiple objectives are introduced, and a model (IDO) is presented to cope with the high amount of possible solutions. Evolutionary search is used in the optimization process in order to obtain satisfactory solutions since exhaustive search is not feasible.

Custom formulation grants design flexibility and user defined criteria. Grid based modules are replaced by surface domain, able to adapt to curved boundaries and other singularities of the site.

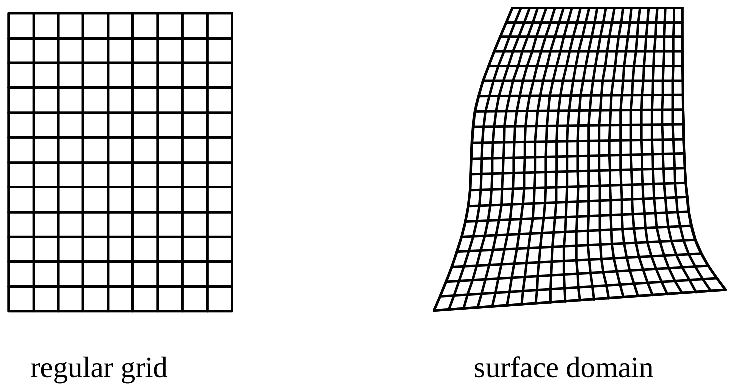


Fig. 28 New space formulation proposal. Drawn by the author.

Last advantage is the use of an open tool which allows user customization and implementation of new parameters, versus the use of closed software. This allows the designer to take control of the tool.

PREVIOUS	PROPOSED
Limited design freedom (grid, building type)	Increased design freedom (user/project defined)
Single objective	Multiple objectives
Closed tool	Open tool, customizable

Fig. 29 Comparison between previous researches and this thesis proposal. Drawn by the author.

CHAPTER 4

COMPUTATIONAL MODEL

In this chapter, the previously exposed formulations are implemented into an algorithm to aid in the design process of a building layout. The algorithm is initiated to generate solutions. As solutions are generated, the user is able to modify parameters and/or criteria as new relations and/or ideas appear. The repetition of this process assists the designer in the creative process of establishing the relations of the different functions (departments) and their relative importance in the project.

This research is part of the graduation project for the Joint Program of Computational Design and Fabrication Technologies in Architecture, METU-TUDelft, which took place during the academic year of 2012-2013. The site of the American Building Embassy in The Hague was given as the location to design an Art Centre. Along with the site, a program was proposed.

The first step is to define how solutions are generated. In this thesis module aggregation is used. Given an architectural program, a solution is a set of values that determine the position and size of all the program functions, or departments. This set of values is referred as parameters. In this thesis these departments are formulated as rectangles, and their sides are parallel to the axes of an orthogonal coordinate system. Their areas, aspect-ratios and the spatial relations are not predefined. To cope with different building types, these parameters and relations are defined by the user for every particular project. This brings design freedom and flexibility, which previous researches did not have.

4.1 Parameter definition

The departments are formulated as rectangular boxes defined by their starting lower left corner point (starting point), the measure of the first axis and the area of the department (figure 30).

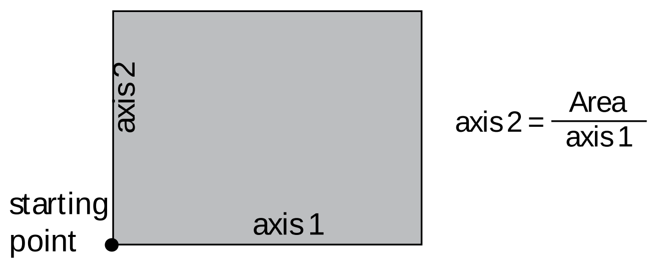


Fig. 30 Department definition. Drawn by the author.

The first approaches on this topic reduced the boundary space into a grid cell structure and assign a certain number of modules to each of the departments. This leads to L shape rooms or irregular ones.

In this thesis, different grid sizes are tested to evaluate the validity of the algorithm and a new approach is proposed. A two-dimensional domain of points (from 0.00 to 1.00) is proposed, to overcome the limited number of possibilities of the grid.

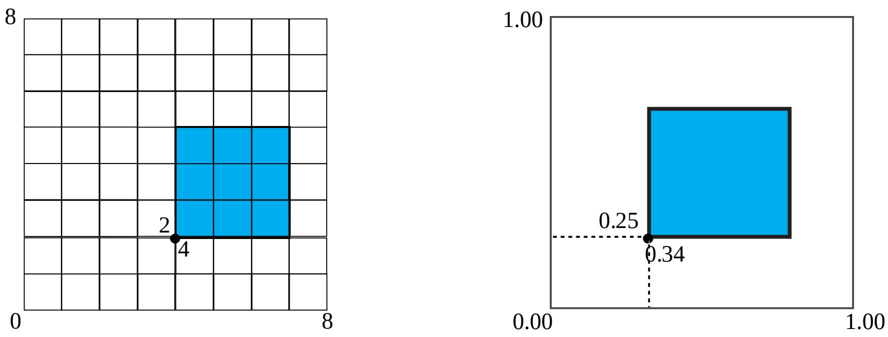


Fig. 31 Grid (left): 81 possible starting points; Domain (right):10.000 possible points. Drawn by the author.

Some architectural projects, such as competitions, start with a given program. In this program it is specified the number, function and area of each department. These are, in most cases, taken from regulations, similar buildings, and/or experience, and it should be possible to modify by the designer. For example, if the area requirement for a building entrance is 50 square meters, it is possible that the architect proposes a solution that is slightly larger or smaller. Therefore, for the department areas, a certain range should be considered. In this thesis, this range is set by the user. For the cases studied, the department areas are set as domains with their bounds set to plus and minus 15% of the given program area, but again, this is subject to the client/designer. The departments' proportion ratios are also user defined. One way is to analyze the solutions and evaluate the adequacy of each department ratio to a defined user input. Other way is to restrict the parameter values range for the "dimension axis 1". In this text the second approach is taken, not to increase the number of criteria unnecessarily. Each department has its own proportion ratio. In the following cases, this parameter is set by the author to values that result at most in 1:2 ratio.

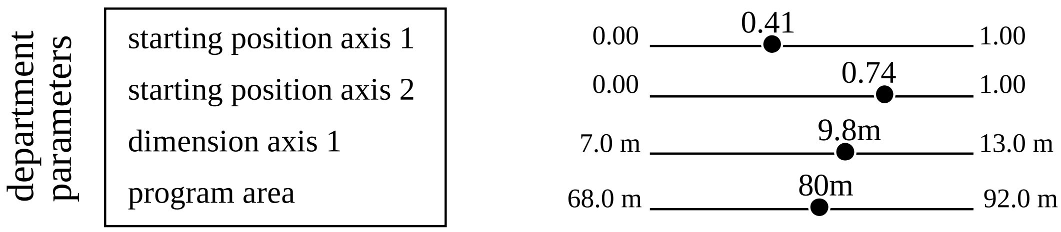


Fig. 32 Variables definition. Drawn by the author.

4.2 Criteria definition

Within the scope of the study, several criteria are considered to evaluate the solutions. As it is not based in modules, it is possible that the departments occupy the same location and the first objective is to minimize intersections. The intersected solutions are not discarded but measured. It is possible that a solution with small overlaps scores high in the other criteria and lead to a good layout. The second is to keep the departments within the site boundary.

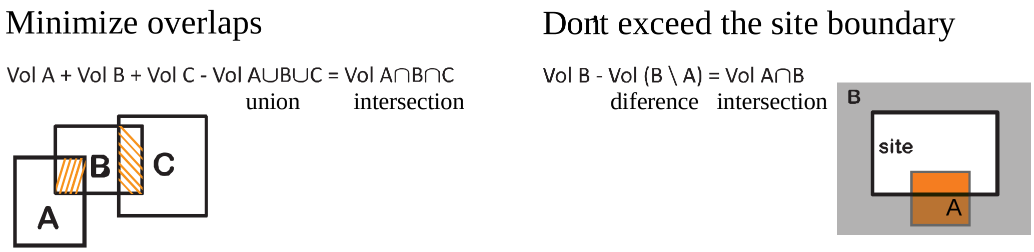


Fig. 33 Criteria: minimize overlaps and do not exceed the site boundary. Drawn by the author.

Third objective is to locate some of the departments close to each other. There are two main ways to measure distances among the spaces: straight line and city block.

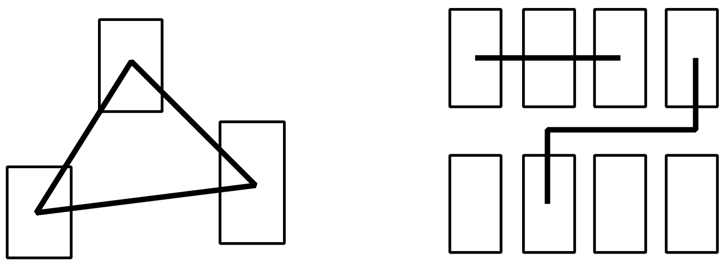


Fig. 34 Center to center distance (left); C block (right). Jo & Gero 2006.

In the present study the straight line method is used measured from the centroids. If more than two departments are required to be close, then the objective is to minimize the area of the geometric figure defined by their centroids (figure 35).

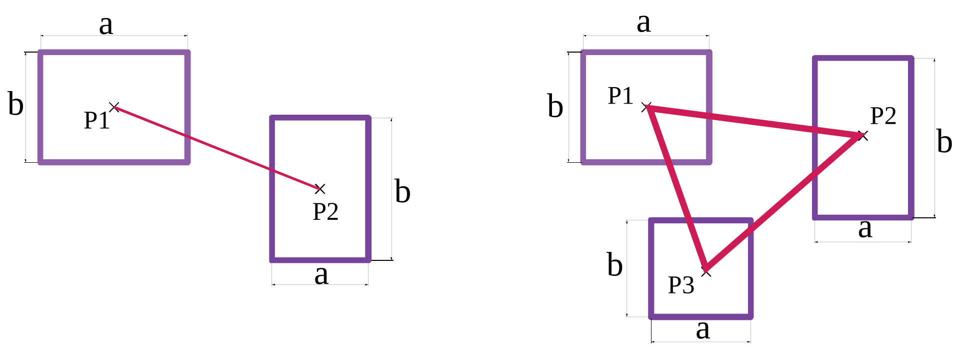


Fig. 35 Two departments (left) Three departments (right). Drawn by the author.

The distance is measured with straight line from centroid to centroid and it is added a penalty if the departments are in different floors.

Given the centroids P1 and P2 the time needed to travel between them is calculated as follows:

$$P1p.Z = 0 \tag{1}$$

$$P2p.Z = 0 \tag{2}$$

$$v_h = 1\ (m/s) \tag{3}$$

$$v_v = 0{,}3\ \left(\frac{m}{s}\right) \tag{4}$$

$$dist_h = P1p - P2p \tag{5}$$

$$l = dist_h.length \tag{6}$$

$$th = \frac{l}{v_h}(s) \tag{7}$$

$$dist_v = Math.Abs(P1p.Z - P2p.Z) \tag{8}$$

$$tv = \frac{dist_v}{v_v}(s) \tag{9}$$

The total travel between departments (totalt) is calculated as the result of the time traveled in horizontal and the time traveled in vertical.

$$total_t = th + tv \tag{10}$$

The user defines the importance of the closeness between certain departments and the total travel among them is evaluated according the user definition. In the example in figure 36, P3 is closer to P1 than P2 is. But when searching for a solution that is close to P1, both P2 and P3 are equally good.

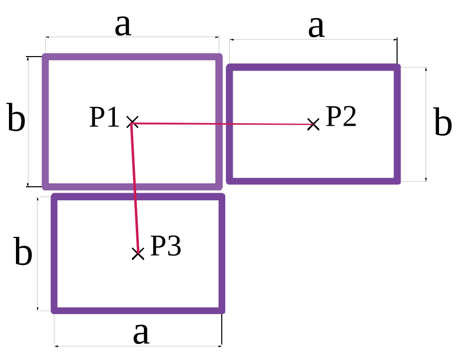


Fig. 36 Equally good travel distances. Drawn by the author.

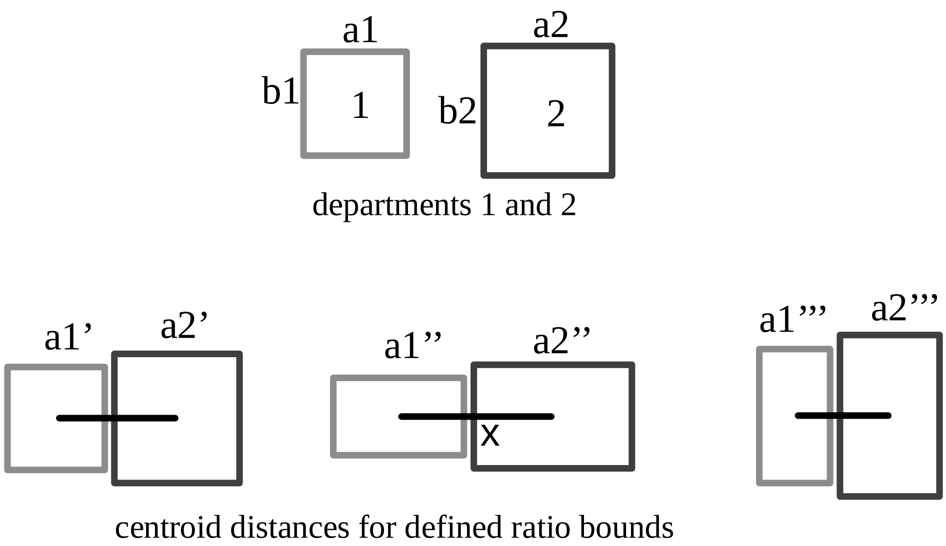


Fig. 37 Defining equally good travel for different department´s proportions. Drawn by the author.

For example: departments 1 and 2 (figure 37) size and proportions are not fixed, but the bounds of their possible values are defined. According to those bounds the user defines the closeness relation for every set of departments in the project.

The travel distances, in this example, despite of being different, they are equally good solutions. Every travel value smaller than x is then graded with 1, the highest value. The travel distances are mapped to values between 0 and 1. In this dissertation, the author defines three functions regarding the relative importance of the travel distance between sets of departments. This is referred as fuzzyfication. For this thesis three degrees of closeness are defined, (ALDEP had six degrees).

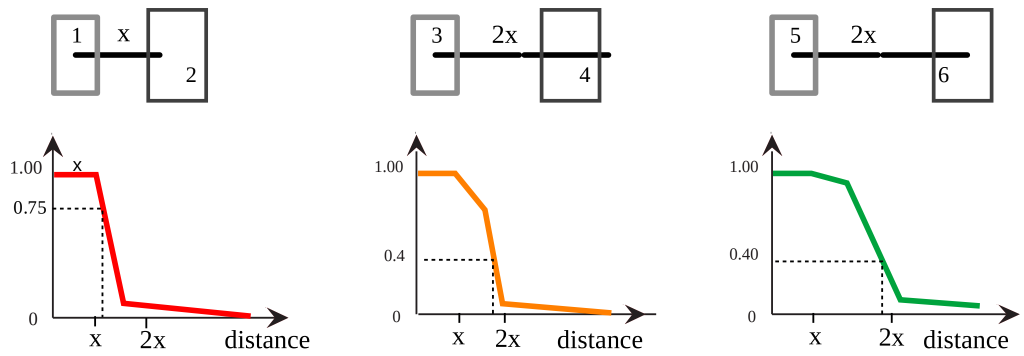


Fig. 38 Closeness membership functions for high medium and low travel distance importance. Drawn by the author.

The user defines which departments are important to be close assigning the correspondent membership function.

In her research, Shaviv (1986) defines the departments according their hierarchical importance. In this dissertation that hierarchy is established with a fuzzy neural tree and assigning weights to the departments relations defined (figure 38).

A neural network or neural tree is used to structure information. The values on the lower level are combined towards the root note becoming a non-linear system. The non-linearity of the output is given by the functions in level 1 where the inputs are multiplied by weights and combined for the resulting output of the network.

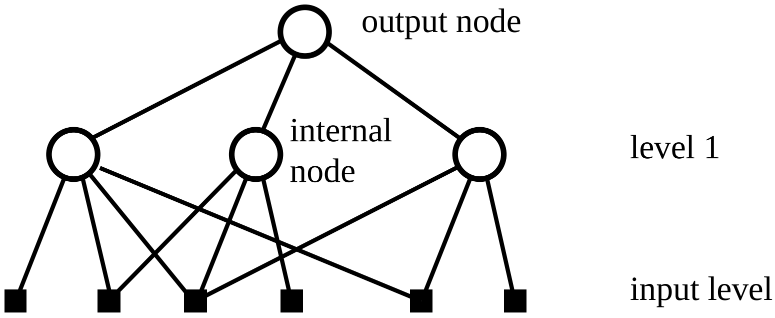


Fig. 39 Neural tree structure. Drawn by author.

In the scope of the study the neural tree is proposed to combine soft objectives (such as closeness) by analyzing the degree of membership and combining it with the crisps objectives with the use of user defined weights.

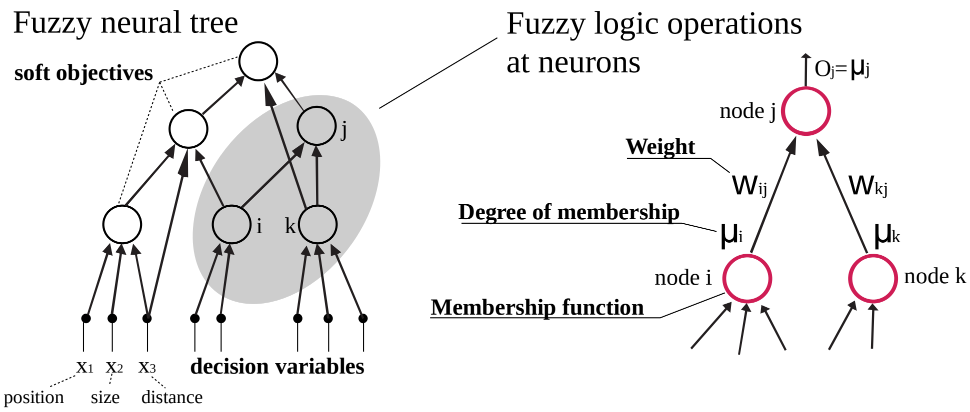


Fig. 40 Fuzzy neural tree and fuzzy logic operations. Bittermann 2009.

In the case of a factory layout (as in figure 8), an exact measurement of the distances and finding the adequate tool order increases the factory efficiency.

However, in architectural practice, the exact distance among departments is not as decisive for determining the goodness of the solution. The relation of the departments is measured and converted into a value that quantifies their (user defined) degree of closeness from 0 to 1.00 (figure 38). Then these values are combined with the use of user defined weights to express the importance that the designer gives to each particular node. The output is the final value to be maximized or minimized in the optimization process.

In this thesis, two nodes have been included in the neural tree. The first one displays the relations between two departments. The second one shows the relation between groups of departments. The decision on which departments to include in the neural tree and their weight, are defined by the user and specific to the project.

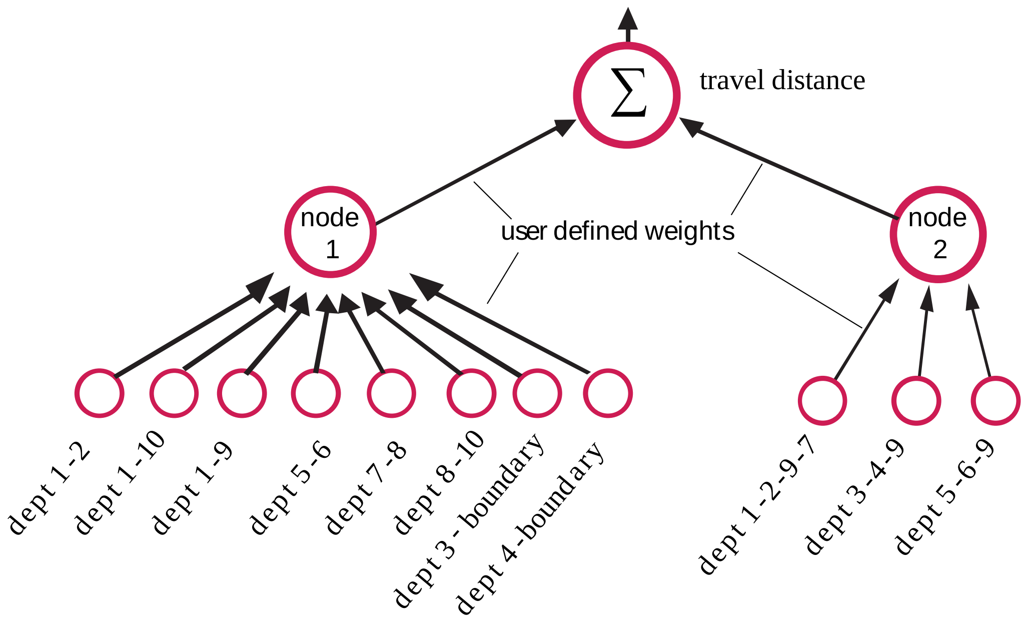


Fig. 41 Travel distance neural tree. Drawn by the author.

In this thesis the use of the neural tree and fuzzy objectives is limited to one of the criterion, referred as the travel distance. The main focus is put in approaching the problem as a multi-objective optimization with the other criteria. To understand the usefulness of the neural tree and fuzzy objectives, the site analysis study for the graduation project for TUDelft is presented in which several criteria are combined into one single objective. The study is performed as a group work with E. Varaku, A.A. Momin, A. Riazibeidokhti and M. Foolady, to assist with the decision making for the site intervention. In order to decide which intervention is more beneficial to the neighborhood, a neural tree is proposed to evaluate their impact on the goodness of the neighborhood.

The first step is to establish the nodes of this tree. These are set after several group discussions with the assistance of the professors Huib Plump and Michael Bittermann. The analysis is aimed to determine which of the following interventions is better for the neighborhood:

1- Do not intervene.
2- Renovate the building as an Art Center.
3- Demolish the building and build an Art Center.

Within this frame, a set of nodes are defined. The discussion concluded that five nodes define the neighborhood goodness: High liveliness, Prosperity, Safety, Sustainability and Coherence of space. These are subdivided in other nodes, configuring the neural tree for the site analyzed.

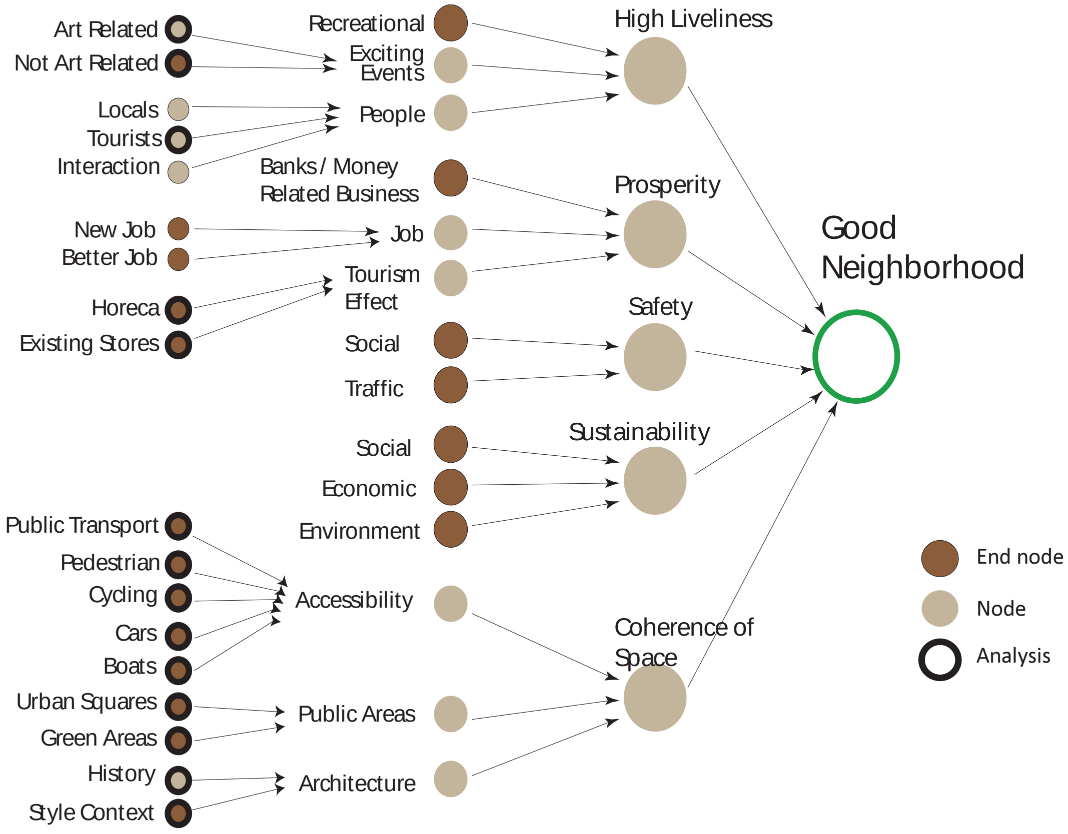


Fig. 42 Group neighborhood goodness neural tree definition. Drawn by Erald Varaku and the author.

On the next step values are assigned to every node, for the existing site situation. This is done after site analysis and discussion among the students and professors. Furthermore, the weight of the relative importance of each node is defined. In this case, since multiple users input values, the expected value or mean value is calculated. The standard deviation is calculated to determine when further discussion to a node is needed, regarding large value variation from the inputs. This is needed since the subjective values from several persons (in this case the architecture students) is implemented. For example, for the public transport node:

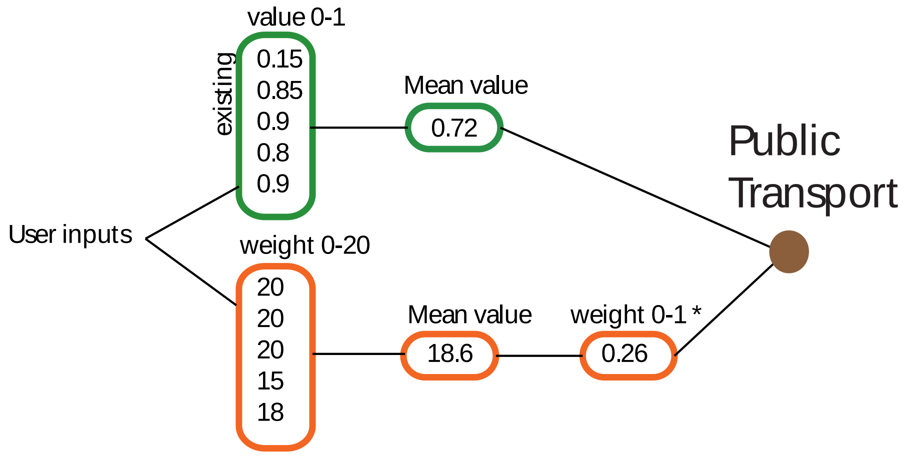


Fig. 43 Value input for public transport node. Drawn by the author.

Once the values for accessibility are assigned, the process is repeated with the weights. In previous image, the weight value of 0.26 is the result of assigning weights to all the nodes that belong to accessibility:

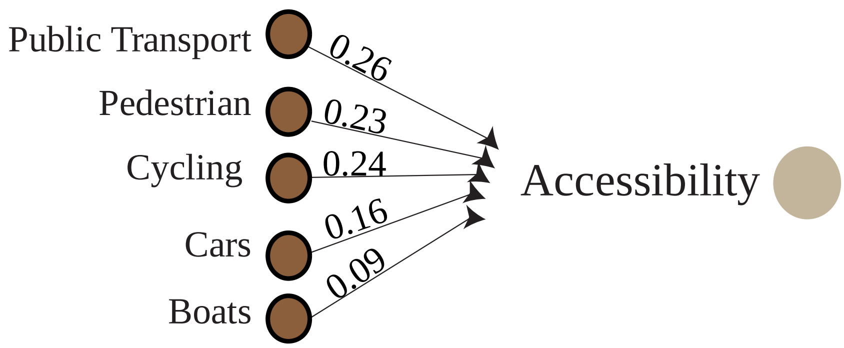


Fig. 44 Accessibility node weight values. Drawn by the author.

Once the process is completed for every node, and for the three interventions proposed (not intervene, renovate as an Art Center and demolish and build a new Art Center) the effect on the overall neighborhood goodness is computed, as a result of all the nodes values.

Fig. 45 Good neighborhood value outcome. Drawn by the author.

From the benefits of the use of the neural tree, two stand out:

1- Ability to express subjective abstractions in a numeric form, which allows to be compared.

2- The user concentrates in the nodes individually, resulting in a complex network.

As a result, besides the overall value of the intervention over the end goal, a study of the relative effect of every node is obtained. This is referred sensitivity. This sensitivity is expressed in the value of the slope and is sometimes called the "rate of change" because it measures the rate of change in “*y*” as a result of a change in “*x*”. On the neural tree, the relative effect of the overall solution for each node is revealed.

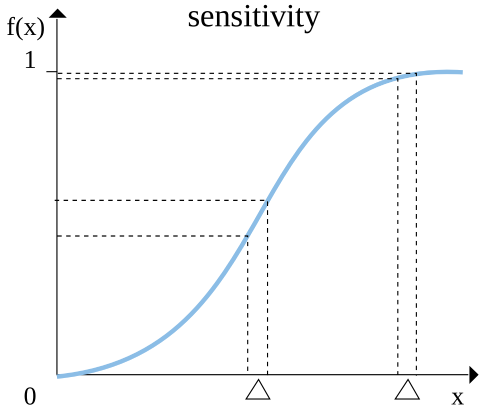


Fig. 46 Sensitivity analysis. Drawn by the author.

The function of the overall performance (final node) is obtained by input of the complete domain of values from 0 to 1.00 for every node, individually. The result shows the influence of the node in the overall tree. In the example of the urban analysis, the given values for the first intervention are input on the sensitivity graphs. The nodes which present a steeper slope in the function, for the given input, reflect the more effective fields to intervene in order to increase the end node value (in the example, neighborhood goodness).

In figure 47, the sensitivity graphs of four of the nodes are shown. The highlighted point in each of them is the value for the existing situation, given by the group. The slope at that point, indicates that efforts in increasing horeca (hotel, restaurant, café) are more beneficial for the neighborhood goodness.

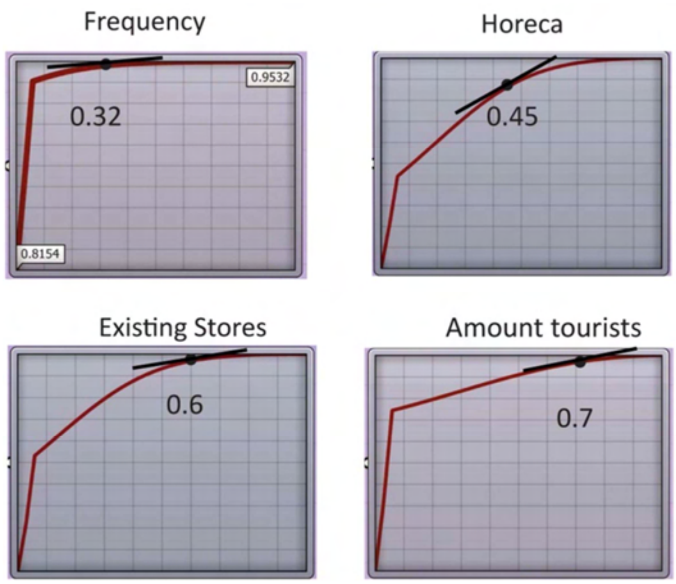


Fig. 47 Sensitivity of three nodes. Drawn by the author.

4.3 Extended decisions formulation.

Along with the criteria, the user has the means to include other architectural decisions by the parameter definition. This is important as it does not increase the number of goals which makes the search more expensive in computation costs.

For example, in case one of the departments is desired to be allocated in the south façade of a building (user defined), instead of implementing it as a goal and analyzing the distance to the south façade boundary, the parameter definition that locates this department is fix to the value that satisfy this premise (0,00 in figure 48).

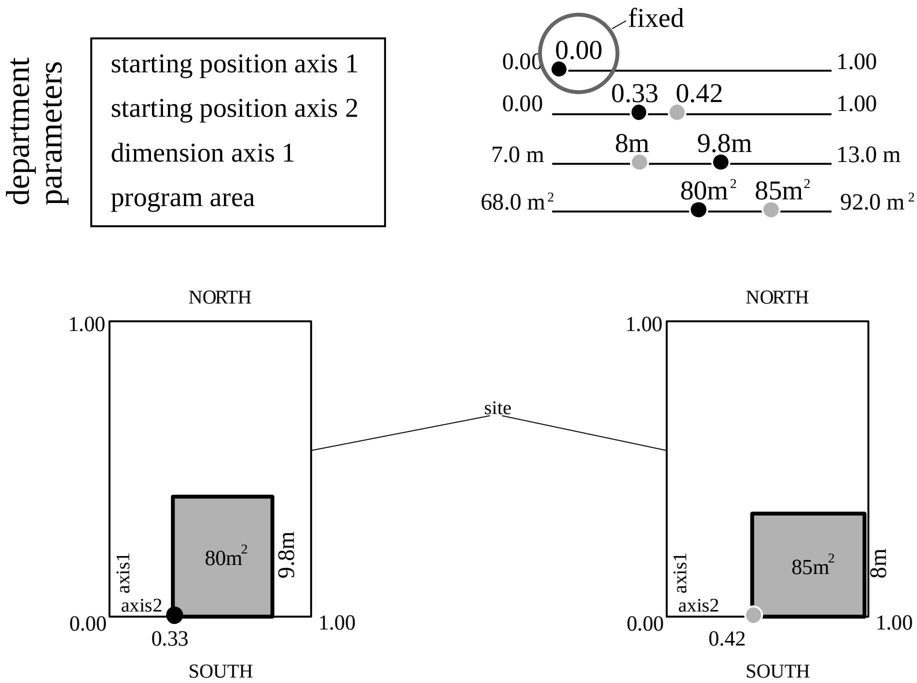


Fig. 48 Architectural decisions by parameter definition. Drawn by author.

With the same approach, is possible to define alignments of two or more departments using the same value for one of the starting point position axis. In figure 49, two departments are aligned towards axis 1. The values of starting position axis 2, for both departments, are linked. On the left, both departments are set at 0.33 value for axis 2, but the user is able to fix them to the west façade (right), constrain to certain values or set them free along that axis.

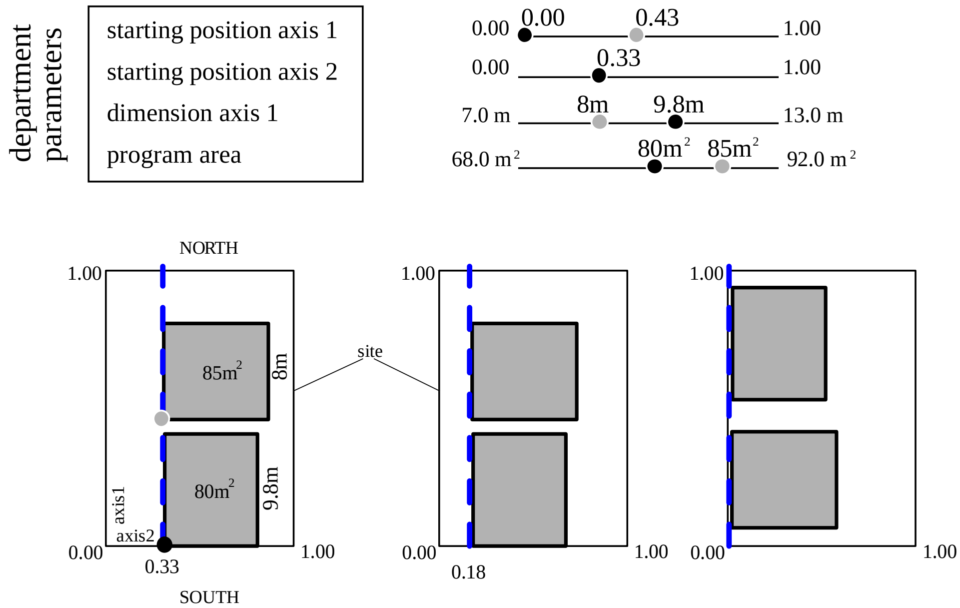


Fig. 49 Alignment by parameter definition. Drawn by author.

Along with these formulations, the user is able define his/her own. In this thesis, the departments are defined by the parameter values that locate them in the site with their sides parallel to an orthogonal coordinate system. However, custom defined formulation is able to include irregular site orientations. For example: if *axis1* > 0.5 and *axis2* < 0.6; then rotate the department.

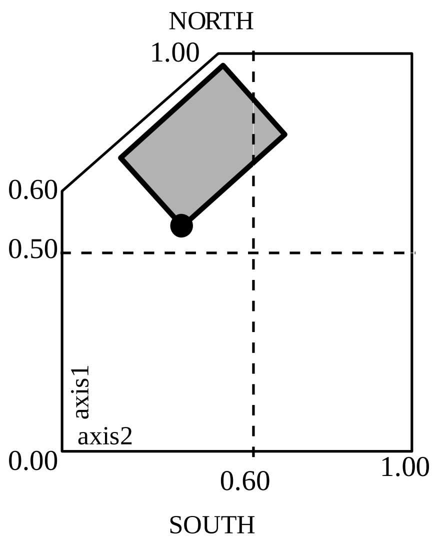


Fig. 50 Irregular site formulation. Drawn by author.

A specific formulation of each department helps to reduce computation costs. For example, given a department which starting point is too close to the boundary (close to 1), the resulted element for that solution will be out of the site boundary limit. In order to make the algorithm more efficient, the set of values for the starting points positions are reduced for each element regarding the minimum dimension that they could take for axis1 and axis2. Beyond those values the departments would always fall out of the site, so this prevents the algorithm to compute them.

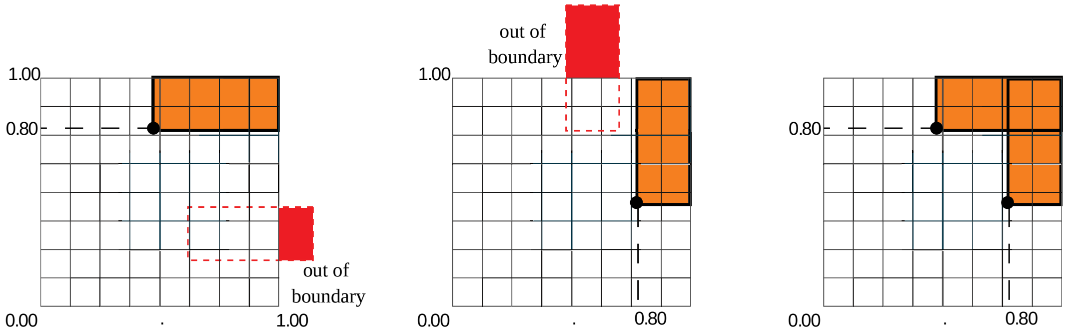


Fig. 51 Custom value range for starting position for each element. Drawn by the author.

At this point, each element is custom defined with range values that determine its possible position in the site and its size. By customizing certain values for each of them, the architect establishes a first order of relations, such as having some elements in the same floor, aligned, or one on the top of other (by using the same starting point and different height, or one in the range of the resulted element).

4.4 Other possible formulations proposed for the spatial allocation problem.

The previous formulations were intended to not limit the design freedom without taking into account the computational cost. There are other formulations that obtain solutions at a faster peace but with some design limitations.

The first one is an attempt to reduce the number of criteria. In order to reduce the intersections the departments are assigned step-wise. It is referred as a constructive method, since the departments are included one by one. The first department is assigned with the variables defined in figure 32 (starting position axis 1 and 2, dimension axis 1 and program area). To assign the second, the starting point is set on the contour of the first one. The next department starts on the contour of the union of the previous. This approach is limited to departments on the same floor.

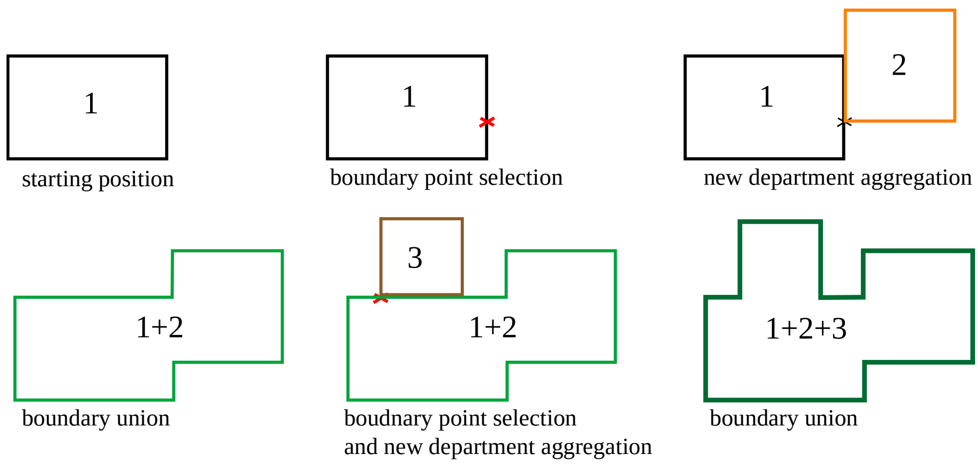


Fig. 52 Step-wise department assignment. Drawn by the author.

To avoid overlaps, an if/else condition is implemented to locate the new departments in places that do not intersect the previous boundary. The solutions obtained are very dependent on the order of assignment of the departments as in the Spiral Facility Layout Algorithm (figure 6).

To completely eliminate both, the overlaps and the intersection with the boundary limit from the criteria, a recursive subdivision is suggested.

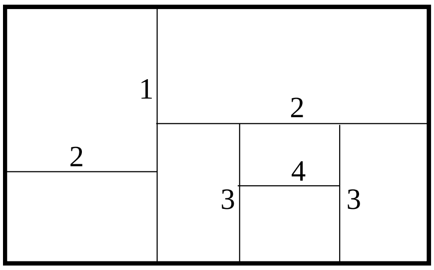


Fig. 53 Recursive subdivision of a rectangle in smaller rectangles. Drawn by the author.

A recurrent division of a rectangle in smaller pieces is suggested also by Doulgerakis (2007).

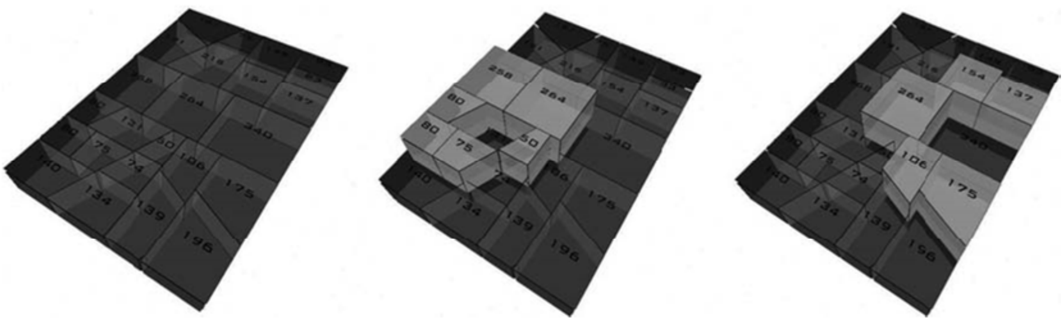


Fig. 54 Polygonal subdivision. Doulgerakis 2007.

In these approaches the user interaction is reduced. There is no possibility of locking or defining some departments locations. However, if the relations are well defined from the beginning, the implementation of these approaches grant quick outcomes.

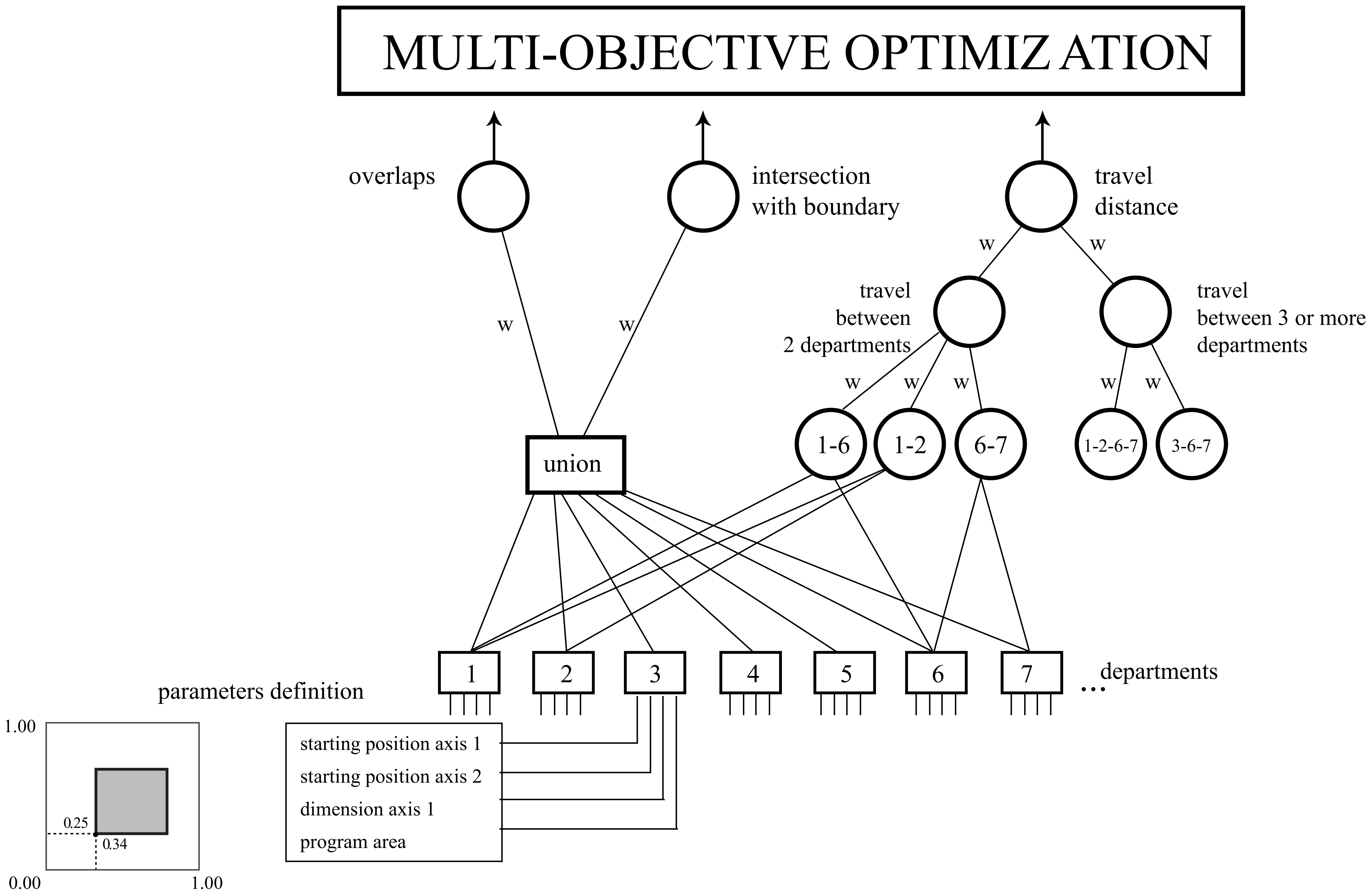


Fig. 55 Variables and criterion summary. Drawn by the author.

CHAPTER 5

CASE STUDIES

Two cases are selected to evaluate the adequacy of the model to assist in the creation of building layouts. The first case is used to measure the response in time for different formulations.

5.1 Case study 1

For the first case study two sets of departments are studied. These are composed by six and nine departments respectively. The areas are constrained to the following domains:

Table 2 Case study 1: Departments area values.

department	d1	d2	d3	d4	d5	d6	d7	d8	d9
area	80-100	230-260	280-300	450-475	350-375	350-375			
	230-260	230-260	250-275	250-275	200-225	150-175	150-175	220-250	220-250

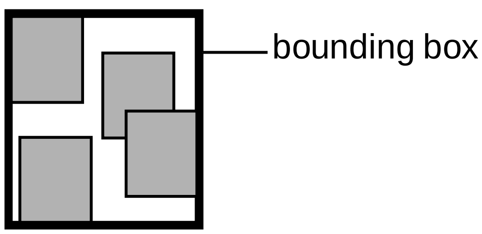


Fig. 56 Case study 2: Bounding box. Drawn by the author.

The criterion used are minimizing the overlaps or intersections among the departments, minimizing the overlaps with the boundary, to minimize the bounding box area and to minimize the travel distance of two pairs of departments (dept. 1-2, dept. 3-4). The boundary site is set to a rectangle of 40 by 60 meters. The criterion are combined and the times resulted for obtaining 10, 50 and 100 generations are compared.

Table 3 Case study 1: Formulation and generation values. (X: conducted attempt).

NUMBER OF DEPARTMENTS	**CRITERIA**				**NUMER OF GENERATIONS**						
	OVERLAPS	SITE BOUNDARY	BOUNDING BOX	TRAVEL DISTANCE	10		50		100		
					POPULATION SIZE						
					50	150	50	150	50	150	
6	X				0,4	0,8	2	4	-	-	regions
6	X	X			0,4	1	2	5,2	4	11	
6	X	X	X		0,5	1,3	2,3	5,6	5	15	
6	X	X	X	1-2, 3-4	-	-	-	-	9	20	
6	X	X		1-2, 3-4	9	-	47	-	91	-	solids

Population sizes of 50 and 150 are compared. The crossover probability is set to 90% and mutation is set to 5%.

On the first attempt, the algorithm is only set to search for solutions that minimize the overlap between the departments. After 50 generations a solution that does not present overlaps is reached.

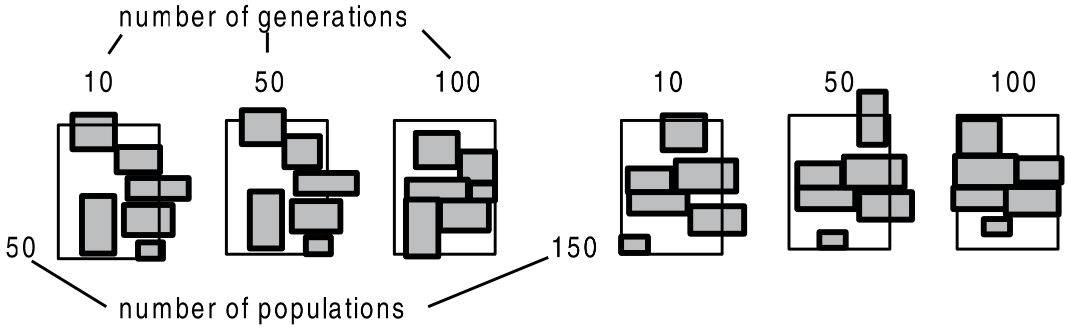


Fig. 57 Case study 1: 6 departments; minimize overlaps. Drawn by the author.

The second criteria, intersection with boundary (figure 58) and the third, minimize the bounding box (figure 59) are included and a sample of solutions is obtained.

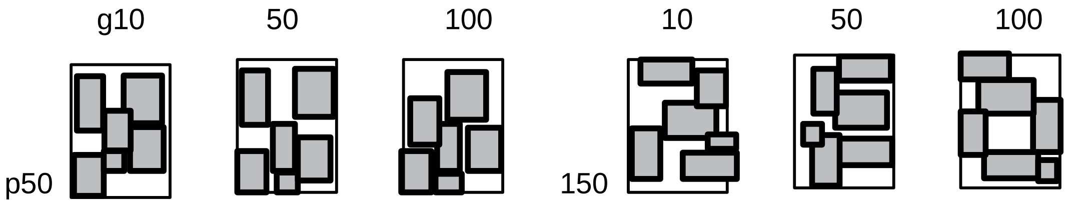


Fig. 58 Case study 1: 6 departments; minimize overlaps and intersection with boundary. Drawn by the author.

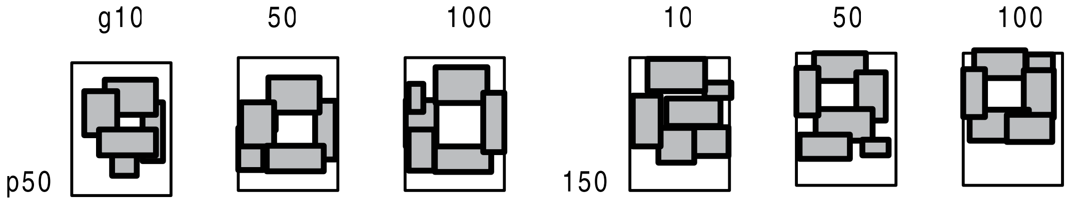


Fig. 59 Case study 1: 6 departments; minimize overlaps, intersection with boundary and bounding box area. Drawn by the author.

After the first tests, the population size is set to 150, as it presented more defined Pareto fronts. The next attempt includes the criteria referred as travel distance for two pairs of departments (depts. 1 and 2, and depts. 3 and 4).

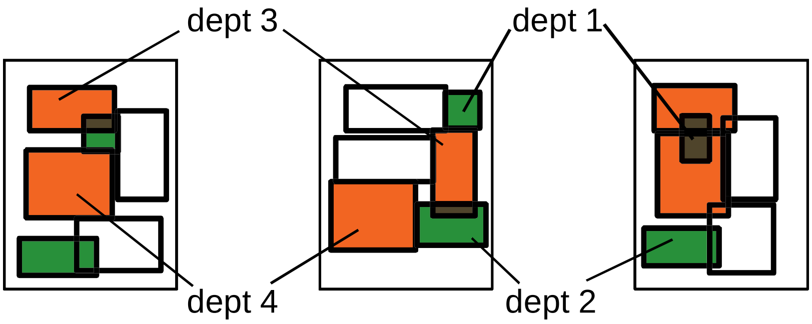


Fig. 60 Case study 1: 6 departments; overlaps, boundary and travel distance after 100 generations, 150 population size. Drawn by the author.

Despite the increase in population size, the number of generations is not sufficient to obtain clear Pareto fronts and to select a solution that satisfies all the criterion is unachievable. Additionally, a fault in the criteria formulation is found. The calculus of the overlaps was formulated as the difference of the summation of the volumes of all the departments and the volume of the union.

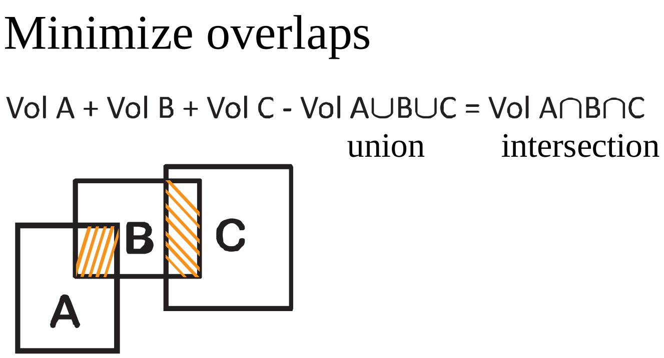


Fig. 61 Case study 1: Minimize overlaps. Drawn by author.

On the first attempts, the use of regions was preferred due to the low computation time required (as shown in Table 3). Therefore, the volume was substituted by the calculus of the area.

In solutions as in figure 62, the region union computed with Grasshopper results in several regions although the containment of one figure into the other is not recognized and results in miscalculation of the union area.

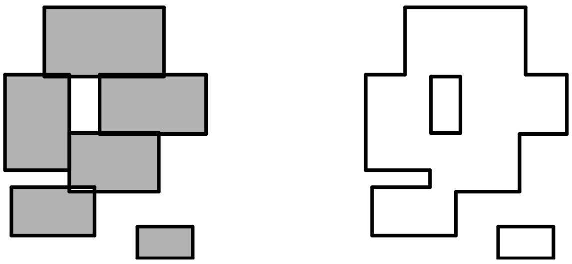


Fig. 62 Case study 1: Region union. Drawn by the author.

It is also possible that some regions remain isolated, and to compute the union the author declared the departments as solids and added one solid base to ensure that the union of all of the departments resulted in one solid figure.

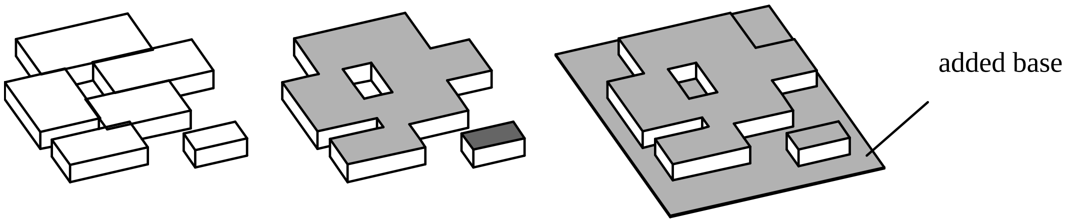


Fig. 63 Case study 1: Using solids to compute intersection. Drawn by the author.

The use of solids instead of regions increased the computation time. When run again the case for 6 departments and all the criterion, the time needed for 100 generations with population size of 50 is now 91 minutes.

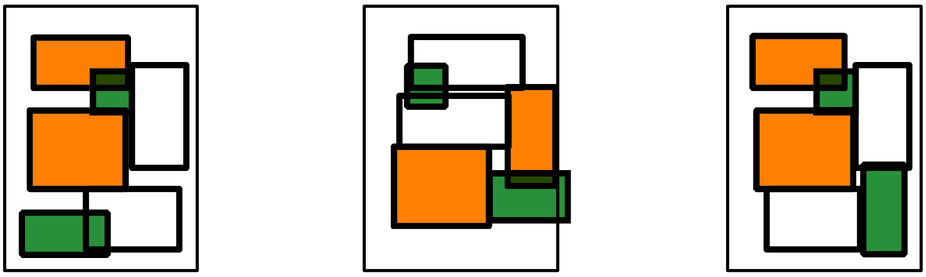


Fig. 64 Case study 1: Solution sample for 6 departments using solids. Drawn by the author.

The decrease of the population size due to the high computation time needed presents an ill-defined Pareto front. In figure 65 it is shown the Pareto front for 9 departments. On the left, the population size is 50 and the number of generations is 442. On the right, the population size is 150 and the number of populations is 105. They took 15 and 11 hours respectively.

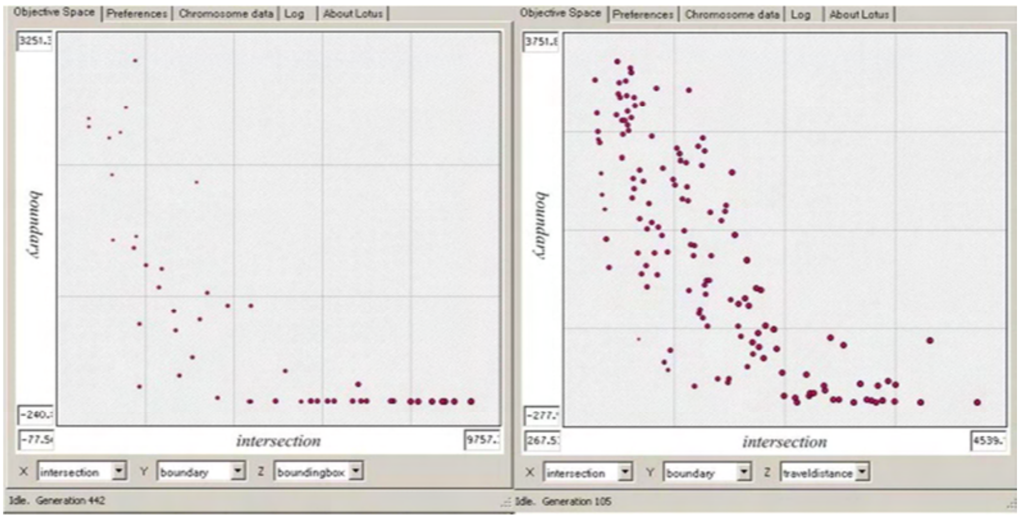


Fig. 65 Case study 1: 9 departments. Pareto front. Obtained by the author with TO&I Lotus.

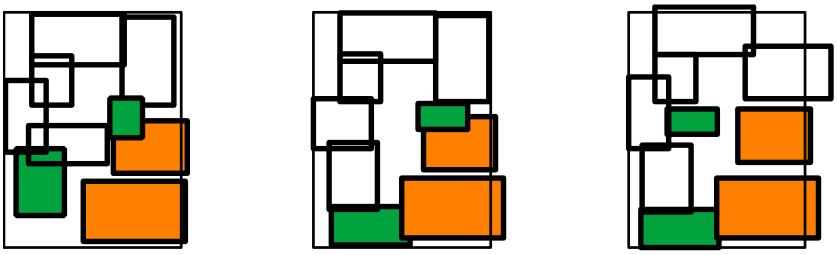


Fig. 66 Case study 1: Solution sample after 442 generations, 50 population size. Drawn by the author.

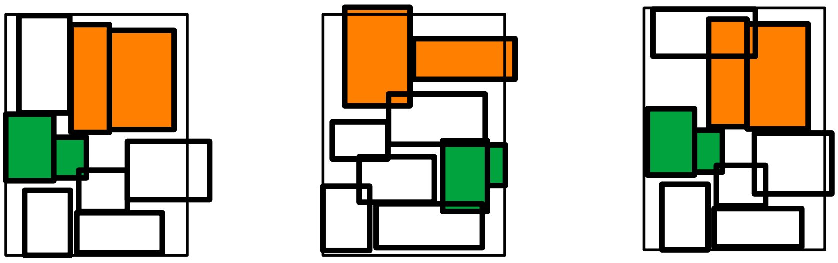


Fig. 67 Case study 1: Solution sample after 105 generations, 150 population size. Drawn by the author.

The increase in the population size produces higher number of solutions and a more defined Pareto front. That is desirable to select among multiple criteria. The sample of solutions in figure 67 show better solutions for the travel distance goal.

At last, other formulations were attempted. The first one was to use a grid for locating the starting points of the departments. A constructive placement approach is taken and the departments are added one by one. Once a department is added the points of the grid contained by the department are eliminated.

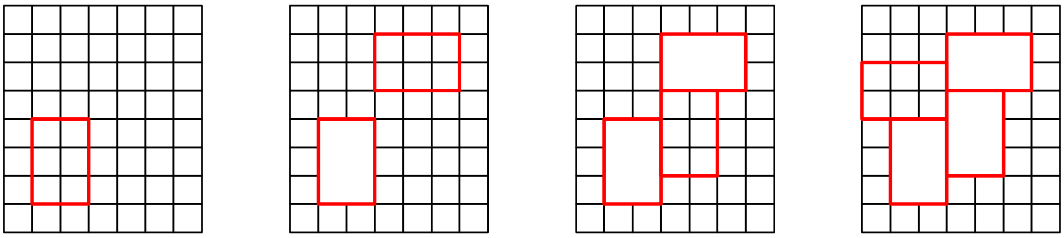


Fig. 68 Constructive placement in grid network. Drawn by the author.

For this example a boundary site is proposed (blue shape). For 6 departments, 100 population and 30 generations some solutions are presented:

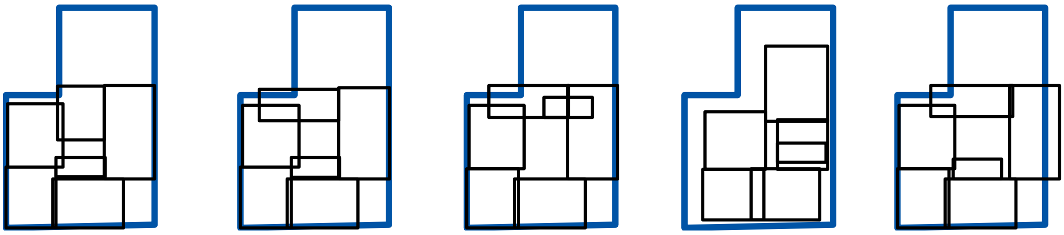


Fig. 69 Allocation of six departments in a square grid of 1m cell. Drawn by the author.

Another constructive placement approach, as explained in figure 70 is attempted. In this case the starting point of the new department is located on the perimeter of the previous region. The results are notably dependent on the incorporation order.

Recursive subdivision test (figure 71) presents an improvement in the algorithm performance, but design limitations arise, as it is difficult to control the exact number of rectangles obtained and their proportions.

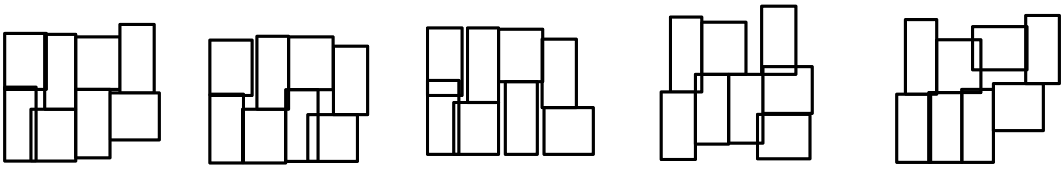


Fig. 70 Constructive placement. 8 departments of 60 m^2. Drawn by the author.

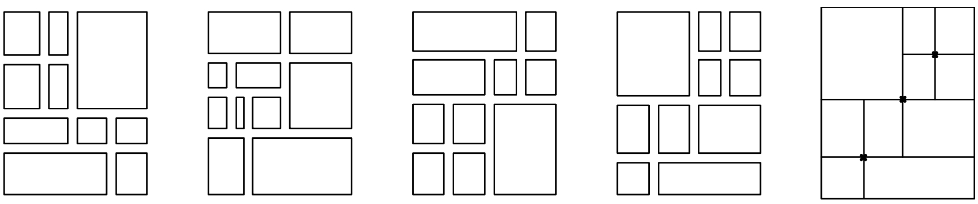


Fig. 71 Recursive divisions of a rectangle with three points resulting in 10 subdivisions. Drawn by the author.

Evaluation of the results:

Common for all the test, an increase in the number of generations delivers superior solutions faster than increasing the population size. Meanwhile, an increase in the population size results in more detailed Pareto front. The use of a bounding box outperforms the use of the boundary site margin. The formulation in figure 35 for the calculus of travel distance of more than two departments is not valid, since they tend to align (which minimizes the area), resulting in a formulation suitable for department aligning. For the case studied the departments resulted align by their centroids. The attempted area flexibility is not exploited due to the fact that the minimize overlaps criteria leads to the use of the lower area bound.

5.2 Case study 2

The second case study used for the evaluation is the graduation project for TUDelft at the Computational Design and Fabrication Technologies in Architecture program. The site proposed is the American Embassy in The Hague, and an Art Center function and program is assigned.

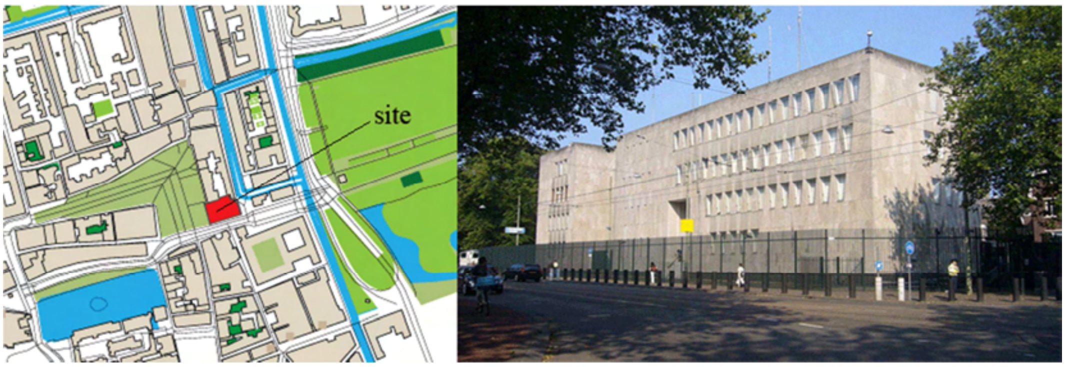


Fig. 72 Case study 2, site. American embassy in The Hague by M. Breuer. Photo by Pvt Pauline.

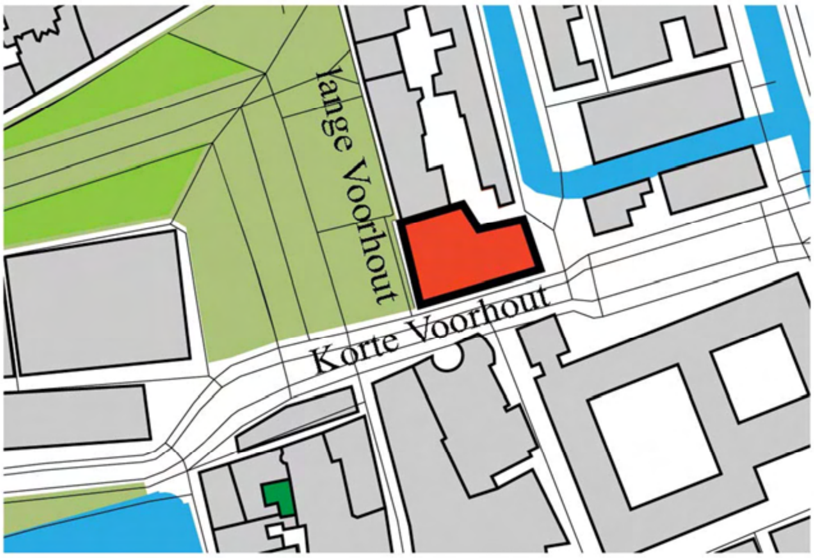


Fig. 73 Site plan. Drawn by the author.

The given program summary consists in:

Table 4 Case study 2: Proposed building program.

DEPARTMENTS	AREA
General/public:	340 m^2.
Exhibition space 1:	800 m^2.
Exhibition space 2:	600 m^2.
Exhibition support (receiving, loading, preparation, shipping) :	140 m^2.
Collection storage:	340 m^2.
Multipurpose (performance space, educational, meeting rooms):	420 m^2.
Café:	120 m^2.
General/public (reception, lobby, wardrobe, and shop):	335 m^2.
Administration facilities:	200 m^2.
Service and mechanical areas:	215 m^2.
Communication:	27 m^2.

The site is formulated as a two dimension domain.

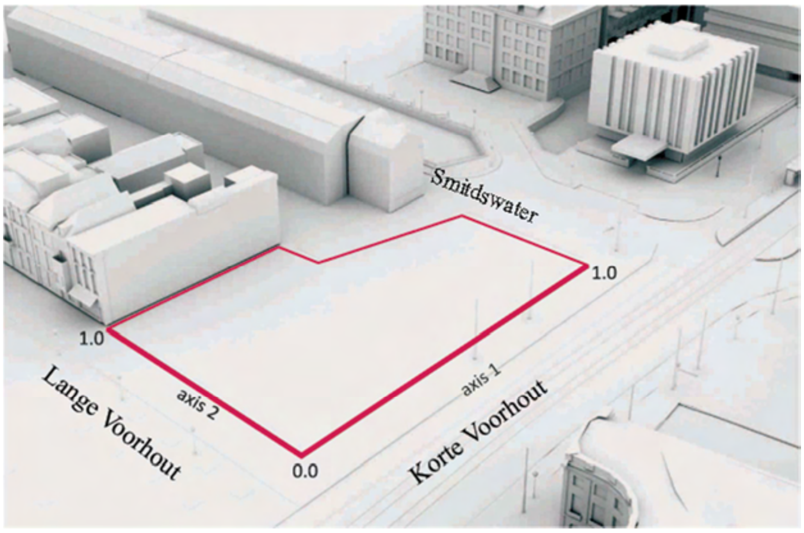


Fig. 74 Case study 2: Site definition as a two dimension domain. Drawn by the author.

As the case explores the solutions in three dimensions, the variables definition includes the assignment of the departments to different floors and the possibility to cover one or two storeys (in figure 75, starting floor and number of floors). The ceiling height is set to 5 meters for all of the departments.

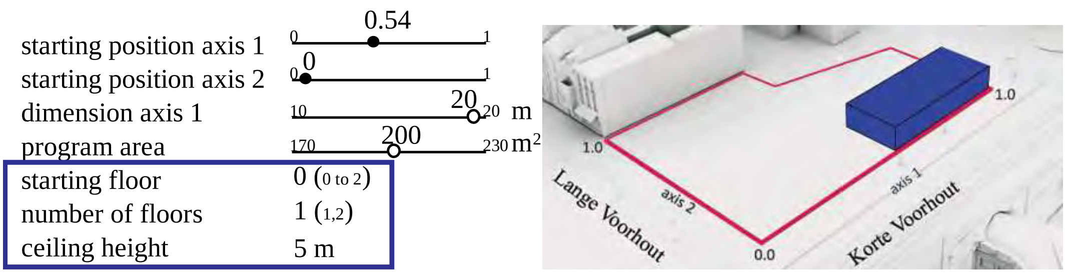


Fig. 75 Case study 2: variables definition. Drawn by the author.

Some of the departments are (user) constrained to certain floors. For example, the entrance and the shop are locked to the ground floor. Some are constrained to a limited value range. For example, in order to give privacy to the administration department, the values that locate the starting point close to the street facades are avoided. This is done by increasing the lower limit of the starting position axis 1 and axis 2 domain.

The upper limit is decreased to eliminate solutions that place the department out of the site (figure 76). This is an example of aiming the search towards certain solutions without changing the criteria, but the parameters definition.

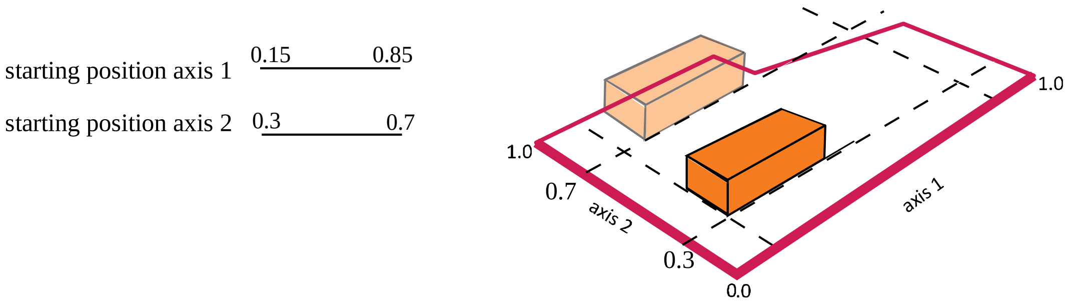


Fig. 76 Case study 2. Variable domain constraint to avoid street facades and boundary intersection. Drawn by the author.

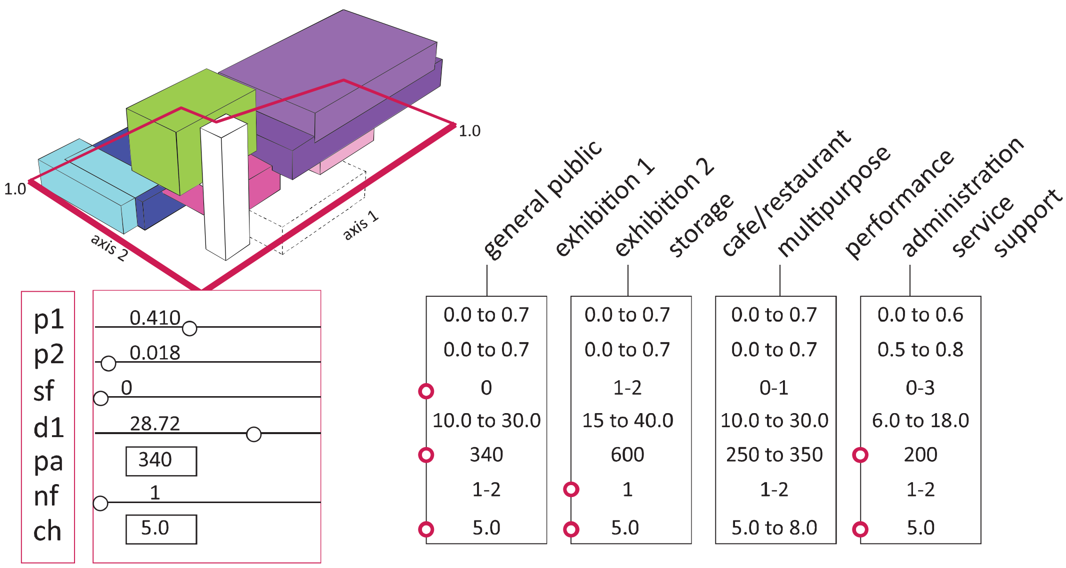


Fig. 77 Case study2. Summary of departments variables. p1,p2: position in axis 1 and 2. sf: starting floor. d1: axis 1 dimension. a: area. f: floor height (1 or 2 floors). ch: ceiling height. Drawn by author.

With the defined variable for the set of departments, the algorithm is run for the two first criteria: avoid overlaps and do not exceed the boundary site. On figure 78 a sample of solutions is presented, for which the criterion are to be minimized.

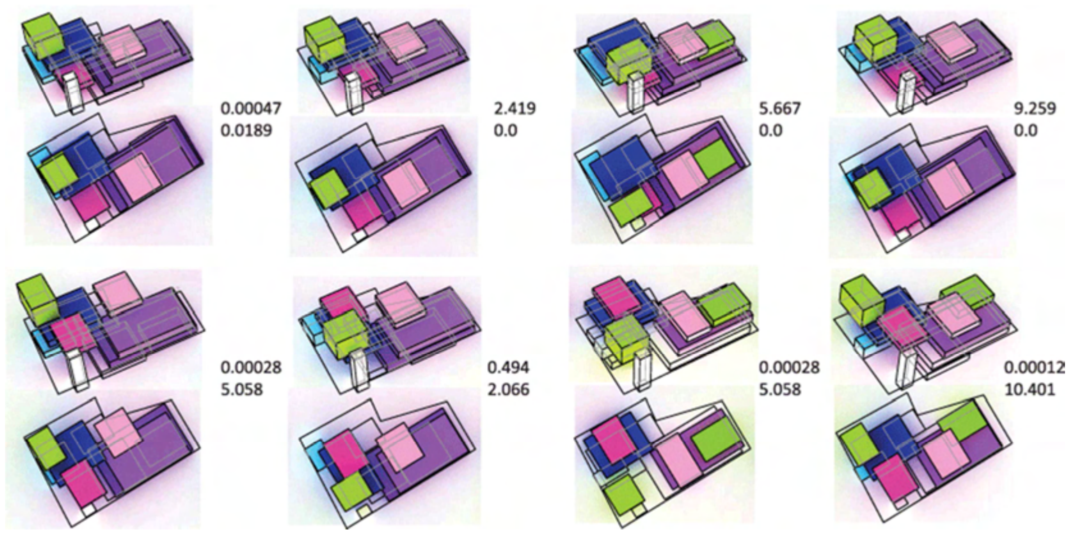


Fig. 78 Case study 2.Two goals. 150 population, 200 generations. Drawn by the author.

The travel distance is included as a new criteria for the following departments:

Exhibition Gallery 1 and 2; Multipurpose and Performance 1; Administration and Service. The same weight is given to all of them.

A rotation degree is assigned if the department starting point is close to Smidswater street (figure 74) as an attempt to align them to the site´s shape in that corner. If the starting position in axis 1(p1) is larger than 0.6 and the starting position in axis 2 (p2) is larger than 0,5, then the department rotates 0.25 radians counterclockwise. A solution sample is shown in the next figure.

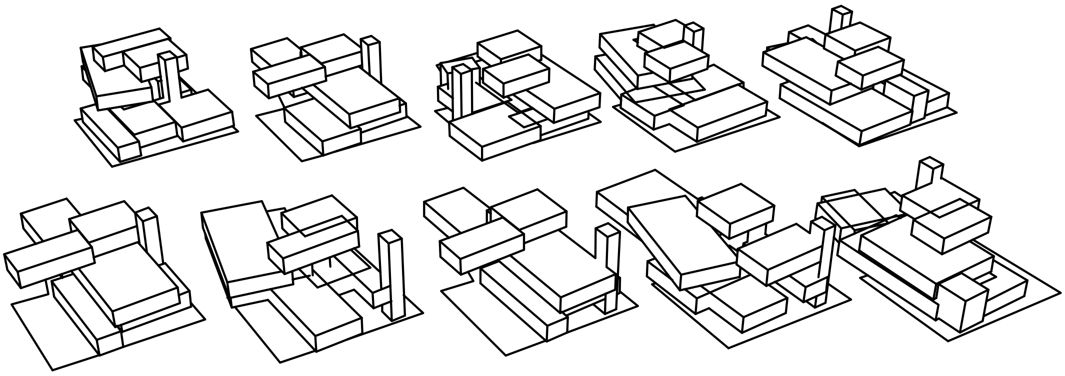


Fig. 79 Case study2. Three goals. 200 population, 20 generations. Drawn by the author.

A new set of elements, in this case voids, is included as part of the architectonic idea for the project. These are fixed elements and the new criteria is not to intersect them.

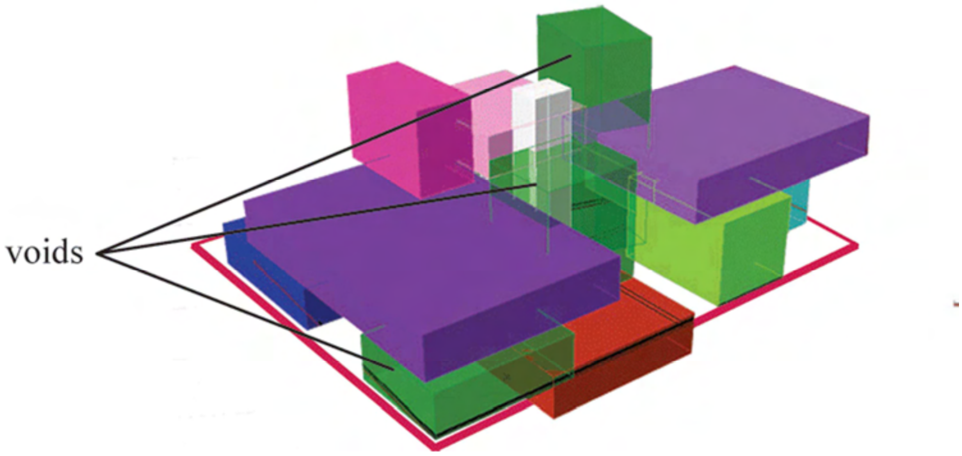


Fig. 80 Case study 2. Incorporation of voids to the design. Drawn by the author.

The resulting Pareto front for these four goals results unclearly defined and with an average of 2,3 seconds per solution, the analysis of 400 generations of 200 solutions per population, resulted in more than two days.

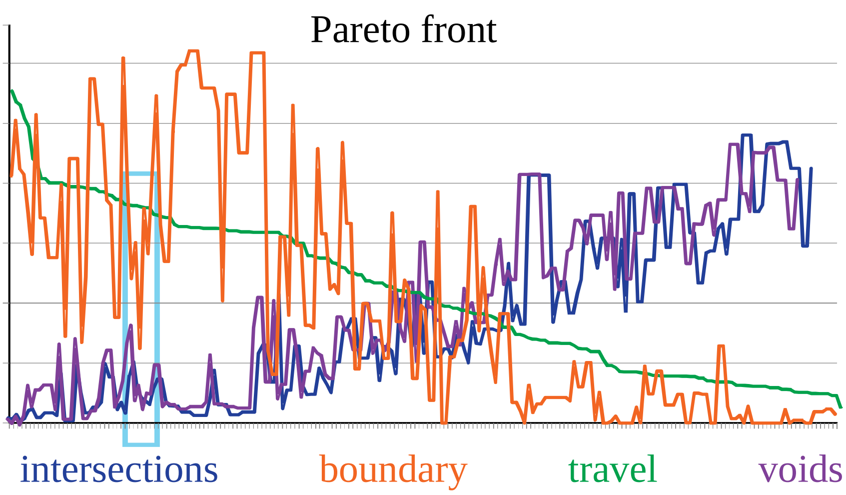


Fig. 81 Case Study 2. Four goals Pareto front after 400 generations. Drawn by the author.

In order to increase the performance, an evaluation of the algorithm´s parts was performed to evaluate their response time. The calculation of the intersections of the departments took the highest computation power. Several attempts were evaluated using regions, meshes and solids. The regions resulted in inconclusive due to the errors in calculations if one appeared completely inside other.

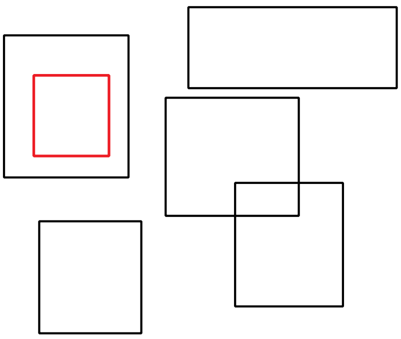


Fig. 82 Region included in region is not computed as intersection in Grasshopper. Drawn by the author.

The meshes intersection in Grasshopper presented a flaw in its calculations. In figure 83 an overview of the outcome of the union using mesh, simple mesh and solid objects is shown. Due to this problem, the use of meshes was dismissed.

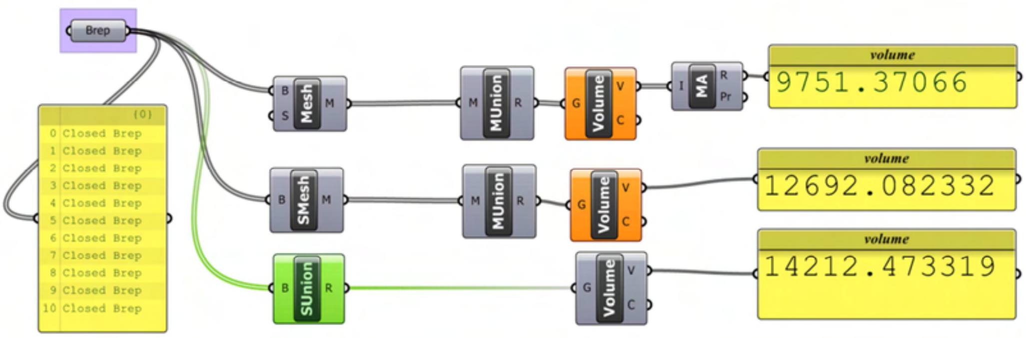


Fig. 83 Case study 2. Mesh calculation flaw in Grasshopper. Drawn by the author.

Despite these difficulties, the use of the tool was helpful for the formulation of the relations and a set of solutions was obtained. From these solutions the following layout was selected.

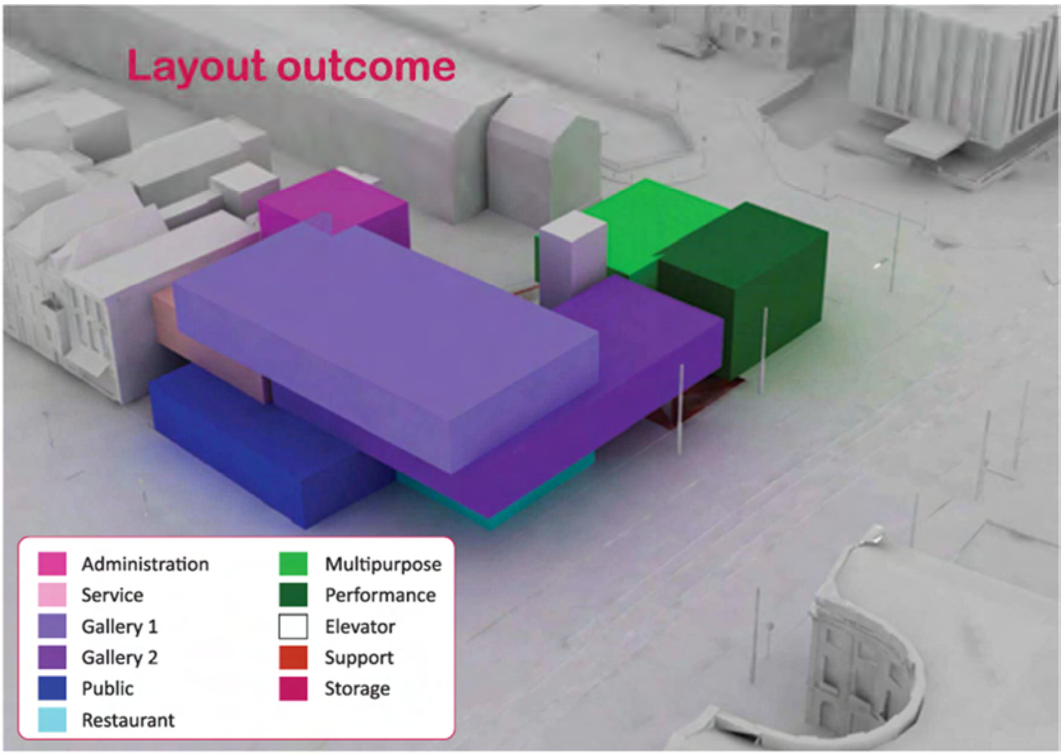


Fig. 84 Solution outcome example. Drawn by the author.

The solution obtained satisfied the previously formulated criteria:

1- It presented a small overlap amount.

2- All of the departments were contained within the site boundary.

3- -The solution granted the required departments horizontally adjacent (multipurpose and performance), or vertically (exhibition one and two, and administration and service), according the travel distance formulation.

The study of each department individually, and the reflection on each relation to define the problem formulation together with the criteria definition provides deep knowledge of the project essence, which is not achieved with other methods. Besides, clear criteria definition and grading the solutions facilitates the understanding to other people, like the client, who can include his/her criteria and weights in an explicit manner.

CHAPTER 6

CONCLUSIONS

This study addresses the limited design freedom of previous spatial allocation studies, and proposes new formulations and the use of Intelligent Design Objects as a model to overcome these limitations.

Previous studies approach the problem locating modules in a grid, computing the distances between departments and improving the obtained solutions. It is useful for certain scenarios, but results are too rigid or not flexible for architecture design. In this thesis, the author proposes a model that takes into account variances in the program areas, and establishes relative importance among the departments to overcome that rigidity of previous studies. Special attention is put to the problem formulation, in order to make it suitable for different design problems and building types.

The proposed variable formulations make the computation expensive. Increases in the number of criteria result in much longer computational time and undefined Pareto fronts. The simplification of the parameters brings faster results, but limits the design freedom. It is the user´s duty to prepare the proper formulation for the task.

From the selected optimization plugins in Grasshopper (Octopus, Goat, Galapagos and TO&I Lotus), the first two could not stand the high computation and failed to obtain results. Galapagos, on the other hand, coped with the high number of parameters, but the criteria had to be combined into a single cost function making the result highly dependent on the weights and unreliable. The only tool that managed the high number of parameters and the multiple criteria was TO&I Lotus.

The method proposed helps to visualize and evaluate different solutions and to conceive the different department relations at an early stage of building layout. Besides, at all times the solutions are numerically graded and provide, also to the client, an understanding of their “goodness”. Once a solution is selected, is possible to designate new criteria, such as yearly sun radiation, and define a set of transformations, such as scaling or movement of the departments to adapt the solution towards this new goal.

The graphic interface facilitates interaction with the user, and makes possible to move and lock departments and explore different relations. For further researchers, the use of a programing language is advised to overcome the computing limitations of the tool.

Fifty years from Armor and Bufa research in 1964, and still the spatial allocation problem remains more interesting to researches than to practitioners. This is in part due to the difficulty of the problem formulation and also to the architectural practice itself. The first one, in the literature, is approached by a simplification of the problem. The formulation of a grid to locate the elements and to assign them to modules has been part of the formulation of most of the studies. Making the architectural spatial relations look alike distance cost functions drives designers away from these methods.

In this study, the model is not intended to serve as an automatization of the task. Instead, an iterative improvement process is proposed. This is achieved by two means: the first is user interaction. The method proposes a user defined formulation of the departments’ areas, proportions and (as in the second case study) their floor position. This step is aimed to provide a reflection on the architectural program and, at the same time, constrain the search. The second, is a constant numeric and visual feedback of the results.

The process is refined after some solutions are obtained. Besides, at any moment, the user is able to incorporate new architectural decisions (as the inclusion of voids in the last example).

The Intelligent Design Objects method contemplates the possibility of further assistance for the designer. Once the layout configuration is decided, a new set of transformations (alignment, scaling…) is to be paired to new defined criteria (solar analysis, structure…).

Further studies should be carried to reduce limitations related with computational time. The first guideline is to adopt a programing language to cope with the mentioned computation. To correct the meshes intersections and use them should cut down the needed time by three or four times, according the tests run. A higher number of departments considered should be studied to determine the validity limit of the method. At last, an elaboration to combine several of the approaches shown into the same project should be considered. For larger set of departments, the suggested workflow is to set them into larger groups, for example, regarding their function, and proceed to arrange them within the group. The possibilities of neural tree are also presented in this thesis. However, the focus was put on multi-objective optimization, rather than combining the criteria into one single objective. An example is included to show the potential of this method. Further studies should overcome the computational cost limitations and compare the results of both approaches.

To sum up, the use of Intelligent Design Objects method for the spatial allocation problem proposed in this thesis has proved its validity, and some limitations. It has also shown the potential for further criteria elaborations.

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