ANALYSIS OF SPACE LAYOUT USING ATTRACTION FORCE MODEL AND QUADRATIC ASSIGNMENT PROBLEM

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

GÖZDENUR DEMİR

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
COMPUTATIONAL DESIGN AND FABRICATION TECHNOLOGIES
IN
ARCHITECTURE

MAY 2014

Approval of the thesis:

ANALYSIS OF SPACE LAYOUT USING ATTRACTION FORCE MODEL AND QUADRATIC ASSIGNMENT PROBLEM

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ABSTRACT

ANALYSIS OF SPACE LAYOUT USING ATTRACTION FORCE MODEL AND QUADRATIC ASSIGNMENT PROBLEM

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M.Sc., Computational Design and Fabrication Technologies in Architecture, in the Department of Architecture

Supervisor: Prof. Dr. Can Baykan

May 2014, 140 pages

Space layout is a complex architectural problem because of the interdependent structure of individual design objects and the vast number solutions even for small sized problems. The question of this research is the usefulness of computerized space layout programs in an actual problem of space layout. This was tested with two existing space layout optimization methods, Quadratic Assignment Problem (QAP) and Attraction Force Model (AFM) as well as a satisficing method, intuitive approach. The models used for testing computerized space layout approaches were selected because of their capability to handle a space layout of an actual design problem of more than 50 design units of unequal sizes; their basic representations and availability. Necessary inputs for the evaluation processes, the evaluation processes and the resulting space layouts were analyzed for each approach by one designer. Their performance in the design process was criticized and possible improvements were suggested to increase the usefulness of computational space layout approaches in the professional field.

Keywords: Computerized Space Layout Approaches, Quadratic Assignment Problem, Equilibrium Method, Intuitive Approach

ÖZ

ÇEKİM GÜCÜ MODELİ VE KARESEL ATAMA PROBLEMİNİ KULLANARAK MEKAN YERLEŞİMİ ANALİZİ

Demir, Gözdenur

Yüksek Lisans, Mimarlıkta Sayısal Tasarım ve Üretim Teknolojileri,

Mimarlık Bölümü

Tez Yöneticisi: Prof. Dr. Can Baykan

Mayıs 2014, 140 sayfa

Mekan yerleşimi, tekil tasarım objelerinin birbirine bağımlı olan yapısından ve küçük boyutlu problemlerde bile yüksek sayıda çözümü olmasından dolayı karmaşık bir mimari problemdir. Bu araştırmanın sorusu bilgisayar destekli mekan yerleşimi yaklaşımlarının gerçek bir mekan yerleşimi problemindeki kullanışlılıklarıdır. Bu soru varolan iki mekan yerleşimini iyileştirme metodu, Karesel Atama Problemi (QAP) ve Çekim Gücü Modeli (AFM) aynı zamanda 'satisficing' metodu, sezgisel yaklaşım kullanılarak test edilmiştir. Bilgisayar destekli mekan yerleşimi yaklaşımlarını test etmek için kullanılan modeller, eşit olmayan boyutlardaki 50'den fazla tasarım ünitesini içeren gerçek bir problemle baş edebilmeleri, basit temsilleri ve ulaşılabilirliklerinden dolayi secilmistir. Bütün yaklaşımlar için; değerlendirme metodları için gerekli girdiler, değerlendirme süreçleri ve sonuç mekan yerleşimleri bir tasarımcı tarafından incelenmiştir. Tasarım sürecindeki performansları eleştirilmiş ve bilgisayar destekli mekan yerleşimi yaklaşımlarının mesleki alandaki kullanışlılıklarını artırmak için mümkün gelişimler önerilmiştir.

Anahtar Kelimeler: Bilgisayar Destekli Mekan Yerleşimi Yaklaşımları, Karesel Atama Problemi, Denge Metodu, Sezgisel Yaklaşım

To my family,

Suna Demir, Mustafa Demir, A.Gökhan Demir

ACKNOWLEDGMENTS

In this challenging master process I would like to thank,

My thesis supervisor, Prof. Dr. Can Baykan, for his contribution in this work with his enlightening, practical, supportive and constructive approach during the process,

Main project mentor, Dr. Huib Plomp, for his effort on the graduation project, The Creative Village, directions he gave with his unusual view and challenges that he created for sensing the potentials of the project,

Project mentor, Msc. Sander Mulders, for his positive directions and suggestive approach in architectural and computational development process of the graduation project and his script, Attraction Force Model,

Chairman of Duindorp, The Netherlands, Martin Spaans, for informing me about the social life in Duindorp and the reflections of the political decisions on the area,

Dr.ir. M.S. Bittermann and Yannis Chatzikonstantinou for their constructive critics and support during the design process,

History Thesis Supervisor, Charlotte van Wijk, for her motivating judgement on the work I have done with great excitement, ‘Symbol to Soul: Tea ceremony &Teahouses’.

Research Assitant, Dr. A. İrem Mollaahmetoğlu for her positive directions and support during the design process. Prof. Dr. Ferhan Yürekli for his unique motivation with his book ‘The Design Studio: A Black Hole’.

And lastly all of my mentors in METU and TU Delft and ITU for their support,

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CHAPTER 1

INTRODUCTION

Space layout is a complex architectural problem because of the interdependent structure of individual design objects and the vast number solutions even with small sized problems. Researchers have been approaching to this complex problem with different methods for almost 50 years. The question of this research is the usefulness of computerized space layout programs in an actual problem of space layout. This was tested with two existing space layout optimization approaches, Quadratic Assignment Problem (QAP) and Attraction Force Model (AFM) as well as an intuitive approach.

The initial researches on the performance of the computerized space layout approaches were published in around 1975. The recent publications in the literature are based on the weak interest of companies and architects to computerized space layout approaches. This research was done to contribute in the literature by exposing the performance of the computerized space layout approaches in an actual design process and seek for the possible reasons of the disinterest of the architects in them.

Different programs were developed for the problem of space layout using different approaches both in commercial or academic use (Canen, Williamson, 1998). The search for the model used in the design process was based on its capability to handle space layout problems greater than 50 design units of unequal sizes. Additional requested criteria were to optimize adjacency relations, to work in 2D, to be available and to be user-friendly. In this regard, two models, QAP and AFM were selected because of their basic representations, ability to deal with large size problems and availability. For the QAP applications, CRAFT procedure was used in Facility

Layout®[1] program. For the Equilibrium Method applications, AFM was used in Kangaroo Physics[2] program.

The operations were done and evaluated by one designer, who is the author of this thesis. The necessary inputs for AFM, intuitive approach and QAP were prepared intuitively by the designer, only necessary input about environmental conditions were investigated during the intuitive approach. For AFM 58 adjacency relation inputs were prepared between only the desired design units and without any quantity. For QAP 1431 flow matrix inputs were prepared between all design units with quantities; which differentiate according to the strength of the relation between the design units.

Three space layouts were obtained by the AFM, intuitive approach and QAP respectively. The decision on the three space layouts were given according to the satisfaction of the majority of the relations in AFM and observing the least cost in multiple trials in QAP. The space layout of the intuitive approach was obtained without any definite criteria, but gradually by the development of the space layout of AFM, by doing public-private, grouping, seclusion, site conditions and boundary relation and spatial analyses. The content of the thesis will be as follows:

The second chapter explains the previous approaches on the space layout planning. Principles of QAP and AFM will be explained in detail. Similar researches about the usefulness of the computerized space layout approaches in the literature and the use of these approaches in practice will be presented at the end of this chapter.

The third chapter explains the methodology of the research.

The fourth, fifth and sixth chapters explains; necessary inputs for the evaluation processes, the evaluation processes and the resulting space layouts for AFM, intuitive approach and QAP respectively.

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[1] Copyright 2004 - All rights reserved by Paul A. Jensen

[2] by Daniel Piker

The seventh chapter presents the comparison of the three approaches and designer evaluation.

The eighth chapter is the final part of this thesis and contains conclusions on this research and recommendations for future work.

CHAPTER 2

BACKGROUND

This chapter sets the background of the computational space layout approaches. Selected models, QAP and AFM will be presented to the reader and their structure will be explained in detail. Lastly various researches on the usefulness of computerized space layout approaches will be presented.

2.1. Space Layout Approaches

Space layout approaches will be classified as representation approaches and evaluation methods. Representation approaches are classified as graphs / wall representations and constraint based approaches like region connection calculus and rectangle algebra. Evaluation methods are classified as satisficing and optimization methods.

Graphs are abstract representations of space, which contain information about the number of neighboring design units, average depth to all other spaces and flow measure through a design unit (Baykan). Wall representations show adjacency relations between rectangular spaces.

Region connection calculus and rectangle algebra defines mutually exclusive and exhaustive qualitative relations between dimensionless regions and 2D rectangles respectively. 8 specific relations are possible between two regions in region connection calculus where 169 relations are possible between two rectangles in rectangle algebra. Every region connection calculus relation corresponds to a subset of the relations of rectangle algebra. Only one of these relations can be defined between two entities (Baykan).

Shape grammars are also used for describing, analyzing and synthesizing the space layouts. Shape grammars are used to generate space layouts out of defined set of rules and are symbolic (not-explicit) rather than iconic (explicit) representations. Most grammars have been developed to describe and analyze historical or existing styles, as defined by corpus of designs. It is also possible to develop original grammars to define new styles (Baykan).

Not all representation approaches are mentioned here. QAP uses grid representation and AFM uses point representations in space. Both representations are very basic compared to above representations.

Finding an acceptable or good enough solution to a design problem where best solutions are unknowable is called satisficing (Simon, 1981). Selection of good enough solutions doesn’t mean that the designer is satisfied with less but he has no other choice. The designer used satisficing during the intuitive approach in the design process.The technique of finding the best result or possibly best results of a design problem according to specified necessities is called optimization (Arvin, 2004). QAP and AFM use optimization method.

2.2. QAP

Koopmans and Beckman (1957) formulated the problem of locating facilities and activities in space as the QAP. QAP is formulated as the assignment of facilities to cells of a grid to minimize the transportation costs. Fixed cost term and interactive cost term is calculated in the QAP formulation. Fixed cost is dependent on the assignment of a design unit to a particular site and independent from the interactions with other design units whereas interactive cost term calculates material transportation flow costs and design units are interdependent (Liggett, 2000). The formulation is as below (Kay, 2009):

Given, M=design units M $\leq$ N=sites

M ={i,j….} N={k,l….}

Minimize TC = $\sum_{i=1}^{M} . \sum_{k=1}^{N} cik.xik$ + $\sum_{i=1}^{M} . \sum_{k=1}^{N} . \sum_{j=1}^{M} . \sum_{l=1}^{N} cijkl.xik.xjl$

subject to

$\sum_{i=1}^{M} xik$=1, for all sites k = 1,...,N

$\sum_{k=1}^{N} xik$=1, for all design units i = 1,...,M

xik = { 0,1 }

where

xik = { 1, if design unit i is assigned to site k,

0, otherwise

cik = fixed cost of assigning design unit i to site k

cijkl= cost of assigning design unit i to site k when design unit j is assigned to site l

A basic illustration is shown in Figure 2.1. to understand the formulation.

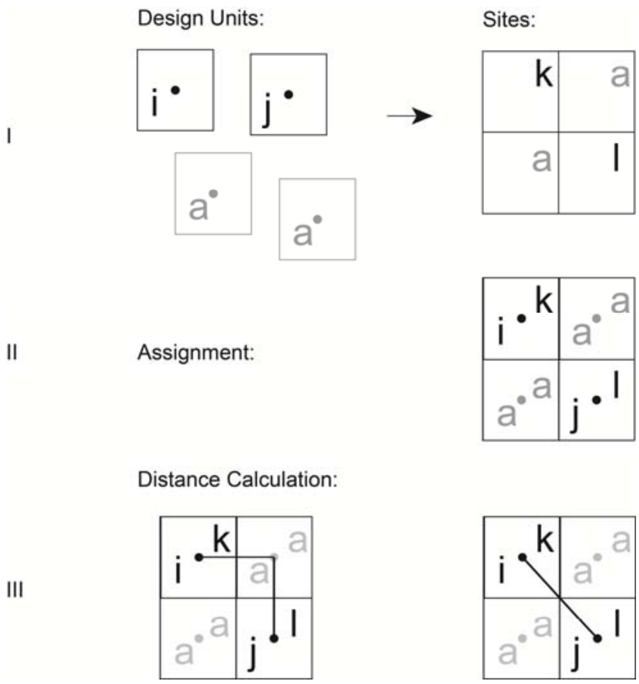

Figure 2.1. A basic illustration of an assignment. Drawn by the author.

I-M number of design units will be assigned to N number of sites

II-A possible assignment

III-Distance calculation methods, rectilinear distance on the left and euclidian distance on the right

Let's assume that, M number of design units will be assigned on N number of sites as in Figure 2.1.-I. A possible assignment is shown in Figure 2.1.-II, where design unit i was assigned to site k and design unit j was assigned to site l. The assignment of any design unit on any site has a cost, so this cost will be calculated as fixed cost term. For instance, in the formulation above xik value will be 1 according to this assignment. Then fixed cost of assigning design unit i to site k, cik will be valid in the formulation.[3]

Secondly the interactive cost term will be calculated between design unit i and design unit j. The values of xik and xjl will be 1. Then cost of assigning design unit i to site k when design unit j is assigned to site l, cijkl will be valid. The value cijkl is calculated by (cij fij)dij, which is the multiplication of the material transportation

[3] Not every QAP program calculates fixed costs, like the one used in this thesis, Facility Layout®.

flow cost(cost matrix. flow matrix) and distance. Material transportation cost and material transportation flow matrixes were both defined by the designer as an input before the optimization. Distance can be calculated either by taking the rectilinear distance or euclidian distance between the centroids of design units i and j as shown in Figure 2.1.-III during the optimization. Total cost (TC) of the space layout is obtained by this method.

The illustration shown in Figure 2.1. has 4 design units and 4 sites. The number of all possible assignments for this problem can be calculated by M!, which is 4!=4.3.2= 24. However realistic space layout problems usually contain more than 15 design units, which makes it hard for QAP to consider all possible assignments because of vast numbers of solutions (Liggett, 2000) and extremely long computation time (Armour, Buffa, 1963).

Since QAP isn't able to evaluate all possible assignments of realistic design problems, optimum result is harder to find. Based on this, researchers developed procedures to find the optimum solution; which are constructive and improvement procedures.

Constructive procedure places the most strongly related design unit in the center of the layout and continues until no design units left while the total cost is being minimized. According to Kalay (2004) this procedure is not flexible because the order of placement is more important than the material transportation flow between the design units and may end up with unwanted results in some problems such as placing a waste tank in the middle of a factory (Baykan, 1995). The placement is done via waste tank's strong relations with the majority of design units but in return hygienic concerns may arouse during the usage. CORELAP, ALDEP, MAT, PLANET are example algorithms of this procedure (Jojodia, Minis, Harhalakis, Proth, 1992).

Improvement procedure makes pair-wise switches between the design units to decrease the total cost. This procedure is more flexible than the constructive procedure because switching may improve the quality of the layout; however the switch is only accepted if it improves the previous solution. The results differ according to initial configurations so it is better to optimize more than one initial configuration (Baykan, 1995). Armour and Buffa (1963) stated that ‘more powerful evaluating and exchanging mechanisms’ are necessary to reach to same suboptimum solution with any initial layout. MULTIPLE, MCCRAFT are example algorithms of this procedure. A widely used algorithm of this procedure is CRAFT.

Computerized Relative Allocation of Facilities Technique, CRAFT, was formulated in 1963 to increase the efficiency of a manufacturing plant, speed up the evaluation process and to generate more alternatives to the space layout problem (Buffa, Armour, Vollmann, 1964). CRAFT makes pair-wise switches between either adjacent design units or design units of equal sizes. Applications of CRAFT for buildings of different functions are exemplified in Buffa, Armour and Vollmann’s article (1964). It is possible to fix design units at desired sites by the designer’s request. The maximum capacity of CRAFT program was 40 design units, when it was first formulated. To deal with larger sized problems different kinds of procedures were developed under improvement procedure, like, simulated annealing and genetic algorithms; however they mostly end up with suboptimal results.

Simulated annealing procedure uses the principle of a metal releasing its internal stress during melting and cooling processes (Jojodia, Minis, Harhalakis, Proth, 1992). System tries to decrease the objective function with the change of configurations according to temperature changes, but accepts a solution even if it increases the cost of the layout, so it is more advantageous than improvement procedure. Sharp and Marksjo applied it to 200 design units in a space layout organization (Liggett, 2000). CLASS algorithm uses simulated annealing procedure, which weakens the dependency of the optimized layout to the initial space layout (Jojodia, Minis, Harhalakis, Proth, 1992).

Genetic algorithms depend on the survival of the fittest solution after a population is generated and subjected to reproduction, mutation, selection and culling operations (Liggett, 2000). This procedure has a powerful search capability compared to the limited search of the classical constructive and improvement procedures in the optimization problems and can produce good solutions for computationally problematic large-scale space layout problems (Jo, Gero, 1998). Solution processes can be visualized like human design processes (Liggett, 2000).

Hybrid procedures apply both constructive and improvement procedures. The solution of the constructive procedure is improved by pair-wise switches of improvement procedure. As the improvement procedure is very dependent on the initial layout, if the constructive procedure doesn't find a good solution, the process ends up with a local optimum (Jo, Gero, 1998). An evaluation on the use hybrid approach in the solution of a hospital layout can be found in Elshafei's article (1977).

A review of space layout approaches and programs developed for these approaches can be found in the article of Singh and Sharma (2006).

2.2.1. Facility Layout®

Facility Layout® is a program; which uses QAP in space layout organization. The program uses improvement approach, which decreases the total cost of an initial layout by doing pair-wise switches during the optimization. Design units of unequal sizes are subdivided into standard modules. The program operates in Microsoft Office Excel®[4] (Jensen, 2004 (II)).

Two procedures can be used for optimization in Facility Layout®, which are Traditional CRAFT and Optimum Sequence. A major difference between the two procedures is Traditional CRAFT usually switches either the adjacent design units or the design units of equal size[5] (Armour, Buffa, 1963), whereas Optimum Sequence switches the sequence of two of the design units. Traditional CRAFT method will be used in this thesis to experiment QAP in Chapter 6.

2.3. Equilibrium Method

Newton's second law of motion states that to change the design object's velocity and position a force should be applied on it. Equilibrium method can be defined as the

[4] ©Microsoft Corporation. All rights reserved.

[5] Design units of unequal sizes can also be switched; but separations more likely to occur between the modules of the same design unit.

application of Newton’s second law of motion on the design objects in the space layout to reach an intended design state to satisfy various topological or geometric design criteria. Arvin and House (2002) states that any design criteria which are related with the position of any design object in the space layout can be translated into forces as shown in Figure 2.2., where a designer’s problem is translated into a dynamics problem.

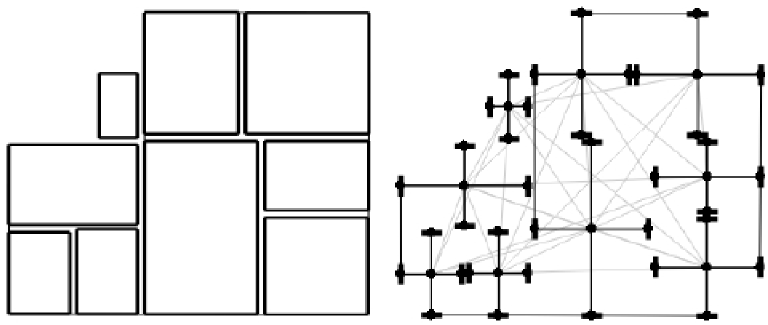

Figure 2.2. Translation of the designer’s problem on the left to a dynamic problem on the right. Arvin, 2004.

The lines on the left image represent the bounding walls of the design unit spaces, where on the right side, points represent the design unit centers and the lines represent the forces to be applied to satisfy the design objectives.

Topological criteria regulate how one design unit relates to another, like adjacency, separation, orientation, etc. are applied on the center of the design units; geometric criteria regulate the design unit boundaries, area and shape, like alignment, offset, area, proportion, etc. are applied on the edges of the design units (Arvin, House, 2002).

Circular geometries are used to satisfy the topological criteria, to maintain the design units to slide over each other, without preventing each other during the displacement. However after the topological criteria are completed, Arvin and House (2002) recommends to transform the circular geometries into rectangular geometries during the implementation of geometric criteria, to evaluate the design unit’s shapes and the boundary relations with each other.

An important concept of the equilibrium method is shown below in the Figure 2.3.

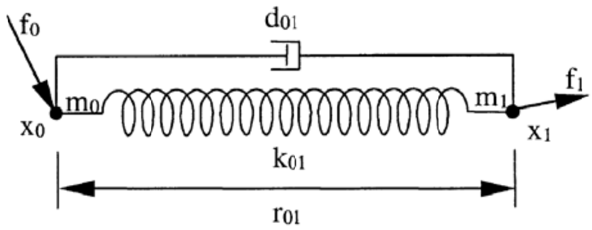

Figure 2.3. Simple mass-spring-damper system. Arvin, House, 2002.

In Figure 2.3. m0 and m1 represent two points. A spring connects the two points with spring constant, k01and current spring length is l01 is the magnitude of the vector between positions x0 and x1 at the current time. Desired rest length between the design units is r01. Dashpot has a damping constant of d01.

Spring uses the f0 and f1 forces, with a magnitude proportional to l01- r01. The direction of the force will be along the line connecting the two masses. The spring applies a force to bring the masses together or apart, when they move further or closer to each other respectively. The parallel attached dashpot damps the motion of the masses by producing forces proportional with damping constant, d01 to their relative velocity towards or away from each other, thus reducing the kinetic energy introduced by the spring forces (Arvin, House, 2002).

Equilibrium method is able to define representation, computation and interaction with one paradigm, which is not possible in majority of computerized space planning methods (Arvin, 2004). Arvin (2004) supports this position by reminding that today's digital design applications don't construct a physical link between the designer and the tool, like the link between the hand and the tool in the traditional design and claims that such an interaction can be constructed by a dynamic relation or integrating physics into the process. Arvin and House (2002) claim that when the design criteria change, this is immediately applicable on the model and define this process as 'responsive design'.

Harada, Witkin and Baraff (1995) criticize the vagueness between the rules and the geometric outputs in shape grammars and motivated by the addition of manual designer manipulation in the transformation process of a space in a continuous manner and exploration of design space related to shape grammars with geometric deformation. Instead of the sequence of rules that generate layouts, Harada, Witkin and Baraff (1995) claims that manual modifications done on the 'grammer's geometric output' by the architects would to increase the efficiency of the shape grammars.

2.3.1. Kangaroo Physics

Kangaroo Physics is a Grasshopper®[6][7] add-on by Daniel Piker, which interactively simulates physical rules in a 3D environment and gives the user to chance to interact with the behavior during the simulation. Optimization, form-finding, structural analysis and animation and more can also be done in the program (Piker).

Kangaroo Physics Engine, that is a component, has to be placed in every simulation prepared in this program. Also a timer component can be connected to the Kangaroo Physics Engine and the simulation can be followed with the desired speed.

AFM[8] was constructed in Kangaroo Physics with necessary components to organize separate masses by physical forces according to adjacency relations. AFM will be used in this thesis to experiment the equilibrium method in Chapter 4. The structure of AFM in Kangaroo Physics can be summarized as follows:

The design units, represented by spheres, are distributed randomly on a sphere as shown in Figure 2.4.

[6] Grasshopper® is the 'explicit history' plug-in of Rhinoceros® 3D Modeling Program.

[7] Copyright© 2009 Robert McNeel & Associates

[8] The program can be found in Mulders, 2012 (I).

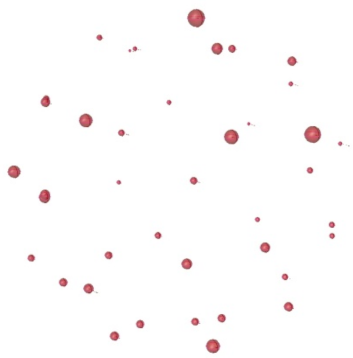

Figure 2.4. Random distribution of design units on a sphere. Drawn by the author.

Power law component assigns interconnection lines between each design unit centroid as illustrated in Figure 2.5. to prevent collusions. When the connection is shorter than the sum of the radius of two design unit spheres, power law force works and prevents the collusion.

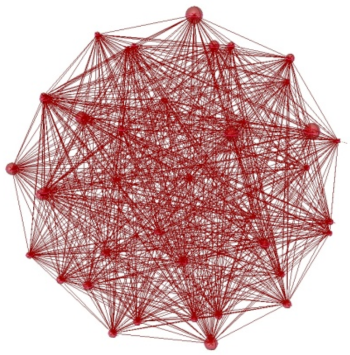

Figure 2.5. The interconnections between each design unit to prevent collisions. Drawn by the author.

Related design unit names are transferred into strings and theirs centroids are connected the by a component, Springs From Line, which attracts them to each other, shown in Figure 2.6.

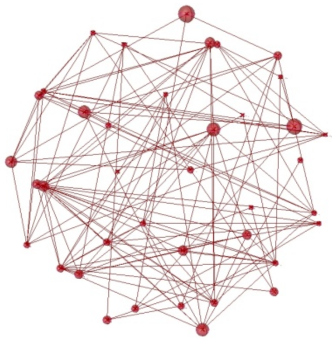

Figure 2.6. Springs between the related design units. Drawn by the author.

Kangaroo Physics Engine component merges power law and spring forces. If the program was constructed in 3D with spheres, the display occurs as shown in the left side of Figure 2.7. If the program was constructed in 2D with circles, the display occurs as shown in the right side of Figure 2.7.

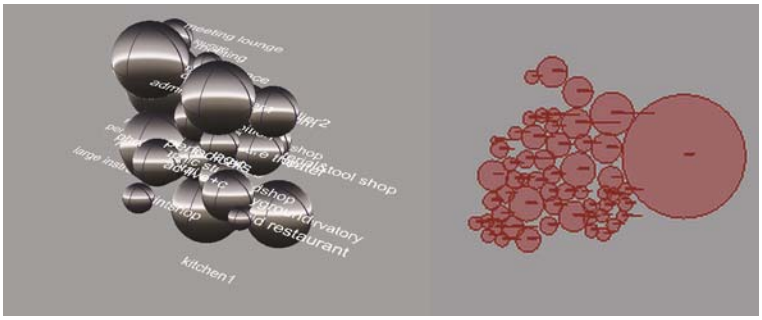

Figure 2.7. 3D display of the output on the left and 2D display of the output on the right. Drawn by the author.

(see also: APPENDIX A. GRASSHOPPER® DEFINITION OF AFM)

Sander Mulders designed AFM to overcome the complexity of allocating various design units on a site, respecting their adjacency relations with each other as shown in Figure 2.8. (Mulders, 2012 (II)).

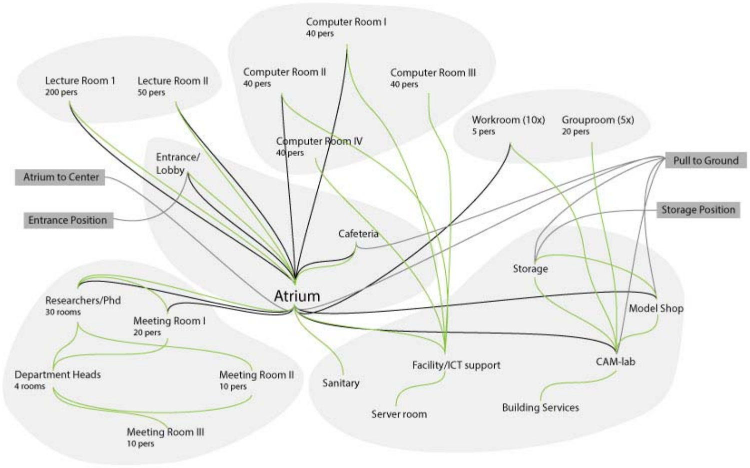

Figure 2.8. Relations and complexity of School for Digital Design. Mulders, 2012 (II).

Maya®[9] dynamic engine was used in this case instead of Kangaroo Physics to run AFM. After the 3D spheres representing the design units equilibrated, a 3D Voronoi[10] structure has been generated by directly using the centroids of the spheres as illustrated in Figure 2.9. 3D regions represented the spaces to be used, and the surfaces in between the adjacent regions represented the architectural relations like open or closed or transparent. The edges of the Voronoi structure represented the load bearing structure (Mulders, 2012 (II)).

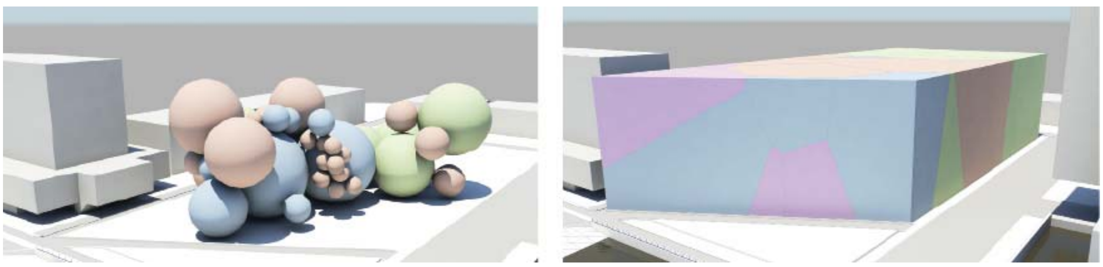

Figure 2.9. State of equilibrium on the left and 3D Voronoi structure on the right. Mulders, 2012(II).

[9] Copyright© 2013 Autodesk Inc.

[10] Voronoi structure is composed of points and boundaries on a space, where the space is divided into regions with the boundaries around the points. The region boundaries are obtained by the perpendicular lines of the connection lines of two points. This natural structure, which can be observed in formation of soap bubbles, was selected as the best way to divide a 3D space to obtain maximum effectiveness and to benefit from the boundaries of the structure by applying relations between the design units (Mulders, 2012 (II)).

2.4. Use of Computerized Space Layout Approaches in Practice

Performance of computerized space layout programs was an interest of the space layout researchers. After the presentation of QAP program CRAFT in 1963 by Armour and Buffa, Scriabin and Vergin (1975) published an experiment based on the comparison of three different space layout algorithms of improvement procedure, H-63, HC-66, CRAFT and human subjects for the solution of space layout problems of various sizes. The research aimed to reveal if there is any advantage of approaching space layout with various algorithms over the traditional methods. Both algorithms and human subjects tried minimize total interdepartmental material handling costs and the results were compared at the end. The results showed that in general computers generated worse results than humans (Scriabin, Vergin 1975). As the number of design units increased, the cost differences between the humans and computers also increased, where humans had better results as shown in Table 2.1.

Table 2.1. Comparison of computer and human generated space layout solutions. Scriabin, Vergin 1975.

Number of Departments	Best Solution			Median Solution		
	Computer	Human	Diff. (%)	Computer	Human	Diff. (%)
5	64.02	64.02	0	64.02	64.02	0
6	80.32	80.32	0	80.32	80.32	0
7	163.28	163.28	0	168.28	163.28	−3.0
8	215.86	215.86	0	228.08	216.87	−4.9
8(alt.)	214.76	214.76	0	215.86	214.76	−0.5
10	272.26	269.92	−0.9	283.36	283.78	0.1
12	314.10	314.10	0	341.68	333.02	−2.5
15	531.14	511.40	−3.7	587.29	560.22	−4.6
20	1177.64	1109.68	−5.8	1241.42	1158.56	−6.7

Authors connect the results firstly with the advantage of humans over computational procedures by the ability of man to recognize and visualize complex patterns in large-scale problems and secondly with humans considering the various criteria of real space layout problems which are not handled by the algorithms (Scriabin, Vergin 1975). This publication was immediately criticized by Buffa (1976), claiming that the structure of the experiment was problematic. Scriabin and Vergin (1976) defended the structure of their experiment against this critic by another publication.

Coleman (1977) published another critic on the methodology of Scriabin and Vergin (1975)'s experiment, which claims that their methodology resulted with results in favor of humans and recommended an impartial methodology for such comparison. Lewis and Block (1980) made another experiment to show the performance of human subjects and benefits of using algorithms in space layout problem using experienced space layout planners and construction and improvement algorithms. Trybus and Hopkins (1980) mentioned that the humans try to beat the computer when they were informed about the results of the computer. In their experiments, algorithms produced results as good as humans when humans were not informed beforehand and algorithms produced even better results than humans when the problem size increased.

Baykan (1995) presents an evaluation of QAP by interviewing two designers in different companies. Both designers use the program in the block plan design phase, by input preparations and optimizing multiple initial configurations. Despite advantages like dealing with complexity and increasing the confidence of the designer on the layout, the software used have difficulties like extensive input preparation and transfer of output to other sketching programs.

Another research by Canen and Williamson (1998) seeks for the use of computerized space layout approaches by the companies and their contribution in the competitive purposes. Authors claimed that the link between the industrial companies and academy is quite weak. Academic research is not really known by companies and doesn't reflect on their practice and the companies are not interested in academic research either (Canen, Williamson, 1998). The companies mostly deal with the problem by their own methods and by using drafting software like AutoCAD®[11]. The authors mentioned that these approaches are adequate for the companies next to inflexible space layout software in terms of the integration of individual constraints and the application difficulties.

Lobos and Donath (2010) state that 50 years of research shows that none of the computational solution methods for the problem of space layout are practically used

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or accepted by the architects. The author's claim that; space layout researchers are uninterested in the dynamics of architecture, like the popular innovative architects and frequently known architectural publications. Authors offer grounds for the space layout researchers and architects to understand each other's disciplines better. According to them, space layout researchers should attempt to comprehend good architecture like the architects and architects should understand space layout researchers' approaches to design problems. Authors suggest integrating programming language education next to design courses to improve architect's approaches to problems of space layout.

CHAPTER 3

METHODOLOGY

This chapter explains the structure of the design problem to be solved and the methodology used for the solution of this problem.

3.1. Design Problem

Design problem is to reach to the space layout of the graduation project held in TU Delft Computational Architecture Graduation Studio. The project is located in Duindorp, The Netherlands; which creates an open, flexible medium for the interaction of local community and creative class, enhances learning activity via seeing, feeling, awareness, querying and trying through today's modern trends on creativity and is called 'The Creative Village'.

Space layout design was initiated by the definition of the design program. 69 design units were defined in total, which were 13 artist residences and 56 design units with various functions in the core, which are shown in Table 3.2. Four main zones were created in the core; which are exhibition, production, performance and work.

Table 3.2. Design program according to the functions. Drawn by the author.

I A **Live+Work**	I B **Exhibit**	I C **Produce**	I D **Perform**	I E **Work**	I F **Service/Common**
1artist residence live + work*8	darkroom	woodshop	black box theater & control room	meeting*3	restaurant1
2artist residence work80*2	lightroom	metalshop	bbt lounge	meeting lounge	kitchen1
3artist residence work50*3	testhibition	fablab	rehearsal hall & artist preparation	office*5	kid restaurant
4	observatory	workshop	recording studios*2	periodicals	restaurant2
5		atelier1	large instrument		kitchen2
6		atelier2	percussion		administration*2
7		digital lab*2	photographic studio		printshop
8			playground		material & tool shop
9			amphitheater		entrance
10			lecture theater*4		skate park
11					storage
12					rest
13					wc exhibit
14					wc produce
15					wc bbt lounge
16					wc artist preparation
17					wc perform
18					wc work
19					carpark
					=69 units

After the preparation of the design program, spatial qualities of the design units were defined as shown in Table 3.3. Defined qualities are: size, quantity, height, user amount, public or private design unit, has or hasn't sound isolation, is or isn't a dark design unit, works during day and, or night. The selected qualities define the type of the user, the atmosphere to be created, the working periods and the volume that the design units occupy in the village.

(see also: APPENDIX B. DESIGN PROGRAM)

Table 3.3. Spatial qualities of design units from different functional zones. Drawn by the author.

	name	m^2	k	h	p(max)	pub/pri	sound iso	dark	day&night
Live+Work	artist residence live+work	80	8	3	1	pri	+	-	+
Exhibit	lightroom	200	1	6	40	pub	-	-	day
Produce	fablab	150	1	3.5	30	pub	+	-	day
Perform	black box theater & control room	300	1	8	232	pub	+	+	+
Work	office	30	5	3.5	5	pri	+	-	day
Service/Common	wc exhibit	50	1	3	6	pub	+	+	day

The design units were individually defined in detail with similarities in their qualities; however there was no direct relation between them to organize a space layout. At this design moment adjacency relations were constructed between the design units. Only the desired adjacency relations were noted down. The problem was complex enough with the preparation of these inputs for more than 50 design units as shown in Figure 3.10.

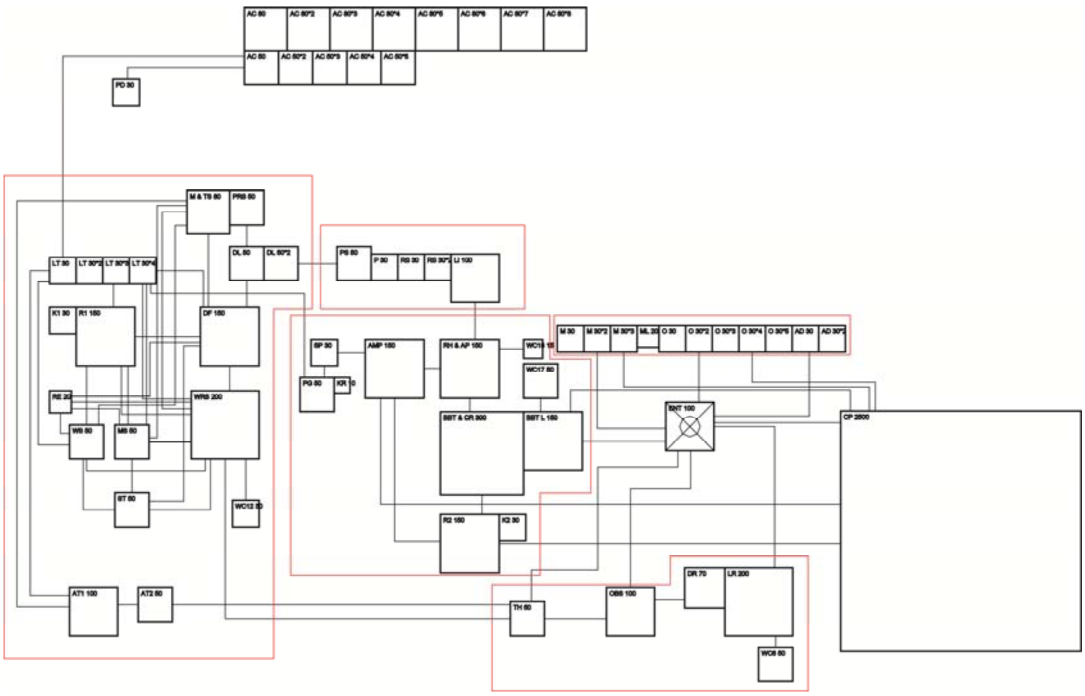


Figure 3.10. An illustration of the adjacency relations between the design units from different zones. Drawn by the author.

First attempt was to solve this problem manually. The result was unreliable and the process was time-consuming because of the problem's complexity. After these trials a computerized method was inevitable for the solution of this problem of space layout.

3.2. Approaches

AFM was initially selected to optimize adjacency relations between more than 50 design units of unequal sizes in 2D. Names, sizes of and 58 adjacency relations between the design units were given as inputs to AFM and after multiple trials, when the majority of the relations were satisfied first space layout was obtained. The space layout was evaluated by the designer and seen that its architectural qualities are weak for the rest of the design process and requires extra analysis.

The designer approached to this space layout by various intuitive analyses, like public-private, grouping, seclusion, site conditions and boundary relations and spatial analyses and the second space layout was obtained. Expected architectural qualities of the graduation project were satisfied by the design of this space layout. The space layout in this phase will also be named as P5 layout[12] in the rest of this thesis.

For the development of this research, the initial design problem was solved with an alternative model, QAP. The initial design problem input was detailed where necessary, 1431 adjacency relation inputs were prepared and 5 different layouts, including the P5 layout were optimized using QAP and compared with each other. One of the optimizations with the least cost was selected as the third space layout.

The evaluation processes will be presented in next chapters for AFM, intuitive approach and QAP respectively.

[12] P5 is the final official presentation of the graduation project in TU Delft Graduation Studio.

CHAPTER 4

ATTRACTION FORCE MODEL

This chapter explains the required input for AFM, optimization process, resulting space layout and evaluation of the designer on the process and the space layout.

4.1. Input Preparation

Requirements for AFM are list of design units, sizes of the design units and the related design units.

As explained in Chapter 3, firstly 69 design units of unequal sizes were defined by the designer both intuitively and by web research in some cases of size definitions. The design units could also be represented with equal sizes, however designer insisted in integrating unequal sizes to observe the design units' volume in the whole space layout. Design program contains identical design units. Kangaroo Physics doesn't limit the number of design units, but as the number increases the computation effort increases.

Secondly 58 adjacency relation inputs were prepared. Various intuitive reasoning between the design units was expressed in the same way as an 'adjacency relation'. The examples of reasoning are:

identical function: artist residence live + work; artist residence work80

same functional zone: darkroom;lightroom

functionally complementary: photographic studio;digital lab

visually related: workshop;lecture theater

service requirements: restaurant2;amphitheater

(see also: APPENDIX C. ADJACENCY RELATION INPUTS OF AFM)

Only the related design units have to be mentioned as an input, so the number of input is variable. AFM also doesn't require quantity of adjacency relation. These two features of AFM speed up the input preparation phase and prevent additional complexity for the designer because a relation can be defined whenever it is thought as important.

AFM doesn't assign an initial space layout boundary. So designer doesn't have to define the composition size initially. The space layout initially consists of randomly distributed design units in circular geometries with names written on without any cost as shown in Figure 4.11. The configuration only depends on the order of design units in the Microsoft Office Excel® file, so it is not possible to initiate the optimization process with an initial space layout configuration.

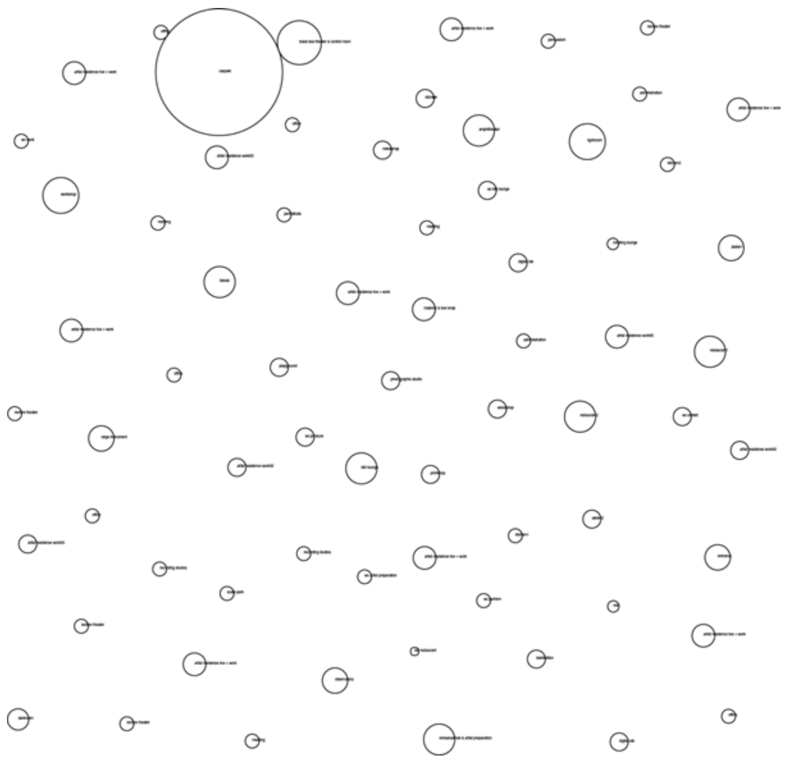


Figure 4.11. Initial configuration of randomly distributed design units of unequal sizes in circular geometries with names written on in AFM. Drawn by the author.

4.2. Optimization Process

Randomly distributed design units displaced according to 58 adjacency relation inputs with initial adjustments of AFM. After the state of equilibrium a space layout was obtained. Designer evaluated some of the relations in the layout visually and saw that most of the relations were not satisfied and adjusted features like damping or stiffness in the spring component or strength of the power law force of AFM and tried again. The space layout changed but still majority of the relations were not satisfied.

The designer observed that various intersecting forces like spring and power law decrease each other's efficiency or prevent each other to operate during the optimization and it is not possible to manipulate the locations of the design units manually in AFM.

Another attempt was to give the input one by one and test the result in each case. This method was also easier to follow visually. If the result was as expected, then another relation input was added and the result was observed. If the result was not as expected, designer adjusted features of AFM and tried again since the relation was satisfied. By this way the space layout could be under designer control. Even if the model could optimize a layout in seconds, the whole process is time-consuming. After seen that majority of relations were satisfied with the latest adjustments, adjustments were set and 58 adjacency relation inputs were given to the model again. The space layout obtained in this phase was used for the rest of the design process and shown in 4.3. Space Layout, however more observations from the optimization process will be presented now.

Firstly the effect of design unit scales on the optimizations were researched and shown in Figure 4.12. It was seen that scale modifications change the space layout. Also the system doesn't equilibrate as the scales of the design units decrease as shown in the middle image of Figure 4.12.

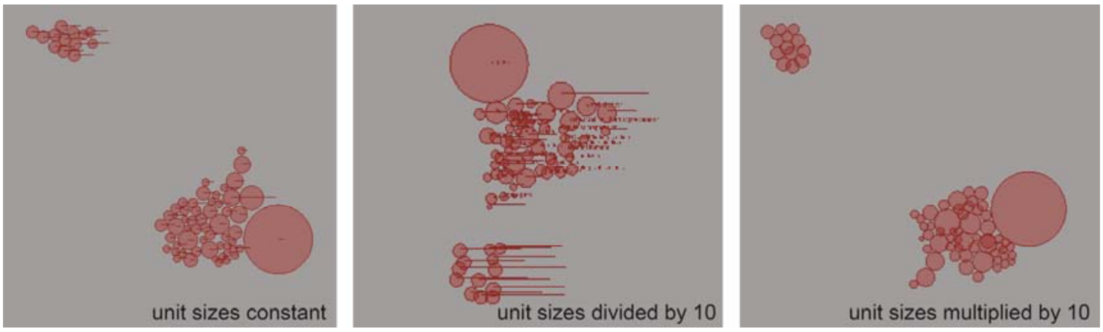


Figure 4.12. Scale changes affect the system equilibrium in AFM. System is stable, non-stable and stable from left to right. Drawn by the author .

Secondly it was seen that only one space layout can be obtained by given adjacency relation inputs with the same order of design units in the Microsoft Office Excel® file and with the same adjustments in each trial. Space layout changes can be observed in Figure 4.13. with the change of the order of design units.

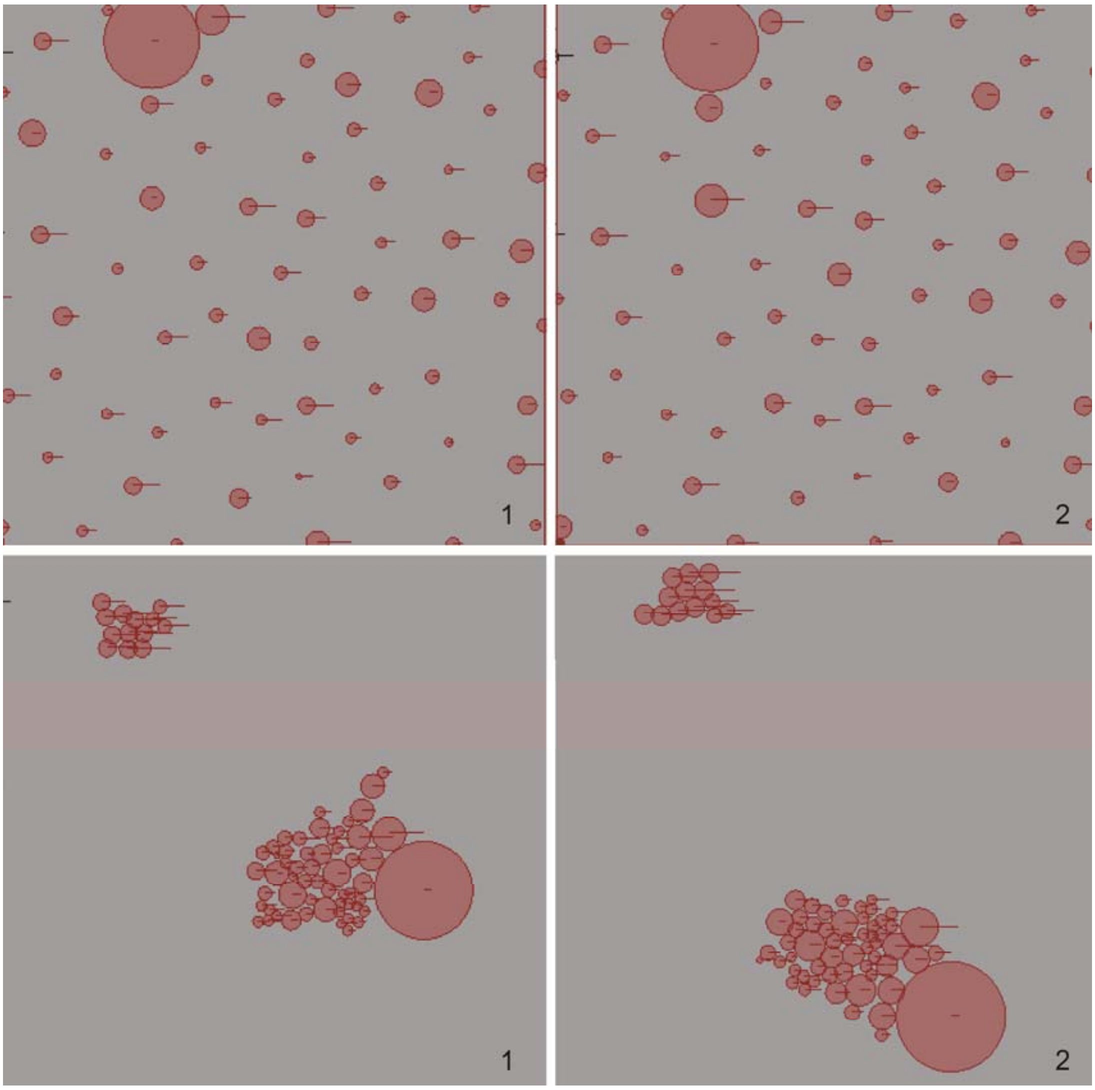


Figure 4.13. Different initial configurations and different optimizations by AFM. Drawn by the author.

Thirdly the effect of the sizes and numbers of design units on the optimization was researched. Same adjustments were used in optimizations with Carpark 2500m²(1), with Carpark 30m²(2) and without Carpark(3) as illustrated in Figure 4.14. and relation satisfactions of the space layouts were analyzed as illustrated in Figure 4.15.

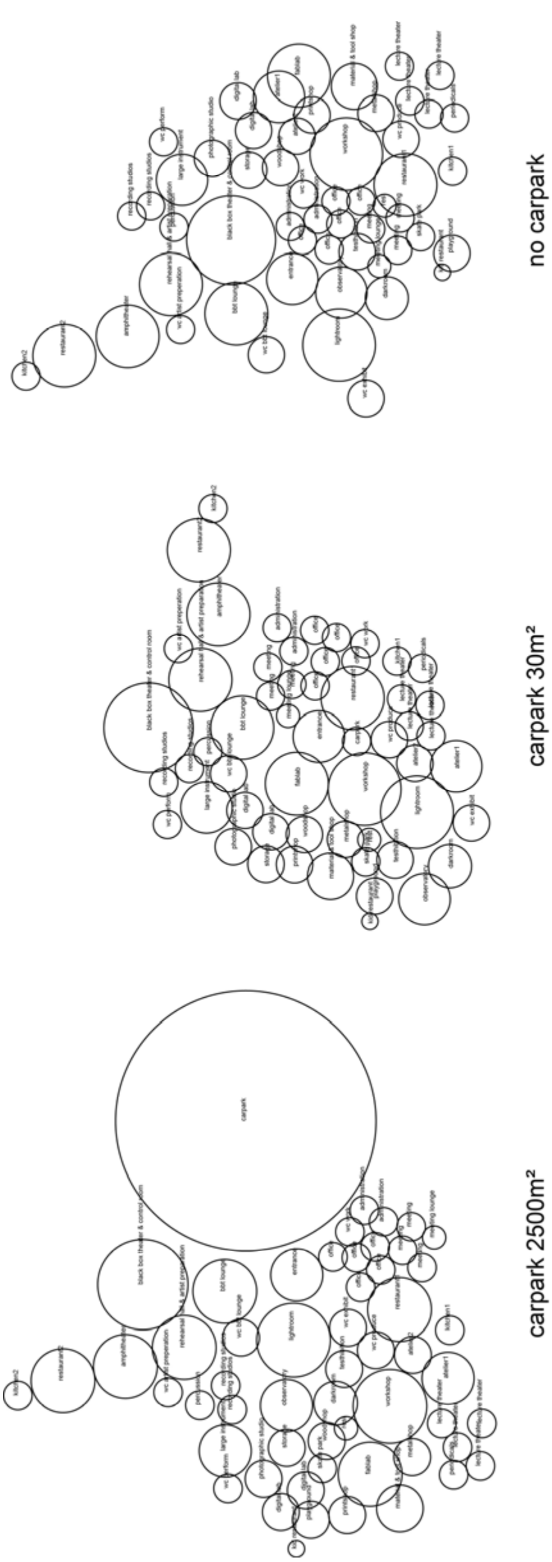


Figure 4.14. Space layouts with Carpark 2500m², with Carpark 30m² and without Carpark. Drawn by the author.

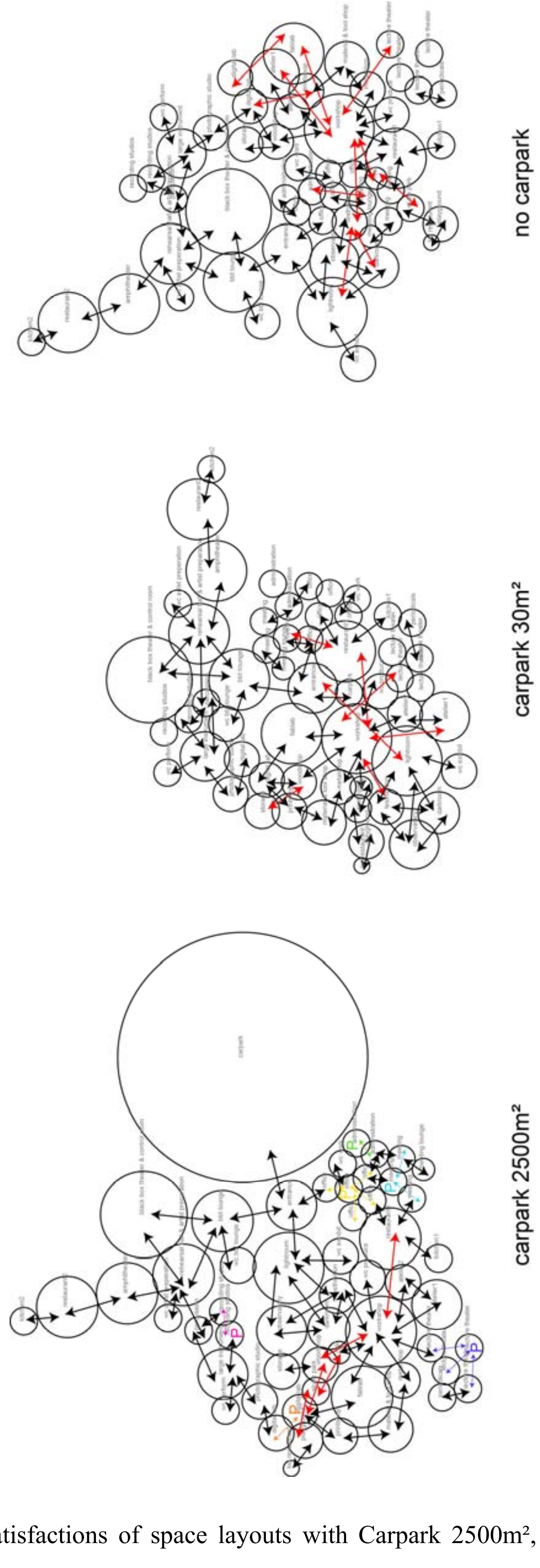


Figure 4.15. Relation satisfactions of space layouts with Carpark 2500m², with Carpark 30m² and without Carpark. Big black arrows indicate satisfied relations. Big red arrows indicate not satisfied relations. Drawn by the author.

The results showed that the configuration of the space layout and the number of satisfied relations in the space layout were affected by the changes in sizes and numbers of the design units with the same adjustments. Relation satisfactions showed that 5/58 relations were not satisfied in the 1st layout, 7/58 relations were not satisfied in the 2nd layout, 12/57 relations were not satisfied in the 3rd layout.

Another analysis about the previous optimization was done if the non satisfied relations contain common design units or not. Workshop was analyzed at this point because it was common in 11 relations out of 58 relations. The analysis shows that Workshop exists in 2 not satisfied relations out of 5 in the 1st layout, 4 not satisfied relations out of 7 in the 2nd layout, 6 not satisfied relations out of 12 in the 3rd layout. This shows that if a design unit is common in multiple adjacency relation inputs; then around half of non-satisfied relations most likely to contain that design unit. This result also proves the effect of intersecting forces on the optimizations once again.

4.3. Space Layout

The optimized space layout under designer's control is shown in Figure 4.16. It was seen that there is no change in the circular geometries of the design units. Figure 4.17. shows relation satisfactions after the optimizations.

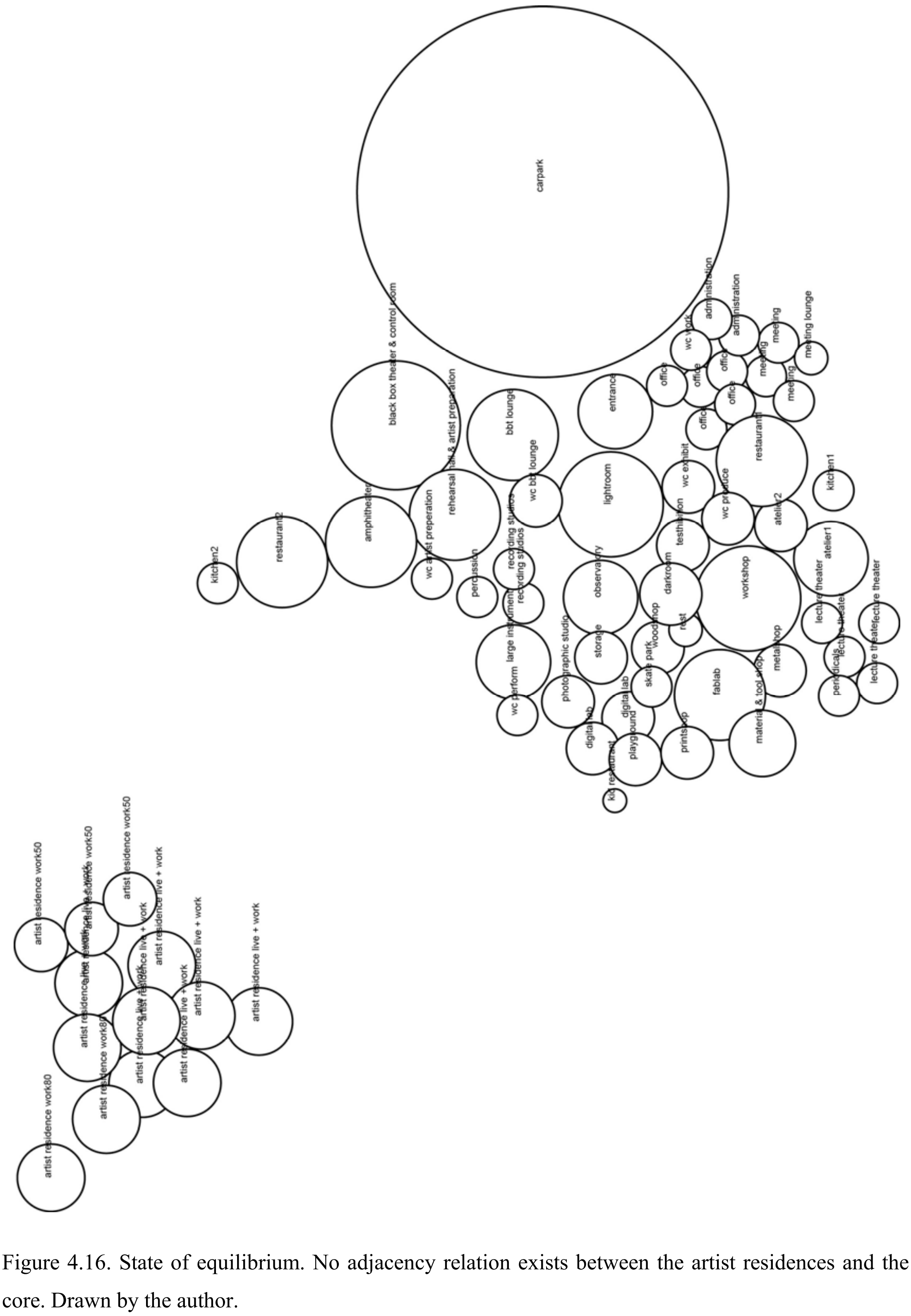


Figure 4.16. State of equilibrium. No adjacency relation exists between the artist residences and the core. Drawn by the author.

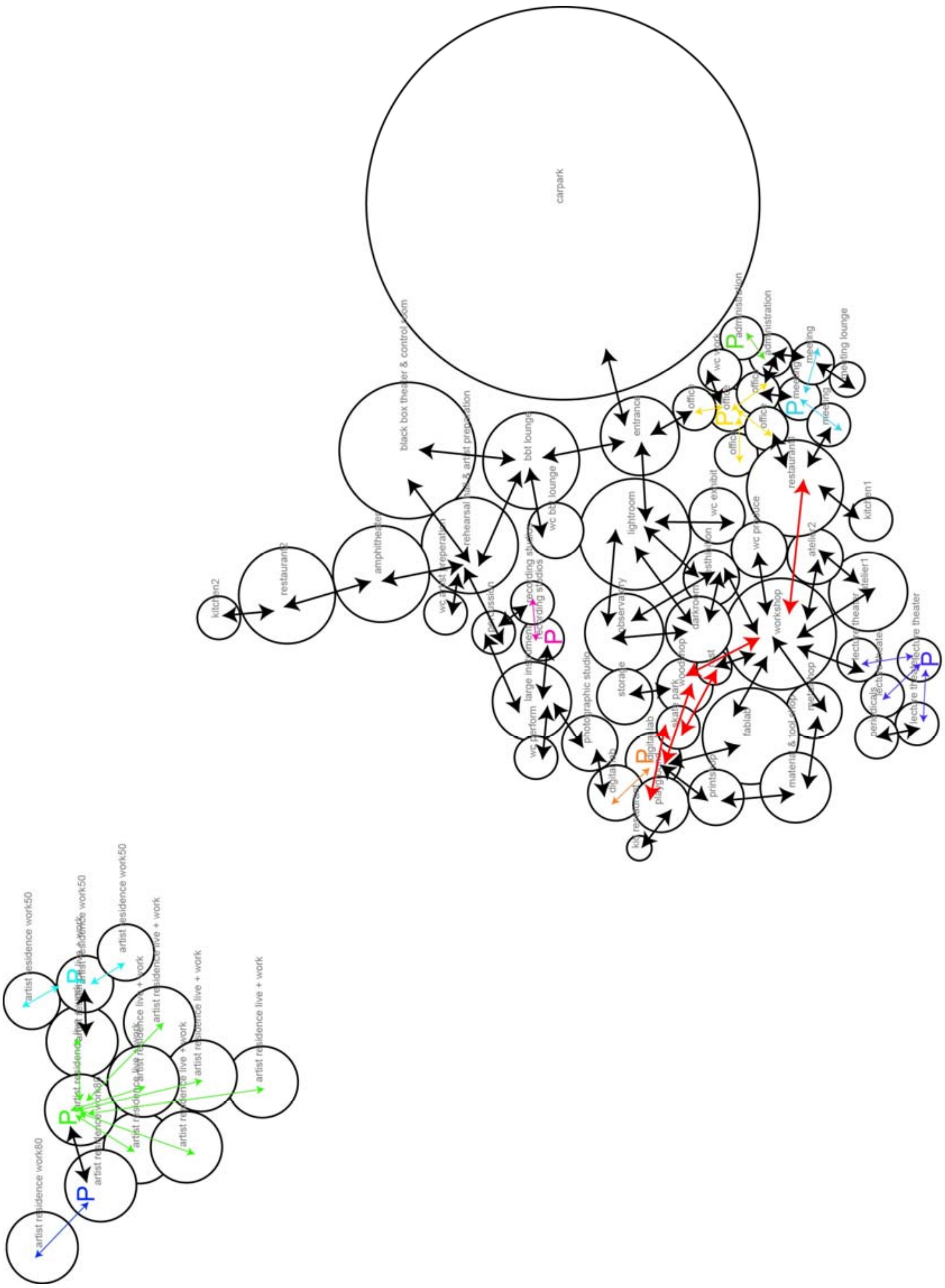


Figure 4.17. Relation satisfactions. P indicates the parent design unit. The little colorful arrows show the attraction of identical design units to the parent design unit. Big black arrows indicate satisfied relations. Big red arrows indicate not satisfied relations. Drawn by the author.

According to the space layout, 5 relations were not satisfied out of 58 relations. This shows that the model successfully applied the majority of adjacency relations on the design units. Even if the majority of the adjacency relations were satisfied, it is not known if the result is an optimum result or not because the model can only produce one space layout per notepad relation file.

4.4. Evaluation of AFM

Input preparation is not problematic in AFM because the designer only defines the relations between the desired design units without any quantity.

AFM is a user friendly and easily modifiable model for the designers who have knowledge of Kangaroo Physics add-on of Grasshopper® Plug-in and is helpful in dealing with the complexity of a large-scale space layout problem according the adjacency relations. However in order to obtain a satisfactory space layout, designer should do multiple trials, constantly check the results and do the necessary adjustments when necessary. It was also proven that the model is sensitive to design unit scales, initial configurations, sizes and number of design units and intersecting forces.

All features of the optimized space layout are analyzed extensively in Table 4.4. First of all the architectural qualities of the space layout are weak and doesn’t inform the designer except the adjacency relations. The design units were represented with the circular geometries to make them slide over each other easily, however it is not known if the boundary shapes are represented with these geometries or not in reality. The construction axes are not defined. Orientations of the design units are vague. The space layout is abstract and hangs on space, without any site reference and contextual information. Space layout boundary doesn’t exist.

Table 4.4. Analysis of space layout using AFM. Drawn by the author.

+ - ?	AFM	Intuitive Approach	QAP
adjacency relation	+		
design unit boundary relation	?		
design unit boundary shape	?		
design unit size	+		
circulation	?		
construction axes	-		
elevation	-		
lighting	-		
material	-		
orientation	-		
site reference	-		
space layout boundary	-		
zoning	-		

The optimized space layout was restrictive in the design process. The process of finding a satisfying layout consumed time with adjustments and multiple trials and forced the designer to proceed with certain acceptances about the space layout seen after each trial. When a satisfactory layout is obtained at the end, a belief would appear like the most efficient solution is found. In this regard, the optimized space layout of AFM was used for the rest of the design process and became the initial representation of the final architectural layout after detailed intuitive analyses which will be explained in the next chapter.

Lastly the transfer of the output is not problematic in AFM because of Rhinoceros®[13] export options to various drafting programs.

[13] Copyright© 1993-2013 Robert McNeel & Associates

CHAPTER 5

INTUITIVE APPROACH

This chapter explains the required input for intuitive approach, satisficing process, resulting space layout and evaluation of the designer on the process and the space layout.

5.1. Input Preparation

The necessary input for the intuitive approach was both prepared intuitively and by web research. The input like which design units are public or private, which design unit belongs to which zone, which design units should be secluded; height, sound isolation, light / dark design units was prepared intuitively during the preparation of the design program in the beginning of the design process. The input on the site and environmental conditions, like site elevations, sun path, wind directions, were investigated during the design process and obtained through a web-based research.

5.2. Satisficing Process

The space layout by AFM contains no information about the relations between public and private design units. The designer wanted to analyze how the public and private design units interact and decide on the possible zoning. The inputs on which design units are public or private were applied on the space layout and the relations between these design units were observed as in Figure 5.18. This analysis revealed the public flow and secluded private regions.

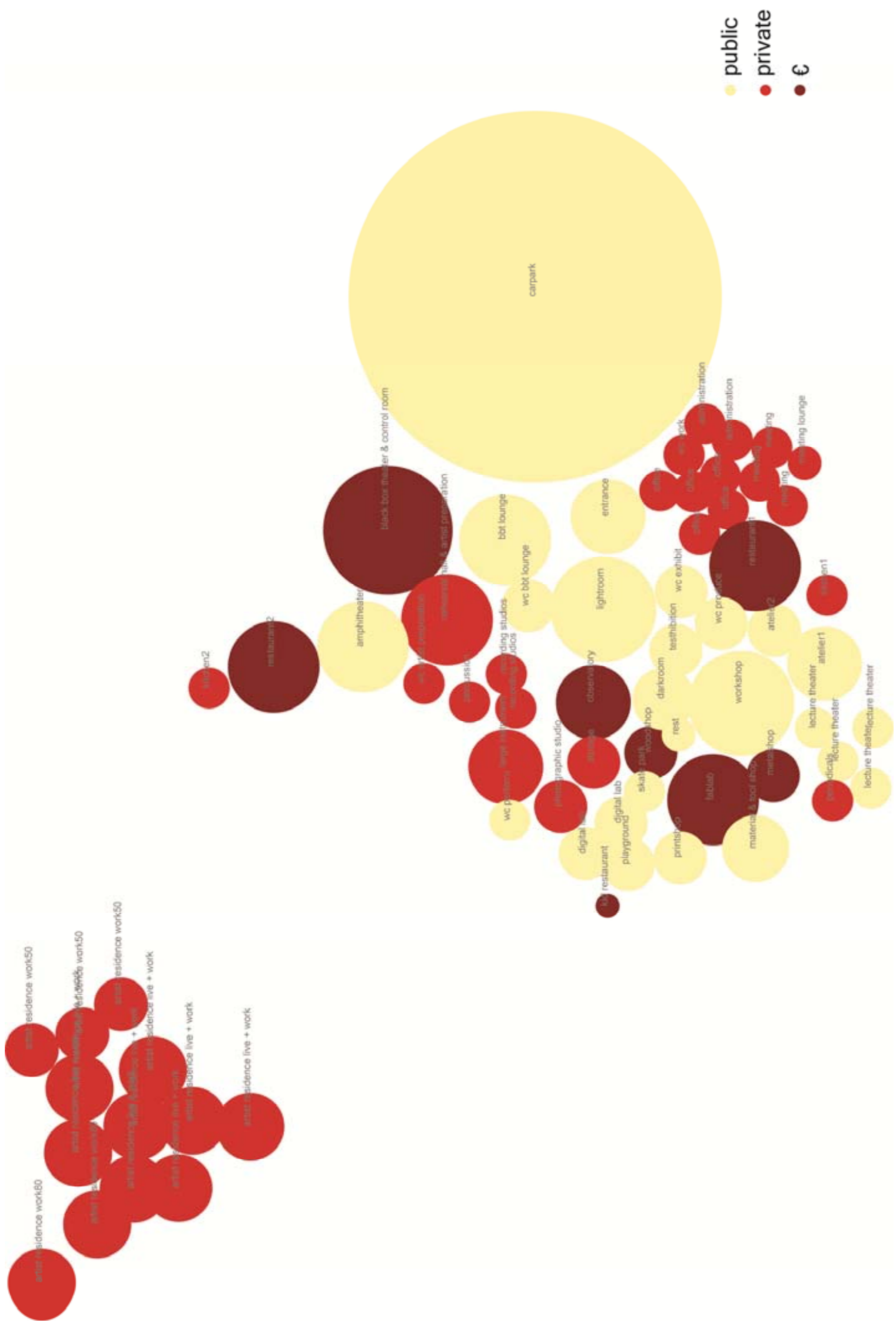


Figure 5.18. Public private analysis. Drawn by the author.

The design units were also related functionally, so grouped according to their functional purposes, such as exhibition, performance, production, and work as shown in Figure 5.19. To enhance interaction of the local community with the creative class as mentioned in Chapter 3, a compact form was planned for the village. So without changing the adjacency relations between the design units, the coordinates modified. This phase revealed main flow axes in the village.

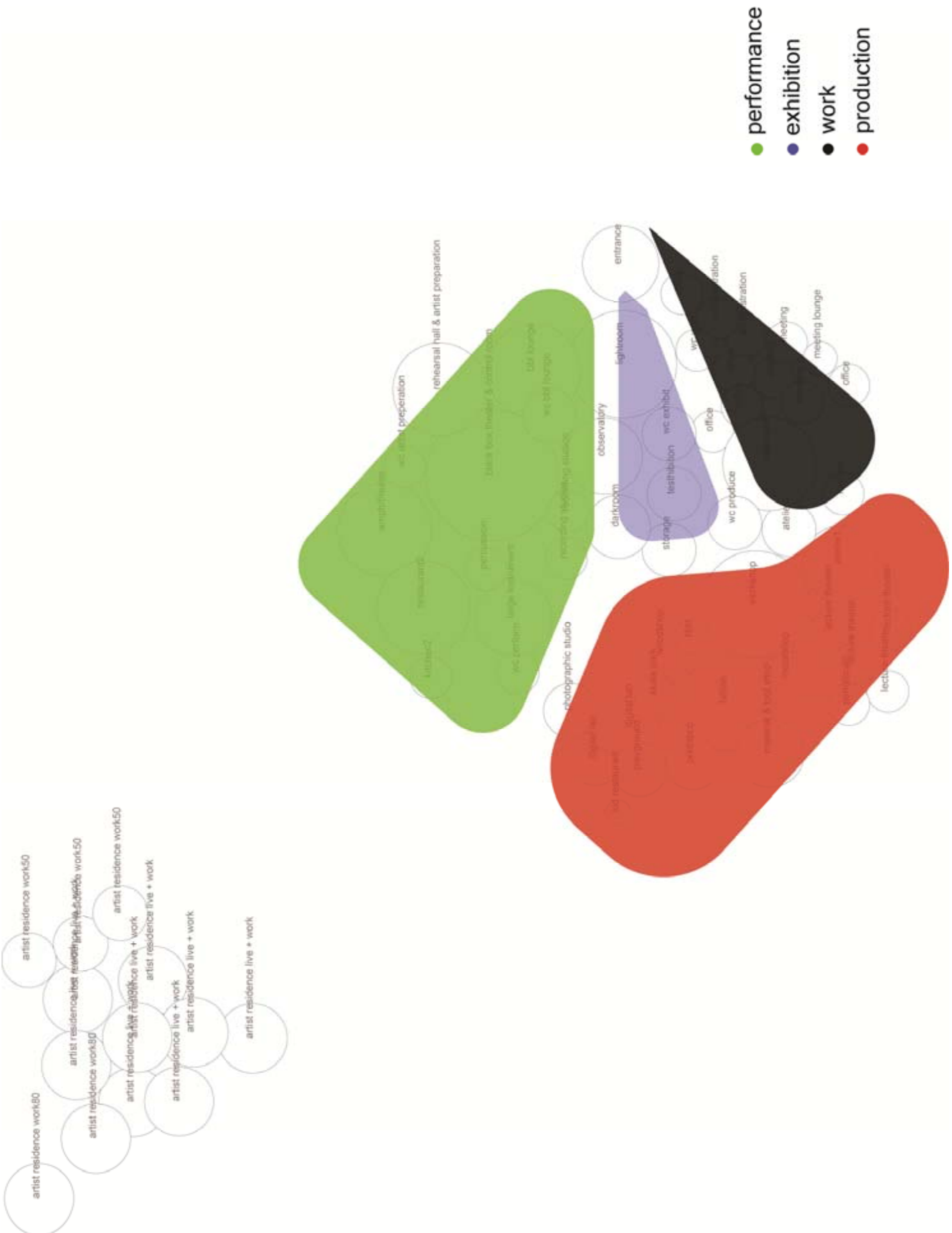


Figure 5.19. Grouping analysis. Drawn by the author.

The artist residences were designed as private and secluded design units, so they were carried away from the core as shown in Figure 5.20.

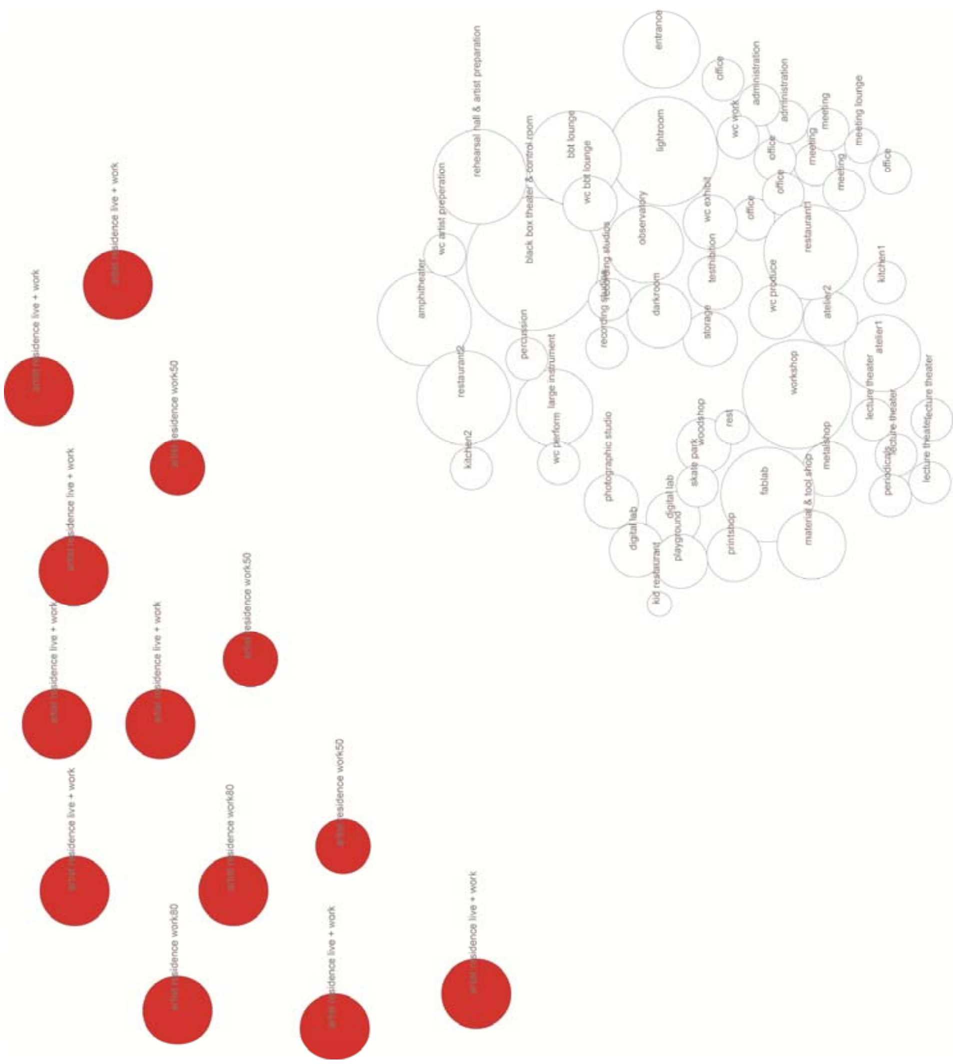


Figure 5. 20. Secluded artist residences. Drawn by the author.

After the interior concerns, environmental concerns were analyzed and main construction axes were defined coherently with the topographical lines and the design units were allocated in this modular layout, mostly in square, but also in rectangular shapes. Streets were drawn in between the design units for the circulation.

Analysis of the spatial qualities of the design units was continued in 3D modeling program Rhinoceros®. Floor and roof elements were analyzed. A critical decision was given in this phase of the design process regarding the ceiling of the village. The light design units were connected with a BIPV[14] roof, which shelters the interior

[14] Building-Integrated Photovoltaics

from various weather conditions and generates energy; and dark design units were embedded under sand as an extension of the dune landscape. The BIPV roof was a monolith roof with an elevation of +20.7 where the sand covered ceilings had flexible elevations as illustrated in Figure 5.21.

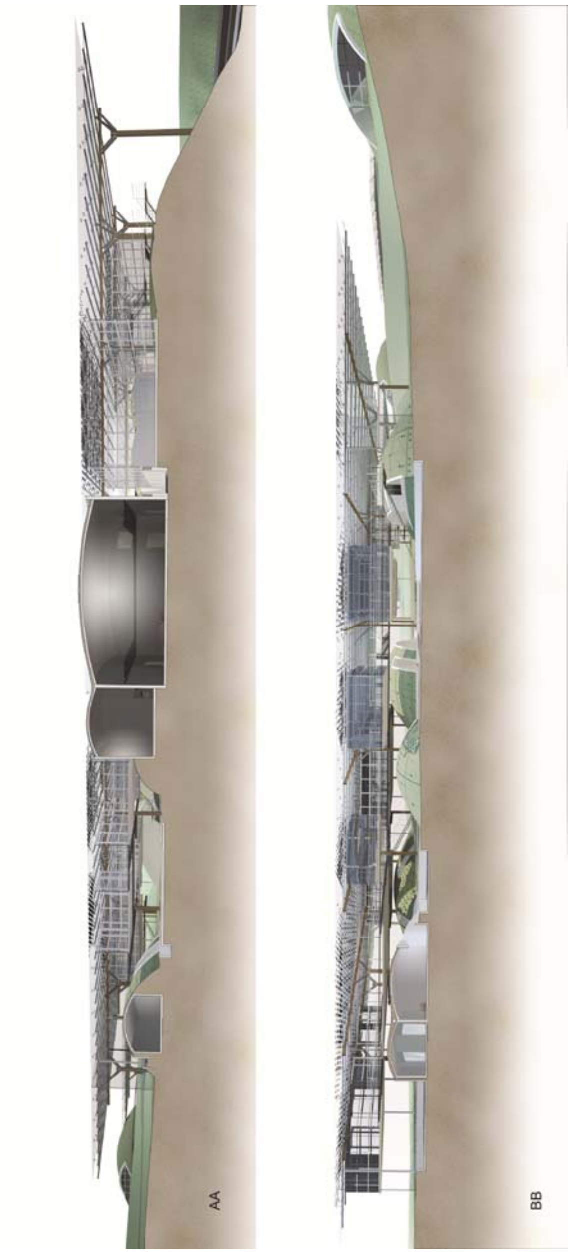


Figure 5.21. Sections AA and BB. Light design units with BIPV roof on have a fixed ceiling elevation and dark design units with sand roofs on have varying ceiling elevations. Drawn by the author.

5.3. Space Layout

P5 layout of The Creative Village carries features of an architectural layout like, design unit boundary shapes, structural grid, circulation axes, vertical connections and courts.

Dark design units are under the sand and covered with walls; shown in +14.50 elevation architectural layout in Figure 5.22. The light design units are connected with the BIPV roof on the ceiling level, but with different floor elevations, can be followed in +18.50 elevation architectural layout in Figure 5.23. The +22.50 elevation architectural layout shows the BIPV roof layout in Figure 5.24. The artist residences are either under the BIPV roof or sand[15] as shown in Figure 5.25.

[15] Both BIPV and the sand roof show the diversity and flexibility in the system and the possibility that it can transform or expand on the area.

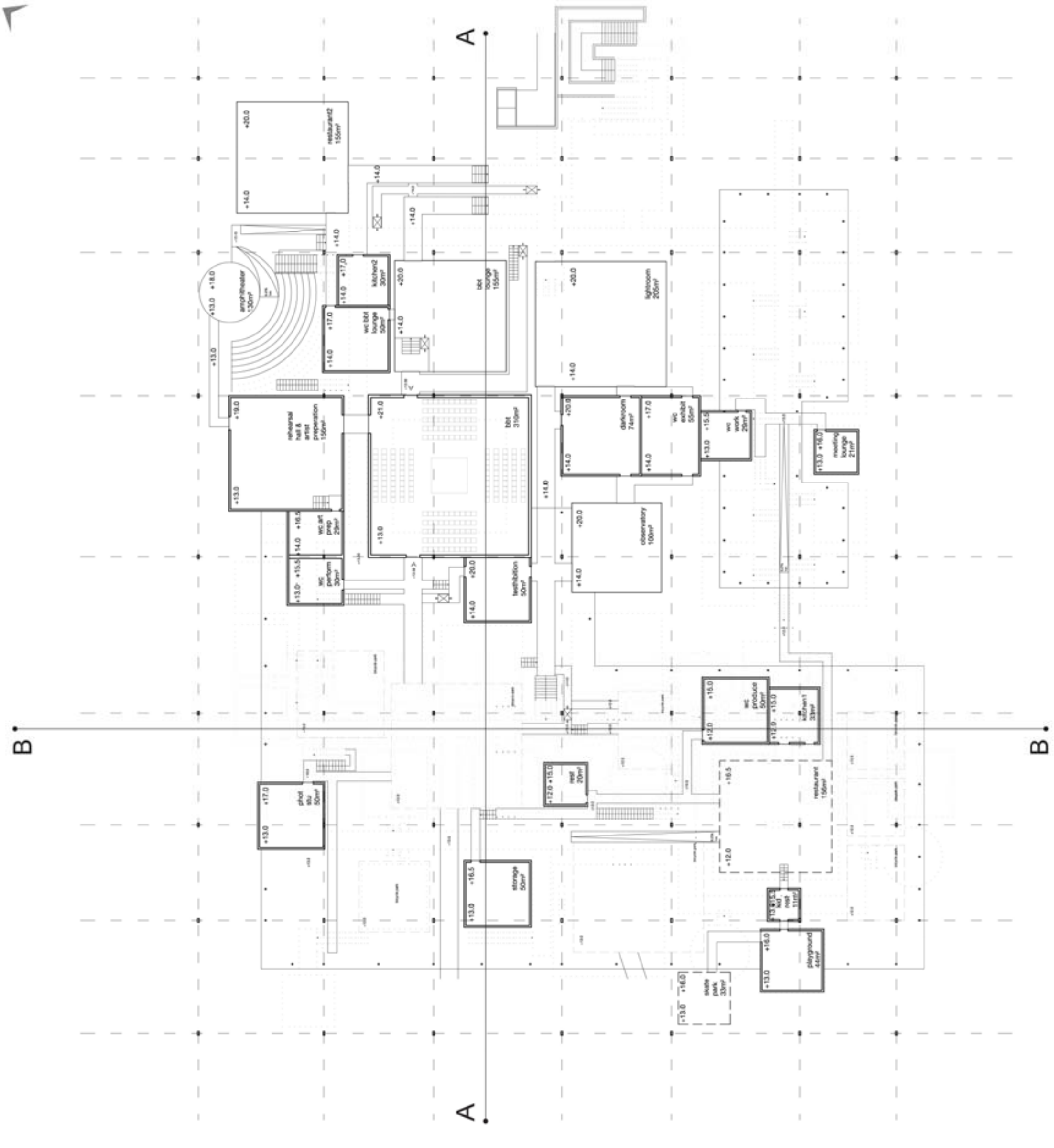


Figure 5.22. +14.50 elevation architectural layout. Drawn by the author.

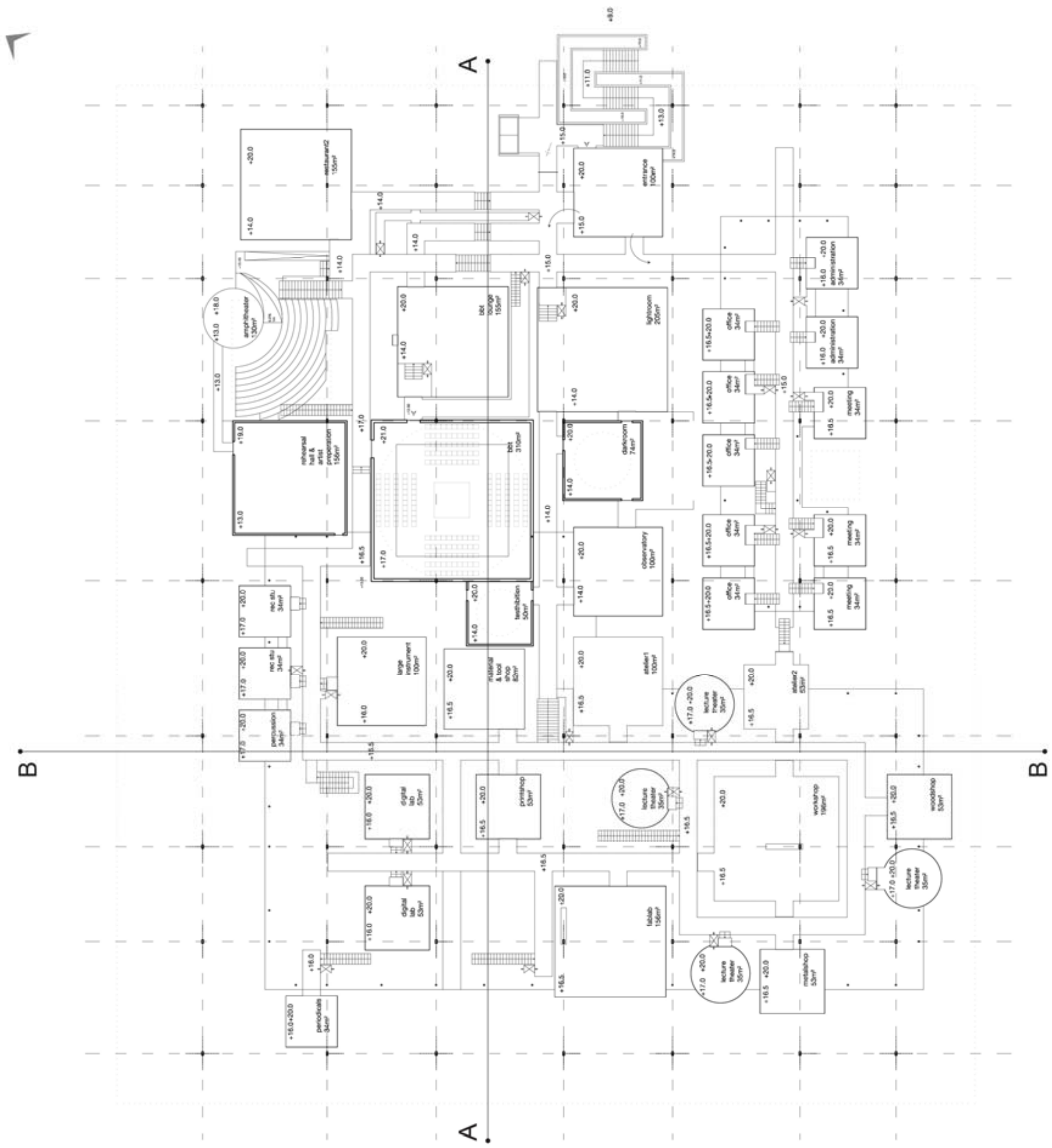


Figure 5.23. +18.50 elevation architectural layout. Drawn by the author.

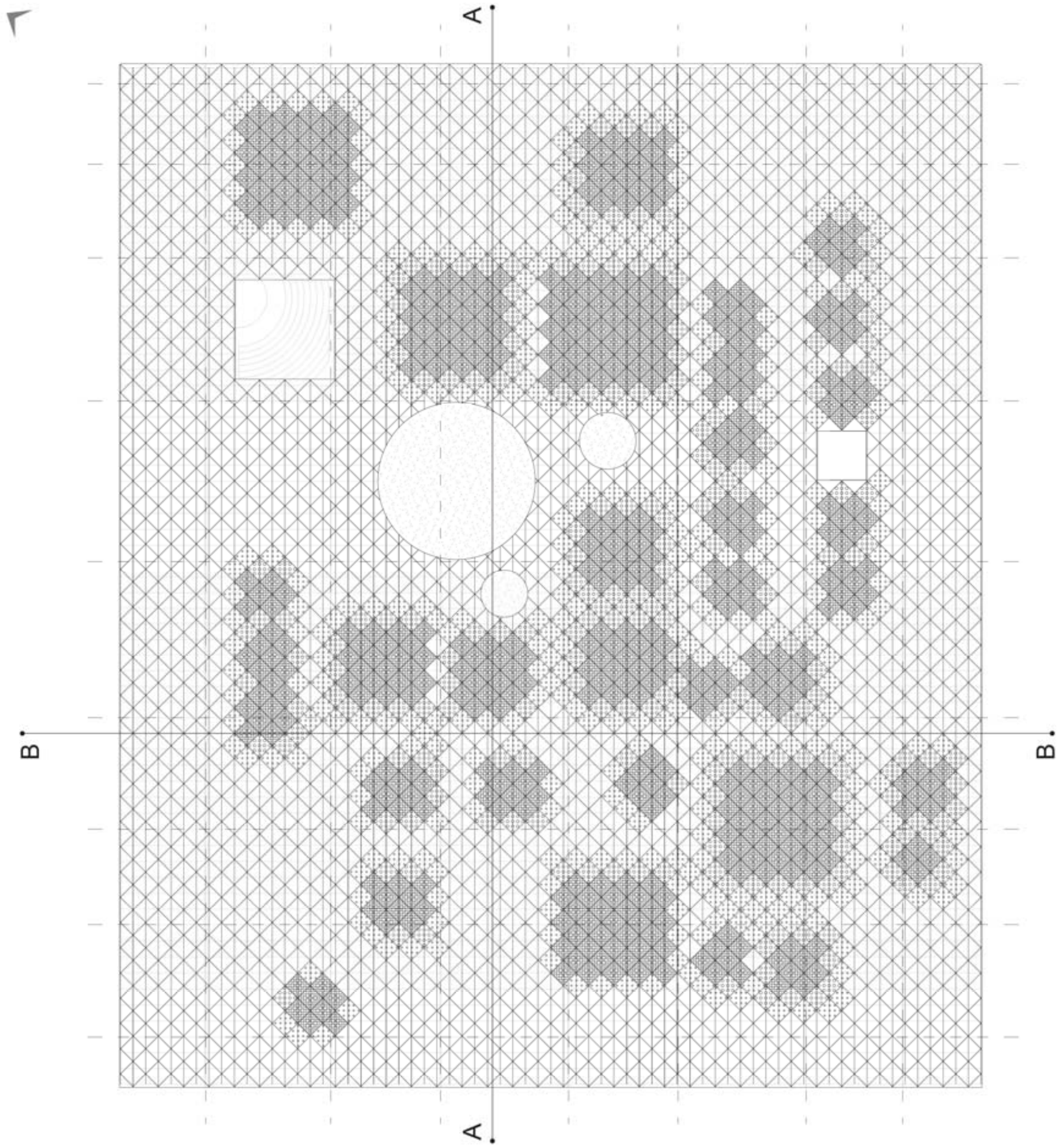


Figure 5.24. +22.50 elevation architectural layout. Drawn by the author.

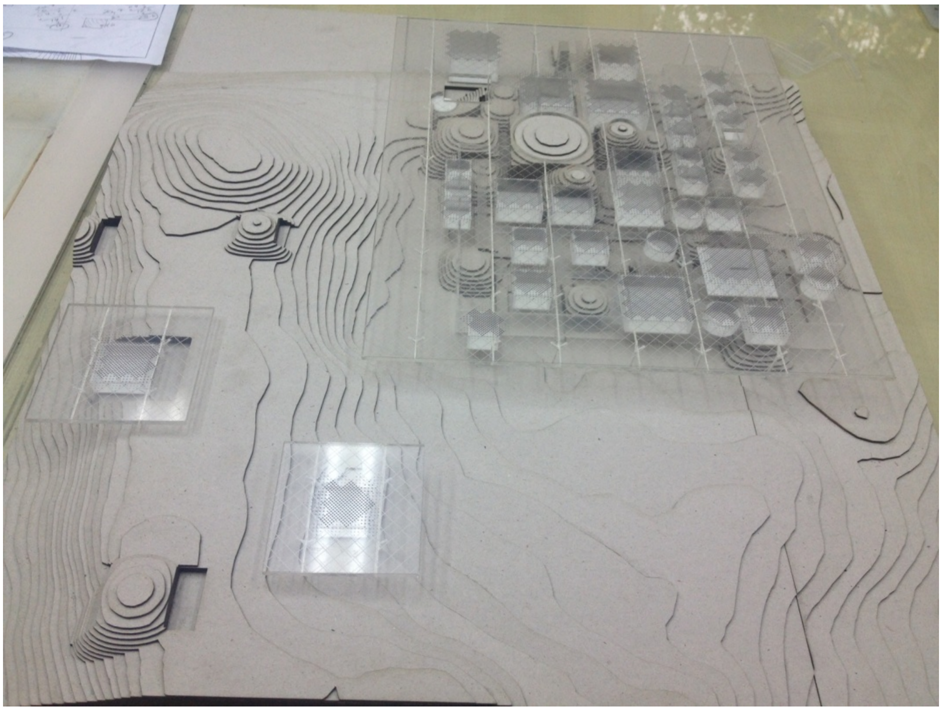


Figure 5.25. Physical model. Four artist residences and the core are shown. Artist residences are covered with either sand or BIPV roof.

5.4. Evaluation of Intuitive Approach

The necessary inputs for the intuitive approach were not rule-based as in for computerized space layout approaches, and were various for different analyses. A drafting program was used in general during the analyses.

The designer was not in the search for the best result, but to satisfy the criteria and move on gradually to reach to a reasonable space layout. So each analysis was complete as soon as the designer was confident with the result, without going into detailed evaluation. Production of an alternative space layout depends on the performance of the designer.

The space layout by the intuitive approach contains various information on; design unit boundary relations and shapes, circulations, construction axes, elevations, site references and zoning and so forth, only material information were not represented clearly as shown in Table 5.5.

Table 5.5. Analysis of space layout using AFM and Intuitive Approach. Drawn by the author.

+ - ?	AFM	Intuitive Approach	QAP
adjacency relation	+	+	
design unit boundary relation	?	+	
design unit boundary shape	?	+	
design unit size	+	+	
circulation	?	+	
construction axes	-	+	
elevation	-	+	
lighting	-	+	
material	-	?	
orientation	-	+	
site reference	-	+	
space layout boundary	-	+	
zoning	-	+	

CHAPTER 6

QUADRATIC ASSIGNMENT PROBLEM

This chapter explains the required input for QAP, optimization process, resulting space layout and evaluation of the designer on the process and the space layout.

6.1. Input Preparation

Requirements for Facility Layout® are, list of design units, sizes of the design units, flow matrix of the design units, material handling cost matrix of the design units, and the size of the proposed space layout in length and width (Jensen, 2004(II)).

Facility Layout® allows 100 design units maximum, however computation time and performance changes as the number of design units increases towards the maximum. The number of design units used in the optimizations was decreased to 54, to compare only the core of the project. Related input for 54 design units of unequal sizes were taken from the previous processes.

Design unit areas were divided into 10 to decrease the computational effort and also be able to work with a feasible size. For instance, a design unit which has an area of $200m^2$ occupied 20 modules in the layout.

The relations between the design units are qualitative and cannot be directly measured (Kay, 2009). The easiest assignments were for the strongest and not desirable relationships, but hardest in intermediate inputs. 1431 flow inputs were given to the flow matrix for 54 design units (54*(54-1)/2= 1431) as shown in Table 6.6. Material handling cost matrix inputs were taken as 1 for each relation; to avoid additional complexity when multiplied with the flow matrix.

Interdepartmental flow is mostly used for materials, but in buildings of different functions, it can be used for other criteria like people flow, etc. (Buffa, Armour, Vollmann, 1964). As in the previous processes, different reasonings like being in the same zone, functionally complementary, people and material flow and so forth were expressed in the same way. If the relation was strong, then the highest flow input was given.

(see also: APPENDIX D. INTUITIVE REASONING OF 1431 FLOW INPUTS OF QAP)

For the assignment of flow matrix inputs between the design units, sensitivity analyses were done using different flow input sets. After the analysis, selected input values were assigned between the design units.

The design units occupy 354 modules in total, but this number has increased to 384 modules with the selection of 'full width' option, which adds modules to design units to obtain a full rectangular shape. Size of the space layout was selected as 420 modules (20(length)* 21 (width)). The size is larger than the calculated modules to provide enough space for switching.

A random space layout of Facility Layout® initially consists of sequentially allocated design units in modular geometries with numbers representing the names written on and with a cost as shown in Figure 6.26. The designer can also initiate the optimization with an initial space layout configuration.

Table 6.6. Flow matrix for 54 design units using flow inputs, 1000, 100, 10, 1, 0.

Drawn by the author using Facility Layout®.

Flow Matrix

TO

FROM	D 1	D 2	D 3	D 4	D 5	D 6	D 7	D 8	D 9	D 10	D 11	D 12	D 13	D 14	D 15	D 16	D 17	D 18	D 19	D 20	D 21	D 22	D 23	D 24	D 25	D 26	D 27	D 28	D 29	D 30	D 31	D 32	D 33	D 34	D 35	D 36	D 37	D 38	D 39	D 40	D 41	D 42	D 43	D 44	D 45	D 46	D 47	D 48	D 49	D 50	D 51	D 52	D 53	D 54
D 1		1000	1000	1000	10	10	10	10	10	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	1000	0	0	0	0	0	0	0	0	0	0
D 2			1000	1000	10	10	10	10	10	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	1000	0	0	0	0	0	0	0	0	0	0
D 3				1000	10	10	10	10	10	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	1000	0	0	0	0	0	0	0	0	0	0
D 4					10	10	10	10	10	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	1000	0	0	0	0	0	0	0	0	0	0
D 5						1000	1000	1000	100	100	10	10	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	10	0	0	0	0	0	0	10	10	0	0	10	0	0	1000	0	0	0	0	100	100	100	0	0
D 6							1000	1000	100	100	10	10	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	10	0	0	0	0	0	0	10	10	0	0	10	0	0	1000	0	0	0	0	100	100	100	0	0
D 7								1000	100	100	10	10	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	10	0	0	0	0	0	0	10	10	0	0	10	0	0	1000	0	0	0	0	100	100	100	0	0
D 8									100	100	10	10	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	10	0	0	0	0	0	0	10	10	0	0	10	0	0	1000	0	0	0	0	100	100	100	0	0
D 9										1000	10	10	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	10	0	0	0	0	0	0	10	10	0	0	10	0	0	1000	0	0	0	0	100	100	100	0	0
D 10											10	10	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	10	0	0	0	0	0	0	10	10	0	0	10	0	0	1000	0	0	0	0	100	100	100	0	0
D 11												1000	0	0	0	0	0	0	0	1000	0	0	100	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	100	100	100	0	0
D 12													0	0	0	0	0	0	0	1000	0	0	100	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	100	100	100	0	0
D 13														1000	1000	10	10	10	10	0	0	100	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D 14															1000	10	10	10	10	0	0	1000	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	1000	0	0	0	0	0	1000	0	0	0	0	0	0	0	0
D 15																10	10	10	10	10	0	1000	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	0
D 16																	1000	1000	1000	10	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0
D 17																		1000	1000	10	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0
D 18																			1000	10	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0
D 19																				10	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0
D 20																					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D 21																						0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	0	0	0	0	0	0
D 22																							0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D 23																								0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	1000	1000	0	0
D 24																									1000	1000	1000	1000	1000	0	10	0	0	0	0	1000	1000	0	0	10	0	0	0	0	0	0	0	0	1000	0	0	0	1000	1000
D 25																										10	10	10	10	0	10	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	1000	0	0	0	1000	1000
D 26																											1000	1000	1000	0	10	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	1000	0	0	0	1000	1000
D 27																												1000	1000	0	10	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	1000	0	0	0	1000	1000
D 28																													1000	0	10	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	1000	0	0	0	1000	1000
D 29																														0	10	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	1000	0	0	0	1000	1000
D 30																															0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	10	10	0	0
D 31																																1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	10
D 32																																	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D 33																																		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D 34																																			1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D 35																																				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D 36																																					1000	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	1000	1000
D 37																																						0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	1000	1000
D 38																																							1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D 39																																								0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D 40																																									0	0	0	0	0	0	0	0	0	0	0	0	10	10
D 41																																										0	1000	0	0	0	0	0	0	0	0	0	0	0
D 42																																											0	0	0	0	0	0	0	0	0	0	0	0
D 43																																												0	0	0	0	0	0	0	0	0	0	0
D 44																																													0	0	0	0	0	0	0	0	0	0
D 45																																														0	0	0	0	0	0	0	0	0
D 46																																															0	0	0	0	0	0	0	0
D 47																																																0	0	0	0	0	0	0
D 48																																																	0	0	0	0	0	0
D 49																																																		0	0	0	1000	1000
D 50																																																			1000	1000	0	0
D 51																																																				1000	0	0
D 52																																																					0	0
D 53																																																						1000
D 54																																																						

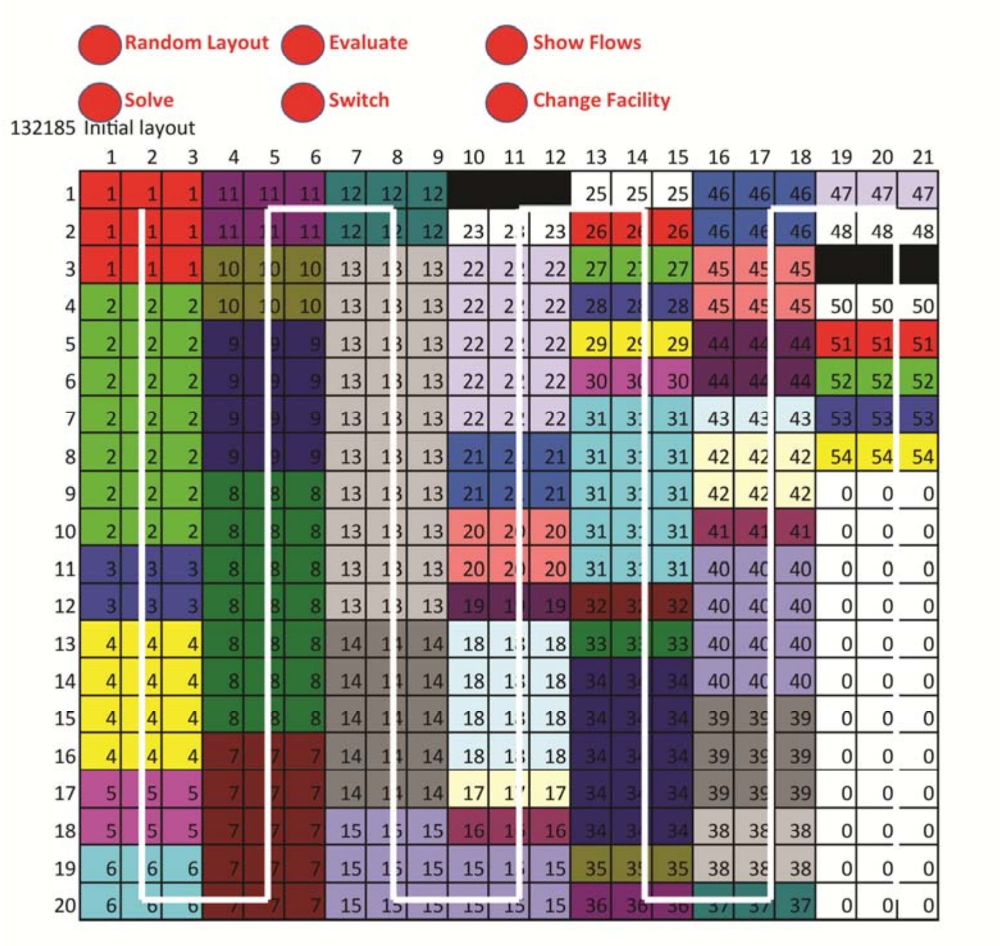


Figure 6.26. Layout C with a total cost of 132185. Sequentially allocated design units of unequal sizes in modular geometries with numbers written on in Facility Layout®. Drawn by the author.

Facility Layout® uses two procedures for cost minimization, which are the 'Traditional CRAFT' method and the 'Optimum Sequence' method (Jensen, 2004(I)). Even if the 'Optimum Sequence' produces better layouts and ends up with lower costs, 'Traditional CRAFT' was selected for all optimizations in this research. The reasons were firstly, 'Traditional CRAFT' allows the designer to start with an initial layout configuration, which is necessary for the methodology used in this research. Secondly, 'Optimum Sequence' would change the location of the fixed design units during the optimization, but the 'Traditional CRAFT' keeps them totally fixed.

Euclidian or rectilinear distances are used in QAP to calculate the distances between the centroids of the design units as explained before. Rectilinear measurement will be used in this research to have a realistic calculation of the circulations.

6.1.1. Sensitivity Analysis

3 layouts were optimized using different flow input sets as shown in Table 6.7. 6 different flow input sets and the total costs of the layouts are shown in Table 6.8.

Table 6.7. Layouts used in the sensitivity analysis. Drawn by the author.

3 LAYOUTS	3 OPTIMIZATIONS
A P5 LAYOUT	B P5 LAYOUT OPT
C RANDOM CRAFT LAYOUT	D RANDOM CRAFT LAYOUT OPT
A1 P5 LAYOUT IDENTICAL UNITS ADJACENT	A2 P5 LAYOUT IDENTICAL UNITS ADJ. OPT

Table 6.8. Results of the sensitivity analysis. Drawn by the author.

	A	B	C	D	A1	A2
1 5,4,3,2,1	26040	25362	28969	24883	25811	25283
2 50,20,10,5,0	50935	45555	84445	45218.95	48415	44459.66
3 100,20,5,1,0	73020	67054.28	132185	77541.01	67445	62880.32
4 100,40,20,10,0	101870	91110.01	168890	90437.91	96830	88919.33
5 1000,100,10,1,0	633830	577044.3	1184700	648054.4	576140	545240
6 5000,400,30,2,0	3100140	2696316	5812850	3113160	2810170	2714210

1 5,4,3,2,1	**D < A2 < B < A1 < A < C**
2 50,20,10,5,0	**A2 < D < B < A1 < A < C**
3 100,20,5,1,0	**A2 < B < A1 < A < D < C**
4 100,40,20,10,0	**A2 < D < B < A1 < A < C**
5 1000,100,10,1,0	**A2 < A1 < B < A < D < C**
6 5000,400,30,2,0	**B < A2 < A1 < A < D < C**

It was observed that Facility Layout® is sensitive to different flow inputs. Layout D has the lowest cost only by using set 1 and is just after Layout A2 by using set 2 and 4. However this layout has the highest cost after Layout C by using sets 3, 5 and 6. To get out of this conflict, relation satisfactions of Layout D by using set 1 were analyzed by adding the number of satisfied and partly satisfied relations.

Total Cost: D <A2 < B < A1 < A < C

Relation Satisfaction: A1 > A2 > B > A > D > C

The reliability of the layouts by using sets 1, 2 and 4 were decreased because Layout D has the lowest cost but also have lower relation satisfaction compared to other layouts.

Cost sequences were different by using sets 3, 5 and 6. However Layout C and D have the highest costs compared to designer's own configurations, Layout A, B, A1 and A2. As the difference between the quantities of the inputs increased, the cost sequence and the relation satisfactions were more convenient. Flow input sets 3 and

5 will be used in the further optimizations because Layout B is not expected to have a lower cost than the optimization of Layout A1.[16][17]

6.1.2. Fixed Cost Inputs

Fixed cost inputs are explained in a separate section because this input is not requested nor calculated by the program. But the designer manually calculated the results of the fixed cost analysis to analyze the relation of the design units with the site. Initially three zones were identified on project site as shown in Figure 6.27., related with main transportation axis and dune landscape.

[16] After the use of AFM in the design process, intuitive approaches were used to organize the space layout of the project. During the intuitive approach, identical units were placed separately to increase interaction in the core (Layout A). However identical design units were placed adjacently in Layout A1.

[17] Highest material flow cost was given between the identical design units.

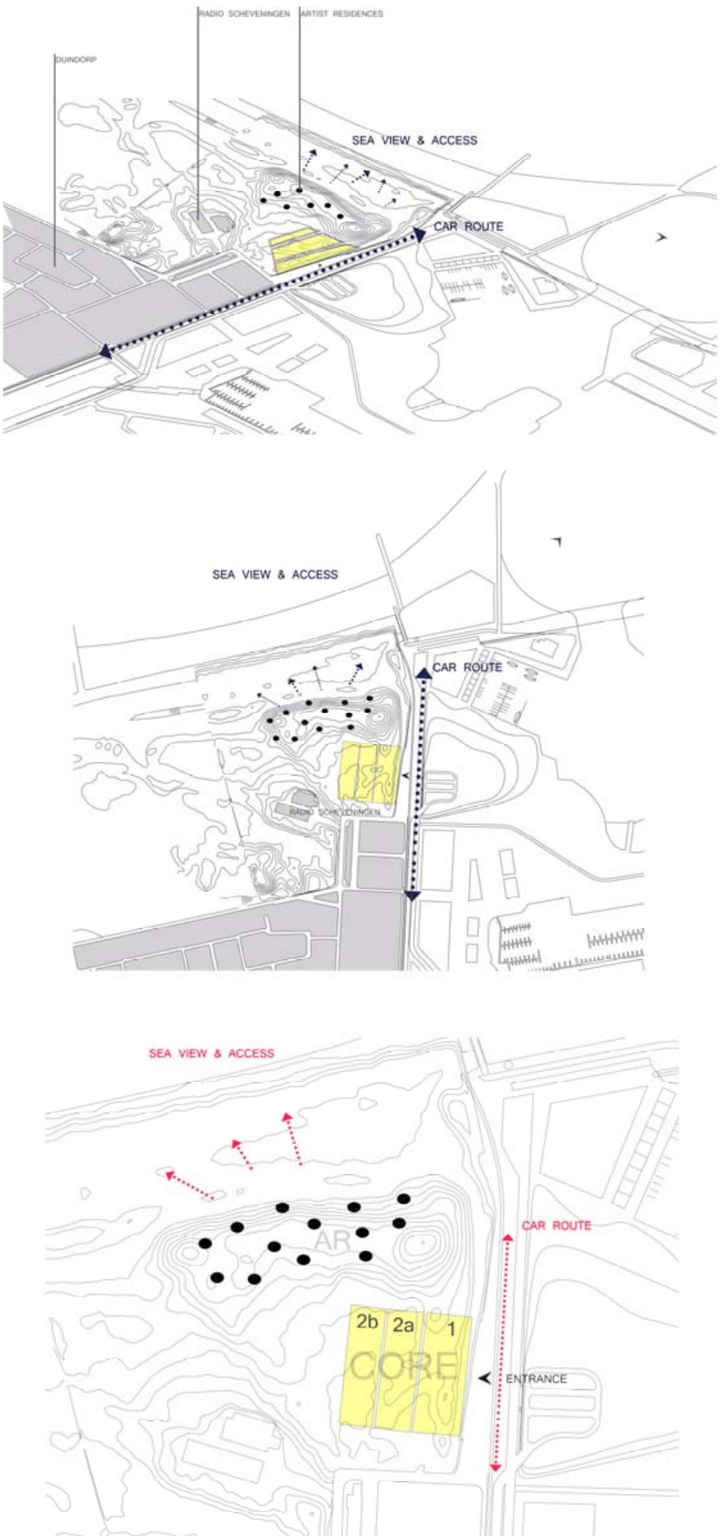


Figure 6.27. Project site. Drawn by the author.

Modular layout of the Facility Layout® program was translated into the project site as shown in Figure 6.28. A fixed cost was given for each design unit for each one of the three zones.

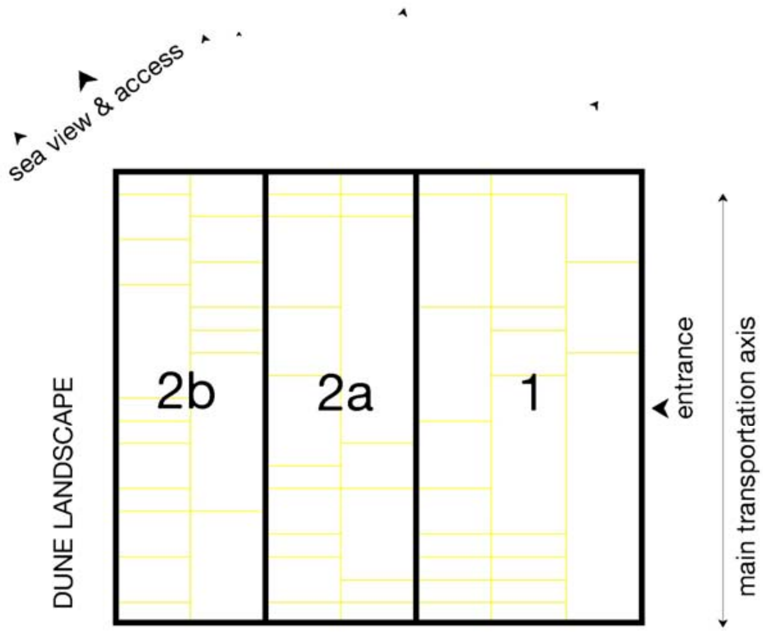


Figure 6.28. Modular layout of the Facility Layout® program. Drawn by the author.

Fixed cost inputs were given based on the same intuitive reasoning used during the design of the P5 Layout during the intuitive approach. Lower costs were given to the design units to be placed in a desired zone. 3 different fixed cost input sets, Q, P and R were prepared as in the sensitivity analysis.

Q 0, 5, 10, 20

P 1, 2, 3, 4

R 1, 10, 100, 1000

Some examples of the given fixed cost inputs and the reasoning behind them are shown below.

3 zones:	2b (dune)	2a (center)	1(entrance)
Lightroom:	20 or 4 or 1000	10 or 3 or 100	0 or 1 or 1

Lightroom was designed as the first design unit to be seen in the Exhibition Zone after passing from the Entrance.

Darkroom:	20 or 4 or 1000	0 or 1or 1	5 or 2 or 10

Darkroom is related with the Lightroom but Zone1 is not directly suitable for this design unit.

BBT and Control Room:	20 or 4 or 1000	10 or 3 or 100	0 or 1 or 1

Black Box Theater and Control Room is related with the Entrance, to be directly reachable from the Entrance.

Workshop:	0 or 1 or 1	0 or 1 or 1	20 or 4 or 1000

Workshop is a working area for both local community and creative class and is better to be placed away from the dense circulation of the village like Entrance, Exhibition halls, etc. so either 2a or 2b spots are suitable.

(see also: APPENDIX E. INTUITIVE REASONING OF FIXED COST INPUTS OF QAP)

6.2. Optimization Process

This section explains the optimization process of the space layouts by QAP, manual calculation of fixed costs and the comparison of the results. The layouts to be used, the methodology of the optimization process and the outcomes will be explained in the further sub-sections.

6.2.1. Layouts Used in the Optimizations

5 layouts were optimized using QAP as shown in Table 6.9.

Table 6.9. Layouts in the QAP optimizations. Drawn by the author.

5 LAYOUTS	5 OPTIMIZATIONS
C 0 FIXED (Random CRAFT Layout)	D 0 FIXED OPT (Random CRAFT Layout OPT)
4 FIXED	4 FIXED OPT
10 FIXED	10 FIXED OPT
A P5 LAYOUT	B P5 LAYOUT OPT
A1 P5 LAYOUT IDENTICAL UNITS ADJACENT	A2 P5 LAYOUT IDENTICAL UNITS ADJ. OPT

1-0 FIXED (C): Design units were allocated by Facility Layout® according to their sequence in the list {1, 2, 3, 4… 54}.

2-0 FIXED OPT (D): The optimization of Layout C.

3-4 FIXED: Same as the Layout C, but 4 design units were fixed on the desired sites as shown in Figure 6.29. The fixed design units were; Lightroom, Workshop, BBT Lounge and Entrance.

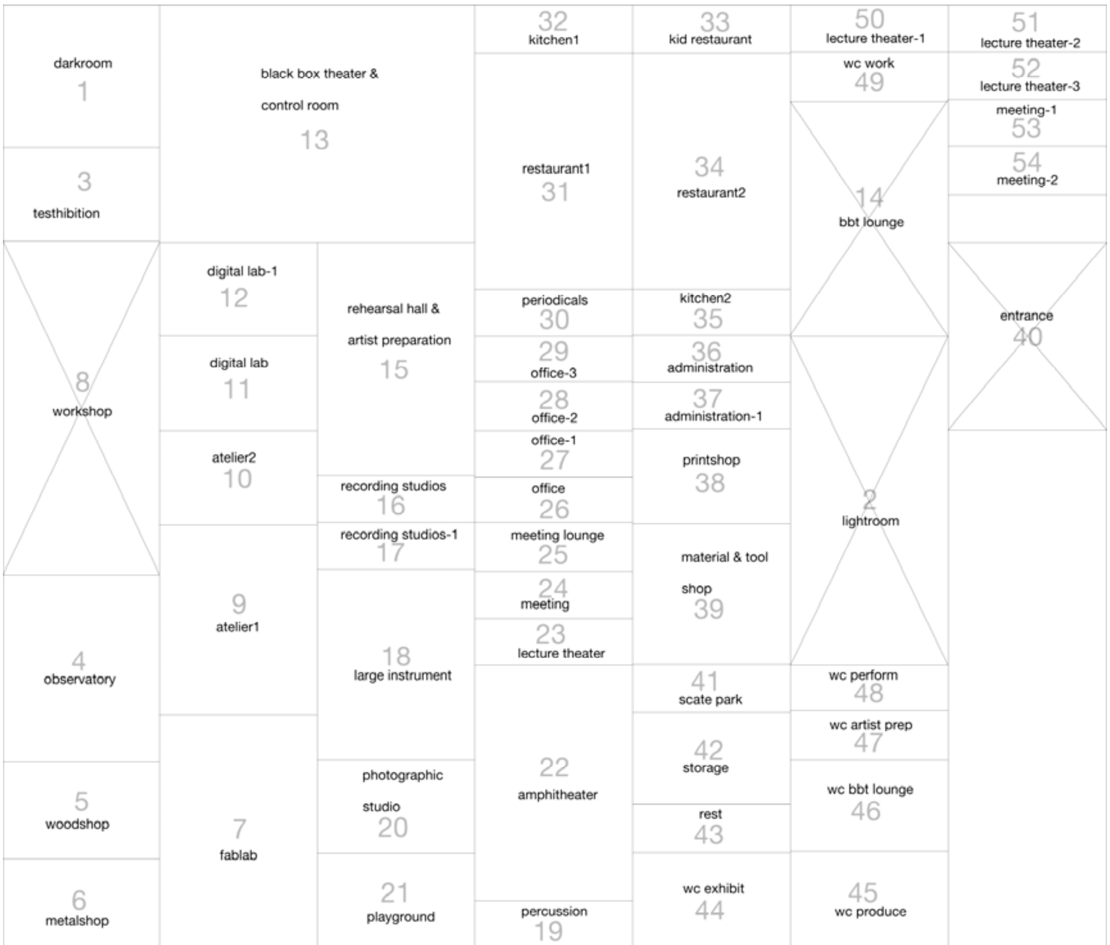


Figure 6.29. Layout with 4 fixed design units. Drawn by the author.

4-4 FIXED OPT: The optimization of Layout 4 FIXED.

5-10 FIXED: Same as the Layout C, but 10 design units were fixed on the desired sites as shown in Figure 6.30. The fixed design units were; Lightroom, Workshop, BBT Lounge, Entrance, Lecture Theater-2, Percussion, Wc Exhibit, Observatory, Meeting and Restaurant2.

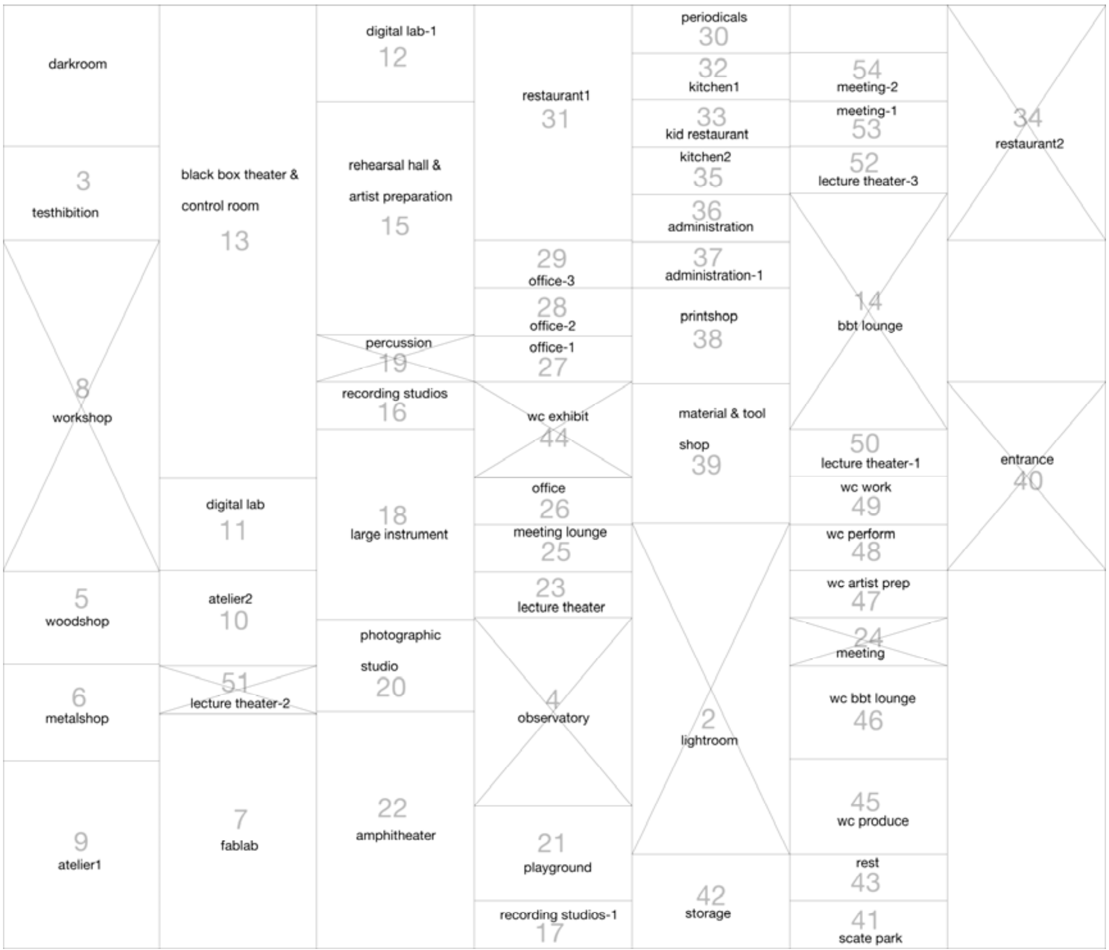


Figure 6.30. Layout with 10 fixed design units. Drawn by the author.

6-10 FIXED OPT: The optimization of Layout 10 FIXED.

7-P5 LAYOUT (A): The design units on P5 Layout were allocated onto modular layout of Facility Layout® as in Figure 6.31.

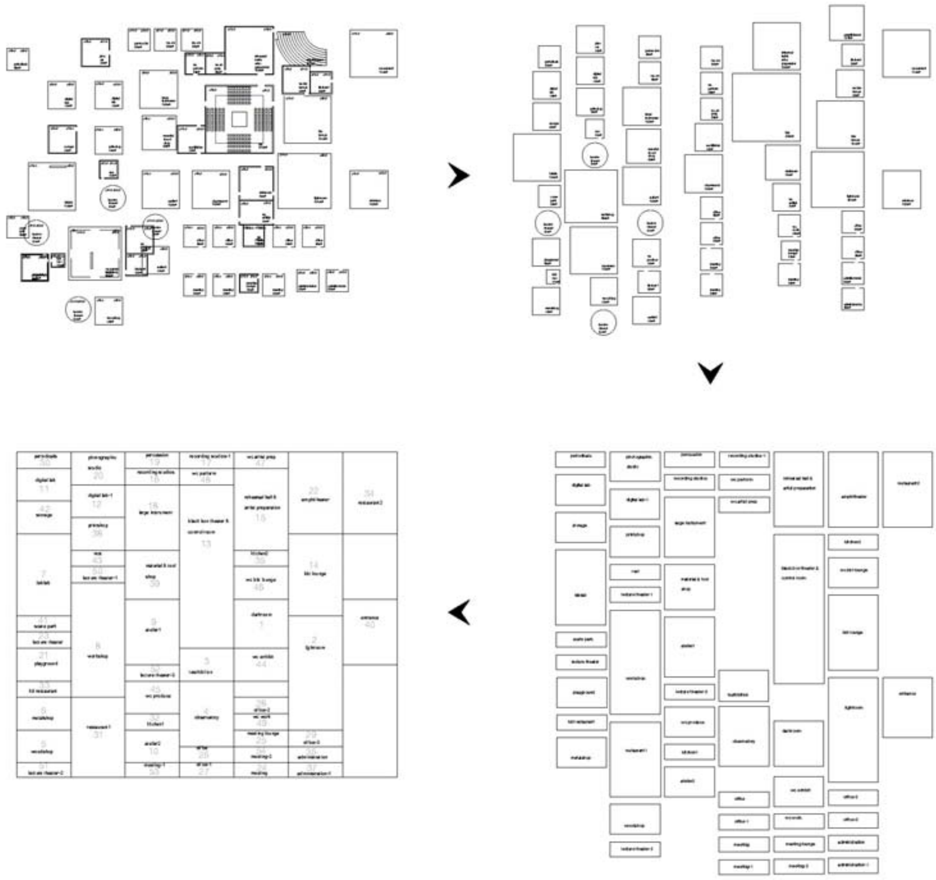


Figure 6.31. Translation of P5 Layout onto Facility Layout®. Drawn by the author.

8-P5 LAYOUT OPT (B): The optimization of Layout A.

9- P5 LAYOUT IDENTICAL UNITS ADJACENT (A1): Same as the Layout A, but identical units were placed adjacently.

10- P5 LAYOUT IDENTICAL UNITS ADJACENT OPT (A2): The optimization of Layout A1.

6.2.2. Methodology of the Optimizations

Optimization process of Layout C was presented as an example and was repeated for each layout. As seen on the left-up of the Figure 6.26. before, the total cost of Layout C is 132185. Total costs, fixed costs were noted down and the relation satisfactions were calculated for Layout C.

Layout C	100, 20, 5, 1, 0 (3)	1000, 100, 10, 1, 0 (5)
Total costs:	132185	1184700
Fixed costs:	405(Q), 117(P), 18441(R)	same
Relation Satisfactions :	25 Satisfied	same
	12 Partly satisfied	
	13 Unsatisfied	
	53 Not related at all	

For each layout to be optimized, the optimization was run only once. The program could optimize a layout in seconds like in AFM and the optimizations can be followed visually. Switching design pairs were randomly selected by Facility Layout® during the optimization process. Layout C was optimized according to flows inputs as shown in Figure 6.32. An optimization was done with total cost of 77541 as shown in Figure 6.33. using set 3 (100, 20, 5, 1, 0). The flows between the design units were in the optimized space layout shown in Figure 6.34. Lastly each layout was redrafted in AutoCAD® as shown in Figure 6.35.

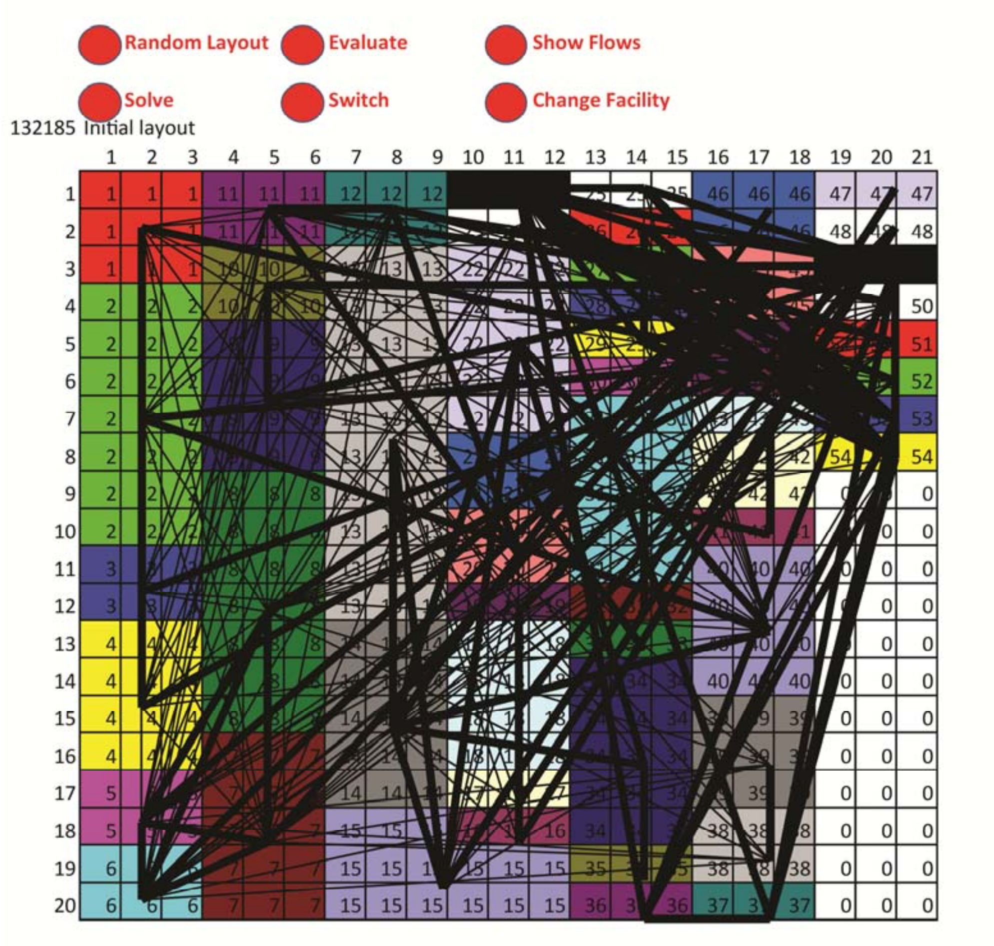
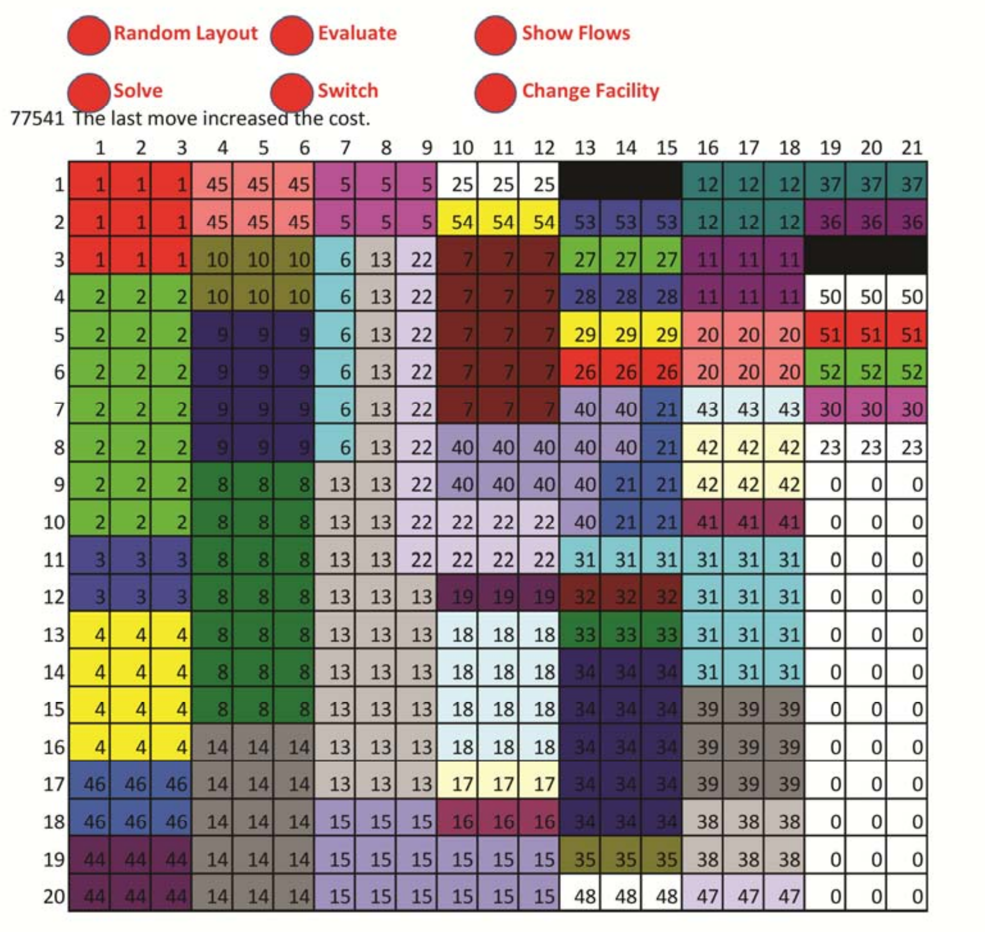


Figure 6.32. Different flow inputs were shown with different thicknesses on Layout C. Drawn by the author.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	1	1	45	45	45	5	5	5	25	25	25				12	12	12	37	37	37
2	1	1	1	45	45	45	5	5	5	54	54	54	53	53	53	12	12	12	36	36	36
3	1	1	1	10	10	10	6	13	22	7	7	7	27	27	27	11	11	11			
4	2	2	2	10	10	10	6	13	22	7	7	7	28	28	28	11	11	11	50	50	50
5	2	2	2	9	9	9	6	13	22	7	7	7	29	29	29	20	20	20	51	51	51
6	2	2	2	9	9	9	6	13	22	7	7	7	26	26	26	20	20	20	52	52	52
7	2	2	2	9	9	9	6	13	22	7	7	7	40	40	21	43	43	43	30	30	30
8	2	2	2	9	9	9	6	13	22	40	40	40	40	40	21	42	42	42	23	23	23
9	2	2	2	8	8	8	13	13	22	40	40	40	40	21	21	42	42	42	0	0	0
10	2	2	2	8	8	8	13	13	22	22	22	22	40	21	21	41	41	41	0	0	0
11	3	3	3	8	8	8	13	13	22	22	22	22	31	31	31	31	31	31	0	0	0
12	3	3	3	8	8	8	13	13	13	19	19	19	32	32	32	31	31	31	0	0	0
13	4	4	4	8	8	8	13	13	13	18	18	18	33	33	33	31	31	31	0	0	0
14	4	4	4	8	8	8	13	13	13	18	18	18	34	34	34	31	31	31	0	0	0
15	4	4	4	8	8	8	13	13	13	18	18	18	34	34	34	39	39	39	0	0	0
16	4	4	4	14	14	14	13	13	13	18	18	18	34	34	34	39	39	39	0	0	0
17	46	46	46	14	14	14	13	13	13	17	17	17	34	34	34	39	39	39	0	0	0
18	46	46	46	14	14	14	15	15	15	16	16	16	34	34	34	38	38	38	0	0	0
19	44	44	44	14	14	14	15	15	15	15	15	15	35	35	35	38	38	38	0	0	0
20	44	44	44	14	14	14	15	15	15	15	15	15	48	48	48	47	47	47	0	0	0

Figure 6.33. Layout D with a total cost of 77541, was optimized using set 3. Drawn by the author.

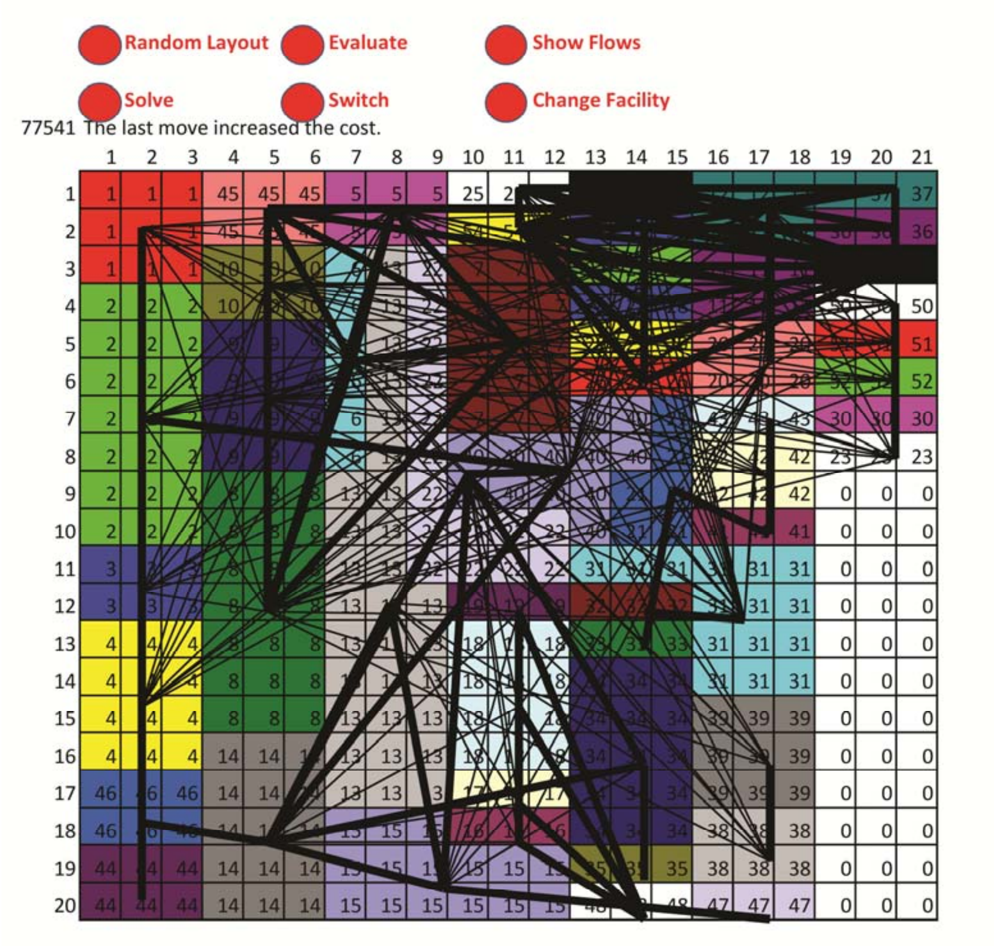


Figure 6.34. Flows between the design units after the optimization on Layout D. Drawn by the author.

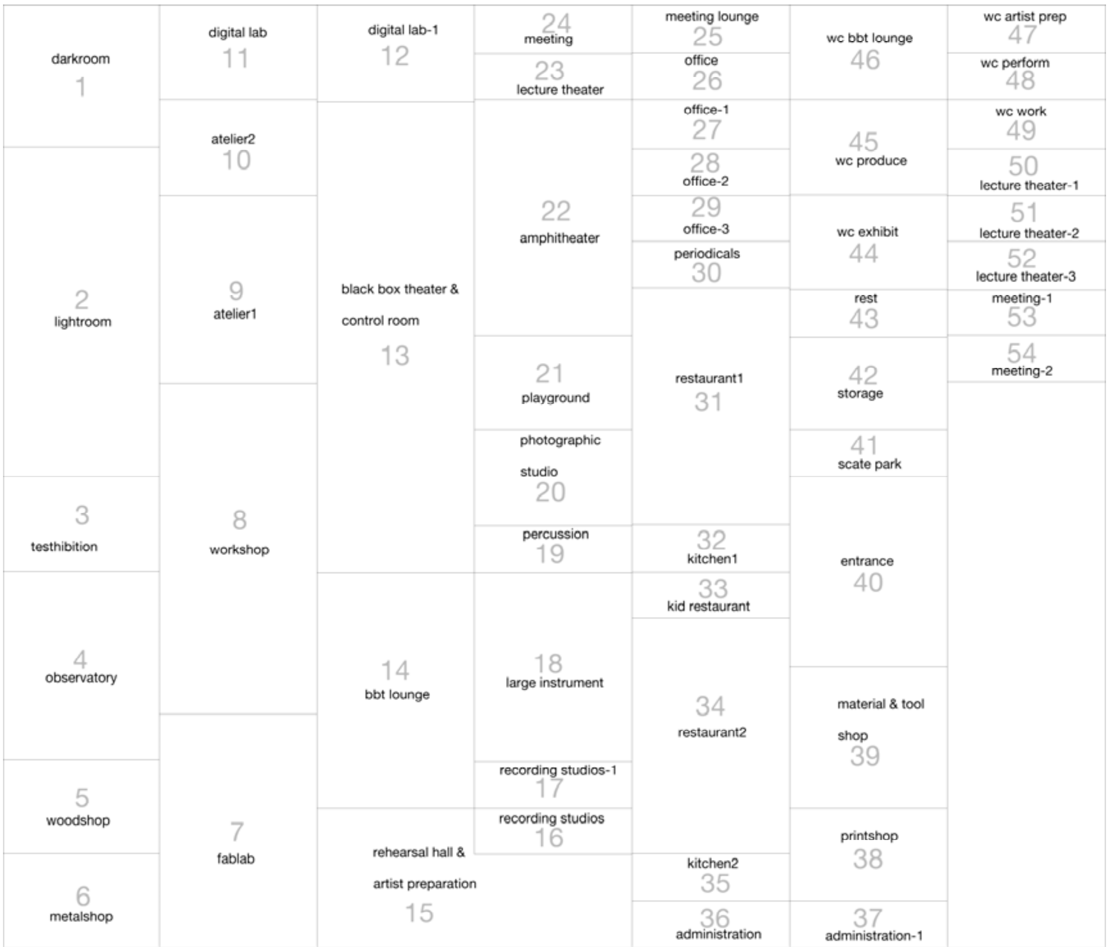


Figure 6.35. Redraft of Layout C in AutoCAD®. Drawn by the author.

6.2.3. Outcomes of the Optimizations

Total costs of the space layouts and number of switches between the design units during the optimizations will be presented in the beginning. The layouts will be redrafted and their functionality will be analyzed. Finally the relation satisfactions will be calculated according to the initial flow input.

(see also: APPENDIX F. OUTCOMES OF QAP OPTIMIZATIONS)

6.2.3.1. Total Costs and Switches

Fixed cost calculation aim to observe the relations of the design units with the site by fixing some of the design units on specific sites. The designer manually calculated the total fixed costs for each layout[18] as shown in Table 6.10.

(see also: APPENDIX G. FIXED COST CALCULATIONS OF QAP OPTIMIZATIONS)

Table 6.10. Fixed costs of the layouts. Drawn by the author.

	100, 20, 5, 1, 0 (3) Q,P,R	1000, 100, 10, 1, 0 (5) Q,P,R
0 FIXED (C)	405, 117, 18441	←same
0 FIXED OPT (D)	510, 132, 24327	470, 127, 21528
4 FIXED	325, 104, 15246	←same
4 FIXED OPT	400, 115, 19233	400, 115, 19233
10 FIXED	320, 103, 15237	←same
10 FIXED OPT	165, 80, 7254	180, 83, 7362
P5 LAYOUT (A)	20, 58, 171	←same
P5 LAYOUT OPT (B)	20, 58, 171	←same
P5 LAYOUT ID U ADJ (A1)	20, 58, 171	←same
P5 LAYOUT ID U ADJ OPT (A2)	20, 58, 171	20, 58, 171

The decreases in fixed costs of from Layout C to 4 FIXED to 10 FIXED and from Layout D to 4 FIXED OPT to 10 FIXED OPT were expected because the number of fixed design units increased. This evaluation was done with different space layouts, however when the space layout and its optimization is considered the only decrease in fixed cost was seen in the optimization of Layout 10 FIXED.

Facility Layout® calculated the total costs for each layout by the multiplication of material flow cost*rectilinear distance between the centroids of the design units. The results are shown in Table 6.11.

[18] If a design unit was on two zones, fixed cost was detected according to the centroid location. If the centroid was on the boundary of two zones, then the higher fixed cost was taken.

Table 6.11. Total costs of the layouts. Drawn by the author.

	100, 20, 5, 1, 0 (3)	1000, 100, 10, 1, 0 (5)
0 FIXED (C)	132185	1184700
0 FIXED OPT (D)	77541.0078125	648054.4375
4 FIXED	138165	1240560
4 FIXED OPT	85915.5	712895
10 FIXED	127495	1158500
10 FIXED OPT	74508.09375	675794
P5 LAYOUT (A)	73020	633830
P5 LAYOUT OPT (B)	67054.28	577044.3
P5 LAYOUT ID U ADJ (A1)	67445	576140
P5 LAYOUT ID U ADJ OPT (A2)	62880.32	545240

Total Costs:

100, 20, 5, 1, 0 (3) A2 < B < A1 < A < 10F OPT < D < 4F OPT < 10F < C < 4F

1000, 100, 10, 1, 0 (5)A2 < A1 < B < A < D < 10F OPT < 4F OPT < 10F < C < 4F

Layout A, A1 and their optimizations have lowest costs in both input sets. Layout A2 has the lowest cost in both processes as expected by the designer. But what if there are better optimizations than Layout A2? The only way to find out the answer was to do multiple trials with the random Layout C. The cost range of ten random optimizations of Layout C is shown in Table 6.12.

Table 6.12. Total cost range for Layout C and Layout D. Drawn by the author.

100, 20, 5, 1, 0 (3)			1000, 100, 10, 1, 0 (5)		
0 FIXED (C)		0 FIXED OPT (D)	0 FIXED (C)	→	0 FIXED OPT (D)
132185	→	77541.0078125	1184700	→	648054.4375
152022.5	→	85458.8203125	1337161.75	→	632387.625
163916.71875	→	87170	1398910	→	861993.375
179496.5	→	73102.3125	1438093	→	534326.875
151171	→	83970.171875	1509736	→	785657.75
156454.28125	→	91946.953125	1516554	→	727020.75
146125.328125	→	76413.6640625	1421484.75	→	593852.875
168855.71875	→	83429.0703125	1355398.75	→	739637.125
160599.140625	→	78382.7578125	1325610.25	→	578563.375
156501.671875	→	91554.0078125	1364200.5	→	791890.375
Cost Range;					
{179496.5,…, 132185}→		{91946.95…, 73102.31}	{1516554 ,…, 1184700}→		{861993.3…, 534326}

The operation revealed a layout, which gave a total cost of 534326, using set 5, which is even lower than the total cost of Layout A2. This layout will be named as Layout D-R and be analyzed further in section 6.3. Space Layout.

Facility Layout® calculated the number of switches during the optimizations as shown in Table 6.13.

Table 6.13. Number of switches during the optimizations. Drawn by the author.

	100, 20, 5, 1, 0 (3)	1000, 100, 10, 1, 0 (5)
0 FIXED (C) 0 FIXED OPT (D)	18	21
4 FIXED 4 FIXED OPT	21	19
10 FIXED 10 FIXED OPT	21	19
P5 LAYOUT (A) P5 LAYOUT OPT (B)	4	4
P5 LAYOUT ID U ADJ (A1) P5 LAYOUT ID U ADJ OPT (A2)	7	5

Number of switches:

100, 20, 5, 1, 0 (3) B < A2 < D < 4F OPT = 10F OPT

1000, 100, 10, 1, 0 (5) B < A2 < 10F OPT = 4F OPT < D

The number of switches decreased in the optimizations of Layout A and A1, which shows that the initial layout affects the optimization.

6.2.3.2. Redrafts and Functionality

As Liggett (2000) mentioned the modularization of the design units would produce irregular, non-functional shapes, as seen in the space layouts optimized using QAP. In this section modular space layouts were redrafted in AutoCAD® to make the evaluation easier. Names were written on design units instead of numbers. Designer calculated the total number of irregular design units as shown in Table 6.14.

Table 6.14. Total number of irregular design units in the layouts. Drawn by the author.

	100, 20, 5, 1, 0 (3)	1000, 100, 10, 1, 0 (5)
0 FIXED (C)	-	-
0 FIXED OPT (D)	**6 irregular units**	**15 irregular units**
4 FIXED	-	-
4 FIXED OPT	**6 irregular units**	**4 irregular units**
10 FIXED	-	-
10 FIXED OPT	**11 irregular units**	**4 irregular units**
P5 LAYOUT (A)	-	-
P5 LAYOUT OPT (B)	**2 irregular units**	**2 irregular units**
P5 LAYOUT ID U ADJ (A1)	-	-
P5 LAYOUT ID U ADJ OPT (A2)	**2 irregular units**	-

Number of irregular design units:

100, 20, 5, 1, 0 (3)   10F OPT > 4F OPT = D > A2 = B

1000, 100, 10, 1, 0 (5)   D > 10F OPT = 4F OPT > B > A2

The decrease in the number of switches during the optimizations resulted in the decrease of the number of irregular design unit shapes. Irregular design unit shapes have a negative effect on the order of the space layout as illustrated in Figure 6.36.

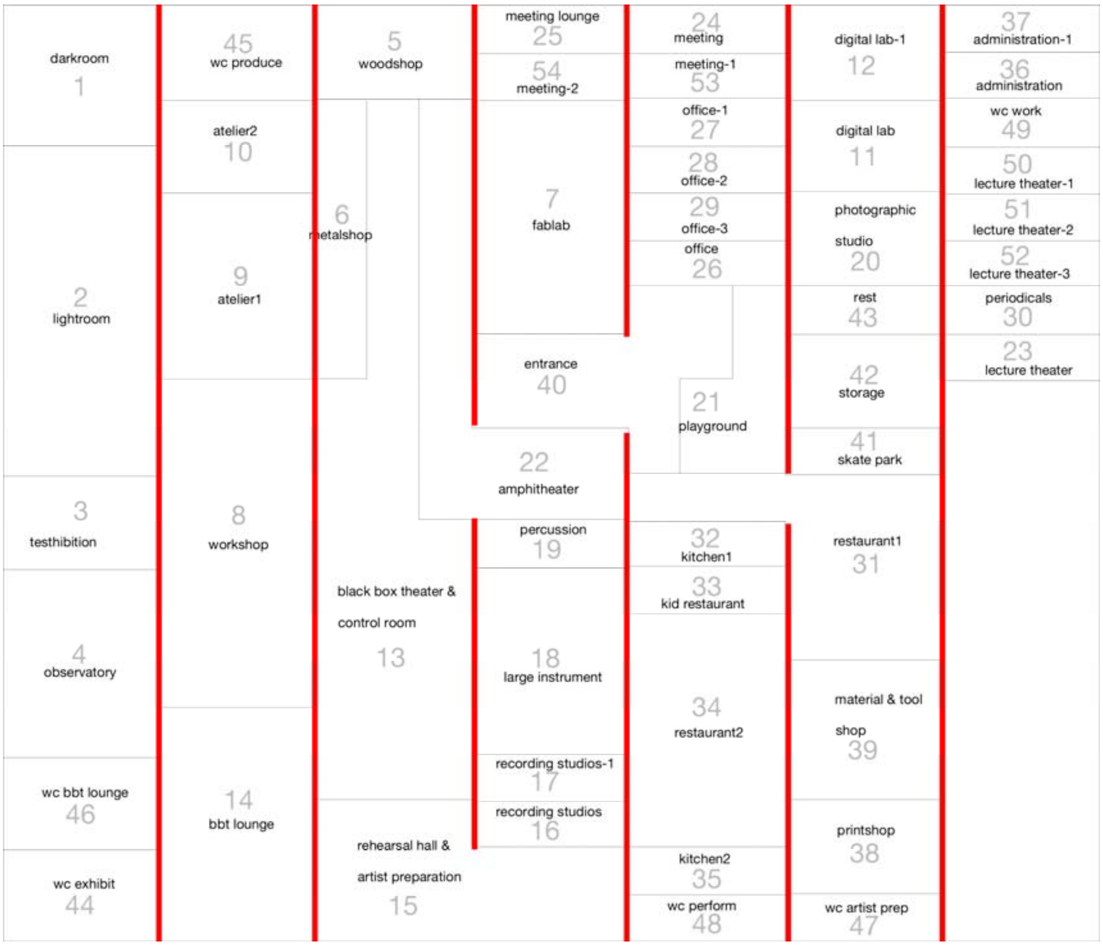


Figure 6.36. The effect of irregular design units on the main circulation axes. Drawn by the author.

The designer also observed the effect of the module subdivisions on the optimizations by increasing the module subdivisions from 354 to 3540 modules. The optimization of Layout C was both done by using set 3 and 5 as shown in Figure 6.37. and Figure 6.38.

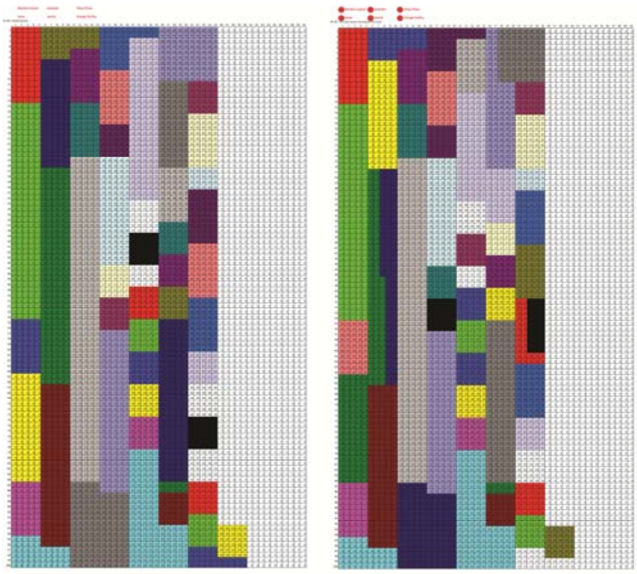


Figure 6.37. Layout C on the left and Layout D on the right using set 3. Drawn by the author.

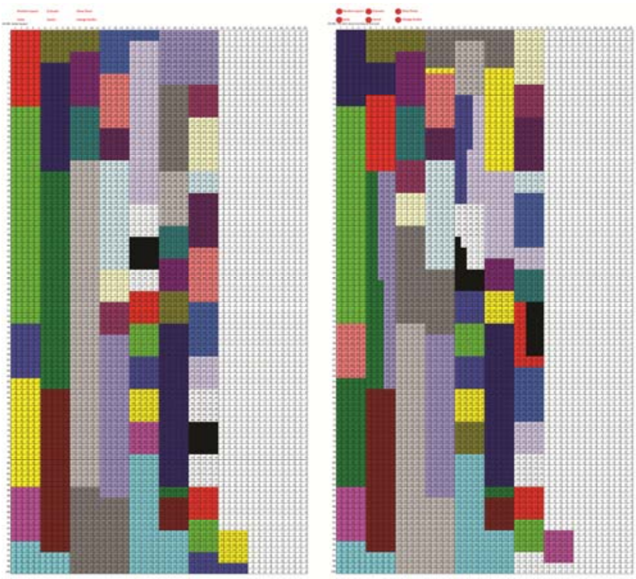


Figure 6.38. Layout C on the left and Layout D on the right using set 5. Drawn by the author.

Optimization time increased at least two times of the previous optimizations with the increase in module subdivisions. Also the size of the space layout was larger than the computer screen, so it was hard to follow the optimization process.

6.2.3.3. Relation Satisfactions

Design criteria are better to be quantifiable during the formulation of the problem so the results can be understood accordingly and well judged (Kalay, 2004). To understand the performance of the program, the highest flow inputs were checked one by one by looking at the relations of the design units on the resulting space layouts. A color was given to each relation according to the final positions of the design units in the space layout as illustrated in Figure 6.39. The total numbers of each color was shown in Table 6.15.

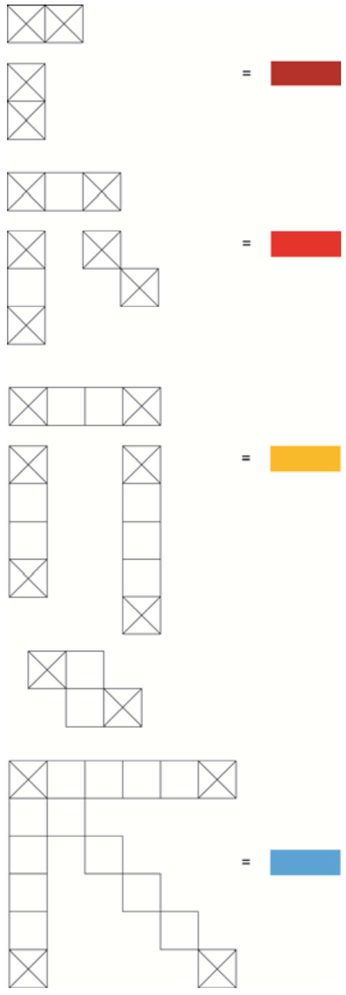


Figure 6.39. Colors according to the final positions of the design units in the space layout. Satisfied: Claret red, Partly Satisfied: Red, Unsatisfied: Yellow, Not related at all: Blue. Drawn by the author.

Table 6.15. Total numbers of Satisfied, partly satisfied, unsatisfied - not related at all relations. Drawn by the author.

	100, 20, 5, 1, 0 (3)	1000, 100, 10, 1, 0 (5)
0 FIXED (C)	25, 12, 13 - 53	-
0 FIXED OPT (D)	33, 25, 28 - 17	41, 25, 23 - 14
4 FIXED	23, 9, 12 - 59	-
4 FIXED OPT	34, 25, 29 - 15	34, 25, 29 - 15
10 FIXED	17, 7, 21 - 58	-
10 FIXED OPT	30, 23, 30 - 20	33, 22, 25 - 23
P5 LAYOUT (A)	38, 25, 22 - 18	-
P5 LAYOUT OPT (B)	39, 30, 22 - 12	-
P5 LAYOUT ID U ADJ (A1)	43, 28, 19 - 13	-
P5 LAYOUT ID U ADJ OPT (A2)	44, 29, 22 - 8	44, 27, 22 - 10

Total number of satisfied and partly satisfied relations:

100, 20, 5, 1, 0 (3) A2 > A1 > B > A > 4F OPT > D >10F OPT > C > 4F > 10F

1000, 100, 10, 1, 0 (5) A2 = A1 > B > D > A > 4F OPT > 10F OPT > C > 4F > 10F

Space layouts with low costs have the highest relation satisfactions and layouts with high costs have the least relation satisfactions. Relation satisfactions color schema in Figure 6.40. shows that, relations with blue color turn to red and claret red colors after the optimizations.

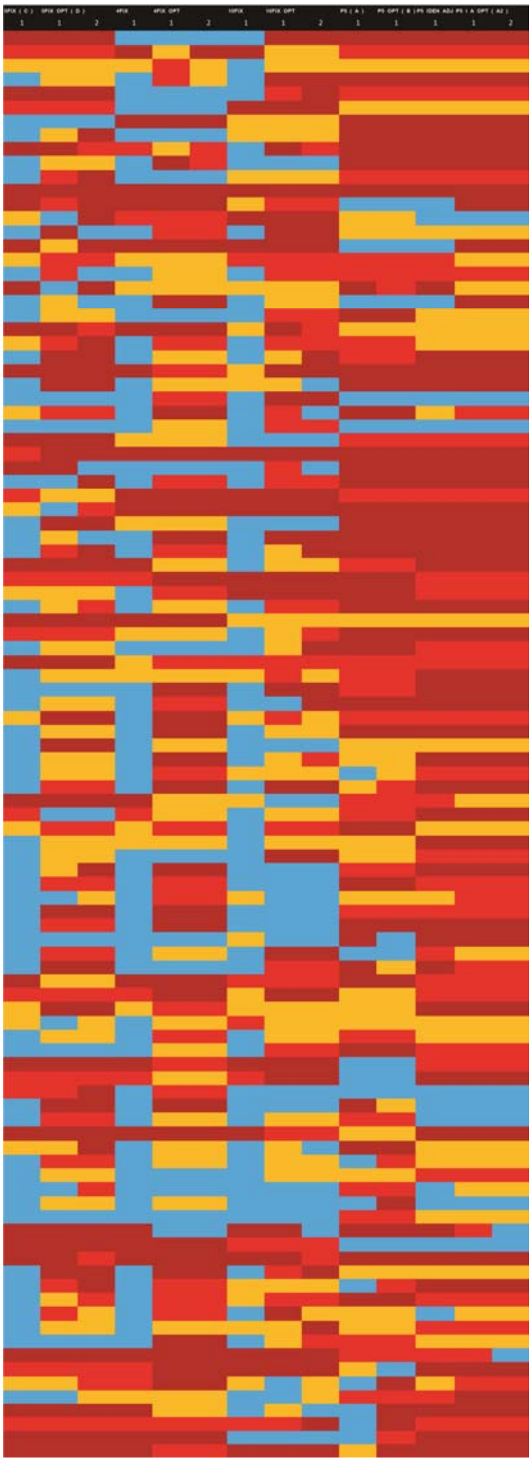


Figure 6.40. Relation satisfactions color schema. Layouts from left to right: C, D, 4FIXED, 4FIXED OPT, 10FIXED, 10FIXED OPT, A, B, A1, A2. From Layout C to A2; relation satisfactions increase with the increase of designer control on the initial space layout. Drawn by the author.

During the relation satisfaction analysis, it was discovered that Facility Layout® generated irregular and non-functional design units to satisfy multiple highest flow inputs as shown in Figure 6.41. and Figure 6.42..

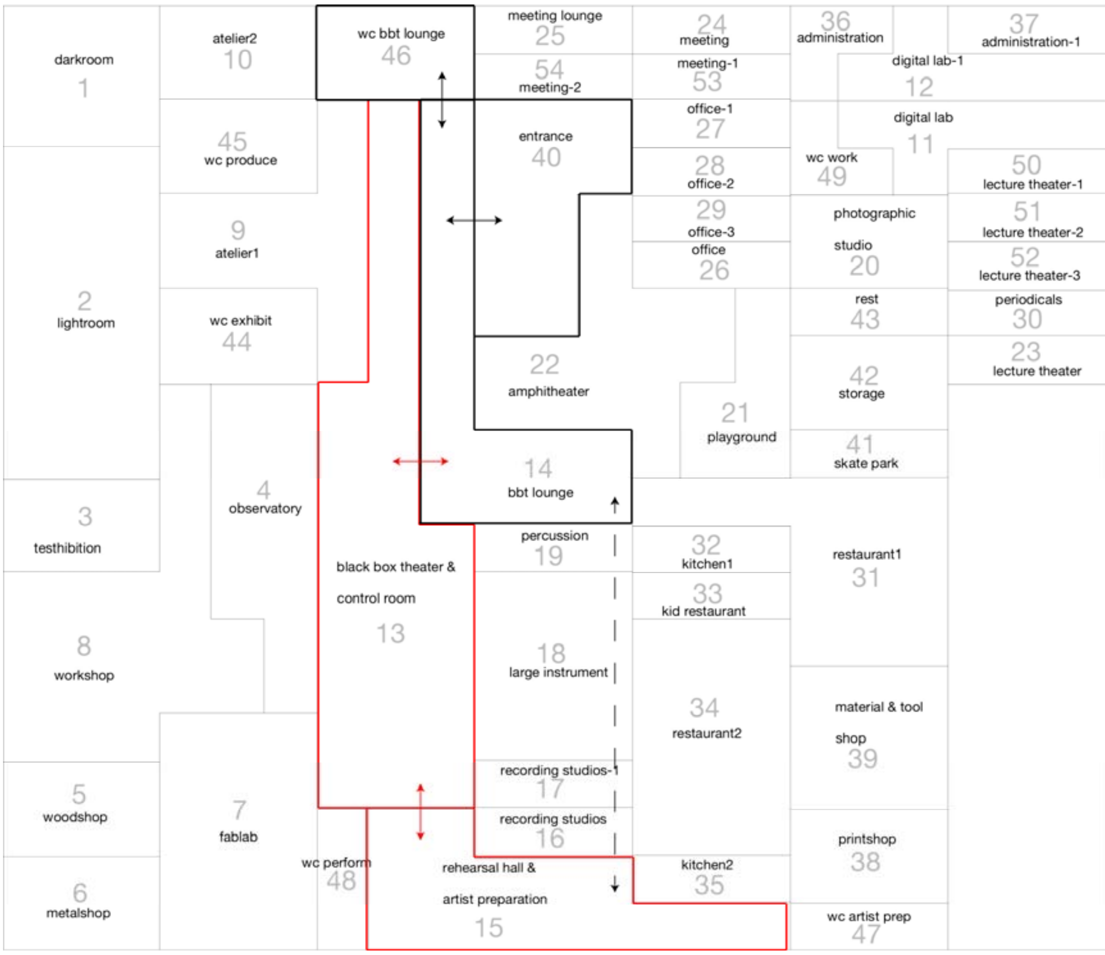


Figure 6.41. BBT Lounge and Wc BBT Lounge relation in Layout D using set 5. Drawn by the author.

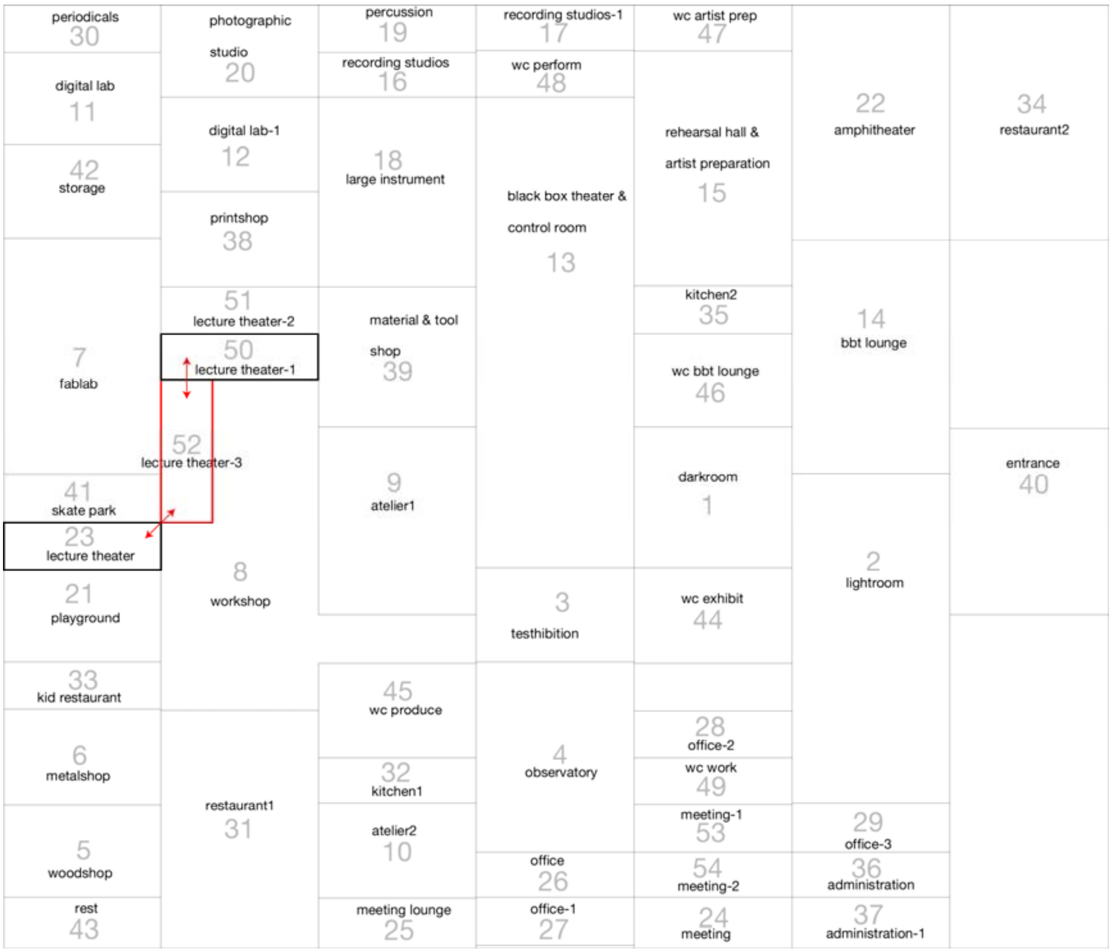


Figure 6.42. Lecture Theater-3 with Lecture Theater and Lecture Theater-1 relation in Layout B. Drawn by the author.

(see also: APPENDIX H. EXAMPLES OF NON-FUNCTIONAL DESIGN UNITS)

6.3. Space Layout

Layout D-R in Figure 6.43. is the optimization of Layout C with a lower cost than Layout A2. Figure 6.44. compares the zone boundaries and design unit shapes of Layout D-R and Layout A2.

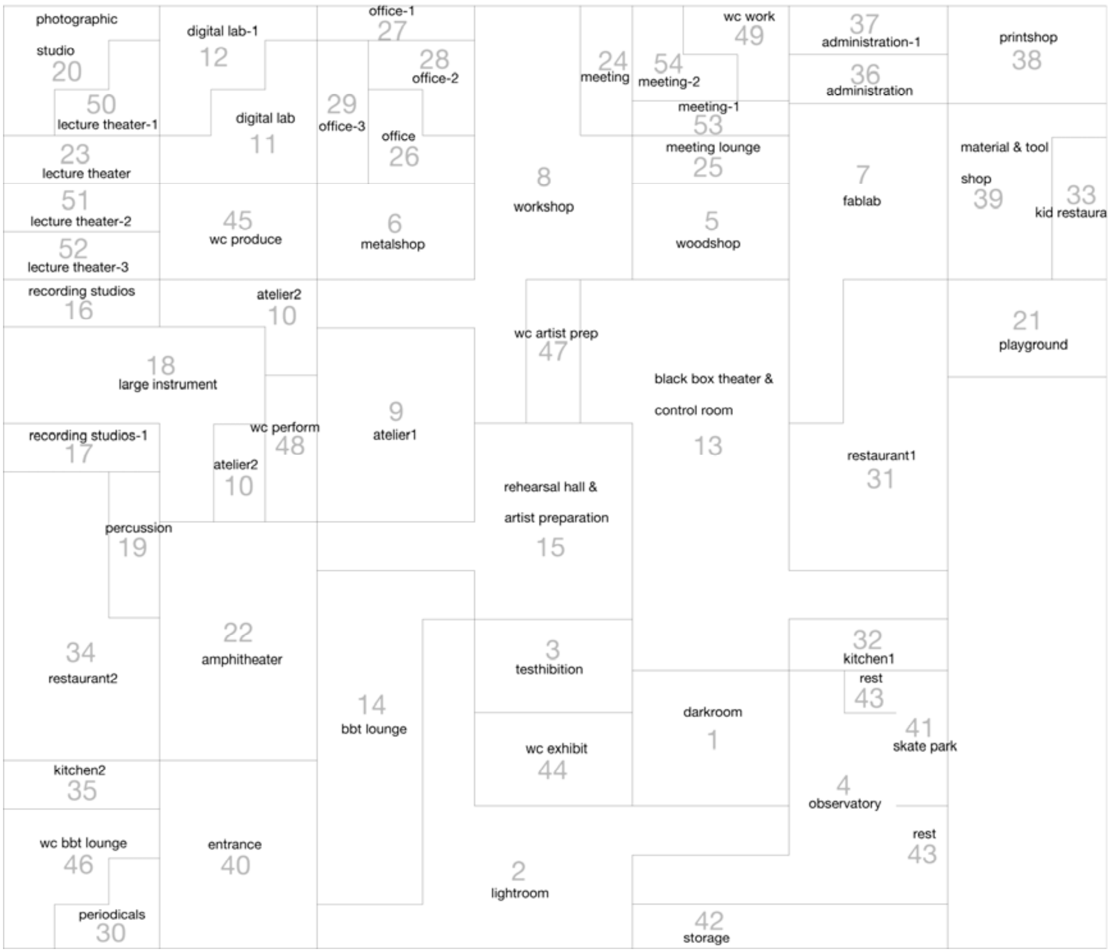


Figure 6.43. Redraft of Layout D-R. Drawn by the author.

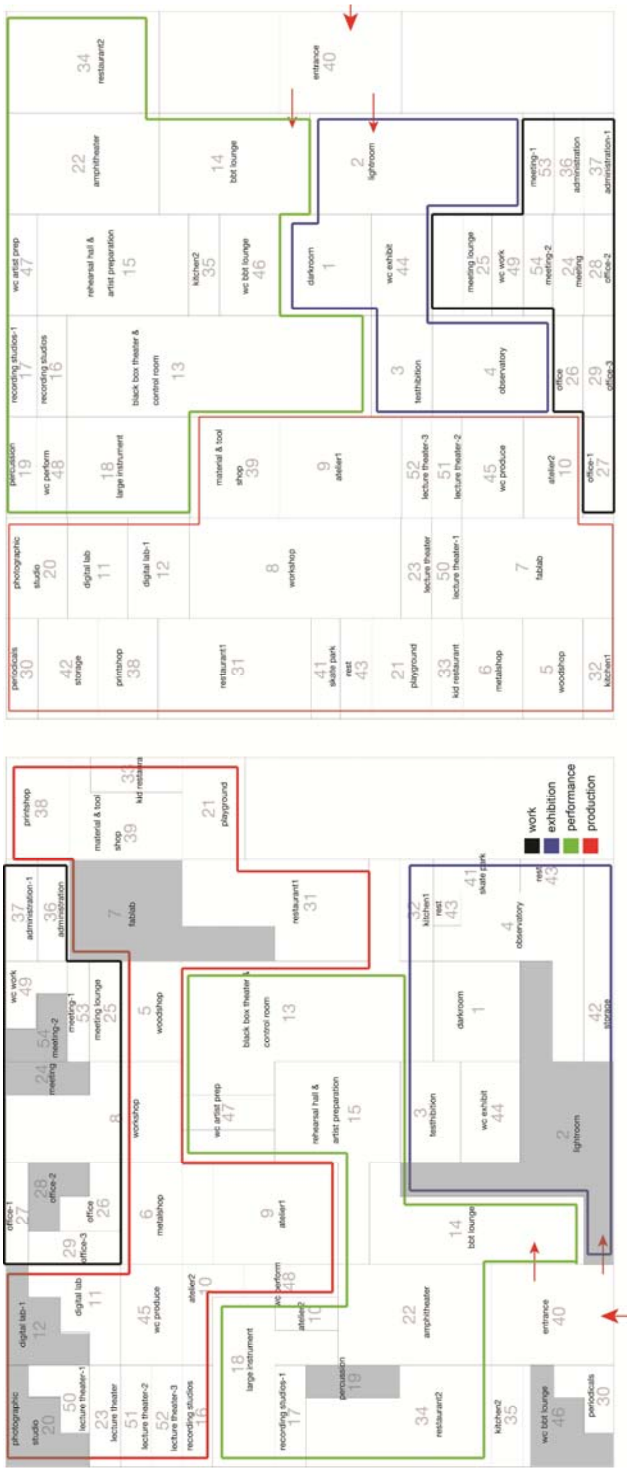


Figure 6.44. Comparison of Layout D-R on the left and Layout A2 on the right. Drawn by the author.

Layout D-R, with a total cost of 534326, has 78 satisfied relations in total out of 103 relations, where Layout A2, with a total cost of 545240, has 71 satisfied relations. The effect of the switches during the optimizations on the final space layout was proven again. 53 switches during the optimizations led to 26 irregular and 2 disconnected shapes in Layout D-R. In subject A2 the design unit shapes were preserved during the optimizations because of only 5 switches. Layout D-R is not an optimum result. The program may produce better results with more trials.

6.4. Evaluation of QAP

QAP is a useful approach in order to deal with complexity of space layout but may also present additional complexities. Preparation of 1431 inputs in the flow matrix was complex but mainly time consuming. It was also harder to evaluate the space layouts based on gradual flow inputs in QAP than AFM. Sensitivity analysis was helpful to see how the program behaves by using different inputs before the main optimizations.

Random selection of switching design pairs, which is only accepted if it decreases the total cost, causes a narrow solution space. Therefore multiple trials are advantageous to obtain better results. This prevents conditioning on one space layout for the rest of the design process. The optimizations done with 5 space layouts showed that the space layouts by the intuitive approach led to lower costs than the random space layout optimizations of the QAP. But QAP can also generate space layouts with lower costs; however these space layouts have disadvantages like irregular and disconnected design unit shapes as a result of the high number of switches during the optimizations.

To analyze the relations of the design units with the site, fixed costs were calculated manually during the optimizations. According to the observations, as the number of fixed design units increased in the initial space layout, the fixed cost of the optimized space layout decreased.

The total cost of the space layout, calculated and shown by the program is helpful in evaluating the space layout. Still, this should be supported with additional methods like checking relation satisfactions. It was observed that checking relation satisfactions takes more time than the optimization process and challenges the practicality of the model. Alternative evaluation methods may be developed.

The optimized space layout of QAP was analyzed extensively in Table 6.16. Like AFM, the representations on the space layout were based on the given input like adjacency relations and design units sizes. However most of the architectural information was not represented, like lighting, orientations, site relations and so forth. The representations on design unit boundary shapes and relations, circulation, construction axes and space layout boundary existed however it is not known if these representations are valid or will be used in the further design process.

Table 6.16. Analysis of space layout using AFM, Intuitive Approach and QAP. Drawn by the author.

+ - ?	AFM	Intuitive Approach	QAP
adjacency relation	+	+	+
design unit boundary relation	?	+	?
design unit boundary shape	?	+	?
design unit size	+	+	+
circulation	?	+	?
construction axes	-	+	?
elevation	-	+	-
lighting	-	+	-
material	-	?	-
orientation	-	+	-
site reference	-	+	-
space layout boundary	-	+	?
zoning	-	+	-

Transfer of output to drafting programs is problematic in the Facility Layout® because the output has to be transferred from Microsoft Office Excel®, which has no direct export options to drafting or modeling programs. In this research the outputs were transferred into AutoCAD® program as .jpeg files and then were drawn from scratch by looking at the images and replacing the numbers of the design units by their names. This was also a gradual, impractical and time-consuming process.

CHAPTER 7

DISCUSSION

The usefulness of computerized space layout programs are researched by using two computerized space layout approaches, AFM and QAP and an intuitive approach by one designer, who is the author of this thesis, in a design process of an actual problem of space layout of more than 50 design units of unequal sizes. In those three processes, the designer observes the input preparations, optimization and satisficing processes and resulting space layouts. The evaluations of the space layouts are based on both the satisfaction of the given input of desired relations and what the space layouts represented. Three space layouts were generated as illustrated in Figure 7.45. All of them represented the same project with different representations with varying levels of details.

All space layout approaches were useful in the design process to a degree. AFM was basic and practical in preparation of inputs and transfer of the outputs. QAP led to design variations prevents the conditioning on the first result found and allows the designer to initiate the optimization process with a desired space layout configuration. Intuitive approach was a unique designer approach, in that way represents the project best.

The main disadvantages of the three approaches can be explained as follows. In AFM the intersecting forces, such as spring and power law, decrease each other's efficiency and led to high numbers in unsatisfied relations in the resulting space layout. In this case the designer should adjust the model parameters and do multiple trials to reach to a better result. The model is also not capable of generating an alternative space layout to the given relations in the given order of the design units in Microsoft Office Excel® file with the same adjustments. So the designer may be conditioned on the resulting space layout.

During the intuitive approach, the designer developed the space layout gradually based on satisficing without any detailed evaluation of the space layout. Depending on the designer, generating an alternative space layout in the same detail may be harder than the computational space layout approaches.

In QAP mainly the preparation of input is complex and time consuming because the flow matrix requires n*(n-1)/2 flow inputs, which gradually differentiate depending on the strength of the relation between the design units. The random selection of switching pairs may create a narrow solution space, and end up with weak solutions. Multiple trials are necessary in QAP to have an idea about the limits of the solution space. Another issue of QAP is the transfer of output to other drafting programs.

None of the methods contain a practical method to understand the satisfaction of desired relations, except the space layout cost in QAP. However the cost is not a strict indicator of satisfaction of desired relations because there may be several reasons of a low cost like more switches and irregular design unit shapes or an initial representational layout with low cost or different flow input sets. So the cost evaluation should be supported with additional evaluation methods. A possible method is to check the result visually; even one by one between the design units when necessary both in AFM and QAP, but this is harder in QAP than AFM, as the number of input to check increases.

AFM and QAP optimized the space layouts according to adjacency relations, but further analysis is required to understand the space layout potentials. The designer realized that the space layout representations of AFM and QAP don't contain majority of the necessary architectural information, but only carry the information on the given input based on the size of the design units and the adjacency relations. Even if design unit boundary relations, shapes, space layout boundaries and circulations are represented in the space layouts, it is not known if these representations are valid or will be used in the further design process. The space layout by the intuitive approach contains various information on; design unit boundary relations and shapes, circulations, construction axes, elevations, materials, site references and zoning and so forth.

Researchers also underlined the fact that the outcomes of the computerized space layout approaches needs additional analysis like Kalay (2004) and Baykan (1995). According to Kalay (2004), the designer should add corridors and reshape the alignment of the design unit walls after the computational analysis. Baykan (1995) mentions that important aspects of the design should be considered by the designer, like daylight requirements, zoning requirements due to noise, hazardous materials, services or ceiling heights because of limited structure of the QAP. Arvin and House (2002) has a different approach. They claim that any design criterion which is related with the position of any design object in the space layout can be translated into forces. If the designer is capable of that, then the more criteria could be concerned by the model, which increases the architectural quality of the space layout.

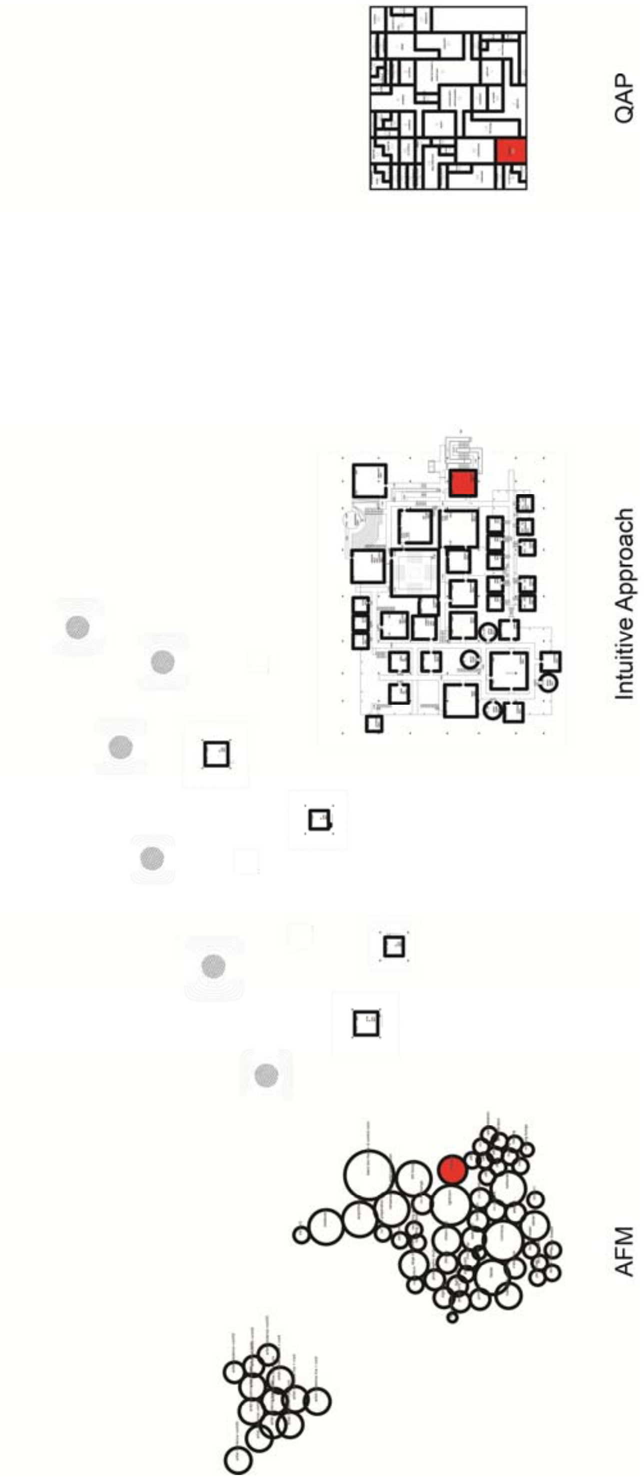


Figure 7.45. There space layouts by AFM, Intuitive Approach and QAP from left to right. Entrance was highlighted with red in all layouts. Drawn by the author.

The space layouts generated by the computerized models helped the designer in the solution of a complex problem. The results were reliable and helpful, especially after the familiarity of the designer with the model. So the discussion on the efficient solution of the problem by human or computer is not a question of the designer after this research. However the discussion on the usefulness of the computerized space layouts in the professional field still exists and the ways to improve the computerized space layout approaches should be the matter of discussion. The author of this thesis agrees with the two recommendations of Lobos and Donath (2010) for architects and space layout researchers, where space layout researchers should try to reach architects by understanding their approaches about good and efficient architecture and reflect on that and architects should try to understand how space layout researchers approach to the problem of space layout. Computational approaches should be integrated in educational programs and merge with the traditional space layout methods. Architects representing this new trend may create boutique approaches for their own design processes, rather than expecting the space layout researchers to approach to their problems.

Brief notes of the author on the improvement of the models are: In AFM; additions of an evaluation mechanism[19] to understand the satisfaction of desired relations and a component[20] to change the order of the design units in Microsoft Office Excel® file, therefore their initial configurations to end up with space layout alternatives. The modification of the model structure according to gradual adjacency relation inputs is also possible but it may also increase the complexity of this basic model and add difficulties like input preparation in QAP. In QAP, additions of fixed costs to strengthen the relation of the space layout with the site and export options to drafting programs would be useful.

[19] A component could be added in the model to relate the adjacency relations to the distances between the design units in their final positions.

[20] The initial configuration of the space layout in AFM depends on the order of design units in Microsoft Office Excel®. A number slider can be connected to the random initial distribution component and as it changes, the initial random placement can change quickly and give multiple results.

CHAPTER 8

CONCLUSION

The usefulness of three different space layout approaches; computerized space layout approaches, AFM and QAP and an intuitive approach was researched in this thesis through an actual design problem by generating three different space layouts. The author of this thesis observed input preparations, optimization and satisficing processes and resulting space layouts during this research. The research showed that each approach uses different evaluation methods and representation approaches, therefore their potentials and disadvantages are different.

The intuitive approach develops the space layout gradually based on a search for satisficing solutions, while the computerized space layout approaches use optimization method and try to reach the best result. To take maximum advantage of the computerized approaches, the designer should have full control of the models used under these approaches and be able to modify their structure by multiple trials, adjusting and understanding the effects of the parameters. More alternatives the programs generate, higher chance to obtain better results and less conditioning on the results. This is the biggest advantage of the computerized models over the intuitive approach. In this thesis, only QAP could generate alternative solutions with the given input and initial adjustments, nevertheless it is also possible to modify AFM and benefit from its potential.

Both AFM and QAP help the designer to deal with the complexity of the space layout problem; however the programs present different complexities. Input preparations for all methods have a degree of difficulty as the number of design units increase, however the hardest and more time-consuming is QAP. As the number of input preparation increases, it also becomes harder to evaluate the space layout. In AFM, the intersecting forces like, spring and power law decrease each other's efficiency or prevent each other to operate during the optimization. In QAP the random selection of the switching pairs narrow the solution space and the transfer of output to other drafting programs is problematic as well next to disadvantages in input preparation. In QAP the indication of costs are helpful and reliable for the initial evaluation of the layout; however they may rarely misguide the designer because there may be several reasons of a low cost. So cost analysis should be supported by additional evaluations, like to visually control the design units in the space layout for the satisfactions of desired relations, as done in this thesis. In AFM no cost is given for the space layout, therefore the space layout should be controlled in the same way as QAP.

Any initial configuration can be given to QAP for optimization. Therefore it is helpful to compare the space layouts of the different approaches with the space layouts of QAP. QAP may generate space layouts with lesser costs than the space layout of the intuitive approach as a result of high number of switches during the optimizations and with irregular and disconnected design unit boundary shapes at the end as a disadvantage.

The space layouts showed that the computerized models represent the information on the given input successfully with basic representations; however they also represent design unit boundary shapes, design unit boundary relations, space layout boundary, circulations, which are not defined by the designer, but the program. So the designer should decide if they are coherent with the design criteria or not and design them from the very beginning for the further processes if necessary. For the further design process additional analysis could be done to detail the space layout representations. The space layout of the intuitive approach has a more complex representation than the space layout of the computerized models, as it contains more architectural information.

Further research questions on the subject would be based on the reasons for the failure of computerized space layout approaches by the companies, the ways to improve their practicality for the professional field, the ways to increase the interaction between the space layout researchers and the architects and to increase the dominance of the architect on the programs.

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APPENDIX A

GRASSHOPPER® DEFINITION OF AFM

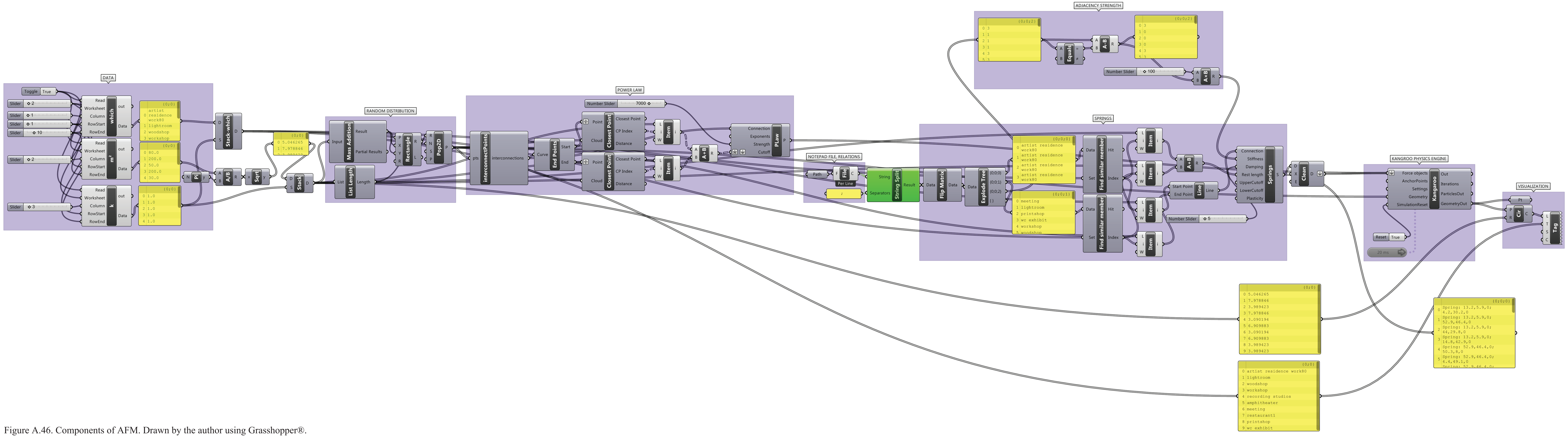


Figure A.46. Components of AFM. Drawn by the author using Grasshopper®.

APPENDIX B

DESIGN PROGRAM

Table B.17. Program of The Creative Village Project.

the creative village

		m²	k	**m² * k**	p	**p * k**	h	d & n(hr)	North South1, East West 0	bottom elevation	hroof	sound iso	dark	day&night	view	rental	explanation
								IV				II	III	IV	VI		
live + work	artist residence live + work	80	8	**640**	1	**8**	4	24	1	9	0	1	0		+	€	60~100m² 2rooms+kitchen+bathroom for 1 person with private bicycle park
	artist residence work80	80	2	**160**	5	**10**	3	24	1	17	0	1	0		+	€	80m² for max 5 people with private bicycle park
	artist residence work50	50	3	**150**	3	**9**	3	24	1	19	0	1	0		+	€	50m² for max 3 people with private bicycle park
exhibit	darkroom	70	1	**70**	20	**20**	6	93	2	11	0	1	1				
	lightroom	200	1	**200**	40	**40**	6	93	1	11	0	0	0		+		
	testhibition	50	1	**50**	15	**15**	6	93	0	14	1	0	0				
	observatory	100	1	**100**	30	**30**	6	93	0	13	0	1	0			€	multi-use, flexible: temporary exhibitions, development of large scale works&installations, film set, performances
produce	woodshop	50	1	**50**	15	**15**	3.5	92	1	9	6	1	0		+		milling, drilling, cutting wood/plastic
	metalshop	50	1	**50**	15	**15**	3.5	92	1	9	2	1	0		+		
	fablab	150	1	**150**	30	**30**	3.5	92	1	13	2	1	0		+		3Dprinter, lasercutter, CNC milling machine
	workshop	200	1	**200**	40	**40**	3.5	92	1	11	6	0	0		+		last phase of the production
	atelier1	100	1	**100**	30	**30**	3.5	92	1	13	4	0	0		+		drawing, sculpture, painting, ceramics, pottery
	atelier2	50	1	**50**	20	**20**	3.5	92	1	9	8	0	0		+		fashion, stitching
	digital lab	50	2	**100**	20	**40**	4	92	0	15	2	1	0				
perform	black box theater & control room	300	1	**300**	232	**232**	8	15	2	8	0	1	1			€	14row*12 for 168 people
	bbt lounge	150	1	**150**	100	**100**	6	15	1	10	0	1	0		+		
	rehearsal hall & artist preparation	150	1	**150**	60	**60**	6	15	2	7	2	1	1				
	recording studios	30	2	**60**	4	**8**	3	91	0	15	0	1	0			€	
	large instrument	100	1	**100**	30	**30**	4	91	0	15	0	1	0			€	
	percussion	30	1	**30**	4	**4**	3	91	0	15	0	1	0			€	
	photographic studio	50	1	**50**	5	**5**	4	92	2	15	2	1	1			€	
	playground	50	1	**50**	20	**20**	3	92	1	9	2	1	0		+		
	amphitheater	150	1	**150**	300	**150**	5	15	1	10	0	0	0		+	€	for 300~350 people, a roof(membrane, temporary or permanent..) is necessary, also as an open air cinema
	lecture theater	30	4	**120**	20	**80**	3	92	1	12	4	1	0		+		lecture rooms and various studio, lab, workshops are linked and free. subscription is required
work	meeting	30	3	**90**	5	**15**	3.5	9	1	9	0	1	0			€	
	meeting lounge	20	1	**20**	6	**6**	3	9	1	9	0	0	0		+		
	office	30	5	**150**	5	**25**	3.5	9	1	11	2	1	0		+	€	
	periodicals	30	1	**30**	8	**8**	4	92	1	15	2	1	0		+		
service / common	restaurant1	150	1	**150**	70	**70**	6	92	1	9	2	1	0		+		
	kitchen1	30	1	**30**	10	**10**	3	92	2	6	2	1	0				
	kid restaurant	10	1	**10**	7	**7**	2.5	92	1	9	3	1	0		+		
	restaurant2	150	1	**150**	70	**70**	6	15	1	10	0	1	0		+		
	kitchen2	30	1	**30**	10	**10**	3	15	2	10	2	1	0				
	administration	30	2	**60**	5	**10**	4	9	1	9	0	1	0				
	printshop	50	1	**50**	10	**10**	3.5	92	2	15	4	1	0				
	material & tool shop	80	1	**80**	10	**10**	3.5	92	2	15	4	1	0				
	entrance	100	1	**100**	30	**30**	5	0	1	10	0	1	0		+		
	skate park	30	1	**30**	10	**10**	2	0	1	11	0	0	0		+		
	storage	50	1	**50**	5	**5**	3.5	92	2	13	4	1	1				10~20m², a graffitti wall outside
	rest	20	1	**20**	10	**10**	3	0	2	11	6	1	0		+		
	wc exhibit	50	1	**50**	6	**6**	3	93	2	12	4	1	1				
	wc produce	50	1	**50**	6	**6**	3	92	2	11	6	1	1				
	wc bbt lounge	50	1	**50**	6	**6**	3	15	2	7	5	1	0				
	wc artist preperation	30	1	**30**	4	**4**	2.5	15	2	7	5	1	0				
	wc perform	30	1	**30**	4	**4**	2.5	91	2	15	0	1	1				
	wc work	30	1	**30**	4	**4**	2.5	9	2	9	2	1	1				
	carpark	2500	1	**2500**	125	**125**	2.5	0	0	8	2	0	0				
	bicycle park	740															
			69			**1347**		**total capacity**									
				3570				**ta - (al + carpark)**									
				4520				**ta - carpark**									
				7020				**total area**									

APPENDIX C

ADJACENCY RELATION INPUTS OF AFM

artist residence live + work;artist residence work80
artist residence live + work;artist residence work50
darkroom;lightroom
testhibition;lightroom
observatory;lightroom
observatory;testhibition
darkroom;testhibition
darkroom;observatory
workshop;metalshop
workshop;testhibition
workshop;fablab
woodshop;digital lab
workshop;woodshop
workshop;restaurant1
atelier1;atelier2
atelier1;workshop
atelier2;workshop
fablab;digital lab
fablab;workshop
black box theater & control room;bbt lounge
rehearsal hall & artist preparation;black box theater & control room
rehearsal hall & artist preparation;bbt lounge
rehearsal hall & artist preparation;percussion
recording studios;large instrument
percussion;large instrument
recording studios;percussion
photographic studio;digital lab
rehearsal hall & artist preparation;amphitheater
periodicals;lecture theater
workshop;lecture theater
meeting;meeting lounge
meeting;office
restaurant1;kitchen1
kid restaurant;playground
restaurant2;amphitheater
meeting;administration
office;administration
digital lab;printshop
material & tool shop;printshop
material & tool shop;metalshop
entrance;office
playground;skate park
entrance;bbt lounge
storage;woodshop
carpark;entrance
skate park;rest
workshop;rest
lightroom;entrance
wc exhibit;lightroom
wc produce;workshop
wc bbt lounge;bbt lounge
wc artist preperation;rehearsal hall & artist preparation
wc perform;large instrument
wc work;office
restaurant2;kitchen2
photographic studio;large instrument

restaurant1;office
restaurant1;meeting

APPENDIX D

INTUITIVE REASONING OF 1431 FLOW INPUTS OF QAP

1	Darkroom	70m²
2	Lightroom	200m²
3	Testhibition	50m²
4	Observatory	100m²
5	Woodshop	50m²
6	Metalshop	50m²
7	Fablab	150m²
8	Workshop	200m²
9	Atelier1	100m²
10	Atelier2	50m²
11	Digital Lab	50m²
12	Digital Lab-1	50m²
13	Black Box Theater & Control Room	300m²
14	BBT Lounge	150m²
15	Rehearsal Hall & Artist Preparation	150m²
16	Recording Studios	30m²
17	Recording Studios-1	30m²
18	Large Instrument	100m²
19	Percussion	30m²
20	Photographic Studio	50m²
21	Playground	50m²
22	Amphitheater	150m²
23	Lecture Theater	30m²
24	Meeting	30m²
25	Meeting Lounge	20m²
26	Office	30m²
27	Office-1	30m²
28	Office-2	30m²
29	Office-3	30m²
30	Periodicals	30m²
31	Restaurant1	150m²
32	Kitchen1	30m²
33	Kid Restaurant	10m²
34	Restaurant2	150m²
35	Kitchen2	30m²
36	Administration	30m²
37	Administration-1	30m²
38	Printshop	50m²
39	Material & Tool Shop	80m²
40	Entrance	100m²
41	Skate Park	30m²
42	Storage	50m²
43	Rest	20m²
44	Wc exhibit	50m²
45	Wc produce	50m²
46	Wc bbt lounge	50m²
47	Wc artist preparation	30m²
48	Wc perform	30m²
49	Wc work	30m²
50	Lecture Theater-1	30m²
51	Lecture Theater-2	30m²
52	Lecture Theater-3	30m²
53	Meeting -1	30m²
54	Meeting -2	30m²

*The reasoning*s

A identical	adjacency of identical design units
B material and, or user flow	necessary material and, or people flow from one design unit to another
C grouping	functional similarity
D sound isolation	environmental similarity
E installment and mechanical setup	infrastructure similarity
F public or private space	either a public or private space
G daytime or nighttime open hours	either open at daytime or nighttime
H not related	none of the above relations exist

Flow inputs

From the most important to least important relationship;
set 3: 100-20-5-1-0
set 5: 1000-100-10-1-0

100/1000

1 darkroom-lightroom B,C,F(public),G(daytime)
This relation is quite strong, because both design units are in the exhibition zone. Dense user and, or material flow is expected between them. They are both public spaces and work through daytime.
2 darkroom-testhibition B,C,F(public),G(daytime)
Same as #1
3 darkroom-observatory B,C,F(public),G(daytime)
Same as #1
4 darkroom-wc exhibit B,C,F(public),G(daytime)
Wc exhibit is a special design unit for the exhibition zone, so it has to be adjacent with the design units in the exhibition zone.
5 lightroom-testhibition B,C,F(public),G(daytime)
Same as #1
6 lightroom-observatory B,C,F(public),G(daytime)
Same as #1
7 lightroom-entrance. B,F(public),G(daytime)
The guests are expected to start their exhibition visit with the lightroom.
8 lightroom-wc exhibit. B,C,F(public),G(daytime)
Same as #4
9 testhibition-observatory B,C,F(public),G(daytime)
Same as #1
10 testhibition-wc exhibit. B,C,F(public),G(daytime)
Same as #4
11 observatory-wc exhibit. B,C,F(public),G(daytime)
Same as #4
12 woodshop-metalshop B,C,D,E,F(public),G(daytime)
Both design units are in the production zone, but the tools and materials they use differ
13 woodshop-fablab B,C,D,E,F(public),G(daytime)
They are complementary design units in the production zone.
14 woodshop-workshop B,C,D,E,F(public),G(daytime)
Same as #13
15 woodshop-wc produce B,C,F(public),G(daytime)
Wc produce is a special design unit for the production zone, so it has to be adjacent with the design units in the production zone
16 metalshop-fablab B,C,D,E,F(public),G(daytime)
Same as #13
17 metalshop-workshop B,C,D,E,F(public),G(daytime)
Same as #13
18 metalshop-wc produce B,C,F(public),G(daytime)
Same as #15
19 fablab-workshop B,C,D,E,F(public),G(daytime)
Same as #13
20 fablab-wc produce B,C,F(public),G(daytime)
Same as #15
21 workshop-wc produce B,C,F(public),G(daytime)
Same as #15
22 atelier1-atelier2 B,C,D,E,F(public),G(daytime)
Same as #13
23 atelier1-wc produce B,C,F(public),G(daytime)
Same as #15
24 atelier2-wc produce B,C,F(public),G(daytime)
Same as #15
25 digital lab-digital lab-1 A
26 digital lab-photographic studio B,C,F(public),G(daytime)
Same as #13
27 digital lab-wc produce B,C,F(public),G(daytime)
Same as #15
28 digital lab-1-photographic studio B,C,F(public),G(daytime)
Same as #13
29 digital lab-1-wc produce B,C,F(public),G(daytime)
Same as #15

30 black box theater & control room-bbt lounge B,C,F(public)
BBT lounge could be used to wait for a play or rest in the break of a play of BBT.
31 black box theater & control room-rehearsal hall & artist preparation B,C
Artists will directly pass from the artist preparation design unit to the theater.
32 bbt lounge-rehearsal hall & artist preparation B,C
Bbt lounge could be directly connected to artist preparation. Both design units are in the performance zone.
33 bbt lounge-amphitheater B,C,F(public)
Same as #30
34 bbt lounge-restaurant2 B,C,F(public),G(nighttime)
Restaurant2 and bbt lounge are complementary service units.
35 bbt lounge-entrance B,C,F(public)
The audience should easily reach to bbt lounge after passing from the entrance.
36 bbt lounge-wc bbt lounge B,C,F(public)
Wc bbt lounge is a special design unit for the bbt lounge.
37 rehearsal hall & artist preparation-amphitheater B,C
Same as #31
38 rehearsal hall & artist preparation-wc artist preparation B,C,F(private)
Wc artist preparation is a special design unit for the artist preparation.
39 recording studios- recording studios-1 A
40 recording studios- large instrument B,C,E,F(public),G(daytime)
They are complementary design units in the performance zone.
41 recording studios- percussion B,C,E,F(public),G(daytime)
Same as #40
42 recording studios- wc perform B,C,F(public),G(daytime)
Wc perform is a special design unit for the performance zone.
43 recording studios-1- large instrument B,C,E,F(public),G(daytime)
Same as #40
44 recording studios-1- percussion B,C,E,F(public),G(daytime)
Same as #40
45 recording studios-1-wc perform B,C,F(public),G(daytime)
Same as #42
46 large instrument-percussion B,C,E,F(public),G(daytime)
Same as #40
47 large instrument-wc perform B,C,F(public),G(daytime)
Same as #42
48 percussion-wc perform B,C,F(public),G(daytime)
Same as #42
49 playground-kid restaurant B,C,D,F(public),G(daytime)
Both design units are designed for kids.
50 playground-skate park B,C,D,F(public),G(daytime)
Both design units are designed for young people.
51 amphitheater-restaurant2 B,F(public),G(nighttime)
The restaurant will be used by the audience before or after the open air performance.
52 amphitheater-entrance B,F(public),G(nighttime)
Amphitheater should be easily reached from entrance.
53 lecture theater- lecture theater-1 A
54 lecture theater- lecture theater-2 A
55 lecture theater- lecture theater-3 A
56 meeting-meeting lounge B,C,F(private),G(daytime)
Meeting lounge is a special design unit for meeting design units.
57 meeting-office B,C,D,E,F(private),G(daytime)
They are complementary design units in the work zone.
58 meeting-office-1 B,C,D,E,F(private),G(daytime)
Same as #57
59 meeting-office-2 B,C,D,E,F(private),G(daytime)
Same as #57
60 meeting-office-3 B,C,D,E,F(private),G(daytime)
Same as #57
61 meeting-administration B,C,D,E,F(private),G(daytime)
Same as #57
62 meeting-administration-1 B,C,D,E,F(private),G(daytime)
Same as #57
63 meeting-wc work B,C,F(private),G(daytime)
Wc work is a special design unit for the work zone.
64 meeting-meeting-1 A
65 meeting-meeting-2 A
66 meeting lounge-wc work B,C,F(private),G(daytime)
Two service design units in the work zone are directly related.
67 meeting lounge-meeting-1 B,C,F(private),G(daytime)
Same as #56
68 meeting lounge-meeting-2 B,C,F(private),G(daytime)
Same as #56
69 office-office-1 A

70 office-office-2 A
71 office-office-3 A
72 office-wc work B,C,F(private),G(daytime)
Same as #63
73 office-meeting-1 B,C,D,E,F(private),G(daytime)
Same as #57
74 office-meeting-2 B,C,D,E,F(private),G(daytime)
Same as #57
75 office-1-office-2 A
76 office-1-office-3 A
77 office-1-wc work B,C,F(private),G(daytime)
Same as #63
78 office-1-meeting-1 B,C,D,E,F(private),G(daytime)
Same as #57
79 office-1-meeting-2 B,C,D,E,F(private),G(daytime)
Same as #57
80 office-2-office-3 A
81 office-2-wc work B,C,F(private),G(daytime)
Same as #63
82 office-2-meeting-1 B,C,D,E,F(private),G(daytime)
Same as #57
83 office-2-meeting-2 B,C,D,E,F(private),G(daytime)
Same as #57
84 office-3-wc work B,C,F(private),G(daytime)
Same as #63
85 office-3-meeting-1 B,C,D,E,F(private),G(daytime)
Same as #57
86 office-3-meeting-2 B,C,D,E,F(private),G(daytime)
Same as #57
87 restaurant1-kitchen1 B,C,G(daytime)
Kitchen1 is a special design unit for the restaurant1.
88 restaurant2-kitchen2 B,C,G(nighttime)
Kitchen2 is a special design unit for the restaurant2.
89 administration-administration-1 A
90 administration-wc work B,C,F(private),G(daytime)
Same as #63
91 administration-meeting-1 B,C,D,E,F(private),G(daytime)
Same as #57
92 administration-meeting-2 B,C,D,E,F(private),G(daytime)
Same as #57
93 administration-1-wc work B,C,F(private),G(daytime)
Same as #63
94 administration-1-meeting-1 B,C,D,E,F(private),G(daytime)
Same as #57
95 administration-1-meeting-2 B,C,D,E,F(private),G(daytime)
Same as #57
96 printshop-material&tool shop B,D,E,F(public),G(daytime)
Two design units could be rented to the same company.
97 skate park-rest B,F(public),G(daytime)
Both design units house leisure activities.
98 wc work-meeting-1 B,C,F(private),G(daytime)
Same as #63
99 wc work-meeting-2 B,C,F(private),G(daytime)
Same as #63
100 lecture theater-1- lecture theater-2 A
101 lecture theater-1- lecture theater-3 A
102 lecture theater-2- lecture theater-3 A
103 meeting-1-meeting-2 A

20/100
104 darkroom-entrance F(public),G(daytime)
The two design units are indirectly related. The designer expects lightroom, which is also an exhibition zone design unit, to be close to entrance, therefore darkroom should also placed close to entrance, but not adjacently. Also both design units are public.
105 testhibition-entrance F(public),G(daytime)
Same as #104
106 observatory-entrance F(public),G(daytime)
Same as #104
107 woodshop-atelier1 C,D,F(public),G(daytime)
Both design units are in production zone but they are not necessarily complementary design units. Their production is based on different kinds of materials.
108 woodshop-atelier2 C,D,F(public),G(daytime)
Same as #107
109 woodshop-lecture theater B,F(public),G(daytime)

Lecture theater has a visual relation with the production zone design units; however it is not strictly adjacent to any of them in this zone.

110 woodshop-lecture theater-1	B,F(public),G(daytime)
Same as #109	
111 woodshop-lecture theater-2	B,F(public),G(daytime)
Same as #109	
112 woodshop-lecture theater-3	B,F(public),G(daytime)
Same as #109	
113 metalshop-atelier1	C,D,F(public),G(daytime)
Same as #107	
114 metalshop-atelier2	C,D,F(public),G(daytime)
Same as #107	
115 metalshop -lecture theater	B,F(public),G(daytime)
Same as #109	
116 metalshop -lecture theater-1	B,F(public),G(daytime)
Same as #109	
117 metalshop -lecture theater-2	B,F(public),G(daytime)
Same as #109	
118 metalshop -lecture theater-3	B,F(public),G(daytime)
Same as #109	
119 fablab-atelier1	C,D,F(public),G(daytime)
Same as #107	
120 fablab -atelier2	C,D,F(public),G(daytime)
Same as #107	
121 fablab -lecture theater	B,F(public),G(daytime)
Same as #109	
122 fablab -lecture theater-1	B,F(public),G(daytime)
Same as #109	
123 fablab -lecture theater-2	B,F(public),G(daytime)
Same as #109	
124 fablab -lecture theater-3	B,F(public),G(daytime)
Same as #109	
125 workshop-atelier1	C,D,F(public),G(daytime)
Same as #107	
126 workshop -atelier2	C,D,F(public),G(daytime)
Same as #107	
127 workshop -lecture theater	B,F(public),G(daytime)
Same as #109	
128 workshop -lecture theater-1	B,F(public),G(daytime)
Same as #109	
129 workshop -lecture theater-2	B,F(public),G(daytime)
Same as #109	
130 workshop -lecture theater-3	B,F(public),G(daytime)
Same as #109	
131 atelier1-lecture theater	B,F(public),G(daytime)
Same as #109	
132 atelier1-lecture theater-1	B,F(public),G(daytime)
Same as #109	
133 atelier1-lecture theater-2	B,F(public),G(daytime)
Same as #109	
134 atelier1-lecture theater-3	B,F(public),G(daytime)
Same as #109	
135 atelier2-lecture theater	B,F(public),G(daytime)
Same as #109	
136 atelier2-lecture theater-1	B,F(public),G(daytime)
Same as #109	
137 atelier2-lecture theater-2	B,F(public),G(daytime)
Same as #109	
138 atelier2-lecture theater-3	B,F(public),G(daytime)
Same as #109	
139 digital lab-lecture theater	B,F(public),G(daytime)
Same as #109	
140 digital lab-lecture theater-1	B,F(public),G(daytime)
Same as #109	
141 digital lab-lecture theater-2	B,F(public),G(daytime)
Same as #109	
142 digital lab-lecture theater-3	B,F(public),G(daytime)
Same as #109	
143 digital lab-1-lecture theater	B,F(public),G(daytime)
Same as #109	
144 digital lab-1-lecture theater-1	B,F(public),G(daytime)
Same as #109	
145 digital lab-1-lecture theater-2	B,F(public),G(daytime)

Same as #109
146 digital lab-1-lecture theater-3 B,F(public),G(daytime)
Same as #109
147 black box theater & control room-amphitheater C,E,F(public)
They don't have to be placed adjacently. Their relations with service and lounge design units are more important.
148 black box theater & control room-restaurant2 B,F(public),G(nighttime)
If a play in bbt is in the evening, the audience would also like to have dinner and goes to restaurant2. Restaurant2 serves lunch and dinner.

5/10
149 darkroom-woodshop F(public),G(dayime)
The designer can't construct a direct or indirect relation between them. They both work for public and during daytime, but these reasons are not adequate for putting them close. But there is also no reason to put them totally apart.
150 darkroom-metalshop B,F(public),G(dayime)
Same as #149
151 darkroom-fablab B,F(public),G(dayime)
Same as #149
152 darkroom-workshop B,F(public),G(dayime)
Same as #149
153 darkroom-atelier1 B,F(public),G(dayime)
Same as #149
154 darkroom-atelier2 B,F(public),G(dayime)
Same as #149
155 darkroom-digital lab B,F(public),G(dayime)
Same as #149
156 darkroom-digital lab-1 B,F(public),G(dayime)
Same as #149
157 lightroom-woodshop B,F(public),G(dayime)
Same as #149
158 lightroom –metalshop B,F(public),G(dayime)
Same as #149
159 lightroom –fablab B,F(public),G(dayime)
Same as #149
160 lightroom –workshop B,F(public),G(dayime)
Same as #149
161 lightroom -atelier1 B,F(public),G(dayime)
Same as #149
162 lightroom -atelier2 B,F(public),G(dayime)
Same as #149
163 lightroom -digital lab B,F(public),G(dayime)
Same as #149
164 lightroom -digital lab-1 B,F(public),G(dayime)
Same as #149
165 testhibition-woodshop B,F(public),G(dayime)
Same as #149
166 testhibition –metalshop B,F(public),G(dayime)
Same as #149
167 testhibition –fablab B,F(public),G(dayime)
Same as #149
168 testhibition –workshop B,F(public),G(dayime)
Same as #149
169 testhibition -atelier1 B,F(public),G(dayime)
Same as #149
170 testhibition -atelier2 B,F(public),G(dayime)
Same as #149
171 testhibition -digital lab B,F(public),G(dayime)
Same as #149
172 testhibition -digital lab-1 B,F(public),G(dayime)
Same as #149
173 observatory-woodshop B,F(public),G(dayime)
Same as #149
174 observatory –metalshop B,F(public),G(dayime)
Same as #149
175 observatory –fablab B,F(public),G(dayime)
Same as #149
176 observatory –workshop B,F(public),G(dayime)
Same as #149
177 observatory -atelier1 B,F(public),G(dayime)
Same as #149
178 observatory -atelier2 B,F(public),G(dayime)
Same as #149
179 observatory -digital lab B,F(public),G(dayime)
Same as #149

180 observatory -digital lab-1 B,F(public),G(dayime)
Same as #149
181 woodshop -digital lab B,C,F(public),G(daytime)
The relation between them is vague but there is also no reason to put them apart.
182 woodshop -digital lab-1 B,C,F(public),G(daytime)
Same as #181
183 woodshop –restaurant1 B,F(public),G(dayime)
Restaurant1 works during the day and open for the daily workers of production, performance and work zone; but specifically there is no direct relation between Restaurant1 and any of the design units these zones.
184 woodshop –printshop B,F(public),G(dayime)
Both design units are placed in the production zone but there is no direct relation between them.
185 woodshop –material&tool shop B,F(public),G(dayime)
Same as #184
186 woodshop –storage B,G(dayime)
Storage is necessary in the production zone, but there is no direct relation between the two design units.
187 metalshop -digital lab B,C,F(public),G(daytime)
Same as #181
188 metalshop -digital lab-1 B,C,F(public),G(daytime)
Same as #181
189 metalshop –restaurant1 B,F(public),G(dayime)
Same as #183
190 metalshop –printshop B,F(public),G(dayime)
Same as #184
191 metalshop –material&tool shop B,F(public),G(dayime)
Same as #184
192 metalshop –storage B,G(dayime)
Same as #186
193 fablab-digital lab B,C,F(public),G(daytime)
Same as #181
194 fablab -digital lab-1 B,C,F(public),G(daytime)
Same as #181
195 fablab –restaurant1 B,F(public),G(dayime)
Same as #183
196 fablab –printshop B,F(public),G(dayime)
Same as #184
197 fablab –material&tool shop B,F(public),G(dayime)
Same as #184
198 fablab –storage B,G(dayime)
Same as #186
199 workshop-digital lab B,C,F(public),G(daytime)
Same as #181
200 workshop -digital lab-1 B,C,F(public),G(daytime)
Same as #181
201 workshop –restaurant1 B,F(public),G(dayime)
Same as #183
202 workshop –printshop B,F(public),G(dayime)
Same as #184
203 workshop –material&tool shop B,F(public),G(dayime)
Same as #184
204 workshop –storage B,G(dayime)
Same as #186
205 atelier1-digital lab B,C,F(public),G(daytime)
Same as #181
206 atelier1-digital lab-1 B,C,F(public),G(daytime)
Same as #181
207 atelier1–restaurant1 B,F(public),G(dayime)
Same as #183
208 atelier1–printshop B,F(public),G(dayime)
Same as #184
209 atelier1 –material&tool shop B,F(public),G(dayime)
Same as #184
210 atelier1 –storage B,G(dayime)
Same as #186
211 atelier2-digital lab B,C,F(public),G(daytime)
Same as #181
212 atelier2-digital lab-1 B,C,F(public),G(daytime)
Same as #181
213 atelier2–restaurant1 B,F(public),G(dayime)
Same as #183
214 atelier2–printshop B,F(public),G(dayime)
Same as #184
215 atelier2 –material&tool shop B,F(public),G(dayime)
Same as #184

216 atelier2 –storage B,G(dayime)
Same as #186
217 digital lab–restaurant1 B,F(public),G(dayime)
Same as #183
218 digital lab-1–restaurant1 B,F(public),G(dayime)
Same as #183
219 black box theater & control room- recording studios B,C
Both design units are in performance zone, but there is no direct relation between them.
220 black box theater & control room- recording studios-1 B,C
Same as #219
221 black box theater & control room- large instrument B,C
Same as #219
222 black box theater & control room- percussion B,C
Same as #219
223 black box theater & control room- entrance F(public),G(daytime&nighttime)
Two design units are indirectly related because of the bbt lounge.
224 bbt lounge- recording studios C
Same as #219
225 bbt lounge - recording studios-1 C
Same as #219
226 bbt lounge - large instrument C
Same as #219
227 bbt lounge – percussion C
Same as #219
228 rehearsal hall & artist preparation- recording studios B,C
Same as #219
229 rehearsal hall & artist preparation- recording studios-1 B,C
Same as #219
230 rehearsal hall & artist preparation- large instrument B,C
Same as #219
231 rehearsal hall & artist preparation– percussion B,C
Same as #219
232 rehearsal hall & artist preparation– photographic studio B,C
Same as #219
233 rehearsal hall & artist preparation–restaurant2 G(nighttime)
Two design units are indirectly related because of the amphitheater.
234 recording studios-photographic studio B,C
Same as #219
235 recording studios-amphitheater B,C
Same as #219
236 recording studios-1-photographic studio B,C
Same as #219
237 recording studios-1-amphitheater B,C
Same as #219
238 large instrument-photographic studio B,C
Same as #219
239 large instrument-amphitheater B,C
Same as #219
240 percussion-photographic studio B,C
Same as #219
241 percussion –amphitheater B,C
Same as #219
242 lecture theater-periodicals B,F(public),G(daytime)
No direct relation exists between these design units but both of them are supposed to be in the production zone.
243 meeting-restaurant1 B,G(daytime)
Same as #183
244 meeting-entrance G(daytime)
Meeting could be rented to outsiders; therefore it should be easily reached from the entrance.
245 meeting lounge-office B,F(private),G(daytime)
Meeting lounge and offices are indirectly related design units in the work zone.
246 meeting lounge-office-1 B,F(private),G(daytime)
Same as #245
247 meeting lounge-office-2 B,F(private),G(daytime)
Same as #245
248 meeting lounge-office-3 B,F(private),G(daytime)
Same as #245
249 meeting lounge-restaurant1 G(daytime)
Same as #183
250 meeting lounge-entrance G(daytime)
Same as #244
251 office-restaurant1 B,G(daytime)
Same as #183
252 office-entrance G(daytime)

Same as #244	
253 office-1-restaurant1	B,G(daytime)
Same as #183	
254 office-1-entrance	G(daytime)
Same as #244	
255 office-2-restaurant1	B,G(daytime)
Same as #183	
256 office-2-entrance	G(daytime)
Same as #244	
257 office-3-restaurant1	B,G(daytime)
Same as #183	
258 office-3-entrance	G(daytime)
Same as #244	
259 periodicals-lecture theater-1	B,F(public),G(daytime)
Same as #242	
260 periodicals-lecture theater-2	B,F(public),G(daytime)
Same as #242	
261 periodicals-lecture theater-3	B,F(public),G(daytime)
Same as #242	
262 restaurant1-meeting-1	B,G(daytime)
Same as #183	
263 restaurant1-meeting-2	B,G(daytime)
Same as #183	
264 entrance-meeting-1	G(daytime)
Same as #244	
265 entrance-meeting-2	G(daytime)
Same as #244	

0/0

All units related with value 0	H

APPENDIX E

INTUITIVE REASONING OF FIXED COST INPUTS OF QAP

3 zones	2b, 2a, 1		
3 fixed cost input sets	Q 0,5,10,20	P 1,2,3,4	R 1,10,100,1000

Fixed Costs Inputs		*2b* Q/P/R	*2a* Q/P/R	*1* Q/P/R
1	Darkroom	20/4/1000	0/1/1	5/2/10
2	Lightroom	20/4/1000	10/3/100	0/1/1
3	Testhibition	20/4/1000	0/1/1	5/2/10
4	Observatory	20/4/1000	0/1/1	5/2/10
5	Woodshop	0/1/1	0/1/1	20/4/1000
6	Metalshop	0/1/1	0/1/1	20/4/1000
7	Fablab	0/1/1	0/1/1	20/4/1000
8	Workshop	0/1/1	0/1/1	20/4/1000
9	Atelier1	0/1/1	0/1/1	20/4/1000
10	Atelier2	0/1/1	0/1/1	20/4/1000
11	Digital Lab	0/1/1	0/1/1	20/4/1000
12	Digital Lab-1	0/1/1	0/1/1	20/4/1000
13	BBT & Control Room	20/4/1000	10/3/100	0/1/1
14	BBT Lounge	20/4/1000	10/3/100	0/1/1
15	Reh. Hall & Artist Prep.	20/4/1000	10/3/100	0/1/1
16	Recording Studios	0/1/1	0/1/1	20/4/1000
17	Recording Studios-1	0/1/1	0/1/1	20/4/1000
18	Large Instrument	0/1/1	0/1/1	20/4/1000
19	Percussion	0/1/1	0/1/1	20/4/1000
20	Photographic Studio	0/1/1	0/1/1	20/4/1000
21	Playground	0/1/1	0/1/1	20/4/1000
22	Amphitheater	20/4/1000	10/3/100	0/1/1
23	Lecture Theater	0/1/1	0/1/1	20/4/1000
24	Meeting	20/4/1000	10/3/100	0/1/1
25	Meeting Lounge	20/4/1000	10/3/100	0/1/1
26	Office	20/4/1000	10/3/100	0/1/1
27	Office-1	20/4/1000	10/3/100	0/1/1
28	Office-2	20/4/1000	10/3/100	0/1/1
29	Office-3	20/4/1000	10/3/100	0/1/1
30	Periodicals	0/1/1	0/1/1	20/4/1000
31	Restaurant1	0/1/1	0/1/1	20/4/1000
32	Kitchen1	0/1/1	0/1/1	20/4/1000
33	Kid Restaurant	0/1/1	0/1/1	20/4/1000
34	Restaurant2	20/4/1000	10/3/100	0/1/1
35	Kitchen2	20/4/1000	10/3/100	0/1/1
36	Administration	20/4/1000	0/1/1	0/1/1
37	Administration-1	20/4/1000	0/1/1	0/1/1
38	Printshop	0/1/1	0/1/1	20/4/1000
39	Material & Tool Shop	0/1/1	0/1/1	20/4/1000
40	Entrance	20/4/1000	20/4/1000	0/1/1
41	Skate Park	0/1/1	0/1/1	20/4/1000
42	Storage	0/1/1	0/1/1	20/4/1000
43	Rest	0/1/1	0/1/1	20/4/1000
44	Wc exhibit	20/4/1000	0/1/1	5/2/10
45	Wc produce	0/1/1	0/1/1	20/4/1000
46	Wc bbt lounge	20/4/1000	10/3/100	0/1/1
47	Wc artist preparation	20/4/1000	10/3/100	0/1/1
48	Wc perform	0/1/1	0/1/1	20/4/1000

49	Wc work	20/4/1000	0/1/1	0/1/1
50	Lecture Theater-1	0/1/1	0/1/1	20/4/1000
51	Lecture Theater-2	0/1/1	0/1/1	20/4/1000
52	Lecture Theater-3	0/1/1	0/1/1	20/4/1000
53	Meeting-1	20/4/1000	0/1/1	0/1/1
54	Meeting-2	20/4/1000	0/1/1	0/1/1

The reasonings

1 Darkroom is related with the Lightroom but Zone1 is not directly suitable for this design unit.
2 Lightroom was designed as the first design unit to be seen in the Exhibition Zone after passing from the Entrance.
3 Testhibition check #1
4 Observatory check #1
5 Woodshop check #8
6 Metalshop check #8
7 Fablab check #8
8 Workshop is a working area for both local community and creative class and is better to be placed away from the dense circulation of the village like Entrance, Exhibition halls, etc. so either 2a or 2b spots are suitable.
9 Atelier1 check #8
10 Atelier2 check #8
11 Digital lab check #8
12 Digital lab-1 check #8
13Black Box Theater and Control Room is related with the Entrance, to be directly reachable from the Entrance.
14 BBT Lounge check#13
15 Rehearsal Hall & Artist Preparation check#13
16 Rec studios check #8
17 Rec studios-1 check #8
18 Large instrument check #8
19 Percussion check #8
20 Photographic Studio check #8
21 Playground check #8
22 Amphitheater should be close to the main transportation axis as it will also function during the nights.
23 Lecture Theater check #8
24 Meeting can be both used by insiders and outsiders, so it is better to be close to entrance.
25 Meeting Lounge check #24
26 Office check #24
27 Office check #24
28 Office check #24
29 Office check #24
30 Periodicals check #8
31 Restaurant1 check #8
32 Kitchen1 check #8
33 Kid Restaurant check #8
34 Restaurant2 check #22
35 Kitchen2 check #22
36 Administration check #24
37 Administration-1 check #24
38 Printshop check #8
39 Material & Tool Shop check #8
40 Entrance should be direclty reached by the main transportation axis.
41 Skate Park check #8
42 Storage check #8
43 Rest check #8
44 Wc exhibit check #1
45 Wc produce check #8
46 Wc bbt lounge check #13
47 Wc artist preparation check #13
48 Wc perform check #8
49 Wc work check #24
50 Lecture Theater-1 check #8
51 Lecture Theater-2 check #8
52 Lecture Theater-3 check #8
53 Meeting-1 check #24
54 Meeting-2 check #24

APPENDIX F

OUTCOMES OF QAP OPTIMIZATIONS

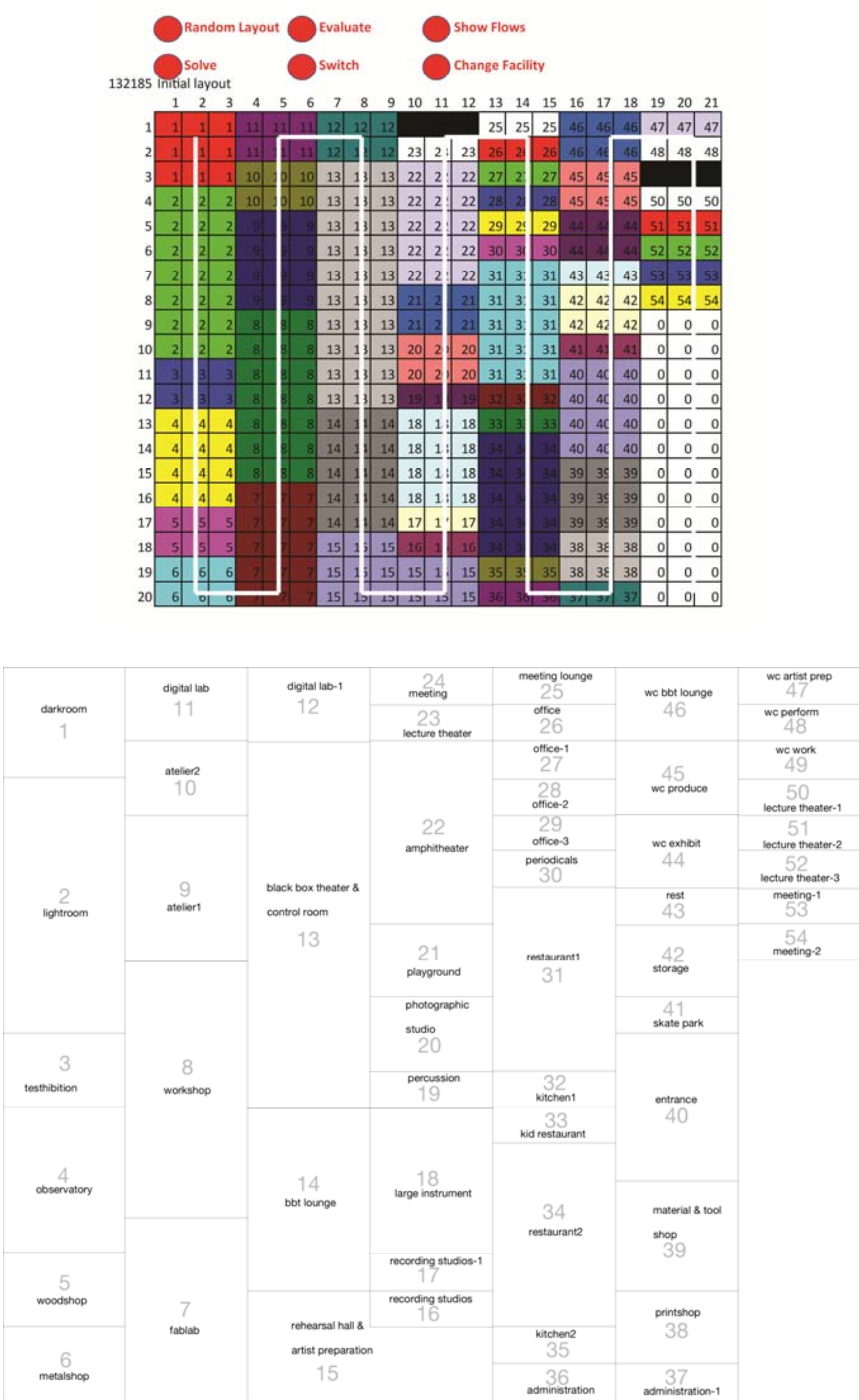
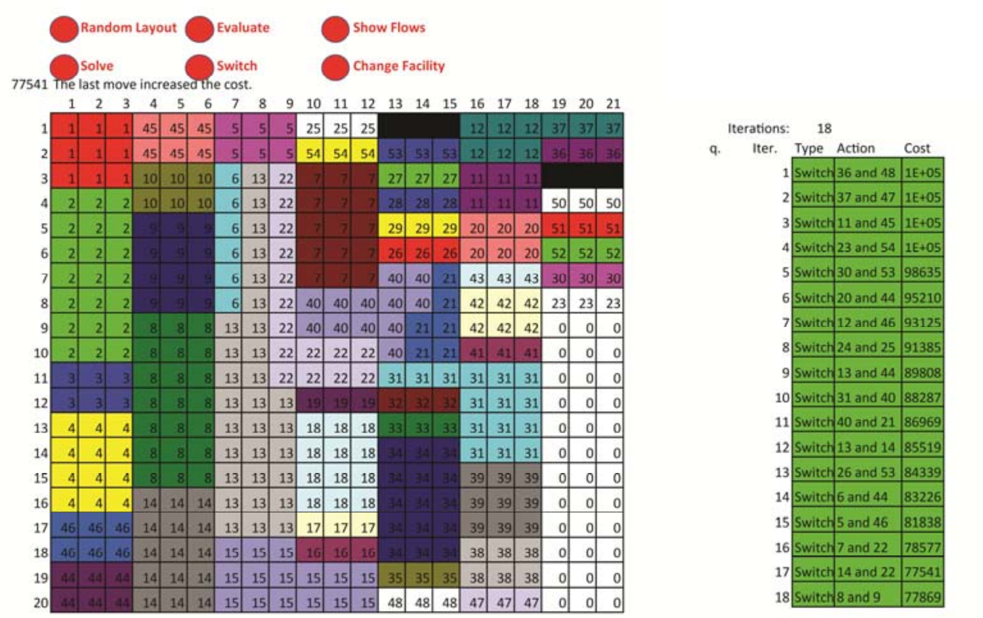


Figure F.47. Layout 0 FIXED (C) with a total cost of 132185. Drawn by the author.



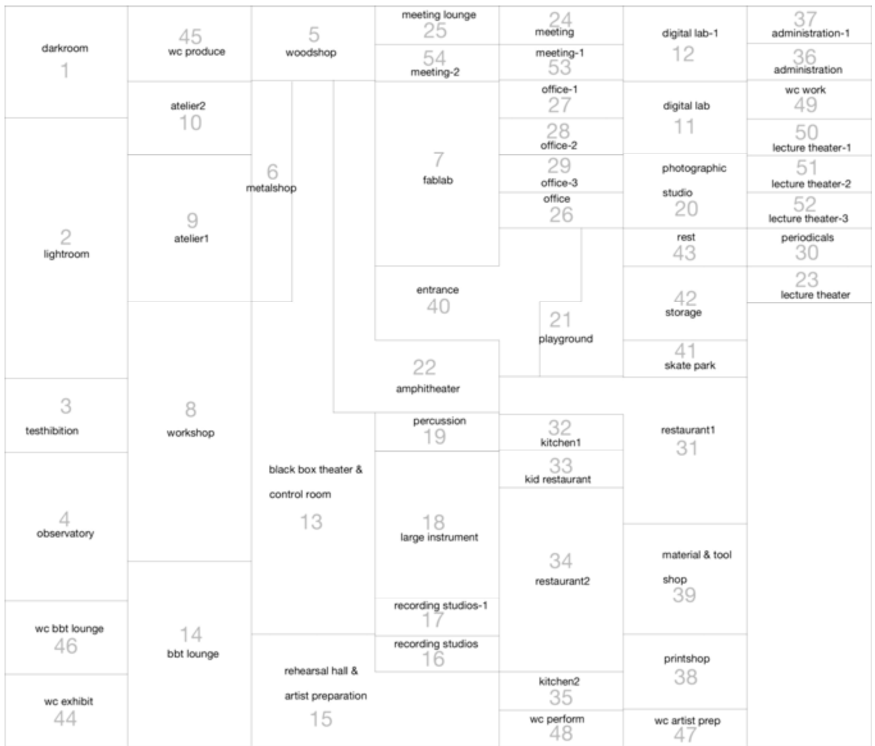


Figure F.48. Layout 0 FIXED OPT (D) with a total cost of 77541 was optimized using flow inputs 100, 20, 5, 1, 0. Drawn by the author.

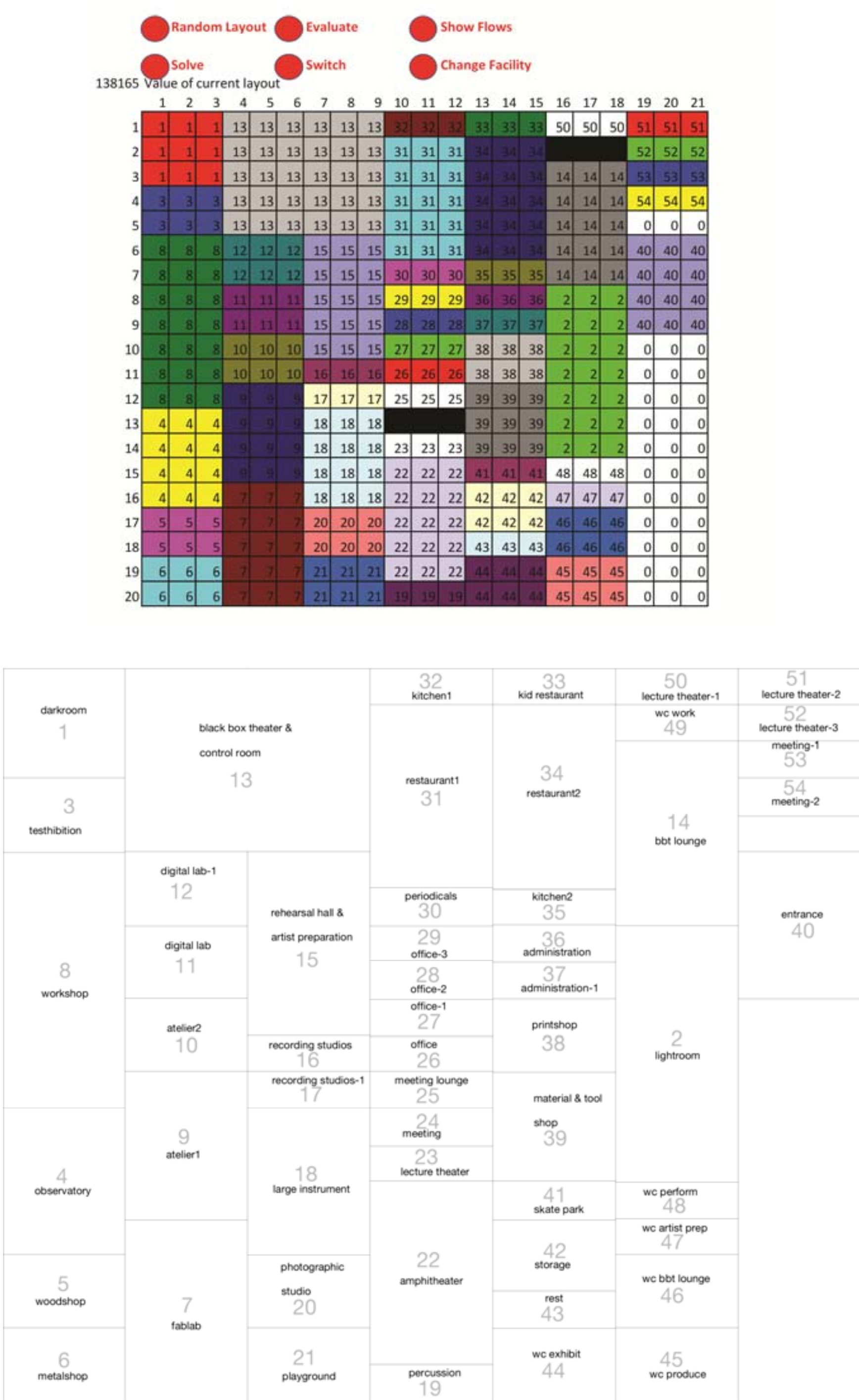
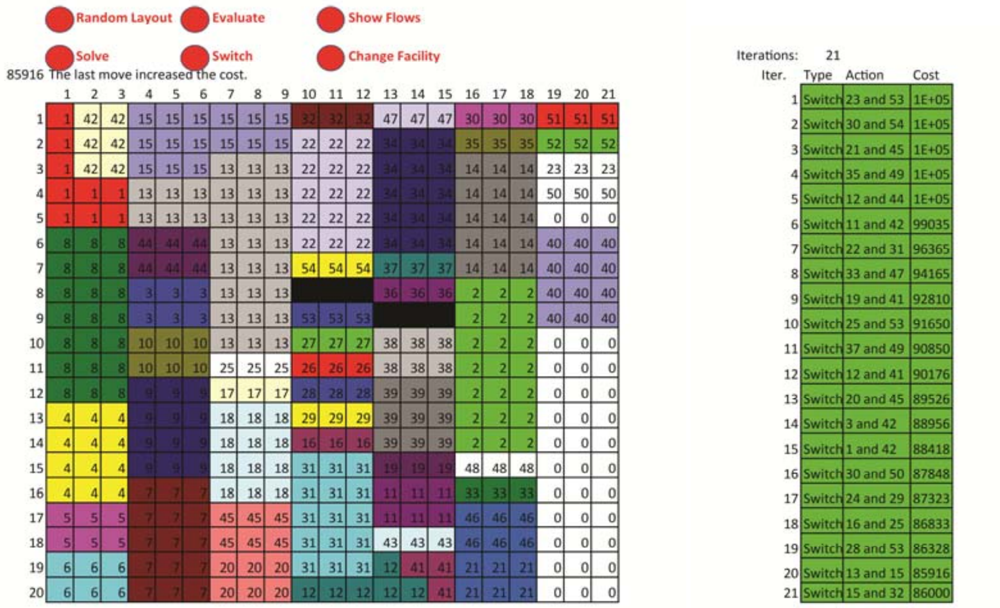


Figure F.49. Layout 4 FIXED with a total cost of 138165. Drawn by the author.


Random Layout Evaluate Show Flows
Solve Switch Change Facility
85916 The last move increased the cost.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	42	42	15	15	15	15	15	15	32	32	32	47	47	47	30	30	30	51	51	51
2	1	42	42	15	15	15	15	15	15	22	22	22	34	34	34	35	35	35	52	52	52
3	1	42	42	15	15	15	13	13	13	22	22	22	34	34	34	14	14	14	23	23	23
4	1	1	1	13	13	13	13	13	13	22	22	22	34	34	34	14	14	14	50	50	50
5	1	1	1	13	13	13	13	13	13	22	22	22	34	34	34	14	14	14	0	0	0
6	8	8	8	44	44	44	13	13	13	22	22	22	34	34	34	14	14	14	40	40	40
7	8	8	8	44	44	44	13	13	13	54	54	54	37	37	37	14	14	14	40	40	40
8	8	8	8	3	3	3	13	13	13				36	36	36	2	2	2	40	40	40
9	8	8	8	3	3	3	13	13	13	53	53	53				2	2	2	40	40	40
10	8	8	8	10	10	10	13	13	13	27	27	27	38	38	38	2	2	2	0	0	0
11	8	8	8	10	10	10	25	25	25	26	26	26	38	38	38	2	2	2	0	0	0
12	8	8	8	9	9	9	17	17	17	28	28	28	39	39	39	2	2	2	0	0	0
13	4	4	4	9	9	9	18	18	18	29	29	29	39	39	39	2	2	2	0	0	0
14	4	4	4	9	9	9	18	18	18	16	16	16	39	39	39	2	2	2	0	0	0
15	4	4	4	9	9	9	18	18	18	31	31	31	19	19	19	48	48	48	0	0	0
16	4	4	4	7	7	7	18	18	18	31	31	31	11	11	11	33	33	33	0	0	0
17	5	5	5	7	7	7	45	45	45	31	31	31	11	11	11	46	46	46	0	0	0
18	5	5	5	7	7	7	45	45	45	31	31	31	43	43	43	46	46	46	0	0	0
19	6	6	6	7	7	7	20	20	20	31	31	31	12	41	41	21	21	21	0	0	0
20	6	6	6	7	7	7	20	20	20	12	12	12	12	12	41	21	21	21	0	0	0

Iterations: 21

Iter.	Type	Action	Cost
1	Switch	23 and 53	1E+05
2	Switch	30 and 54	1E+05
3	Switch	21 and 45	1E+05
4	Switch	35 and 49	1E+05
5	Switch	12 and 44	1E+05
6	Switch	11 and 42	99035
7	Switch	22 and 31	96365
8	Switch	33 and 47	94165
9	Switch	19 and 41	92810
10	Switch	25 and 53	91650
11	Switch	37 and 49	90850
12	Switch	12 and 41	90176
13	Switch	20 and 45	89526
14	Switch	3 and 42	88956
15	Switch	1 and 42	88418
16	Switch	30 and 50	87848
17	Switch	24 and 29	87323
18	Switch	16 and 25	86833
19	Switch	28 and 53	86328
20	Switch	13 and 15	85916
21	Switch	15 and 32	86000

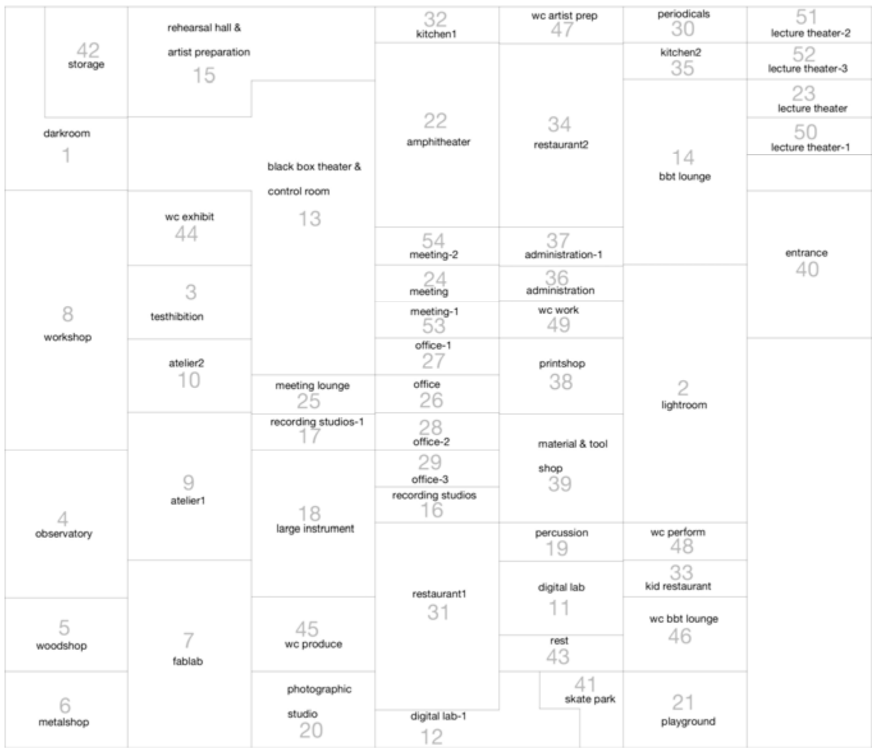


Figure F.50. Layout 4 FIXED OPT with a total cost of 85916 was optimized using flow inputs 100, 20, 5, 1, 0. Drawn by the author.

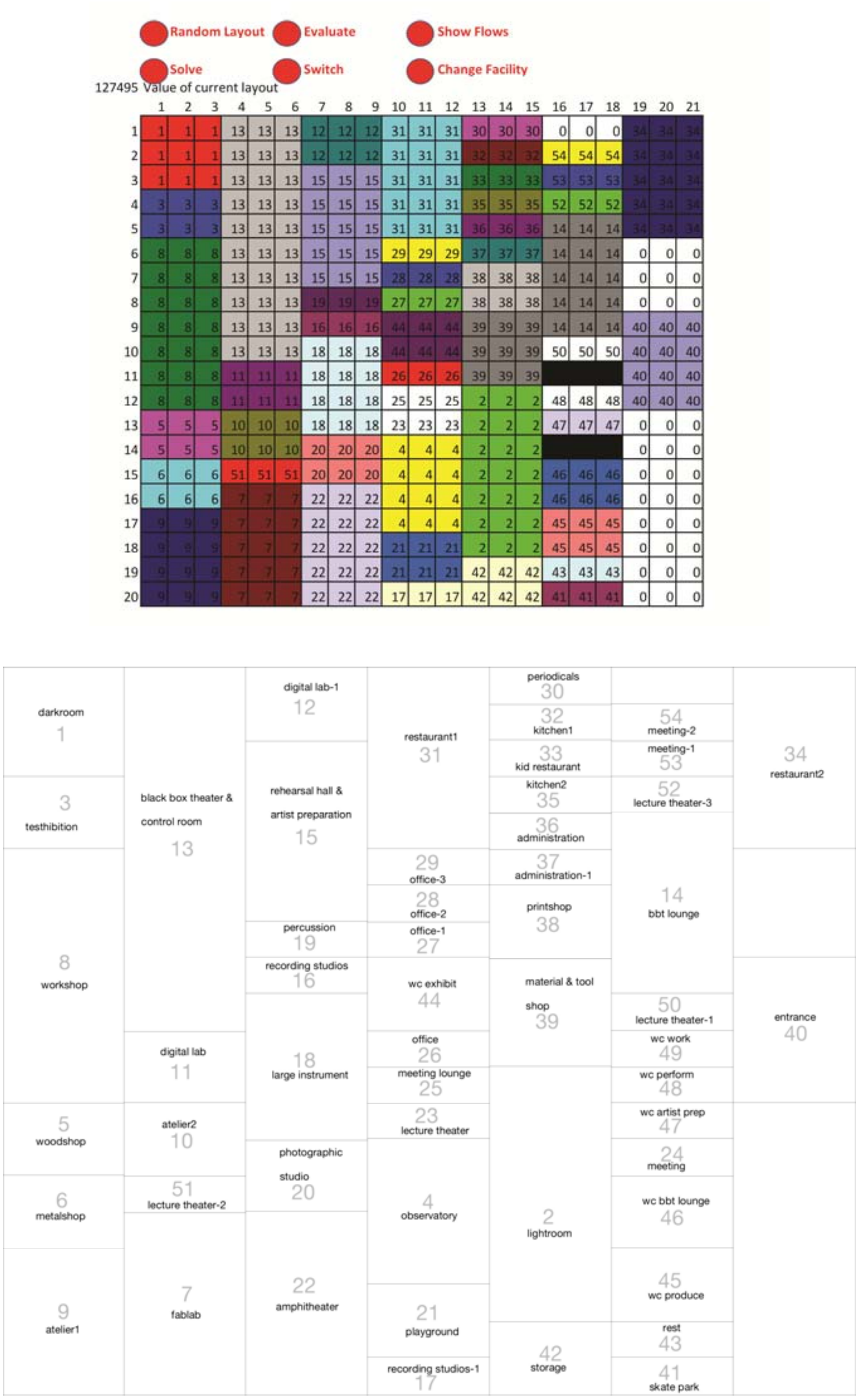


Figure F.51. Layout 10 FIXED with a total cost of 127495. Drawn by the author.

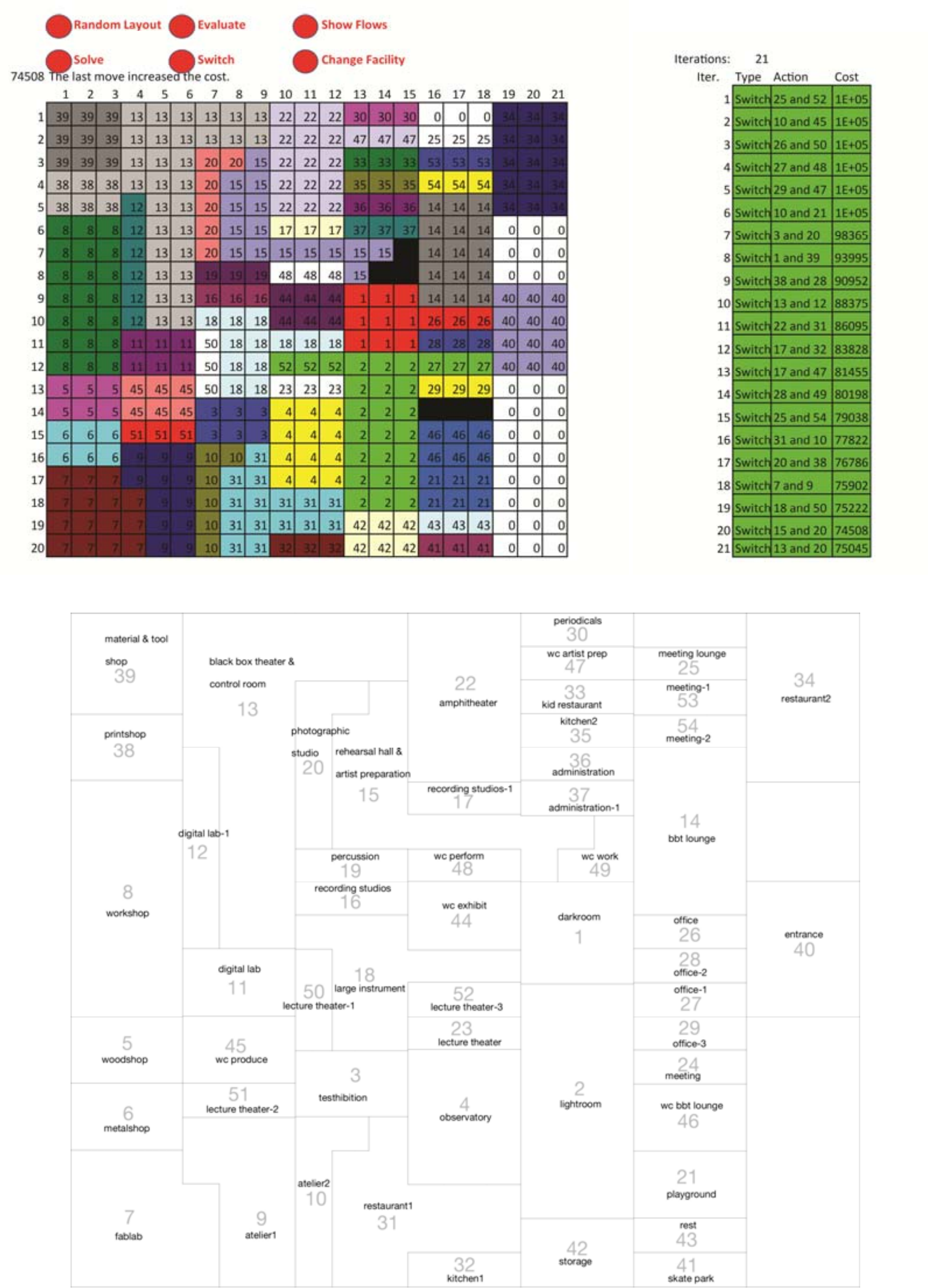


Figure F.52. Layout 10 FIXED OPT with a total cost of 74508 was optimized using flow inputs 100, 20, 5, 1, 0. Drawn by the author.

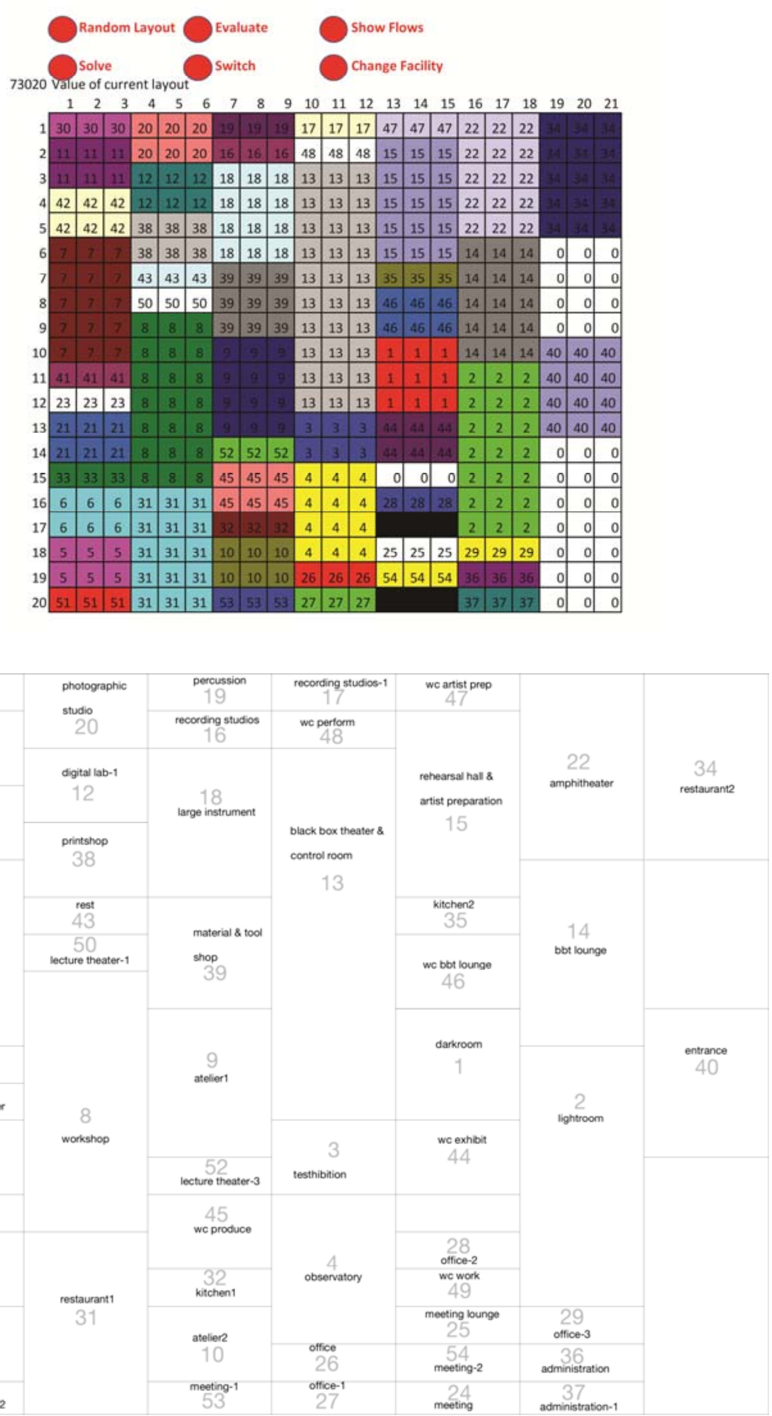


Figure F.53. Layout P5 LAYOUT (A) with a total cost of 73020. Drawn by the author.

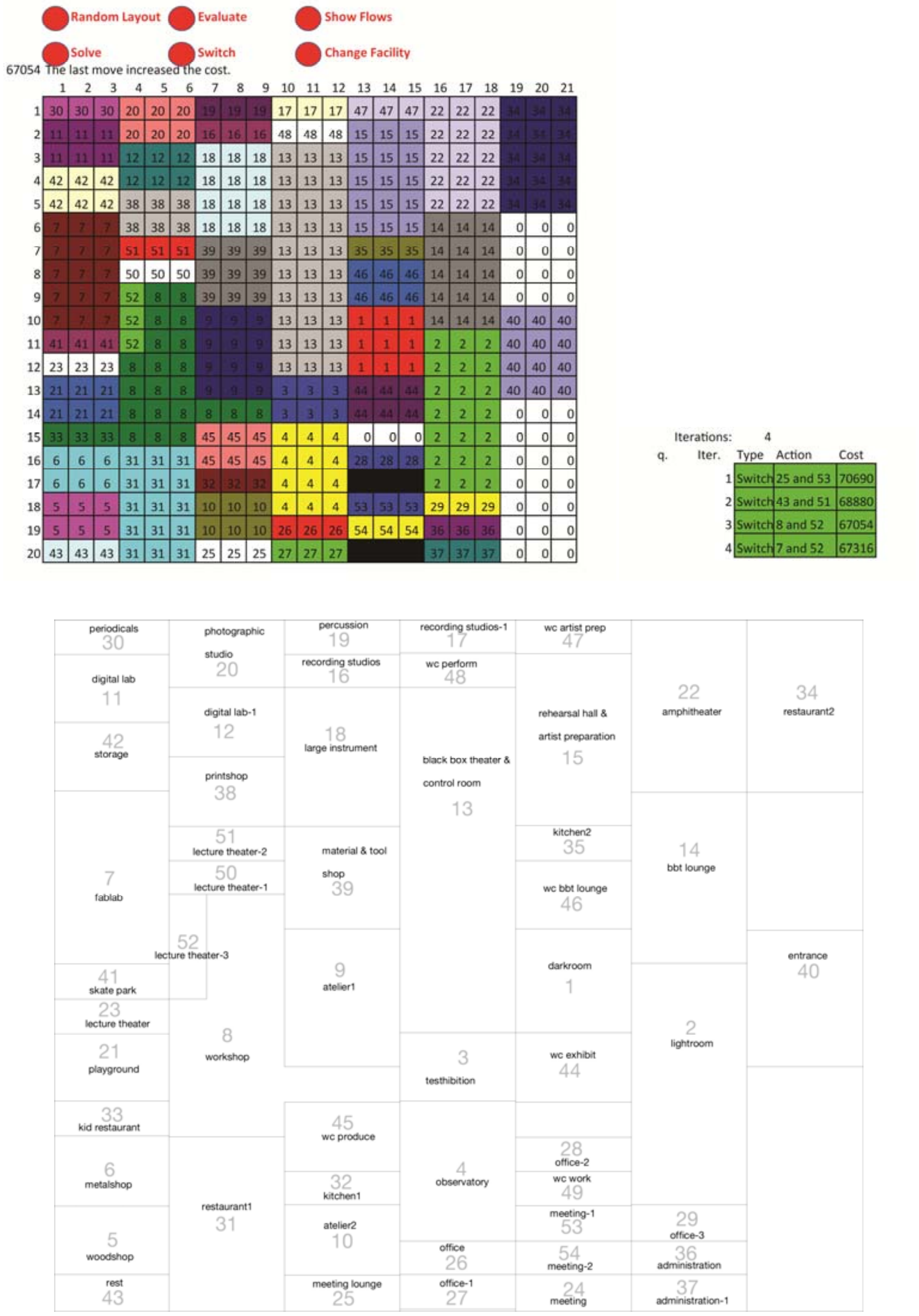


Figure F.54. Layout P5 LAYOUT OPT (B) with a total cost of 67054 was optimized using flow inputs 100, 20, 5, 1, 0. Drawn by the author.

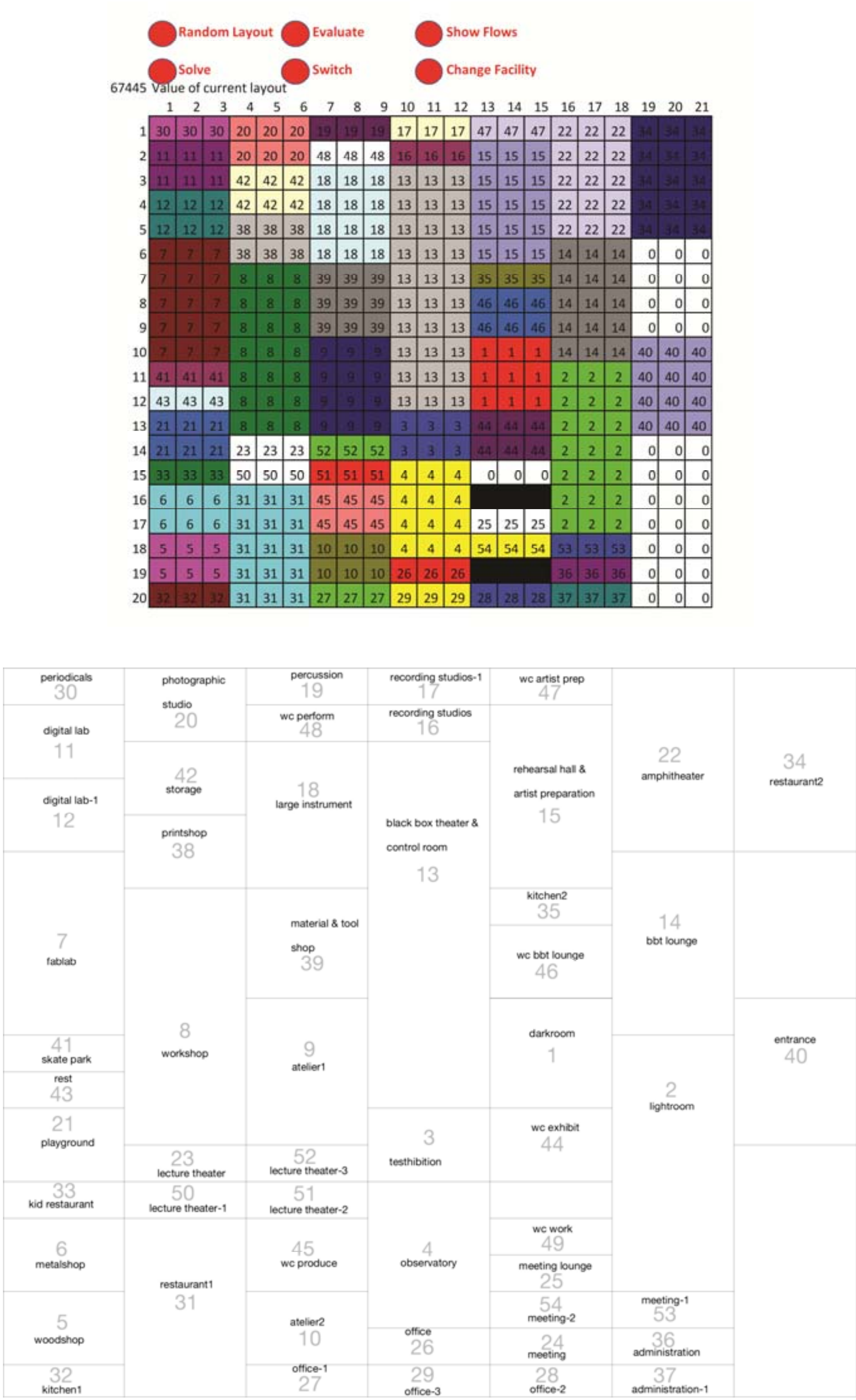


Figure F.55. Layout P5 LAYOUT ID U ADJ (A1) with a total cost of 67445. Drawn by the author.

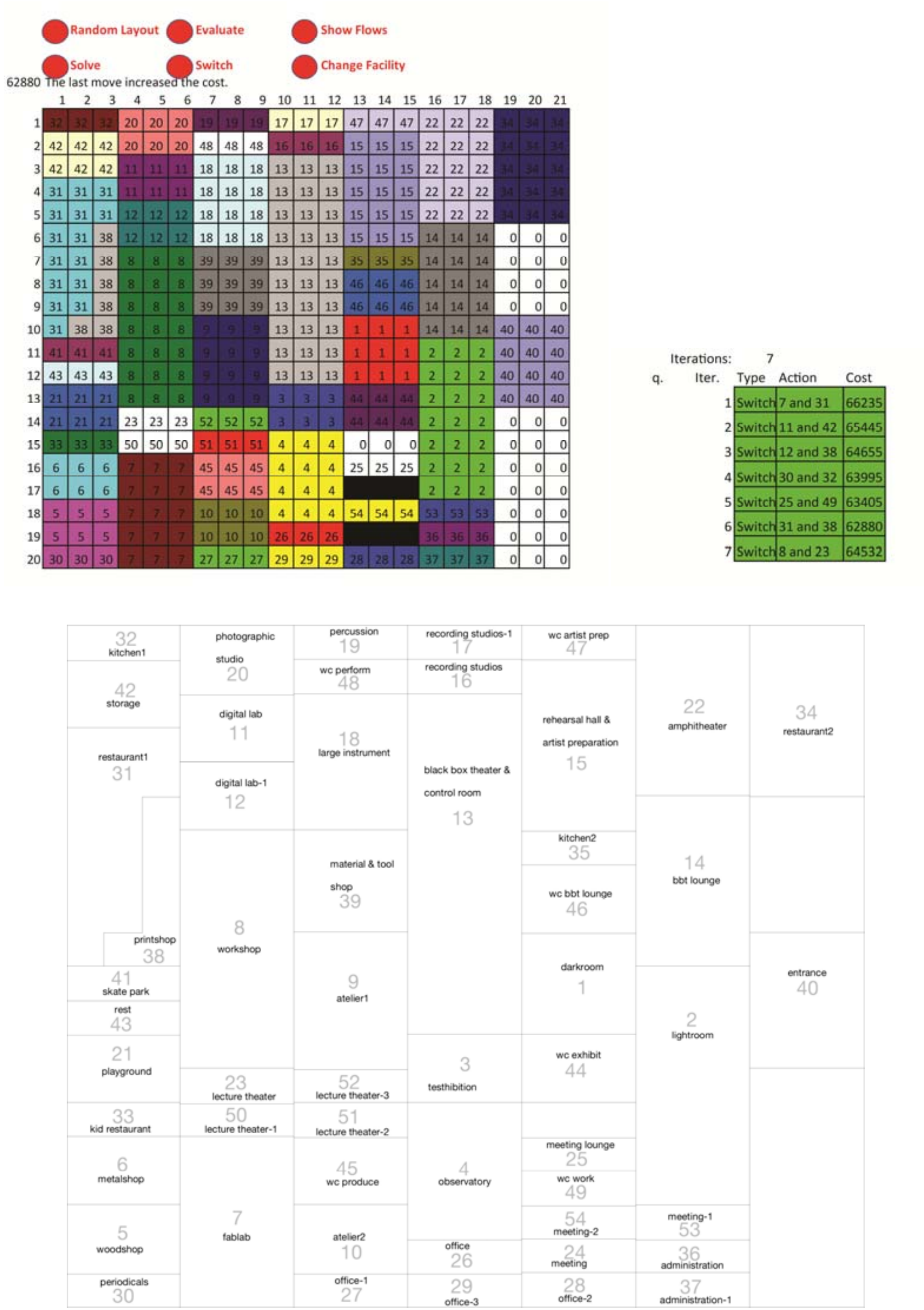


Figure F.56. Layout P5 LAYOUT ID U ADJ OPT (A2) with a total cost of 62880 was optimized using flow inputs 100, 20, 5, 1, 0. Drawn by the author.

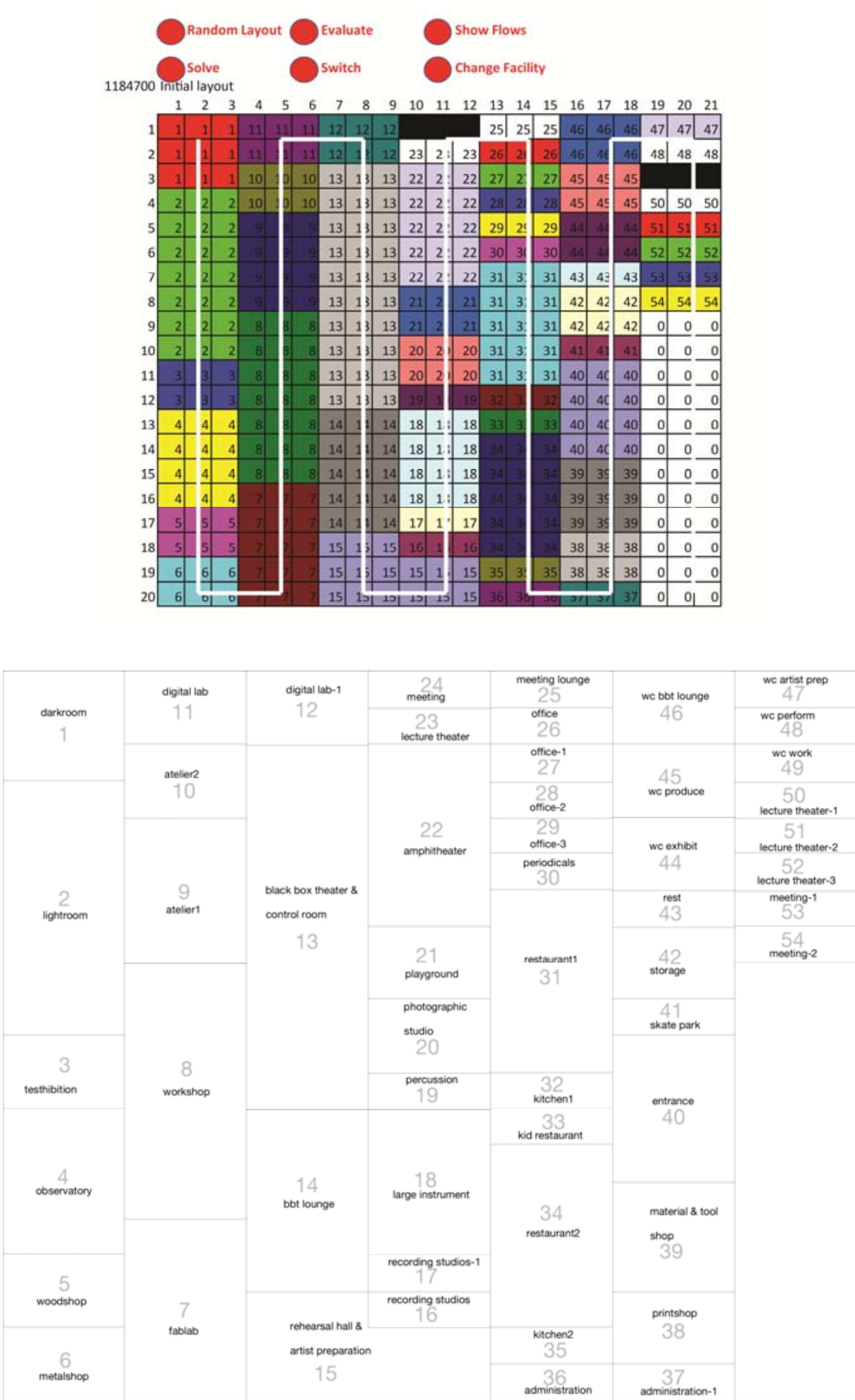


Figure F.57. Layout 0 FIXED (C) with a total cost of 1184700. Drawn by the author.

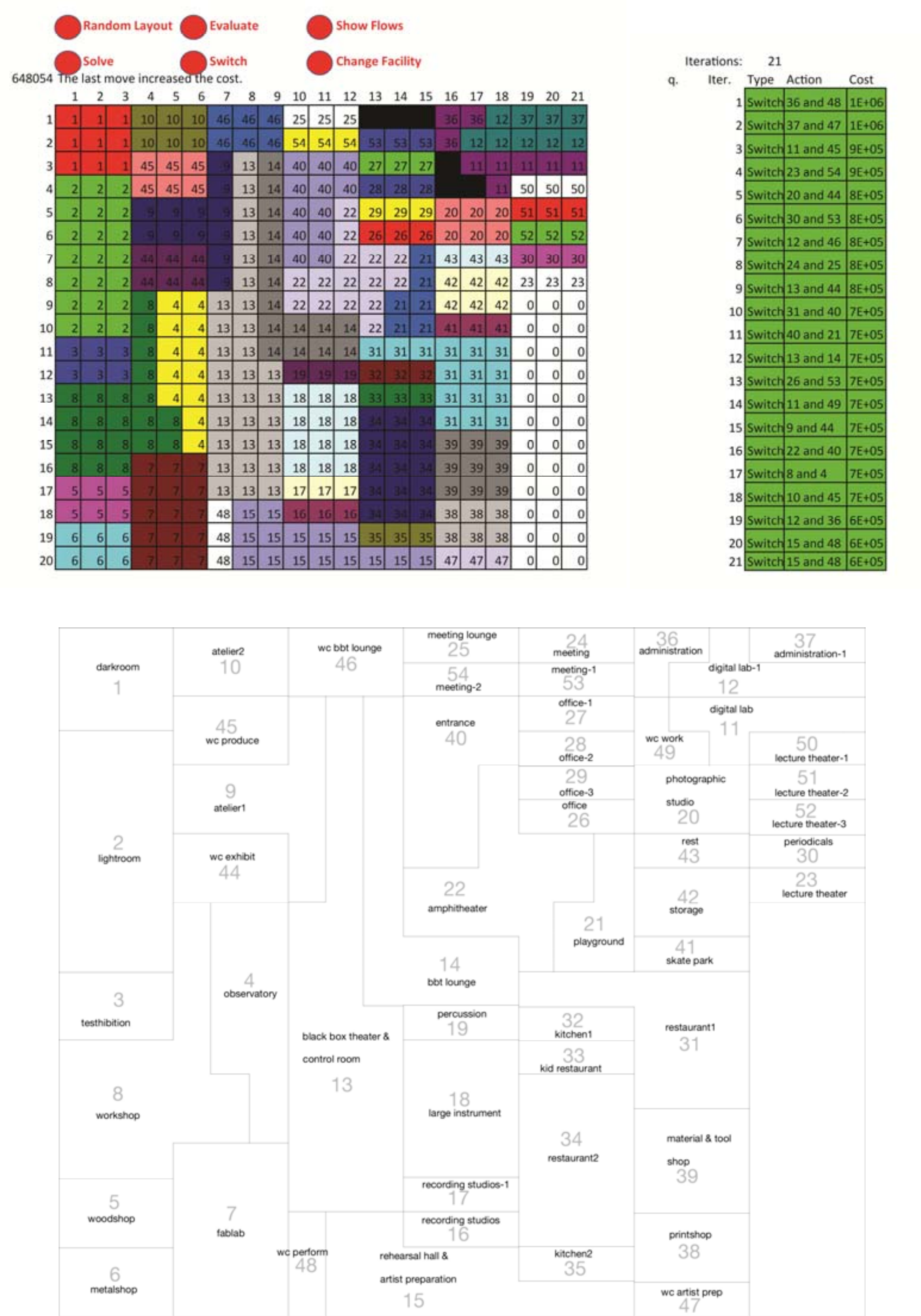


Figure F.58. Layout 0 FIXED OPT (D) with a total cost of 648054 was optimized using flow inputs 1000, 100, 10, 1, 0. Drawn by the author.

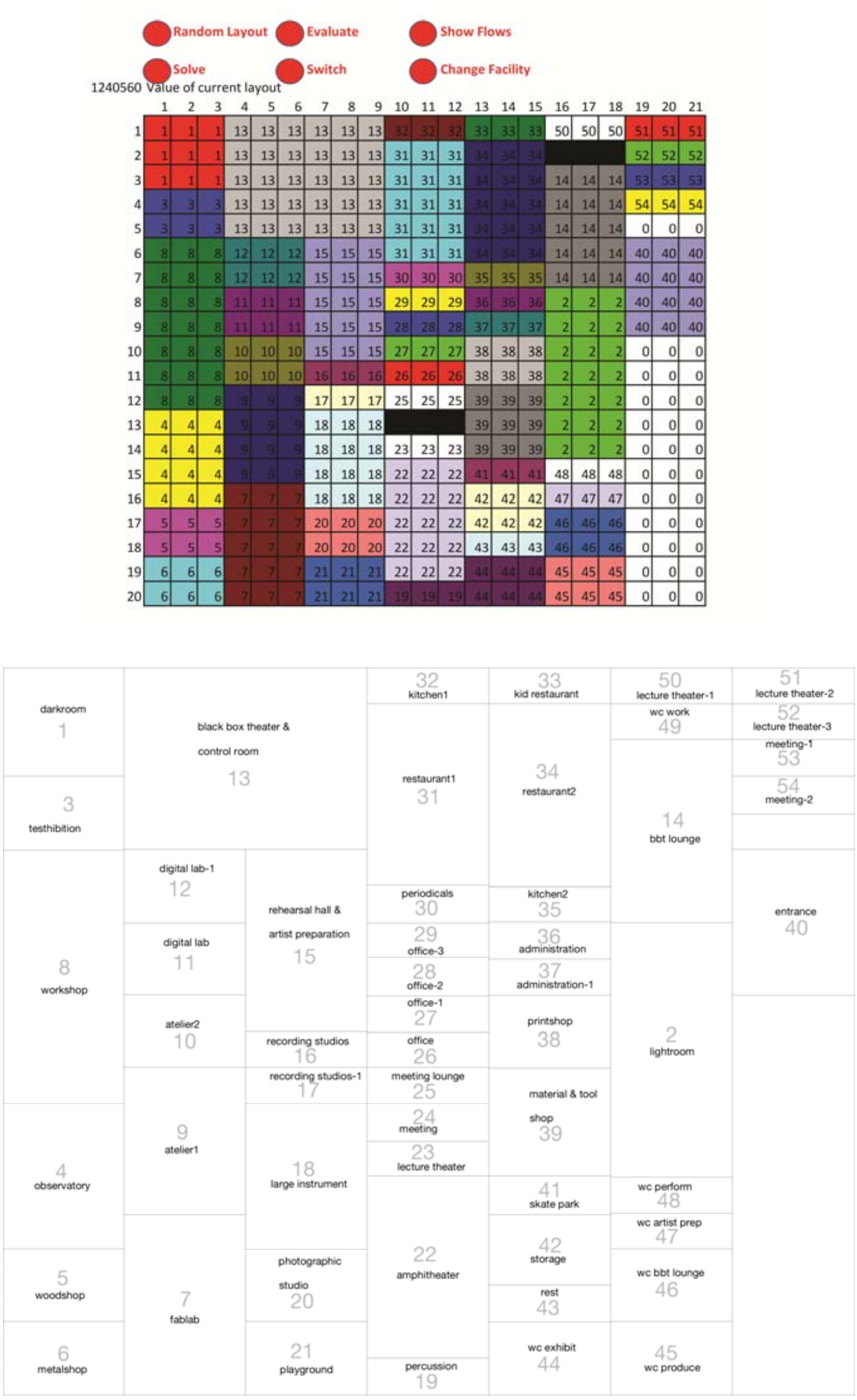


Figure F.59. Layout 4 FIXED with a total cost of 1240560. Drawn by the author.

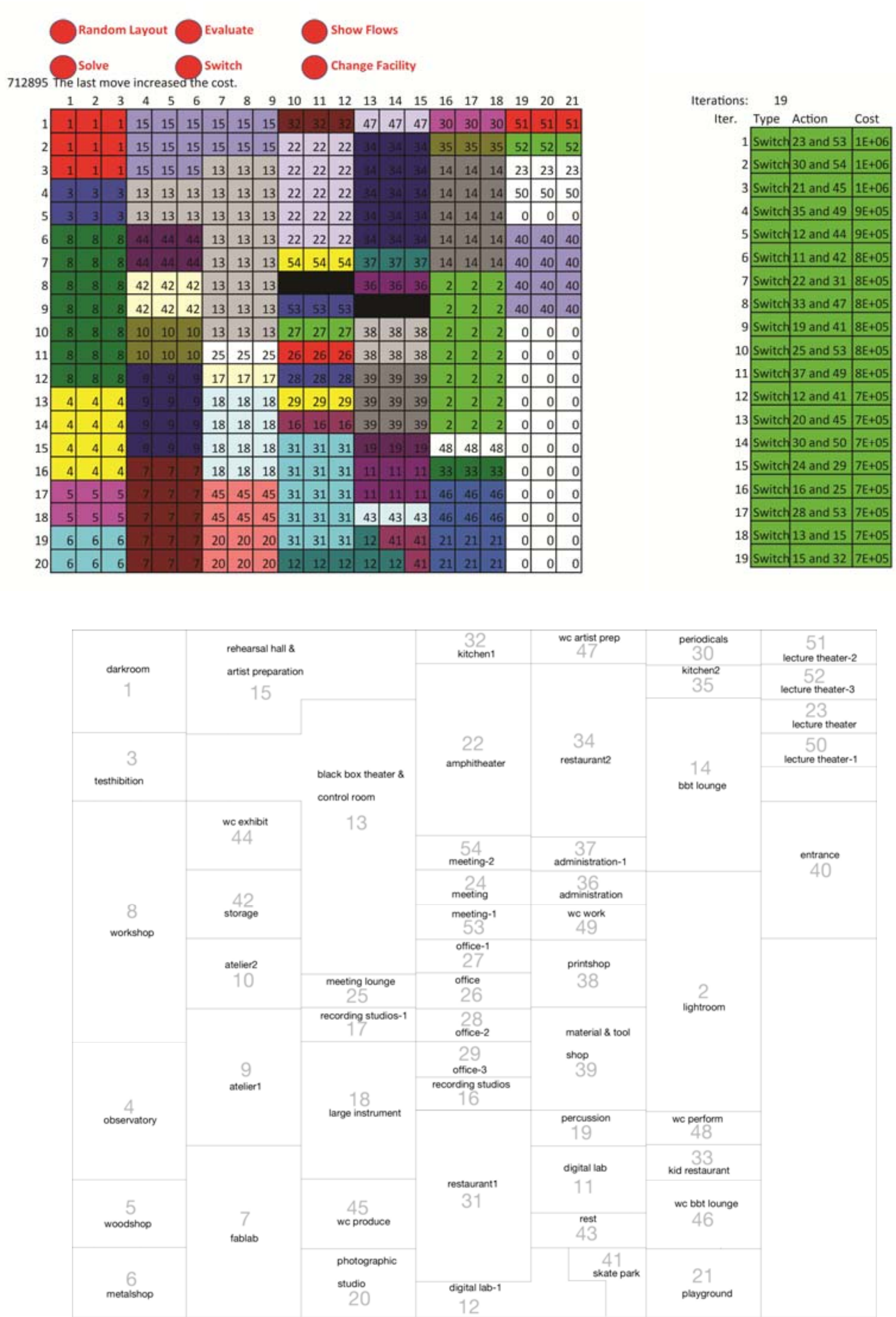


Figure F.60. Layout 4 FIXED OPT with a total cost of 712895 was optimized using flow inputs 1000, 100, 10, 1, 0. Drawn by the author.

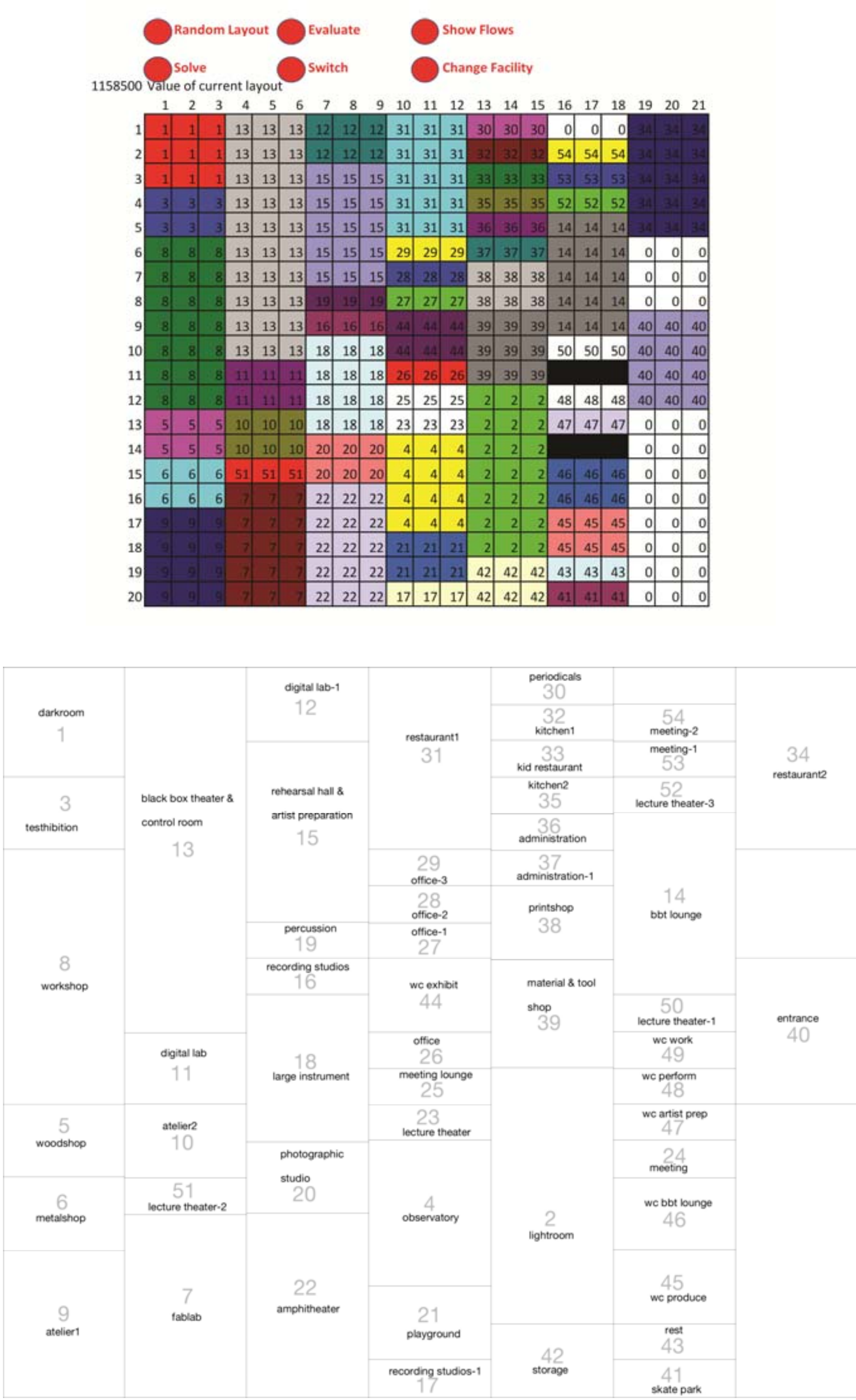


Figure F.61. Layout 10 FIXED with a total cost of 1158500. Drawn by the author.

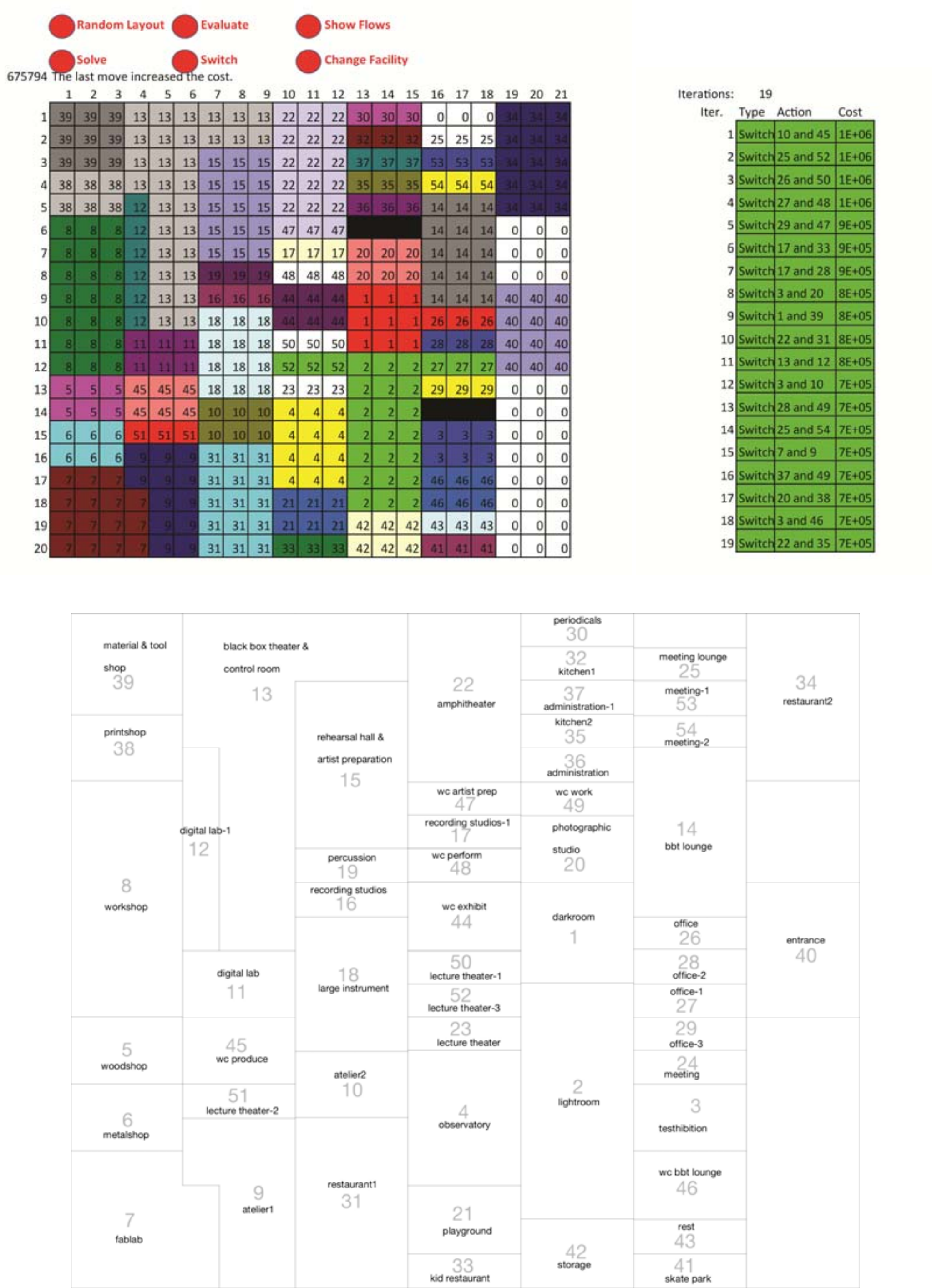


Figure F.62. Layout 10 FIXED OPT with a total cost of 675794 was optimized using flow inputs 1000, 100, 10, 1, 0. Drawn by the author.

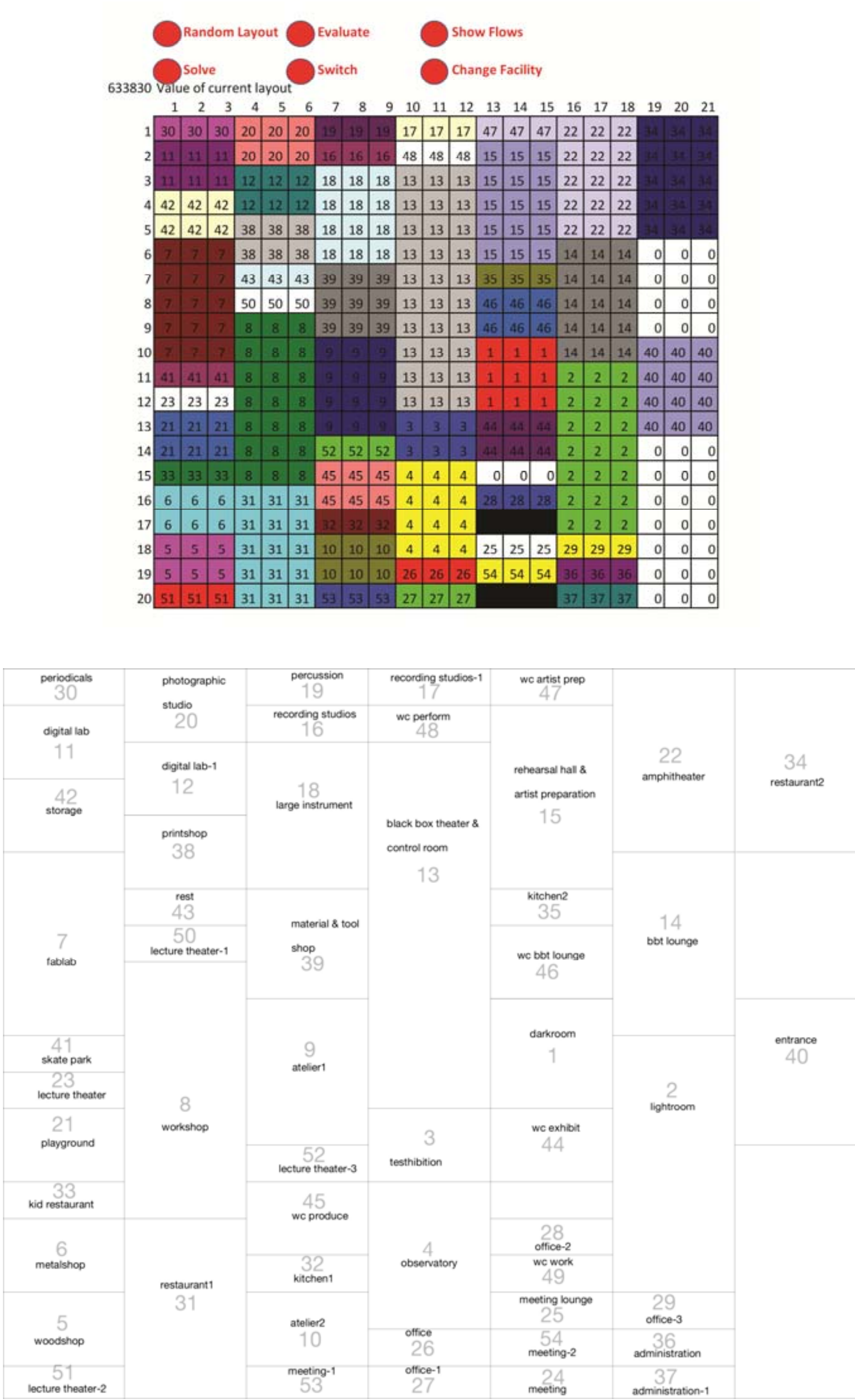


Figure F.63. Layout P5 LAYOUT (A) with a total cost of 633830. Drawn by the author.

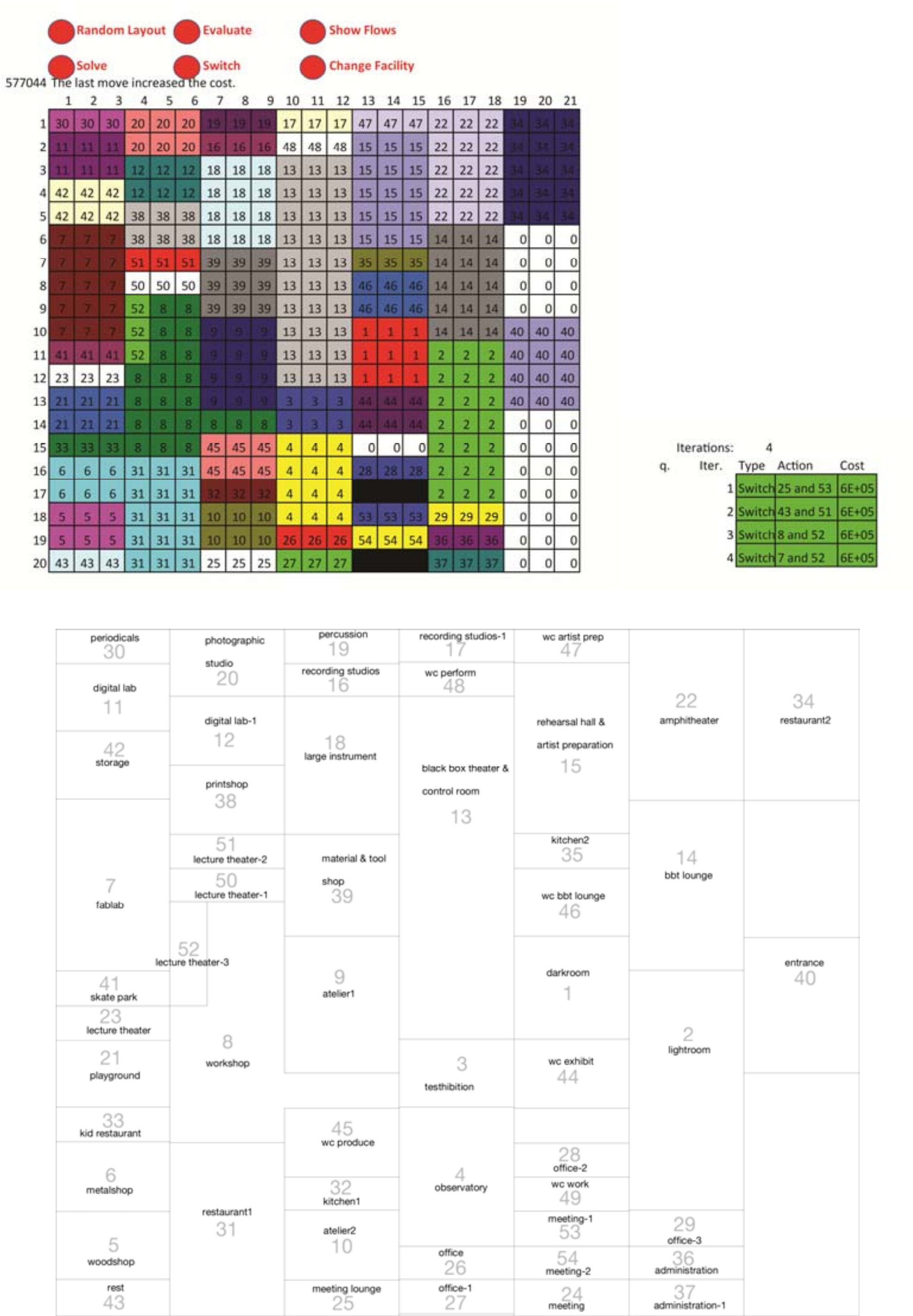


Figure F.64. Layout P5 LAYOUT OPT (B) with a total cost of 577044 was optimized using flow inputs 1000, 100, 10, 1, 0. Drawn by the author.

576140 Value of current layout

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	30	30	30	20	20	20	19	19	19	17	17	17	47	47	47	22	22	22	34	34	34
2	11	11	11	20	20	20	48	48	48	16	16	16	15	15	15	22	22	22	34	34	34
3	11	11	11	42	42	42	18	18	18	13	13	13	15	15	15	22	22	22	34	34	34
4	12	12	12	42	42	42	18	18	18	13	13	13	15	15	15	22	22	22	34	34	34
5	12	12	12	38	38	38	18	18	18	13	13	13	15	15	15	22	22	22	34	34	34
6	7	7	7	38	38	38	18	18	18	13	13	13	15	15	15	14	14	14	0	0	0
7	7	7	7	8	8	8	39	39	39	13	13	13	35	35	35	14	14	14	0	0	0
8	7	7	7	8	8	8	39	39	39	13	13	13	46	46	46	14	14	14	0	0	0
9	7	7	7	8	8	8	39	39	39	13	13	13	46	46	46	14	14	14	0	0	0
10	7	7	7	8	8	8	9	9	9	13	13	13	1	1	1	14	14	14	40	40	40
11	41	41	41	8	8	8	9	9	9	13	13	13	1	1	1	2	2	2	40	40	40
12	43	43	43	8	8	8	9	9	9	13	13	13	1	1	1	2	2	2	40	40	40
13	21	21	21	8	8	8	9	9	9	3	3	3	44	44	44	2	2	2	40	40	40
14	21	21	21	23	23	23	52	52	52	3	3	3	44	44	44	2	2	2	0	0	0
15	33	33	33	50	50	50	51	51	51	4	4	4	0	0	0	2	2	2	0	0	0
16	6	6	6	31	31	31	45	45	45	4	4	4				2	2	2	0	0	0
17	6	6	6	31	31	31	45	45	45	4	4	4	25	25	25	2	2	2	0	0	0
18	5	5	5	31	31	31	10	10	10	4	4	4	54	54	54	53	53	53	0	0	0
19	5	5	5	31	31	31	10	10	10	26	26	26				36	36	36	0	0	0
20	32	32	32	31	31	31	27	27	27	29	29	29	28	28	28	37	37	37	0	0	0

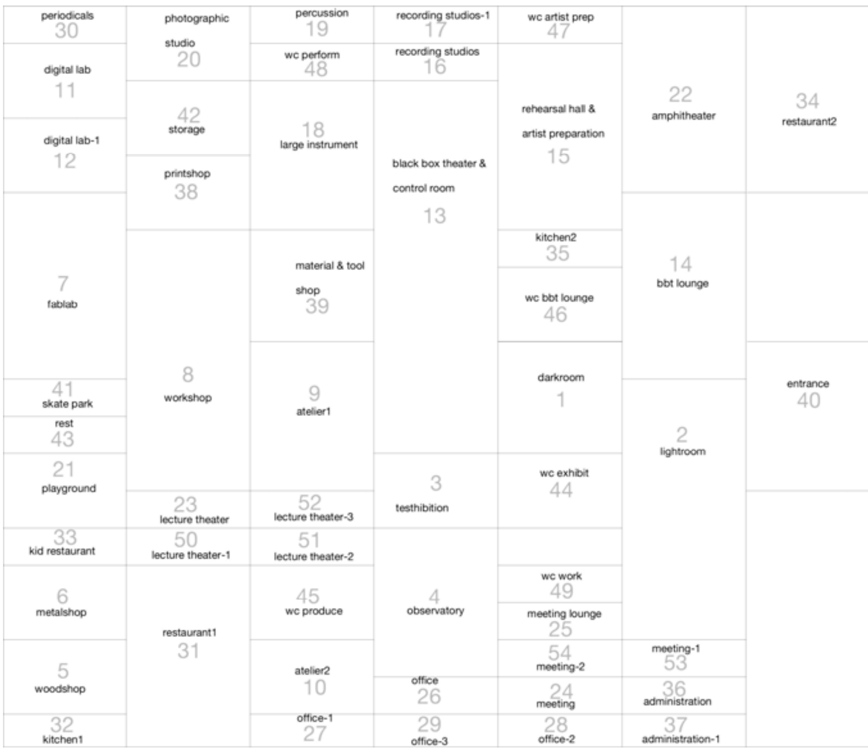


Figure F.65. Layout P5 LAYOUT ID U ADJ (A1) with a total cost of 576140. Drawn by the author.

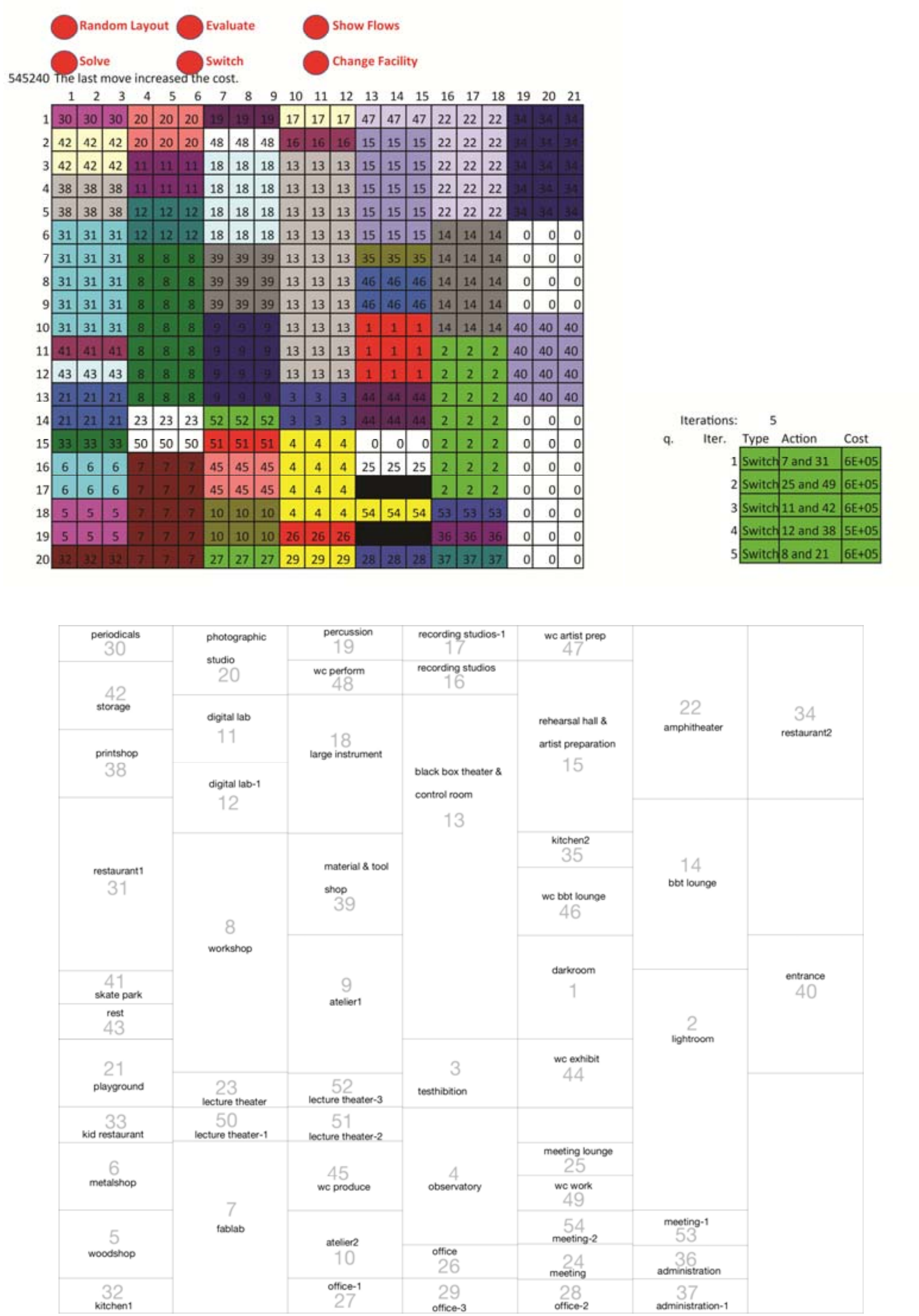


Figure F.66. Layout P5 LAYOUT ID U ADJ OPT (A2) with a total cost of 545240 was optimized using flow inputs 1000, 100, 10, 1, 0. Drawn by the author.

APPENDIX G

FIXED COST CALCULATIONS OF QAP OPTIMIZATIONS

Table G.18. Fixed costs of all design units are shown according to their locations in the layouts.

same as 1 FIXED COSTS
1=(100,20,5,1,0)
2=(1000,100,10,1,0)

	UNIT	4FIX	10FIX	0FIX (C) Q 1	0FIX (C) P 1	0FIX (C) R 1	0FIX OPT (D) Q 1	Q 2	P 1	P 2	R 1	R 2
	layout cost 1 / 2				132185	1184700			77541		648054	
1	70 darkroom			20	4	1000	20	20	4	4	1000	1000
2	200 lightroom	X	X	20	4	1000	20	20	4	4	1000	1000
3	50 testhibition			20	4	1000	20	20	4	4	1000	1000
4	100 observatory		X	20	4	1000	20	20	4	4	1000	1000
5	50 woodshop			0	1	1	0	0	1	1	1	1
6	50 metalshop			0	1	1	0	0	1	1	1	1
7	150 fablab			0	1	1	0	0	1	1	1	1
8	200 workshop	X	X	0	1	1	0	0	1	1	1	1
9	100 atelier1			0	1	1	0	0	1	1	1	1
10	50 atelier2			0	1	1	0	0	1	1	1	1
11	50 digital lab			0	1	1	20	20	4	4	1000	1000
12	50 digital lab-1			0	1	1	20	20	4	4	1000	1000
13	300 black box theater & control room			10	3	100	10	10	3	3	100	100
14	150 bbt lounge	X	X	10	3	100	20	10	4	3	1000	100
15	150 rehearsal hall & artist preparation			10	3	100	10	10	3	3	100	100
16	30 recording studios			0	1	1	0	0	1	1	1	1
17	30 recording studios-1			0	1	1	0	0	1	1	1	1
18	100 large instrument			0	1	1	0	0	1	1	1	1
19	30 percussion		X	0	1	1	0	0	1	1	1	1
20	50 photographic studio			0	1	1	0	0	1	1	1	1
21	50 playground			0	1	1	0	0	1	1	1	1
22	150 amphitheater			10	3	100	10	10	3	3	100	100
23	30 lecture theater			0	1	1	0	0	1	1	1	1
24	30 meeting		X	0	1	1	20	20	4	4	1000	1000
25	20 meeting lounge			0	1	1	0	0	1	1	1	1
26	30 office			0	1	1	0	0	1	1	1	1
27	30 office-1			0	1	1	0	0	1	1	1	1
28	30 office-2			0	1	1	0	0	1	1	1	1
29	30 office-3			0	1	1	0	0	1	1	1	1
30	30 periodicals			20	4	1000	20	20	4	4	1000	1000
31	150 restaurant1			20	4	1000	20	20	4	4	1000	1000
32	30 kitchen1			20	4	1000	20	20	4	4	1000	1000
33	10 kid restaurant			20	4	1000	20	20	4	4	1000	1000
34	150 restaurant2		X	0	1	1	0	0	1	1	1	1
35	30 kitchen2			0	1	1	0	0	1	1	1	1
36	30 administration			0	1	1	0	0	1	1	1	1
37	30 administration-1			0	1	1	0	0	1	1	1	1
38	50 printshop			20	4	1000	20	20	4	4	1000	1000
39	80 material & tool shop			20	4	1000	20	20	4	4	1000	1000
40	100 entrance	X	X	0	1	1	20	20	4	4	1000	1000
41	30 scate park			20	4	1000	20	20	4	4	1000	1000
42	50 storage			20	4	1000	20	20	4	4	1000	1000
43	20 rest			20	4	1000	20	20	4	4	1000	1000
44	50 wc exhibit		X	5	2	10	20	20	4	4	1000	1000
45	50 wc produce			20	4	1000	0	0	1	1	1	1
46	50 wc bbt lounge			0	1	1	20	10	4	3	1000	100
47	30 wc artist preperation			0	1	1	0	0	1	1	1	1
48	30 wc perform			20	4	1000	20	0	4	1	1000	1
49	30 wc work			0	1	1	0	0	1	1	1	1
50	30 lecture theater-1			20	4	1000	20	20	4	4	1000	1000
51	30 lecture theater-2		X	20	4	1000	20	20	4	4	1000	1000
52	30 lecture theater-3			20	4	1000	20	20	4	4	1000	1000
53	30 meeting-1			0	1	1	0	0	1	1	1	1
54	30 meeting-2			0	1	1	0	0	1	1	1	1
				405	117	18441	510	470	132	127	24327	21528

	4FIX Q 1	4FIX P 1	4FIX R 1	4FIX OPT Q 1	Q 2	P 1	P 2	R 1	R 2	10FIX Q 1	10FIX P 1	10FIX R 1	10FIX OPT Q 1	Q 2	P 1	P 2	R 1	R 2
layout cost 1 / 2		138165	1240560			85915.5		712895			127495	1158500			74508		675794	
1	20	4	1000	20	20	4	4	1000	1000	20	4	1000	5	5	2	2	10	10
2	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
3	20	4	1000	20	20	4	4	1000	1000	20	4	1000	0	5	1	2	1	10
4	20	4	1000	20	20	4	4	1000	1000	0	1	1	0	0	1	1	1	1
5	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
6	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
7	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
8	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
9	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
10	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
11	0	1	1	20	20	4	4	1000	1000	0	1	1	0	0	1	1	1	1
12	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
13	20	4	1000	10	10	3	3	100	100	20	4	1000	20	20	4	4	1000	1000
14	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
15	10	3	100	20	20	4	4	1000	1000	10	3	100	10	10	3	3	100	100
16	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
17	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
18	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
19	0	1	1	20	20	4	4	1000	1000	0	1	1	0	0	1	1	1	1
20	0	1	1	0	0	1	1	1	1	0	1	1	0	20	1	4	1	1000
21	0	1	1	20	20	4	4	1000	1000	0	1	1	20	0	4	1	1000	1
22	10	3	100	10	10	3	3	100	100	10	3	100	10	10	3	3	100	100
23	0	1	1	20	20	4	4	1000	1000	0	1	1	0	0	1	1	1	1
24	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
25	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
26	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
27	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
28	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
29	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
30	0	1	1	20	20	4	4	1000	1000	20	4	1000	20	20	4	4	1000	1000
31	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
32	0	1	1	0	0	1	1	1	1	20	4	1000	0	20	1	4	1	1000
33	20	4	1000	20	20	4	4	1000	1000	20	4	1000	20	0	4	1	1000	1
34	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
35	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
36	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
37	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
38	20	4	1000	20	20	4	4	1000	1000	20	4	1000	0	0	1	1	1	1
39	20	4	1000	20	20	4	4	1000	1000	20	4	1000	0	0	1	1	1	1
40	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
41	20	4	1000	20	20	4	4	1000	1000	20	4	1000	20	20	4	4	1000	1000
42	20	4	1000	0	0	1	1	1	1	20	4	1000	20	20	4	4	1000	1000
43	20	4	1000	20	20	4	4	1000	1000	20	4	1000	20	20	4	4	1000	1000
44	5	2	10	20	20	4	4	1000	1000	0	1	1	0	0	1	1	1	1
45	20	4	1000	0	0	1	1	1	1	20	4	1000	0	0	1	1	1	1
46	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
47	0	1	1	0	0	1	1	1	1	0	1	1	0	10	1	3	1	100
48	20	4	1000	20	20	4	4	1000	1000	20	4	1000	0	0	1	1	1	1
49	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
50	20	4	1000	20	20	4	4	1000	1000	20	4	1000	0	0	1	1	1	1
51	20	4	1000	20	20	4	4	1000	1000	0	1	1	0	0	1	1	1	1
52	20	4	1000	20	20	4	4	1000	1000	20	4	1000	0	0	1	1	1	1
53	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
54	0	1	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1
	325	104	15246	400	400	115	115	19233	19233	320	103	15237	165	180	80	83	7254	7362

	P5 (A) Q 1	P5 (A) P 1	P5 (A) R 1	P5 OPT (B) Q 1	P5 OPT (B) P 1	P5 OPT (B) R 1	P5 IDEN ADJ (A1) Q 1	P5 IDEN ADJ (A1) P 1	P5 IDEN ADJ (A1) R 1	P5 I A OPT (A2) Q 1	Q 2	P 1	P 2	R 1	R 2
layout cost 1 / 2		73020	633830		67054.3	577044.3		67445	576140			62880.3		545240	
1	5	2	10	5	2	10	5	2	10	5	5	2	2	10	10
2	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
3	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
4	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
5	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
6	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
7	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
8	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
9	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
10	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
11	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
12	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
13	10	3	100	10	3	100	10	3	100	10	10	3	3	100	100
14	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
15	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
16	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
17	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
18	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
19	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
20	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
21	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
22	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
23	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
24	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
25	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
26	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
27	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
28	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
29	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
30	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
31	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
32	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
33	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
34	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
35	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
36	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
37	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
38	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
39	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
40	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
41	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
42	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
43	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
44	5	2	10	5	2	10	5	2	10	5	5	2	2	10	10
45	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
46	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
47	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
48	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
49	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
50	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
51	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
52	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
53	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
54	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
	20	58	171	20	58	171	20	58	171	20	20	58	58	171	171

SPOT

	Q 2b	Q 2a	Q 1	P 2b	P 2a	P 1	R 2b	R 2a	R 1
	Q VALUES:0,5,10,20			P VALUES:1,2,3,4			R VALUES:1,10,100,10		
1	20	0	5	4	1	2	1000	1	10
2	20	10	0	4	3	1	1000	100	1
3	20	0	5	4	1	2	1000	1	10
4	20	0	5	4	1	2	1000	1	10
5	0	0	20	1	1	4	1	1	1000
6	0	0	20	1	1	4	1	1	1000
7	0	0	20	1	1	4	1	1	1000
8	0	0	20	1	1	4	1	1	1000
9	0	0	20	1	1	4	1	1	1000
10	0	0	20	1	1	4	1	1	1000
11	0	0	20	1	1	4	1	1	1000
12	0	0	20	1	1	4	1	1	1000
13	20	10	0	4	3	1	1000	100	1
14	20	10	0	4	3	1	1000	100	1
15	20	10	0	4	3	1	1000	100	1
16	0	0	20	1	1	4	1	1	1000
17	0	0	20	1	1	4	1	1	1000
18	0	0	20	1	1	4	1	1	1000
19	0	0	20	1	1	4	1	1	1000
20	0	0	20	1	1	4	1	1	1000
21	0	0	20	1	1	4	1	1	1000
22	20	10	0	4	3	1	1000	100	1
23	0	0	20	1	1	4	1	1	1000
24	20	0	0	4	1	1	1000	1	1
25	20	0	0	4	1	1	1000	1	1
26	20	0	0	4	1	1	1000	1	1
27	20	0	0	4	1	1	1000	1	1
28	20	0	0	4	1	1	1000	1	1
29	20	0	0	4	1	1	1000	1	1
30	0	0	20	1	1	4	1	1	1000
31	0	0	20	1	1	4	1	1	1000
32	0	0	20	1	1	4	1	1	1000
33	0	0	20	1	1	4	1	1	1000
34	20	10	0	4	3	1	1000	100	1
35	20	10	0	4	3	1	1000	100	1
36	20	0	0	4	1	1	1000	1	1
37	20	0	0	4	1	1	1000	1	1
38	0	0	20	1	1	4	1	1	1000
39	0	0	20	1	1	4	1	1	1000
40	20	20	0	4	4	1	1000	1000	1
41	0	0	20	1	1	4	1	1	1000
42	0	0	20	1	1	4	1	1	1000
43	0	0	20	1	1	4	1	1	1000
44	20	0	5	4	1	2	1000	1	10
45	0	0	20	1	1	4	1	1	1000
46	20	10	0	4	3	1	1000	100	1
47	20	10	0	4	3	1	1000	100	1
48	0	0	20	1	1	4	1	1	1000
49	20	0	0	4	1	1	1000	1	1
50	0	0	20	1	1	4	1	1	1000
51	0	0	20	1	1	4	1	1	1000
52	0	0	20	1	1	4	1	1	1000
53	20	0	0	4	1	1	1000	1	1
54	20	0	0	4	1	1	1000	1	1
	2b	2a	1	2b	2a	1	2b	2a	1

	1=(100,20,5,1,0) layout cost	fixed cost Q,P,R	2=(1000,100,10,1,0) layout cost	fixed cost Q,P,R
0FIX (C)	132185	405, 117, 18441	1184700	
0FIX OPT (D)	77541.00781	510, 132, 24327	648054.4375	470, 127, 21528
4FIX	138165	325, 104, 15246	1240560	
4FIX OPT	85915.5	400, 115, 19233	712895	400, 115, 19233
10FIX	127495	320, 103, 15237	1158500	
10FIX OPT	74508.09375	165, 80, 7254	675794	180, 83, 7362
P5 (A)	73020	20, 58, 171	633830	
P5 OPT (B)	67054.28	20, 58, 171	577044.3	
P5 IDEN ADJ (A1)	67445	20, 58, 171	576140	
P5 I A OPT (A2)	62880.32	20, 58, 171	545240	20, 58, 171

APPENDIX H

EXAMPLES OF NON-FUNCTIONAL DESIGN UNITS

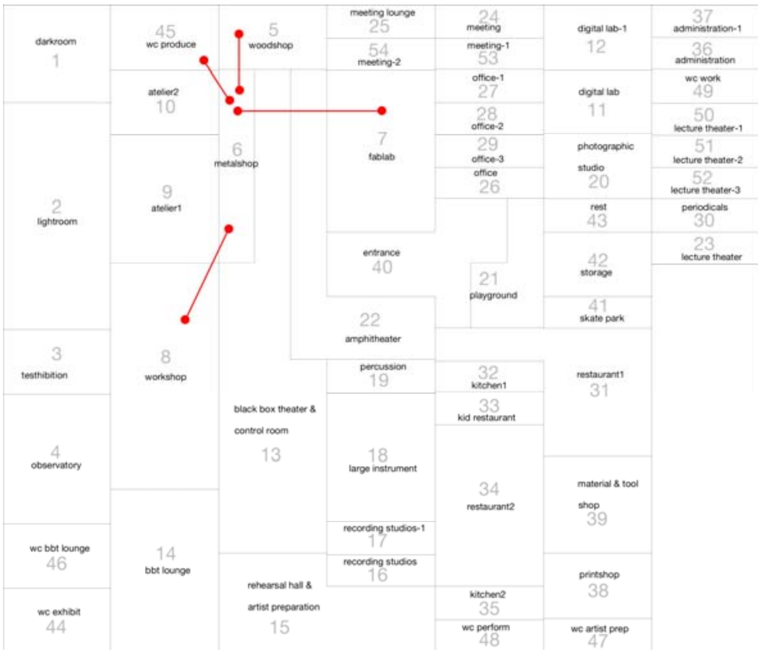


Figure H.67. Non-functional design units in layout 0 FIXED OPT (D), which was optimized using flow inputs 100, 20, 5, 1, 0. Drawn by the author.

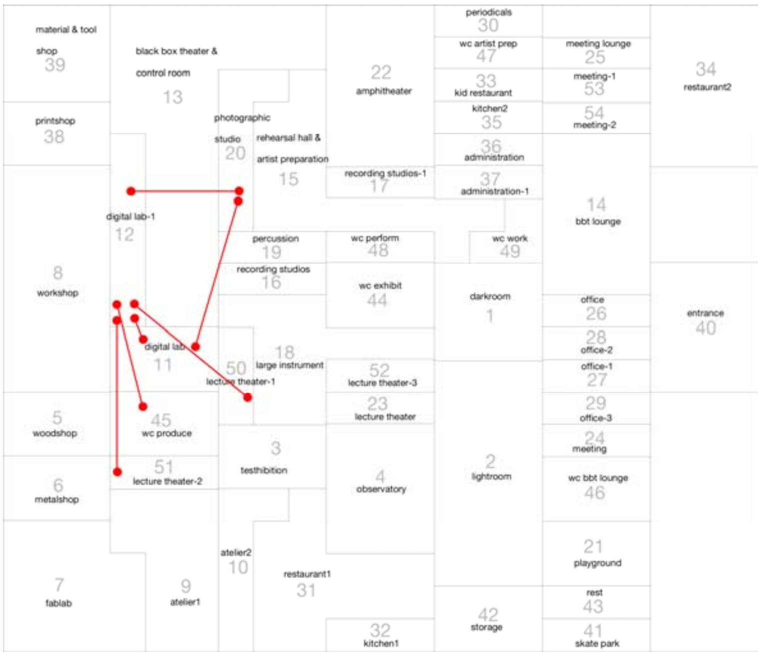


Figure H.68. Non-functional design units in layout 10 FIXED OPT, which was optimized using flow inputs 100, 20, 5, 1, 0. Drawn by the author.

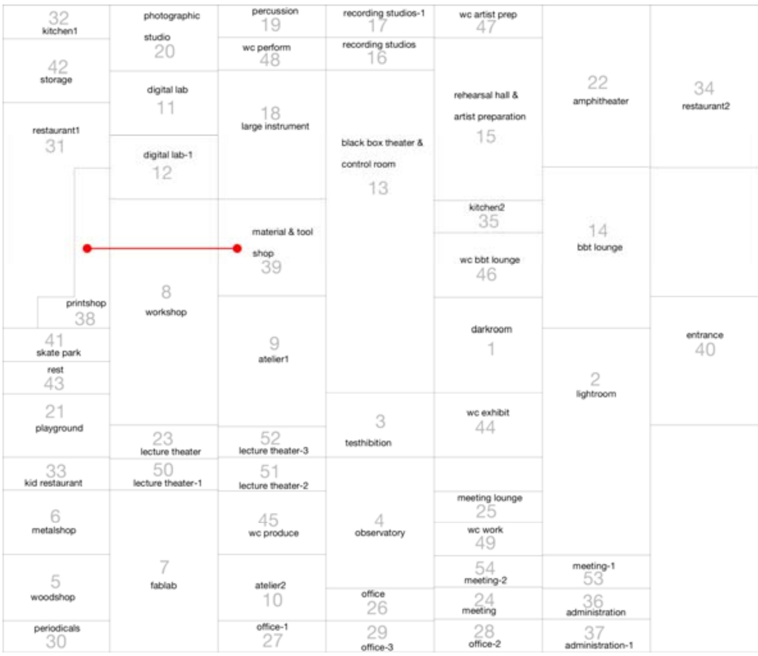


Figure H.69. Non-functional design units in layout P5 LAYOUT ID U ADJ OPT (A2), which was optimized using flow inputs 100, 20, 5, 1, 0. Drawn by the author.

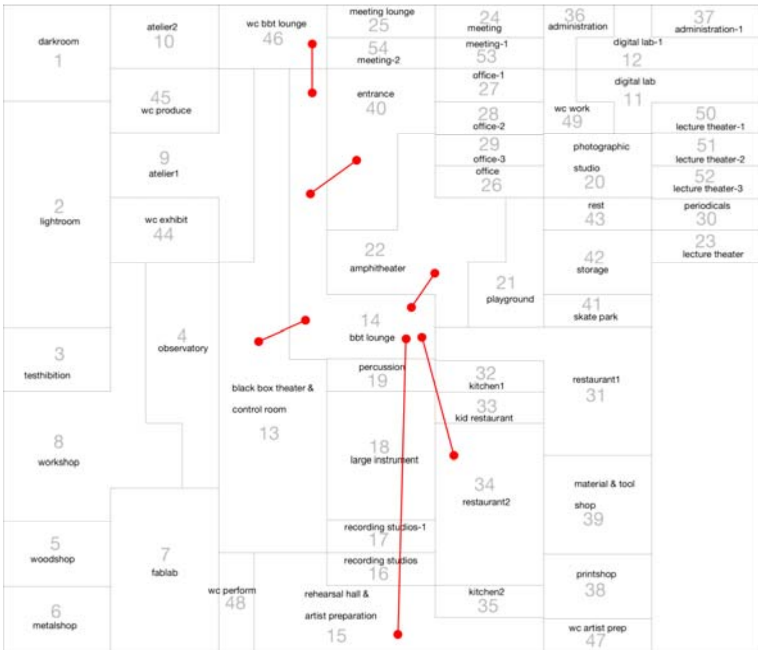


Figure H.70. Non-functional design units in layout 0 FIXED OPT (D), which was optimized using flow inputs 1000, 100, 10, 1, 0. Drawn by the author.

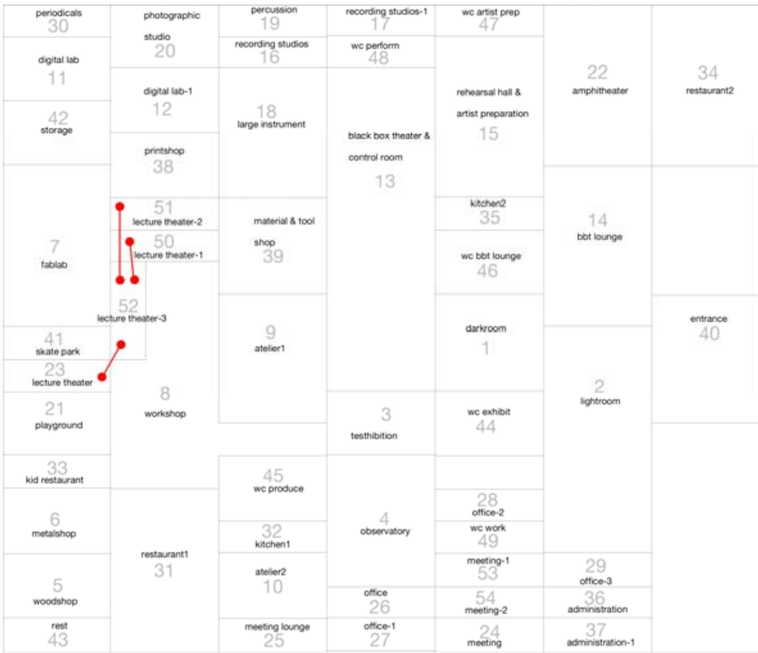


Figure H.71. Non-functional design units in layout P5 LAYOUT OPT (B), which was optimized using flow inputs 1000, 100, 10, 1, 0. Drawn by the author.