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Algorithmic Approaches in Space Layout (with an Emphasis on Graph Theory)

Romeysa Rahmati Govari[a]- Hadi Ghoddusifar[b*]- Mansoureh Tahbaz[c]- Fatemeh Zare' Mirak Abad[d]

[a] Ph.D. of Architecture, Department of Architecture, South Tehran Branch, Islamic Azad University, Tehran, Iran.
[b] Assistant Professor of Architecture, Department of Architecture, South Tehran Branch, Islamic Azad University, Tehran, Iran (Corresponding Author).
[c] Associate Professor of Architecture, Faculty of Architecture and Urbanism, Shahid Beheshti University, Tehran, Iran.
[d] Assistant Professor of Computer Science, Faculty of Mathematics and Computer Science, Amirkabir University of Technology, Tehran, Iran.

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ABSTRACT

The space layout in the functional plans is the most significant part of every architectural design. The inappropriate space layout leads to the plan inefficiency in the considered function. Industrial engineers use many algorithms to arrange the factories' facilities. Given the advances in computer science, it is assumed that algorithms can be applied to achieve the desired space layout in architectural designs. In order to apply algorithms, it is required to provide methods that algorithms or using them direct the space layout to apply algorithms. The current research aims to investigate the given primary models based on these methods. The main purpose of this research is to focus on selecting a model that can be used to model spatial relations by emphasizing the functional proximity of spaces in the early stages of design and without involving the designer with dimensions and sizes. Also, this model can be developed to apply dimensions and sizes in the next steps. The given models for each one of these methods are presented using the systematic review method to conduct this research. There are three main models in this regard; the first model includes single-variable optimization. The second model is based on Graph theory, and the third model is related to multi-criteria optimization. Given the importance of the functional proximity of the spaces in the functional plans, and conceptual equivalence of space syntax theory with graph theory, and the possible analysis of its functional relations, the second model is a desirable and flexible model for designers to use.

Keywords: Space Layout, Functional Proximity, Graph Theory, Space Syntax, Algorithm.

* E_mail: Hadi.ghoddusi@gmail.com

1. PROBLEM STATEMENT

Space layout is one of the main tasks of the architects. "The improper space layout might lead to a reduction in the plan's efficiency. Layout planning is to find a set of places for the placement of the activities so that the considered placement be in line with the design's purposes and needs" (Mourshed, Manthilake, & Wright, 2009). space layout is a multi-objective optimization subject purpose of which is to find the most appropriate combination of design units considering the limits, and without risking the needs of users (Liggett & Mitchell, 1981). "The best space layout is obtained by a comprehensive examination of solution space" (Jagielski & Gero, 1996). "Solution space is great and intricate" (Liggett, 1985). A designer can only study a limited range of the space solution to achieve the desired space Layout due to which the obtained layout is not necessarily optimized. Therefore, computational techniques are needed to study the space solution, including algorithmic space layout (Choudhary & Michalek, 2002). "Attempts to achieve an algorithmic space planning started almost 40 years ago" (Liggett & Mitchell, 1981). The primary methods for developing computational approaches in analyzing and producing architectural designs dated back to the 1960s and 1970s (Steadman, 1983; Alexander, 1964; March & Steadman, 1971). Since the early 1960s, various computer programs were developed to solve the intricate space layout automatically. Many studies focused on the space layout in the plan (Liggett, 1985). Hart and Moore (1973) defined spatial cognitions as the understanding of the internal representation of the recognition of structures, entities, and spatial relations (Hart & Moore, 1973).

Steadman (1973), Flemming (1978), Baykan and Fox (1989), Charman (1993), and Medjdoub and Yannou (2002) are among the researchers who conducted exploratory studies in this regard. They developed the process of using artificial intelligence, including the Genetic Algorithm, Genetic Programming, and Artificial Neural Network (Kazakov & Gero, 1998; Michalek, Choudhary, Papalambros, 2002; Caldas, 2008). Flemming et al (1995) developed a Software Environment to Support Early Phases of Building Design (SEED). Figure 1 represents an example of this software's output. The space layout of a hospital plan along with the connection routes are presented in this figure.

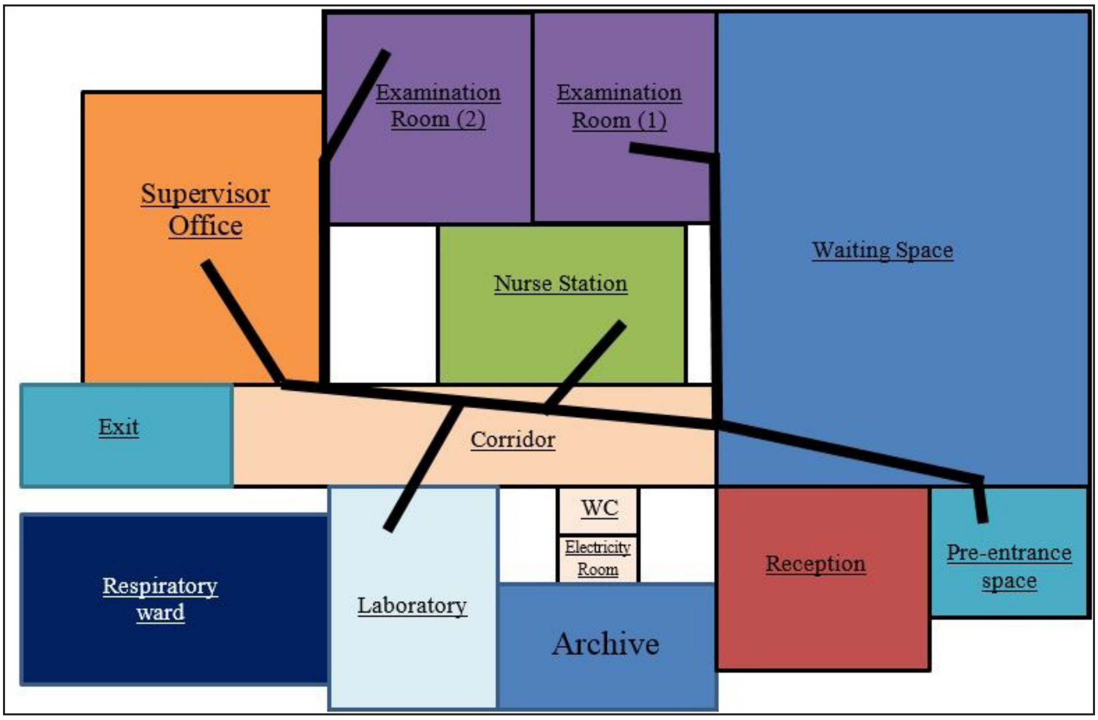

Fig. 1. Display of Space Layout Access Paths in SEED
(Liggett, 2000)

"Computer-assisted space layout is an interactive process between the designer and the computer that contributes to effectively searching for space solution" (Jagielski & Gero, 1997). There are many similarities between the spatial organization of functional plans and factories' facility layout that is often done by the industrial engineer. Koopmans and Beckmann were the first engineers who defined the facility layout as a conventional industrial problem in industrial engineering. There are many factors involved in obtaining the desired space layout. Industrial engineers used algorithms to achieve the desired facility layout and avoid the human mind's limits. Unfortunately, the functional layout of spaces is not considered in architecture as serious as industrial engineering, which is of great importance in designing spaces like hospitals. In the facility layout of factories implemented by industrial engineers, the purpose is to reduce the costs. However, in the design of hospitals, this layout might lead to the circulation improvement of patients, nurses, and doctors, resulting in saving the patients. The current research investigates the algorithmic approaches for the facility layout of the factories. So, by studying its strengths and weaknesses and considering the requirements and limits, an approach is obtained to use in architectural analysis and design applied in the initial stages of design and has the modeling capability and application of the dimensions and sizes in the next phases.

2. RESEARCH METHOD

Paying attention to the space layout in the functional plans is a significant subject in industrial engineering and architecture. Industrial engineers use known algorithms in computer science to achieve the desired facility layout. Facility layout in factories is usually the last phase in the design process of a factory. However, in architecture, the functional layout is implemented in the initial stages of design. In the primary stages, an architect starts designing in a topological space, for example, space syntax theory in architecture. "This theory is based on the topological geometry that is mainly utilized in studies related to the access and connection between urban spaces or architectural buildings" (Xu, Penn, Hillier, & Banister, 1998). As a result, by investigating algorithms for the regularization of space layout, the current research looks for a useful method in architecture, especially in the initial phases of design that also is capable of being developed in the next stages. Therefore, by studying solving facility layout methods in industrial engineering using the systematic review method, the concepts and methods in the algorithmic space layout were examined in the current research.

3. SPACE DISPLAY IN SPACE LAYOUT

Space layout issues involve a set of activities that must be assigned to a place. These places can be displayed in different ways:

1. Space as a discrete object (One to One allocation)
2. Space as a surface (area- zone) (multi to one allocation)
3. Space as a surface and shape (block layout planning or floor plan)

These are the principle methods of problem-solving techniques of space layout. These techniques are related to the presentation of the activity and physical space. The modest layout problem is to allocate a set of discrete activities to a complex of discrete spaces in which an activity is dedicated to one place. That is a one-one allocation problem, and the area of all the functional spaces is considered equal. In general, the space layout cannot be considered as a one-one allocation because the spaces needed for activities are not necessarily equivalent. Multi-one or one-multi allocation problem describes the way of dividing activities into multi classes or vice versa. The real shape of a space in which the activity occurs has not been considered so far. The most intricate problems are allocating or considering the surface and shape (block layout planning) in which shape and form of space are also considered in addition to the area (Liggett, 2000). Solving these problems, considering their complexity without using computer algorithms, is almost impossible. However, what is required to understand these algorithms is to find methods by which algorithms direct the layout process.

4. DIRECTION METHODS OF SPACE LAYOUT AND FACILITY LAYOUT PROCESS BY ALGORITHMS

"Placement and layout of facility and spaces are known as combinational optimization which can be applied in different kinds of solutions such as the placement of hospitals, airports, warehouses, etc. In industrial engineering, the placement of facilities in factories is related to finding the best possible layout for N activity space in N places, so that the cost of transporting materials is minimized. The relative position of each section must be specified to respond to the limitations and requirements of the plan" (Singh & Sharma, 2006). There are three ways to direct the layout process. The first method is based on the optimization of a criterion function. In designing the facility layout of the factiry, this layout must be implemented in a way that in a way that transportation costs are minimized. As a result, the criterion function in this example is to minimize the transportation costs. The second method is based on the Graph theory. To utilize this theory, a graph must be created to display the functional proximity of activities (Grason, 1971). Most of the approaches that follow this method are based on the spatial functional layout developed by Richard Muther. This method leads to the creation of spatial relations diagrams (Muther, 2015). The third method is to find a layout that include a diverse set of limits. For instance, Eastman's automated space planning, and design problem solver of pfefferkorn can be mentioned. One of the recent systems is SEED which is the subset of this method. It is a software system to support the initial stages of building design, and creates a schematic sample of space placements in the rectangular form under various limits such as access, natural light, and privacy (Liggett, 2000). Figure 2 shows the space layout process of SEED software.

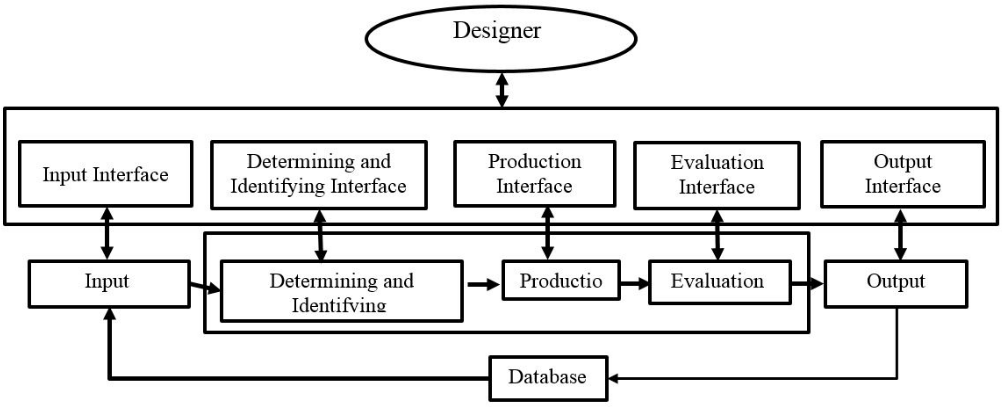

Fig. 2. Space Layout Process of SEED Software
(Flemming & Woodbury, 1995)

4.1. First Method: Single Variable Optimization

This algorithmic method for the facility layout was first developed by Koopmans and Beckmann to allocate factory machinery provided that the distance between the functional dependent parts is minimized. This issue, known as the quadratic allocation problem (QAP), is related to finding optimal locations for functionally interdependent sectors. This can be defined as the allocation of N functional space to N or more of the N site. Each site can be allocated to only one functional space. With each pair of activities (i, j), there is a criterion for showing the effect of this pair on each other (Q (i, j). With each pair of sites (area) (k, l), there is a criterion for measuring the spatial separation (C (k, l). There is also a fixed cost (F (i, k)) that may be related to the placement of activity i on site k. If (A (i)) indicates the site where activity i is on a map (A) (activities in Sites) allocated to it (site), the total cost of this mapping (solution) can be considered as follows:

$$Cost\ (A) = \sum_{activity\ i} f(i, (A(i)) + \sum_{activityi} \sum_{activity\ j} [Q(i,j)C(A(j), A(j))]$$

The purpose is to create mapping A so that the cost function of A(cost) is minimized. Considering the space layout of a plan as a quadratic allocation problem (QAP) was first done by Armour and Buffa (1963). They took into account a factory layout the purpose of which was minimizing the replacement cost of products and materials among the sectors. The result was the development of Computerized Relative Allocation of Facilities Technique (CRAFT) software (Liggett, 2000). In the quadratic allocation problem, the space layout of a plan is considered a combinational problem in which the unseparated activity spaces must be allocated to specific places in this plan. This is done by considering all the possible mapping of assigning activities to the places and developing a plan that responses to all the limits. Practically, achieving a proper layout in real dimensions (e.g. space allocation to more than 15 activities) is impossible. Because the number of place/activity combinations might be extensive. It can be shown that the QAP belongs to a set of mathematical problems known as NP-Complete. It is generally impossible to come up with an efficient solution to NP-complete problems. The strategies for approximate problem solving can be divided into two categories: 1. Useful Initial Values Strategy, 2. Iterative Improvement Strategy (Optimization). Beneficial Initial Values strategy develops a solution using an n-stage decision-making process (e.g. Hill Climbing Algorithm). Improvement strategies begin with a solution and try to improve it continuously (Genetic Algorithm) (Liggett, 2000).

4.2. Second Method: Graph Theory Approach

The main problem is to create a design that can meet the requirements of functional proximity of spaces. Many researches have been done in this regard, some of which are given in Table 1.

Table 1. Studies Based on Graph Theory for Space and Facility Layout

Row	Source	Year	Row	Source	Year
1	Foulds	1983	11	Rosenblatt & Golany	1992
2	Foulds & Griffin	1985	12	Goetschalckx	1992
3	Foulds, Griffin, & Cameron	1985	13	Al-Hakim	1992
4	Jacobs	1986	14	Montreuil, Venkatadri, & Ratliff	1993
5	Montreuil, Ratliff & Goetschalckx	1987	15	Bozer, Meller, Erlebacher	1994

Row	Source	Year	Row	Source	Year
6	Hassan & Hogg	1987	16	Boswell	1994
7	Al-Hakim	1991	17	Al-Hakim	2001
8	Hassan & Hogg	1991	18	Wang & Sarker	2002
9	Leung	1992	19	Chan, Chan, & Ip	2002
10	Kaku & Rachmadya	1992	20	Diponegoro & Sarker	2003

The graph is a branch of topology. Topology refers to properties of space that are preserved under deformation. For instance, general planning within a hospital can be described, disregarding details such as the size or shape of the spaces, the number of users, or the speed of movement. Such a grid configuration can be represented by a graph. A graph is a method of representing a network in which nodes are interconnected by a set of edges (Chias, Abad, & Garcia-Rosales, 2019). “Topological space is a mathematical and non-Euclidean concept and is in contrast to the Euclidean- metric space, by which concepts including continuity and connected space can be defined” (Batty, 2004). “Space syntax theory is based on the topological space” (Penn, Hillier, Banister, & Xu, 1998).

“In the mid-1980s, Hiller and Hanson developed methods for analyzing architecture and urban space. The most significant method was based on understanding the topological relationship between spaces. They applied graph theory to the connection of mathematical properties to socio-spatial phenomena in architecture” (Hajian & Tajik, 2017). This approach required a planar graph in the initial design stages (Nassar, 2010). Nodes in the created planar graph[1] indicate functional spaces, and edges are the connection between spaces. Graph theory is a two-stage process. In the first stage, the planar graph[2] is created. The number of connections may be large, and the requirements for functional proximity of spaces may not be represented by the Planar Graph. Therefore, The Complete Planar Graph must be created for problem-solving. If we look for creating a complete planar graph from a weighted graph, a Complete Planar Graph must include edges with maximum weight. The second stage or dual graph results from the Planar Graph. The Dual Graph shows a design disregarding shape and area. Eventually, dimensions, size, and area of spaces can be applied to the dual graph (Liggett, 2000).

By creating a hexagonal structure for the neighborhood graph, Goetschalckx developed an efficient way to create a rectangular plan for the layout in which the required area of each space is obtained by a dual planar graph. A rectangular is first drawn to create a design. Then, according to the number of graph levels obtained from the spatial relations, the rectangular is divided into horizontal levels, which is presented in Figure (3-A). The given graph has four levels. Therefore, the rectangular block is divided into four horizontal levels. Then, each row is classified based on the number of spaces and their areas. The graph's level and its transformation to a rectangular plan are presented in Figure (3-B). As a result, the general design resulted from the neighborhood graph will be as presented in Figure (3-C).

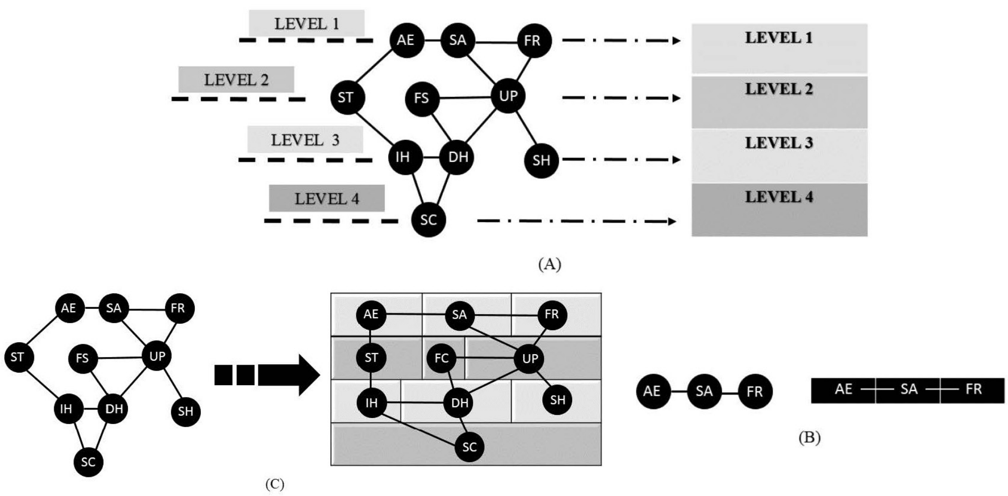

Fig. 3. A. Transformation of Neighborhood Graph Levels to a Rectangular Plan, B. Transformation of the First Row of a Graph to a Rectangular Plan, C. Transformation of the Neighborhood Graph to a Rectangular Plan (Liggett, 2000)

Goetschalckx algorithm (Spiral) is applied in a commercial product known as FactoryOPT. Montreuil et al also used a linear optimization model to create a space layout from a planar proximity graph. The constraint of Goetschalckx and Montreuil approaches was the rectangular perimeter of the building. The graph theory approach to the space layout problem is different from the quadratic allocation problem for various reasons. The main difference is that the graph theory only considers the facility needs with the direct neighborhood and ignores the connection costs of the non-adjacent pairs (Liggett, 2000).

There is a comprehensive history of the application of graph theory in space layout problems. This technique was frequently used in space planning, using different kinds of graphs to display a plan (Levin, 1964; & Rittel, 1967; Krejcirik, 1969; Grason, 1970a, 1970b, 1970c; Teague, 1970). Table 2 shows the display method of design problems by graphs, their types, and characteristics.

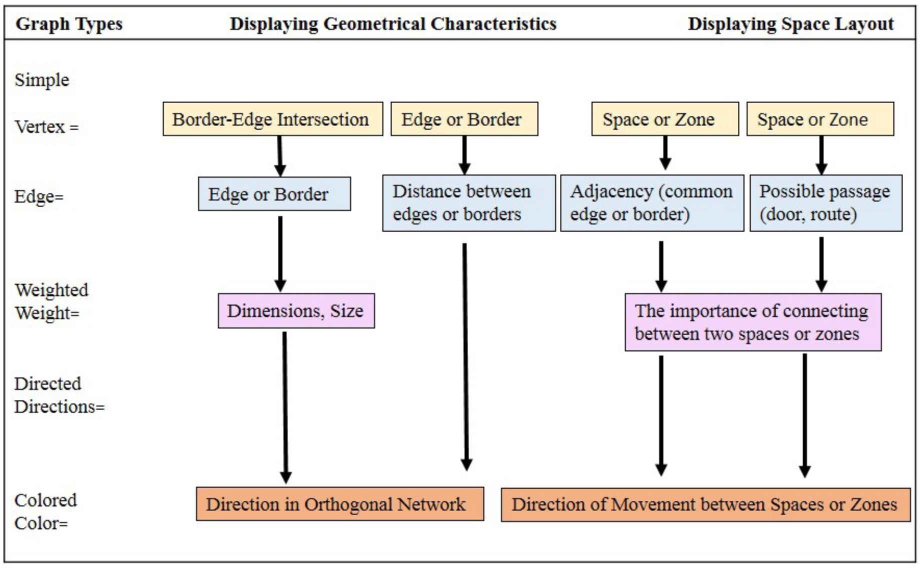

Fig. 4. Graphs Types and Characteristics
(Roth, Hashimshony, & Wachman, 1985)

Converting a plan to a graph is simple. The first step is to create a graph based on the design requirements; for example, functional proximity of spaces. This graph is converted to a plan in the next stage. The created graph does not represent a unique plan (Fig. 5) because when the designer describes the requirements in the form of a graph, there is still a wide range of architectural solutions (Roth, Hashimshony, & Wachman, 1985).

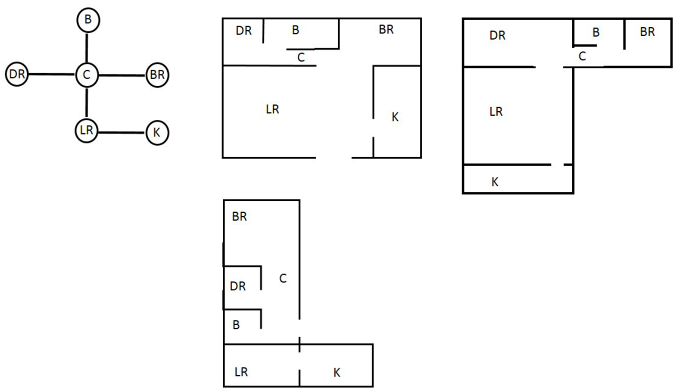

Fig. 5. Different Plans with the Same Graph
(Roth, Hashimshony, & Wachman, 1985)

4.2.1. Grason's Model for Automated Space Layout Using Graph Theory

Grason introduced a model to show the design process. This model is presented schematically in Figure 6 and includes three components: 1. A set of information called plan representation; 2. Parts related to the design stages, called design operations; 3. The design process is generally called a decision-making plan.

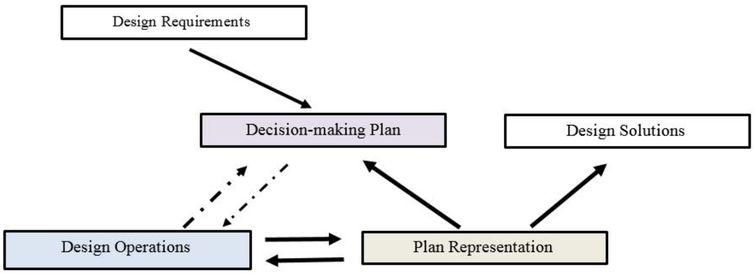

Fig. 6. Design Plan Model
(Grason, 1971)

Graphs can be used to display the plan in this method in different ways. Many of the approaches that follow this method are based on the systematic (space) layout planning method of Richard Muther.

4.2.2. Grason's Model for Automated Space Layout Using Graph Theory

Systematic Layout Planning is the most conventional method for space layout design (especially in factories) over 30 years, resulting in the production of a spatial relations diagram. The general model of the Systematic Layout Planning that has five layers has been presented in Figure 7.

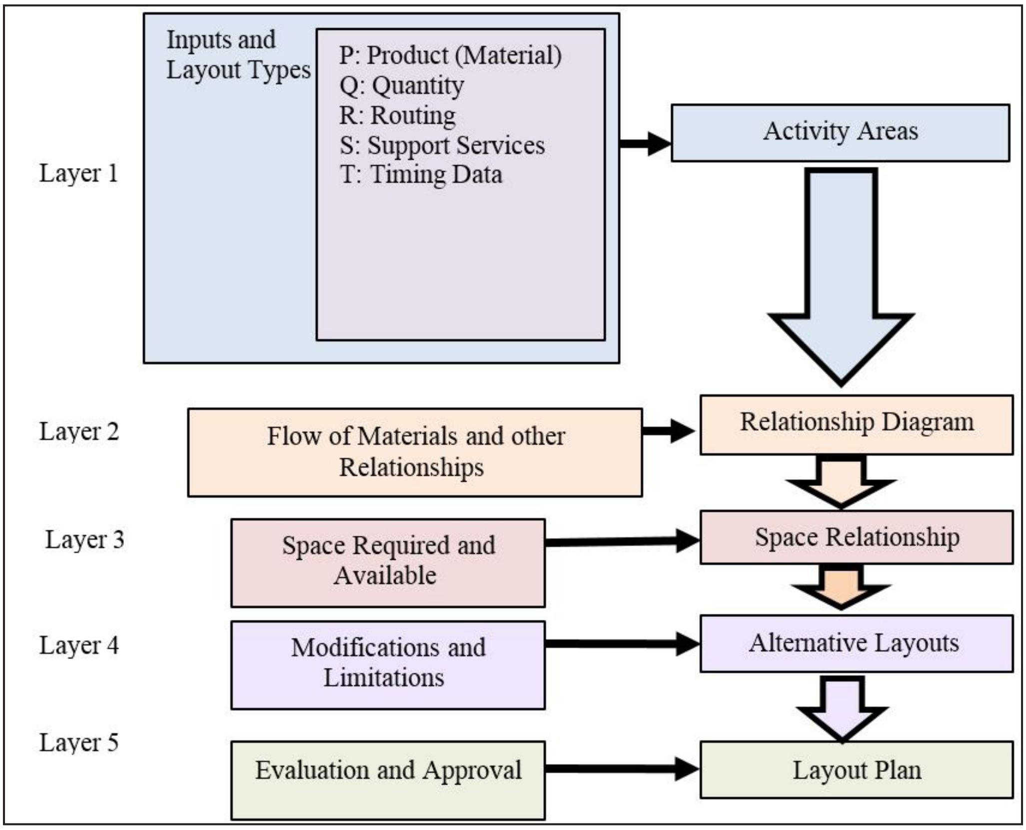

Fig. 7. SLP Model
(Muther, 2015)

The principal purpose of the layout (Space, facility) is to facilitate the production process in every factory. Some of the secondary objectives are as follows: minimizing the relocation of materials, economical use of space, effective use of workers, providing safety, comfort, and convenience for employees (Muther, 2015). Therefore, this method can be used in designing different plans.

4.2.2.1. Space Relationships Diagram

The space relationships diagram is the third layer's output of the SLP model. Space requirements are determined for each function, or the present space is conformed. The designer matches the space and the obtained space relationships diagram.

4.2.2.1.1. Assigning Space to Diagram

In assigning space to a diagram, the planner again starts with movement or functional relationships.

1. Assigning space to movement diagram: movement diagram shows the movement sequence of individuals in a space.
2. Assigning space to the diagram of functional relationship: this diagram is called the dependency diagram in which, the interrelationship of the sectors is presented.
3. Assigning space to a diagram composed of movement relationships: most of the space relationships diagram can be used to display the information related to a particular space layout planning project (Muther, 2015). This approach is supported by the space syntax theory in architecture and graph theory. As a result, the indicators of graph theory and space syntax can be applied to the quantitative analysis of the functional layout of spaces in the first phase of the design.

4.3. Multi-Criteria Optimization Method

The main focus is to design software that can express design problems that have a three-dimensional nature in two dimensions and solve them with the help and interaction with the designer. These problems include the space layout, facility layout, site planning, etc. Distance, proximity, and other functions are the criteria for space layout in such issues. Various computerized structures are developed that can implement practices to test the results of the space layout. Two functions of change and test must be combined to apply algorithms so that since space layout is produced by these programs, they have some of the pre-defined criteria for evaluation (Eastman, 1973).

4.3.1. Formation of Design Problem from Eastman's Perspective

In general, the designer can determine the design requirements. A set of limitations define a set of possible solutions (response space). The main task is to find the most optimized solution. Space is an unlimited or limited spatial area in which the space layout is created. Space usually includes a room, building structure, and site. Design units are the arranged physical elements in the space. Each design unit and occupied space has a set of fixed or variable shapes and sizes. Space relationships created by the space layout to meet the specific limitations are called S-relations. A closed space test is testing whether the developed layout meets the requirements and needs. In case of meeting all the demanded requirements, the searching process to find the proper layout is ended, otherwise, it will continue until finding the answer, and is presented by C1, C2, C3,…,CN. Each logical combination of S-relations or design units must be possible. One of the significant characteristics of the space planning problems is that the operators of d1, d2, d3, …, dv are determined well. Another regularization characteristic of the space layout problem is that the design must begin with the space layout and desired initial conditions; after applying the functions on it, the obtained result is tested and assessed. The obtained outcome must meet the design requirements and limitations. All the plans related to the algorithmic space planning can be described by two components of decision-making regulations:

1. Selecting the operator to change the relations of the design unit from one state to another;
2. Testing the closed conditions on the created relations between the design units, and consequently, a set will be obtained in which changes and the result of using these changes are presented.

Therefore, applying operators to the design units changes the space relations. The created spatial relations are a result of applying operators to the relationships of design units (Fig. 8) (Eastman, 1973).

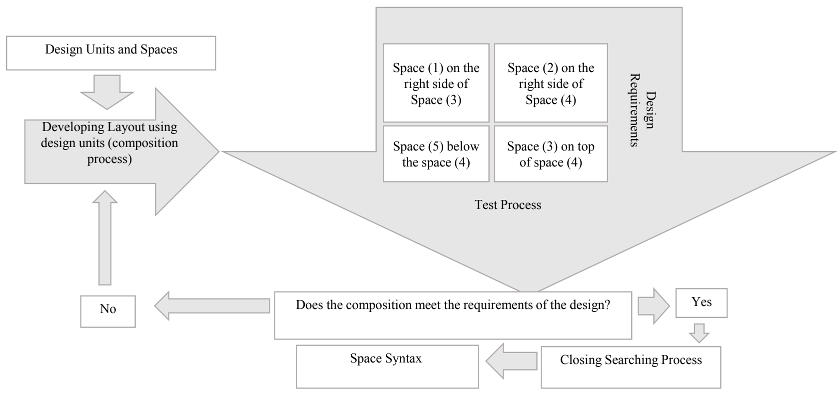

Fig. 8. Composition and Test in the Algorithmic Space Planning

4.3.2. Design Problem Solver using Pfefferkorn Method

Space planning includes a two-dimensional presentation of objects to create optimized solutions for the topological and spatial metric problems. In the design problem solver (DPS) using Pfefferkorn method, first, a space planning phase is implemented. Then, the solution is optimized using innovative ways. “Both layering methods (Pffefercorn and Eastman) use space layout so that they can solve a set of limitations, including factors such as location, direction, adjacency, route, landscape, and distance” (Liggett, 200). “One of the newest systems is to create a software environment to support the initial phases of building design. It includes using computers to imagine, evaluate, and analyze, as well as produce or representation of the plans. These representations are computable and enable the evaluation tools to display, search, and evaluate all the input data. Evaluation tools seek the information needed for the evaluation of the given plans (Flemming & Woodbury, 1995).

These systems have advantages, including considering multi-criteria. The disadvantage of these systems is solving problems on a large scale. “The plan production problem has been the subject of many studies since the 1960s. These studies are generally divided into two phases. The first stage: producing plans without size, and the second stage: plans production considering the size. There are two approaches regarding the first phase: 1) optimization (space layout) and 2) composition. In the first approach, when a target function is applied based on the distance between two activities or in the proximity of the room, the best layout is obtained. In the second approach, the purpose is to produce possible solutions that meet particular conditions. These conditions result from space characteristics, for example, features such as geometrical relations between rooms or the positional or dimensional limitations (Alvarez, San Jose, & Rio, 2015, p. 45).

5. CONCLUSION

Space layout is one of the main steps of plan design. The conducted layout by the architect must be appropriate, creative, and responsive to the function. Therefore, space layout is significantly vital while designing functional plans. Improper space layout leads to an inefficient plan. It is required to consider all the possible mappings and select the most optimal layout to obtain the optimized space layout. It is not possible due to the human mind’s limitations and time-consuming.

Factories have a functional plan, and their facility layout must meet their functions. The facility layout is done by industrial engineers in factories. According to the advances in Computer Science, industrial engineers use algorithms to do so. They could achieve an optimal layout by using algorithms. The architects have not used the algorithms yet despite the similarities between the functional space layout and facility layout. Algorithms of facility layout follow three methods. These methods have advantages and disadvantages. Considering the limitations and requirements, the architect can select and use them in combination in different stages. The architect can achieve the optimal space layout faster and more accurately, and away from the mind’s limitations by selecting the proper method and using algorithms.

The First method: optimization is based on a single variable. This method is one of the known models of facility layout and is related to finding the optimized places for functionally interdependent sectors. This method has been inefficient in the location of more than 15 functional spaces and is turned in to NP-complete problem. It is unlikely that there is a possibility to find an algorithm that obtains the exact answer in a reasonable time. Therefore, approximation algorithms are used. These algorithms function in two ways: in the first method, the initial response to the problem is created, and in the next stage, it is optimized by an architect or another algorithm. These algorithms are known as generative algorithms. In the second method, the algorithm of the initial response generated by an architect of another algorithm is optimized. Generative algorithms suggest a composition of space adjacency by using some techniques and often randomly, and then, are improved based on the designer’s opinion or requirements. Equalization or ignoring the area for activities is not generally acceptable in architecture. Because the required place is not necessarily equal for the functional spaces, and it is better to provide a model by an algorithm which can be developed and has the capability of applying another dimension to it. The purpose of this method is to the placement and facility layout, space layout, and facilities in a way that the distance between the interdependent functional units is minimized, and these units have the minimum distance from each other.

The Second Method: The second method is graph theory. In this approach, the costs of moving and transferring raw materials, manufactured products, etc. between functional spaces are assumed to be zero. This method can be applied in the functional layout of spaces for plans in which the adjacency cost between its spaces is recognizable. In most architectural plans, finding and using the space proximity cost face many challenges and are impossible in many cases, for instance, space layout in therapeutic plans and hospitals. In these plans, if the vital spaces are not properly located, the patient's resuscitation time will be lost. Improper placement of spaces in therapeutic plans is not cost-effective; however, improper placement of these spaces has disrupted the patient's circulation, which can lead to the patient loss. This approach can be done in two phases. The first phase only considers the functional proximity of spaces. In the second phase, the space's area and shape can be used in the graph obtained from the functional proximity of spaces. However, one cannot assign more than a functional space to a place. In space functional proximity graphs, edges represent the connection between two spaces and have weight. The weight of edges indicates the importance of the proximity of two spaces. The purpose is to consider relations in the functional proximity graph to have the highest weight and more significance. In this method, no points are assigned to adjacent spaces, even if they are relatively close to each other. According to Foulds, the graph theory approach is more proper for a new design as the location of any of the facilities must not be predetermined. While the quadratic allocation problem can be utilized for the design and optimization of the existing plan, the graph theory is more applicable when the designer has more freedom of action to solve the layout problem. However, the QAP approach is more proper for a structured situation. Also, the graph theory is supported by the space syntax theory. This method can analyze the spatial configuration quantitatively, and before applying the dimensions, lead to the evaluation of the space layout.

The Third Method: is the multi-criteria optimization method. This method is not related to the single-criterion optimization method but seeks to find a layout based on various criteria. In the initial phases of design, the designer has many unknown problems. Therefore, considering all these problems is very difficult. Also, these systems cannot solve the space layout problems on a large scale. Taking all the spaces in the rectangular form is one of their disadvantages. According to the above-mentioned, it seems that the graph theory is a flexible approach for the use of designers in the initial phases of design. However, architects can use one or a combination of these approaches to achieve the desired space layout, depending on the problem, goals, requirements, and constraints.

END NOTE

1. A graph is planar when any of its edges intersects each other. A planar graph is presented in figure 5.
2. A graph is complete planar if even one edge is not met by the condition of being planar.

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