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Model of arrangement of final material depots for concave construction sites in CSLP

Attila Pém[a]*, Levente Mályusz PhD [b]

[a]*Budapest University of Technology and Economics, Faculty of Architecture, Műegyetem rakpart 3., Budapest 1111, Hungary*
[b]*Budapest University of Technology and Economics, Faculty of Architecture, Műegyetem rakpart 3., Budapest 1111, Hungary*

Abstract

In this paper, we introduce a model and define an algorithm for the Facilities Location Problem with focus on optimizing the arrangement of final material depots at a construction site that is represented by a concave area. The available area of the construction site for placing the depots corresponds to the area of the built-in material location that is served from the depots. The model solves the problem by using the known Voronoi diagram. The goal is to minimise the sum of the delivery distances from the final material depots to each point of the structure (continuous problem) instead of the most models that minimise the sum of the delivery distances from the final material depots to the built in location of each element of the structure (discrete problem). This way the number and the locations of the built in material elements that define the structure are left out of consideration. The algorithm gives near-optimal solutions. Advantages of the model and the algorithm are presented based on an example.
The applicability and the generalisation of the model are summarised. This model can be used as a tool for construction site layout planning if the number of units that define the structure is large or unknown.

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Keywords: continuous demand; construction site elements allocation; construction site layout planning; facility location allocation problem; Voronoi diagram

1. Introduction

One of the preliminary processes in the construction phase of building development is planning the construction process. The construction process planning contains several tasks such as site layout planning, procurement,

* Corresponding author. Tel.: +0036-463-1464; fax: +0036-463-3554.
E-mail address: apem@ekt.bme.hu

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financial planning etc. Each task of the construction process planning has deep relationship with the other planning tasks. Defining spatial requirements in the scheduling is recognised as a possible option for dealing with the relationships [1]. A part of the construction planning process is *construction site layout planning* (CSLP), in which space, time, material, labour, money and equipment are recognised as resources [2, 3]. The target of CSLP is to minimise construction time, cost or required resources.

A part of CSLP is the *construction site elements allocation*. The site elements are categorised into three object groups: *site, construction and constraint* [4, 5]. In the early 1900s, Frank and Lillian Gilbreth [6, 7] began manufacturing optimisation by allocating materials and machines after analysing worker movements for increasing productivity in different industries. The target of CSLP optimisation is similar to their studies and includes decreasing construction time and/or resource requirement and/or construction costs. Most of the developed models identify the number and the size of the temporary facilities that serve the construction site, and then search for the optimal arrangement by minimizing the total transportation costs [8, 9] Due to the number of factors that are involved in the CSLP, computers were identified as an efficient tool to solve the problem as CAD-based [9], AI technique [10] or genetic algorithm used [11, 12, 13, 14, 15] computer-aided systems. The objects, structures and spaces are continuously varied at different phases of the construction project. Therefore, researchers have developed dynamic site planning methods known as dynamic multi-objective optimisation, which include methods such as the max-min ant system [16], among others.

In practice, construction object (as equipment, material, temporary support, facilities, buildings, lay-down areas, working areas, and generally objects that must be located on site) allocation is conducted routinely [17] based on human judgment using a first-come-first-served method [18] or by utilising the construction manager's experience [19]. According to Moore [20], there are two basic methods that can be utilised to manage the CSLP problem. The first method is to place the collection of objects in all possible configurations (or a reduced subset of these combinations) and to choose the best of these solutions. The second method, which will be used in this paper, is to sequentially place objects based on a pre-defined order and to calculate the optimal arrangement after each step. One type of construction object is the *final material depot* where from the material is handled to each point of the structure by one piece after the other. *The optimal arrangement of the final material depots* (AFMD) of a type of material is where the sum of the handling distances is minimised if the handling technology is constant.

In operation research literature, the root of the AFMD problem is known as the *k-median problem* and it is a part of the location allocation problem (LAP). In the operation research literature there are studies for the discrete type optimal location problems and for the continuous type optimal location problems as well. Most studies for the CSLP use the discrete version. The discrete version starts with a two-dimensional figure on the plane that consists m predefined points inside the figure as possible hosts and selects k of them as depots to minimise the total handling distance. A discrete version of the problem as an approximation to the continuous problem is demonstrated [21]. The Voronoi diagram can be used to minimise the average handling distance.

In mathematics, a *Voronoi diagram* (also called a *Dirichlet tessellation*) is a method of dividing an area into a number of regions. An initial set of points (called seeds, $\boldsymbol{S}$) is specified, and for each seed there is a corresponding region consisting of all of the points that are closer to that seed than to any other seed (also known as host). These regions are called Voronoi cells (also called Voronoi regions) [22] (Fig.1.c.). Voronoi regions can be produced by connecting the centres of the circumcircles of the Delaunay triangulation (Fig.1.b.). The Delaunay triangulation [23] is dual to the Voronoi region. The Delaunay triangulation for a set of points ($\boldsymbol{S}$) in a plane is a triangulation such that no seed is inside the circumcircle of any triangle (Fig.1.a.). The sides of the Delaunay triangulation are perpendicular to the boardings of the Voronoi cells (Fig.1.b.).

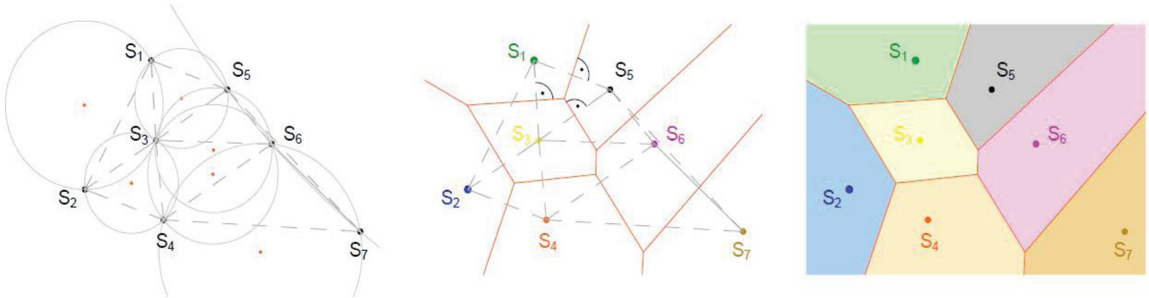


Fig. 1. (a) Delaunay triangulation; (b) Delaunay triangulation and Voronoi cells; (c) Voronoi cells.

In this study, we present an algorithm based on Voronoi diagram and used the continuous model of LAP that results optimal arrangement of the final material depots for one type of material. In cases in which the capacities of the depots have to be equal and the handling paths must be inside the two-dimensional figure and the final material depots can be positioned inside the served working area (inside the Voronoi cells) and the final locations of the built-in material pieces are unknown in advance.

2. Assumptions and objective functions

2.1. Assumption 1.

The final material depots are represented by the projection of their centre of gravity ***S (x, y)*** to the ***XY*** plane. One type of material depot usually consists of a certain number of material elements resulting in equal material depot volumes. The number of the required depots (***k,*** kÎ N) can be easily calculated by dividing the volume of the structure by the volume of the final material depots. We assume that each final material depot should serve equal sized subarea of the two-dimensional figure or at least the maximal deflection of the sizes among the sub-areas (*D,* DÎ Q) should be given in advance.

2.2. Assumption 2.

There are technologies where the final depot can be placed into the area that is served from the certain depot (inside the subarea of the two-dimensional figure) (Fig.2.a.) and there are technologies when the final depot must be placed out of the served area (outside of the subarea of the two- dimensional figure) (Fig.2.b) [24]. On the figures the coloured boxes are the depots, and the coloured areas are the served subareas. The same coloured depot serves the same coloured subarea.

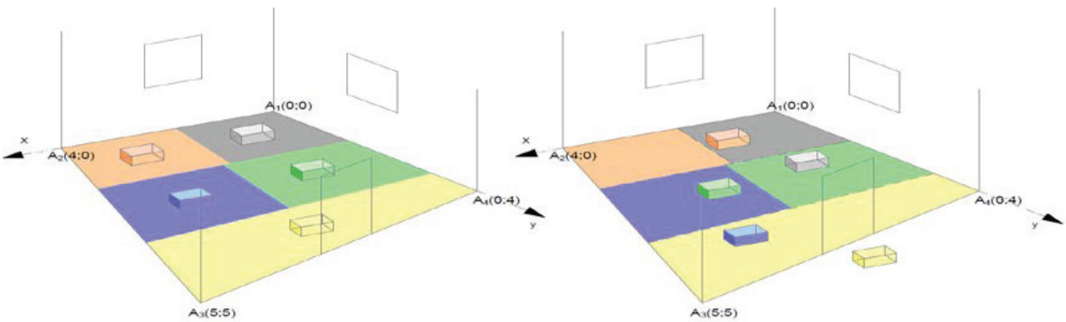


Fig. 2. (a) Depots may be placed inside the served area; (b) Depots must be placed outside of the served area.

In this study we assume that the depots must be inside the served area and the available area is the two-dimensional figure.

2.3. Assumption 3.

The handling paths from a depot to each point of the served subarea can be calculated by two ways: using Euclidean distance (Fig.3.a.) or the **shortest path inside** the two-dimensional figure (Fig.3.b.). It is necessary to decide between these ways in advance in case the two dimensional figure is concave.

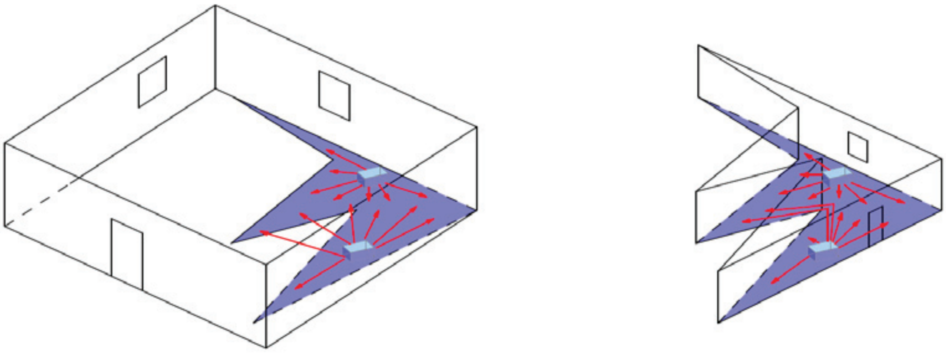


Fig. 3. (a) Handling paths are evaluated by Euclidean distance; (b) Handling paths are the shortest paths inside the figure

In this study we assume that the handling paths must be inside the two-dimensional figure. An example where these conditions exist is the tiling of a concave room bounded by walls (Fig.3.b.).

2.4. Objective function 1.

The objective is to find the allocation of the final material depots, where from the material can be handled by pieces to their built-in locations along the minimal length of paths.

2.4.1. In the case of k=1 (discrete model)

The problem is known as the classical *Fermat-Weber* problem *(1929)* [25], and the solution can be found by any two-parameter minimization. If the built-in locations of each pieces of the material are given in advance and the number of the pieces is not extreme large, than the discrete model can be used:

$$\min_{S} \sum_{i=1}^{n} d_{iS} \tag{1}$$

where $\boldsymbol{n}$ is the total number of the elements and $\boldsymbol{d_{iS}}$ is the handling distance from the location of the material depot $\boldsymbol{S}$ to its built-in location $\boldsymbol{i}$.

2.4.2. In the case of k=1 (continuous model)

If the dimensions of the elements contained in a depot are extreme small, or the built-in locations of the pieces of the material are unknown then the equation turns into a double integral (Eq.2.) that is also a volume integral. This is the continuous model that is used in this study:

$$\min_{S} \iint_{R} (d_{iS})\,dxdy \tag{2}$$

In Eq. 2., where ***(R)*** is a bounded and closed region of the *XY* plane; ***S***, is the location of the material depot; $\boldsymbol{d_{iS}}$ is the handling distance from the material depot location to each point of the figure (***i***).

2.4.3. In the case of k>1 (discrete model)

The goal of the discrete model:

$$\min_{S} \sum_{j=1}^{k} \sum_{i=1}^{n} d_{iS_j} \tag{3}$$

where ***k*** (j=1…k, kÎ N) is the number of final material depots.

2.4.4. In the case of k>1 (continuous model)

For the continuous model the number of the variables in the equation increases. (Eq.4.)

$$\min_{S} \sum_{j=1}^{k} \iint_{R} (d_{iS}) dxdy \tag{4}$$

The locations of the final material depots (S_j) are variables and the boundaries of the subareas are also variables that are served by the depots. In this equation the number of variables is too many. In case of the two-dimensional figure would be partitioned into *k* pieces of equal size subarea than the final material depots could be searched for each subareas by using Eq.2. for each. We use a modified version of the well-known method named *Voronoi regions* for the partitioning.

2.5. Assumption 4. Hypothesis

If k>1 then there are infinite solutions to partition the area of the structure into k equal size subareas (called cells). Our experimental solution is that the partitioning will result the minimal sum of the delivery distances where the cells have the minimal length of the perimeter sum (Eq.5.). This so far has not improved yet the demonstration of it will be published.

$$\min_{S} \sum_{j=1}^{k} p_j \tag{5}$$

2.6. Assumption 5.

If two points S_1, S_2 are set as seeds in a concave two-dimensional figure then the calculated Voronoi cells often result in disconnected cells. We predefined that we use the shortest path inside the polygon, not the straight-line motion for the handling of the material (assumption 3.). In these cases, the outer part of the two-dimensional figure should be used as an obstacle. In case the common boundary of the Voronoi cells crosses the boundary of the polygon represents the available area more than two times and all of the handling paths must be inside the two-dimensional figure, the bounding of the Voronoi cells must be modified. The inside area of the two-dimensional figure should be divided into areas that are "*visible from*" and "not *visible from*" both seeds and "*invisible from one seed*" based on Sadeghpour et al. [3, 24].

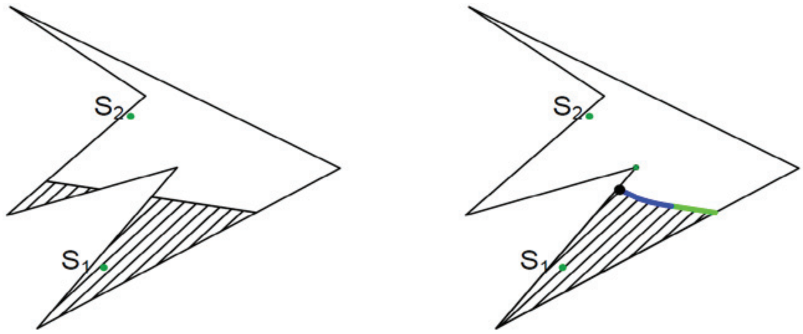


Fig. 4. (a) Voronoi cells; (b) modified Voronoi cells.

The common boundary of the modified Voronoi cells is a hyperbola or partly a hyperbola and partly a line-segment shown on Fig.4.b. The difference between the Voronoi cells in case of the handling paths can be calculated by Euclidean distance (Fig.4.a.) and in case of the handling paths can be calculated by the shortest path inside the two-dimension figure (Fig.4.b.) is shown. The green line is a part of the original bounding of the Voronoi cells and the blue line is the modified part of the bounding of the cells (hyperbola).

3. The model

3.1. Given in advance

The architects and engineers defined the area of the structure that should be built as a 2D figure. Let it be a polygon shown on Fig.3.b. The order of the needed objects (type of the materials) is predefined. The model deals with one type of an object at a time. The volume of the two-dimensional figure and the volume of a depot are also given in advance. The exact built-in locations and the number of the needed pieces of a material are unknown.

3.2. Searched

The locations of the final material depots are searched, where from the sum of the handling distance is minimal.

3.3. Algorithm

The needed number of the depots (k, kÎ N) can be calculated by dividing the volume of the two-dimensional figure with the volume of a depot. A set of points (***q***) inside the polygon are set ($q \in N$ and $q>k$) where from k points are selected as seeds (Fig.5.a.). The set of q points is practical to be on a grid. For all permutation of q points that contain exactly k elements, the Delaunay triangulation should be performed. In all cases where one side of the Delaunay triangle crosses the concave polygon structure, the area of the structure should be divided into *visible from* and *invisible from* areas for those two seeds, and the bounding of the cells should be modified as described Assumption 5. (Fig.5.b.). For those points where the Delaunay triangle does not cross the polygon, the areas should be treated as Voronoi regions. From all of the permutations of q points, as described previously, where exactly k seeds are selected the perimeter of the cells and the area of the cells should be calculated. In assumption 1. it was set that all depots have equal capacities so each cells should have equal area size, but the Voronoi regions (cells) rarely have equal areas and the result is based on the allocation of the pre-set q points. Based on Assumption 1. and Assumption 4. a *Precission value* (Eq.8.) compares each result of the permutation with each other:

$$\text{Precision} = \frac{\left(\dfrac{\text{Min}[\text{areas}]}{\text{Max}[\text{areas}]}\right)}{\sum_{j=1}^{k} p_j} \tag{6}$$

where ***Max[areas]*** is the maximum cell area, ***Min[areas]*** is the minimum cell area and $\boldsymbol{p_j}$ is the perimeter of the cells.

From all of the permutations of q points, where exactly k seeds are selected only that result should be recorded where the *Precision* has the maximum value. If the cell areas are not equal in size or we want to increase the preciseness of the result, then the results should be recalculated by setting up a new set of q points around the recorded seeds. It can be repeated until the difference between the minimum and the maximum cell sizes is negligible (Fig.5.c.).

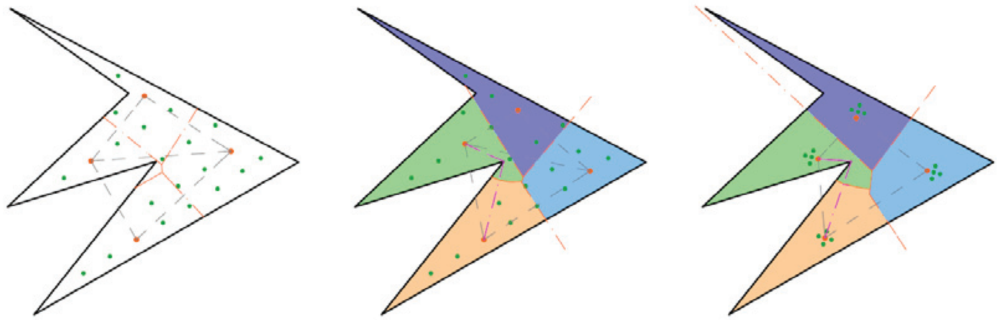


Fig. 5. (a) Points are selected as seeds *(k=4)*; (b) Modified cells; (c) New set of *q* points.

Once the partitioning of the area is done the locations of the final material depots can be searched for each cell by using Eq.2.

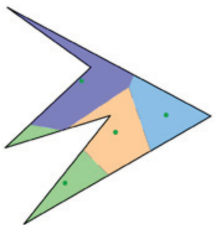
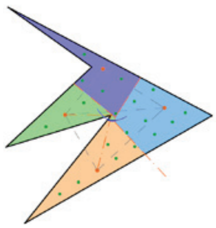
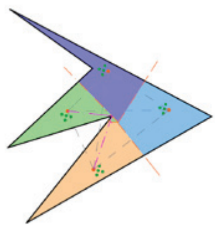
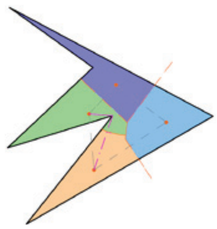
4. Analysing the methods by an application

In this example, we use *Wolfram Mathematica* 7. The structure is a concave two dimension figure defined by the following polygon break points: A_1=(0,0), A_2=(5.641,3.257), A_3=(-0.505,6.535), A_4=(2.018,4.726), A_5=(-0,566,2.301), A_6=(2.609,3.274). Let k=4 seeds.

At firs**t**, we calculated the solutions where all the handling paths are straight-line movements (the carrying paths may use areas out of the perimeter as shown on Fig.3.a.) and the cell areas do not need to be equally size areas. The results are shown in the second column of Table 1. as original model and the Voronoi regions are presented in Fig.6.a.

Next, we calculated the solution when all the handling paths must be inside the polygon. The feasible locations of the seeds were the same as the original models set. The results of the first, second and fifth iterations are marked in the third, fourth and fifth column of Table 1. as our model (Fig.6.b.). In this calculation, we limited the number of algorithm iterations to five so the best solution is shown on the fifth column of Table 1. and on Fig.6.b.3..

Table 1. Results of the model

	Original model	Our model (1^{st} iteration)	Our model (2^{nd} iteration)	Our model (5^{th} iteration)
Locations of the seeds (S_j)	{1.242,1.240}	{2.185,1.604}	{2.048,1.641}	{2.048,1.641}
	{2.762,2.771}	{4.202,3.488}	{4.339,3.452}	{4.229,3.076}
	{4.287,3.287}	{2.355,4.667}	{2.492,4.630}	{2.715,4.200}
	{1.741,4.314}	{1.217,3.281}	{1.253,3.418}	{1.901,3.328}
Areas of the voronoi cells	1.953	2.514	3.138	2.773
	3.113	3.451	3.245	2.961
	2.621	3.134	2.628	2.772
	3.510	2.095	2.186	2.651
Sum of the perimeters of the cells	50.212	31.49	28.82	38.29
Precision of the solution	0.011081220	0.01927636	0.02337283	0.02338223
Graphics	 Fig. 6. (a)	 Fig. 6. (b.1)	 Fig. 6. (b.2)	 Fig. 6. (b.3)

5. Results and Discussion

In this paper, a model and an algorithm were presented to address a Facilities Location Problem in which construction sites have a concave shape and all of the handling paths must be inside the polygon of the structure. None of these two models gives the global optimal solution for the original objective but the results can be as precise as the certain technology needs. In case of the pre-set grid as feasible location of the seeds is too large the calculation may stick into a local optimal solution.

6. Generalisation of the models

In this model, the delivery cost was not considered because the primary focus was the arrangement of the final depots for one type of a material; however, this model can also be integrated with any CSLP model to minimise the total delivery cost. Future studies should account for the delivery cost.

This model uses the structure in a continuous approach that can be used as an alternative to the discrete model when the number of material pieces that define the structure is large, unknown or the unit locations are unknown.

This model divides the area into equal Voronoi cells because the packet materials usually have equal capacities and the Z dimension of the structure that is needed to be built is constant but the model may be used for the variable capacity lumpy materials or for structures that have inconstant predefined Z dimension as well with some modifications.

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Model of Arrangement of Final Material Depots for Concave Construction Sites in CSLP

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이 백서에서는 오목한 영역으로 표시되는 건설 현장에서 최종 재료 저장소의 배치를 최적화하는 데 중점을두고 모델을 소개하고 시설 위치 문제에 대한 알고리즘을 정의합니다. 저장소를 배치하기위한 건설 현장의 사용 가능한 영역은 저장소에서 제공되는 내장 재료 위치의 영역에 해당합니다. 이 모델은 알려진 Voronoi 다이어그램을 사용하여 문제를 해결합니다. 목표는 최종 재료 저장소에서 내장 위치까지의 배달 거리의 합계를 최소화하는 대부분의 모델 대신 최종 재료 저장소에서 구조물의 각 지점까지의 연속 거리의 합을 최소화하는 것입니다 (연속 문제). 구조의 각 요소 (개별 문제). 이런 식으로 구조를 정의하는 내장 재료 요소의 수와 위치는 고려되지 않습니다. 이 알고리즘은 거의 최적의 솔루션을 제공합니다. 모델과 알고리즘의 장점은 예제를 기반으로 제시됩니다. 적용 가능성과 모델의 일반화가 요약됩니다. 이 모델은 구조를 정의하는 단위 수가 많거나 알려지지 않은 경우 건설 현장 배치 계획을위한 도구로 사용할 수 있습니다.