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Arrangement of Material Depots at Construction Site by Using Continuous Conditions

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Abstract

In this paper, we are introducing a model for optimizing the arrangement of final material depots at a construction site that uses continuous conditions. The target is to minimize the construction time, cost and resources by minimizing the delivery distances. In this model, the feasible positions of the material can be used in a continuous or discrete way as the known models do, but the structures are used in a continuous way. A simple example demonstrates that the product can be modeled as a group of 2D elements (lines, curves) with third dimensional information and the calculated result is compared with an expert's solution. The usability and the further generalization of the model are declared. It needs less input data than the discrete model does so it can be an alternative model to the discrete model if the number of the units that build up the structure is large or unknown.

Keywords: construction site layout planning, continuous demand, facility location allocation

1. Introduction

One of the preliminary processes in the construction management is planning the construction process. 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 [1, 2]. The target of CSLP is to minimise construction time, cost or required resources. Due to CSLP has significant impact on the productivity, cost, time, safety and security, several site layout planning models have been developed in the past decades. These were collected in an overview [3]. These models use the space in three different ways: *predetermined location, grid system, continuous site space*. The space types were clustered to five groups like *total space, product space, installation space, available space and required space* [2]. A partial task of the *construction site layout planning* (CSLP) is the allocation of construction objects on site. In practice, the construction objects allocation is carried out routinely [4] based on human judgment using the first-come-first-served method [5] or using the construction manager's experience [6]. Due to the number of factors that are involved in the CSLP, computers were identified as an efficient tool for solving the problem, such as computer-aided systems that are CAD-based [7], AI techniques used [8] or genetic algorithms used [9, 10, 11, 12, 13]. The objects, the structure and the spaces are continuously adjusted at different phases of the construction project. Therefore, researchers have developed dynamic site planning methods as well, like max-min ant system etc. [14] or BIM-based models [15]. 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* between the facilities or from facility to the structure to be built:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{m} d_{ij} R_{ij} \tag{1}$$

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in where n is the total number of construction objects; m is the total number of constraining objects; d_{ij} is the travelling distance from the location of the construction object i to its ideal location concerning the constraining object j; R_{ij} $(R_{ij} \in Q)$ is the parameter that represents transportation cost or the weight of constraint between construction objects i and constraining object j [7]. The travelling distances can be calculated by using either Euclidean distance or rectilinear distance.

The root of the CSLP problem is known as *k-median problem* in the operation research literature as a part of the *location allocation problem (LAP)*, where the demand is understood as the structure that needs to be built, the density is readable as the volume of the structure and the facility is readable as the material depot. If the number of facilities (***k***) is one, the problem is known as the *classical Fermat-Weber problem (1929)* [16]. In the CSLP models the number $k \geq 1$ the facilities' location can be calculated in discrete form by dividing the site into a given grid-based set of feasible location points and dividing the structures into unit areas or even in a continuous way using genetic algorithms or other artificial intelligence because of the infinite number of possibilities. Most of the LAP literature is based on discrete demand [17] like the known models of the CSLP where the target is to define the site objects' space and shape by using a collection of unit areas. In this paper, a model is presented for the *k-median problem* that uses the structures as continuous demand as line segments (as these were provided by the architect and engineers in their CAD drawings) and searches for the optimal arrangement on the entire XY plane.

2. Assumptions and objective functions

Architects and engineers define most structures with 3D CAD elements. The structures are represented by 2D marking with the Z directional information included on the drawings. Some structures are marked by symbols (e.g. pillars or windows), some are marked by line segments or curves (e.g. wall tiling) and some are marked by areas (e.g. floor tiling, concrete slabs or the boarding of the slab formwork). The material, size, volume and exact location of the structure are given in the architectural documentation in advance. In this paper the presented problem is very similar to the problem studied in an earlier paper of the authors [18] just here we deal with the structures that are marked as line segments instead of the areas. The structure is modelled as a two-dimensional figure denoted by the end points (A_i) of the line segments.

2.1. *Assumption 1.*

The structures are marked by a group of line segments. The line segments that belong to a depot must look like a line segment-chain. A group of line segments consists of ***k*** pieces of line segment-chains. A line segment-chain consists of ***l*** pieces of line segments where the end point of each line segment is the beginning point of the next one that has a volume $W>0$ if it is possible. Each line segment piece is defined in advance by its endpoints $A_i(x,y)$, ($i=1\ldots m$, $m \in N$) and each line segment piece has a W_i volume that represents the Z directional volume of the structure V_s.

2.2. *Assumption 2.*

The material laydown is denominated as the final material depot from where the material is delivered to the structure in units. 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 V_d. The number of the required depots (k, $k \in N$) can be easily calculated by dividing the volume of the structure by the volume of the final material depots. $k= V_s / V_d$.

2.3. *Assumption 3.*

According to Moore [19] there are two basic methods to deal with the CSLP problem. One is placing some of everything everywhere (or in a couple of combinations) and picking the best from these. The other method that is used in this paper is by bringing objects in one by one in a certain order and calculating the optimal arrangement after each step [11]. The model deals with one type of material at a time.

2.4. *Assumption 4.*

The handling paths from a depot to each point of the served structure (to each point of the line segments) can be calculated by two ways: using **Euclidean distance** or the shortest path inside the feasible handling area. In this study we use and measure the Euclidean distance in an unusually way. The length of the total delivery path from a certain point to the structure is counted by the measure of the areas ***(T_i)*** that are defined by the modeled structure's

2D marking (Figure 1.a.) and the vertical projection of the marking to the envelope of the Euclidean cone, that is set into that certain point. In this case where the structure is marked by line segment *($A_iA_{(i+1)}$)* or curve and defined by its endpoints ***$A_i(x,y)$*** the total delivery path from a ***S(a,b)*** point to the structure is counted as areas (line integrals) as shown on Figure 1.b.

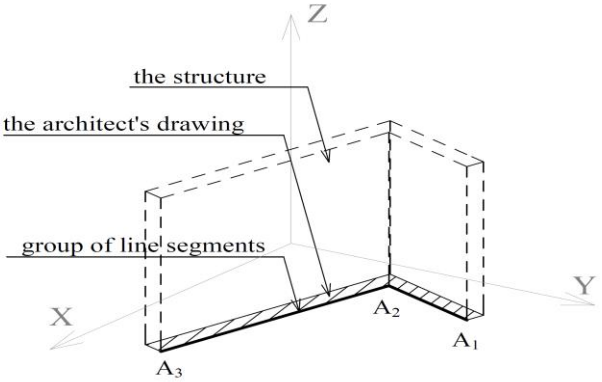


Figure 1.a. 2D marking of the structure

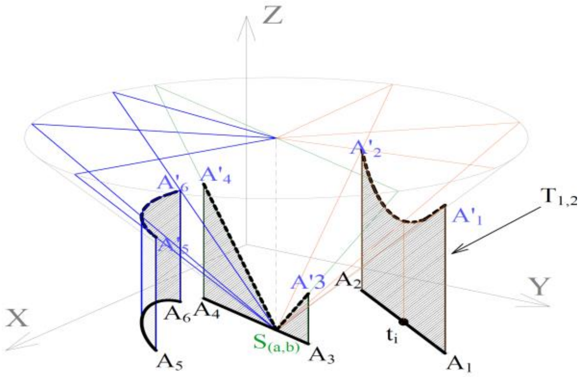


Figure 1.b. The length of the total delivery path

$$T_{i,i+1} = \int_{t_i}^{t_{i+1}} \left(|a-x|^2 + |b-y|^2 \right)^{1/2} d\varphi \tag{2}$$

Where ***T*** represents the size of the area bounded by the 2D marking, the vertical projection of it onto the Euclidean cone, the ***$d\Phi$*** is an extremely small change in arc length of the curve, ***A_i'*** is the distance between A_i and S points,

2.5. *Objective function*

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. This model leaves out of consideration the delivery cost because the model assumes that all of the delivery paths are horizontal and the delivery cost is directly proportional to the length of the delivery path and brings in one type of object at a time. The target is to minimize the length of the total delivery path.

2.5.1. In the case of k=1

The line segment-chain is given and the minimization form can be solved by any kind of two-parameter minimization:

$$\min_{(a,b)} \sum_{1}^{l} \left[W_{(t_i,t_{i+1})} \int_{t_i}^{t_{i+1}} \left(|a_K - x|^2 + |b_K - y|^2 \right)^{1/2} d\varphi \right] \tag{3}$$

2.5.2. In the case of k>1

There are infinite solutions because the start points and the end points of each line segment-chains are unknown. If any point of the line segment-group is renamed as cut-point (***C***) for dividing the structure to unique volume *k* pieces of line segment-chains, then each of the line segment-chains is defined and the minimum of the sum of the delivery paths (areas) for that certain cut-point can be calculated. The minimization form for the case of *k*>1 and cut-point is defined is:

$$\min_{C} \sum_{1}^{k} \min_{(a,b)} \sum_{1}^{l} \left[W_{(t_j,t_{j+1})} \int_{t_j}^{t_{j+1}} \left(|a_K - x|^2 + |b_K - y|^2 \right)^{1/2} d\varphi \right] \tag{4}$$

In where ***C***$\in(A_i, A_{i+1})$ is the cut-point for dividing the group of line segments to line segment-chains, ***E_K***$\in(A_i, A_{i+1})$ is the end point of each line segment-chain, ***k*** ($k\in N$) is the number of the needed depots; ***l*** ($l\in N$) is the number of line segments that belong to the certain depot; ***$W_{(i,\, i+1)}$*** ($W\in Q$) is the *Z* directional volume of the line segment between A_i and A_{i+1} (defined by the volume of the structure); ***a_K*** and ***b_K*** is the ***x*** and ***y*** coordinate of the searched ***S_K*** depots on the entire XY plane.

The object is to find *C* for the global optimal arrangement. If we place C_i to each A_i and solve the equation *m* times each counting will give a minimum of the total delivery paths that belongs to *k* pieces of R_j points. If we place the cut-point anywhere on the line segment between R_j and $R_{j+1,}$ the solution will be a member of a curve ***(fR)*** that has one minimum or one maximum point. If the curve is concave then R_j or R_{j+1} will be the location of the cut-point for the local minimum solution between R_j and R_{j+1}. If the curve is convex, the minimization of the curve between R_j and R_{j+1} will give the location of the best cut-point and will result in the minimum of the total delivery.

The global minimum of the model is the lowest result of all the counted local minimums. This means the minimization has to be solved $2m$ times (m times for all A_j and m times for all the curves between R_j and R_{j+1}) to find the global minimum of the model.

3. Example

In this example the target is to find the optimal allocation of the final material depots ($\boldsymbol{S_{(a,b)}}$) for the wall tiling work of a rectangular room (Figure 2.) from where the material units can be delivered to the structure along the minimal path.

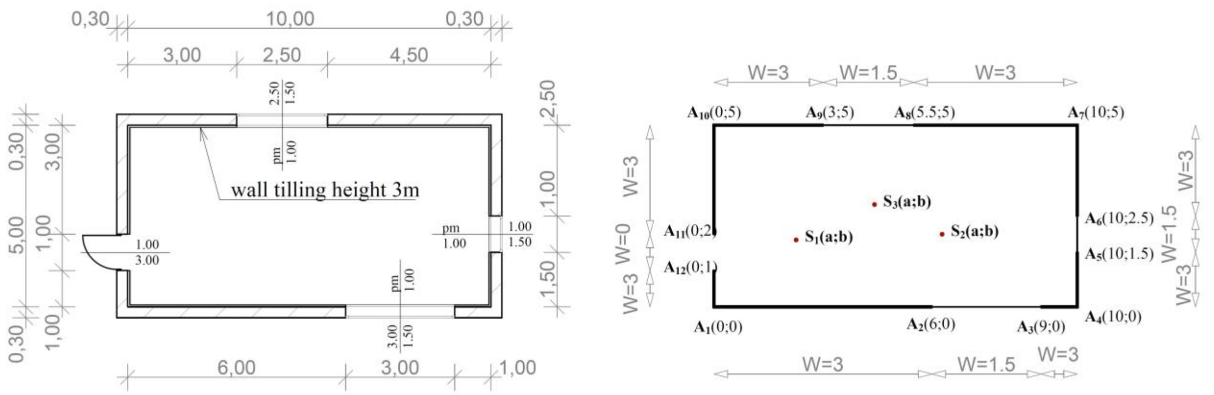


Figure 2.given drawing by the architect and the transformed information into the model

The volume of a material depot, the volume and the geometry of the tiling work with Z directional information is provided in advance ($\boldsymbol{V_d}$, $\boldsymbol{V_s}$, $\boldsymbol{A_i(x,y)}$) (Figure 2). The number of the needed depots is calculated: $\boldsymbol{k= V_s/ V_d}$.
$\boldsymbol{V_s}$=3x(10+5+10+5)-(3x1,5)-(1x1,5)-(2,5x1,5)-(1x3)=77,25 m2; $\boldsymbol{V_d}$=25,75 m2; $\boldsymbol{k= V_s/ V_d}$=3 pieces
In this example x=t or y=t. At first all $\boldsymbol{R_j}$ has to be found by measuring counterclockwise $\boldsymbol{k}$ pieces $\boldsymbol{V_d}$ volume line segment-chains from all A_i and mark their coordinates. We have m=12 pieces $\boldsymbol{A_i}$ and we have (k-1)m=24 pieces $\boldsymbol{E_{ik}}$.

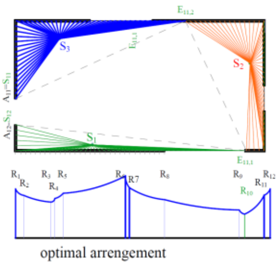
After all of the relevant points are found then the local minimums of the total delivery paths are counted by a program called *Mathematica 7* for each A_i as cut-points. The minimization form ran 12 times and gave the minimums of the sums of the total delivery path for all Rj (Table 1).

$$\sum_{1}^{k}\min_{(a,b)}\sum_{1}^{l}\left[W_{(t_j,t_{j+1})}\int_{t_j}^{t_{j+1}}\sqrt{|a_K-x|^2+|b_K-y|^2}\,d\varphi\right] \qquad (5)$$

In this case the optimal allocation of the depots belongs to the cut-point of $R_{10}=R_{11}=A_{10}=A_{11}$ as readable on Table 1. and shown on Figure 3.a.

4. Accuracy of the results

The architect drawing of this example was provided to a professional bricklayer. The expert was asked to mark the best arrangement of the three depots and the parts of the structure that he would serve from each depot for minimizing the total delivery path. His solution is shown on Figure 3.b. where the surfaces of the walls are turned to the *XY* plane and each color represents the surface of the structure part that he would serve from a certain depot. It is readable on Figure 3.c. that from the first depot *(S_1)* he would serve a bigger volume structure part than a depot volume is, and from the other two depots *(S_2, S_3)* he would serve smaller volume structure parts. Based on the technology itself and the equal volume of depots the first depot will run out of the material before the tiling work is done, so he would need to deliver the material from the other two depots. With the expert's solution, the workers would deliver the materials a 69.91% longer path than was counted as the optimal arrangement shown on Table 1.



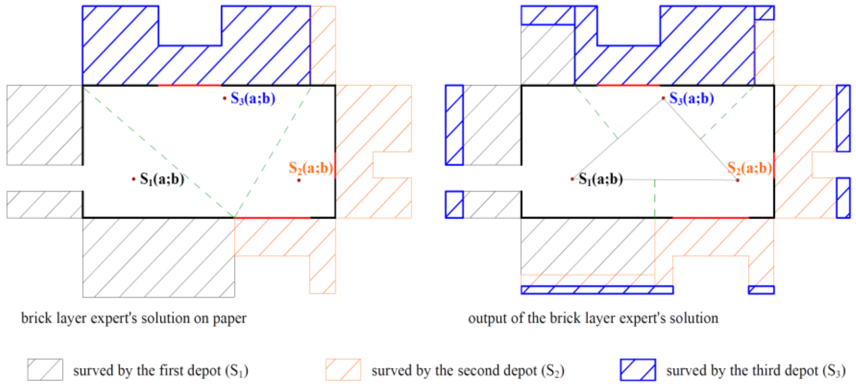


Figure 3.a. An the lowest solution of all counted equations

Figure 3.b-c. The expert's solution paper and in real

This 69.91% increment of the total delivery path is impressive if we declare that the increasing of the total delivery path by 7% causes a measureable raise in the total delivery time [20]. Based on this experiment, the searching for C to find the optimal arrangement is worth the time because the worst minimal solution for different cut-points (row R_6 on Table 1.) is 12.12% worse than the optimal arrangement (row R10 on Table 1.**)**. It must be recorded that the arrangement of the final material depots is not enough for minimizing the sum of total delivery path, the served structure parts are needed to be defined for each depots.

5. Generalization of the model and conclusion

In this example, the location of each depot was searched on the entire *XY* plane, but it could be localized into a certain place as *available space* [2]. This example was solved for a convex shaped structure and the model counted the lengths of the delivery paths by Euclidean distances, but it can deal with obstacles and concave structures in exactly the same way as the discrete model does by dividing the area up into areas named *'visible from', 'partly visible from' and 'not visible from'* [21]. In this example, the delivery cost was left out of consideration because the allocation of only one kind of material depots was searched for and the delivery paths were horizontal to every directions but this model can be integrated to the models that minimize the total delivery cost as well. It needs less input data than the discrete models do because it does not need the number and the exact places of the units that build up the structure. This model can be an alternative model to the discrete model even if the number of the units that build up the structure is large or unknown because in this case the required time for the calculation can be significantly less and the difference between the solution of these two models is negligible.

Table 1. The sum of the total delivery path for each R_i

R_i				**Σ**	**S_k**					
		$R_i(x)$	$R_i(y)$	Σ	$S_1(a)$	$S_1(b)$	$S_2(a)$	$S_2(b)$	$S_3(a)$	$S_3(b)$
R_1	A_1	0	0	**16,64**	4,29	0	9,25	4,125	1,002	4,339
R_2	$E_{8,1}$	0,33	0	**16,49**	0,811	4,161	4,625	0,001	9,054	4,316
R_3	$E_{5,2}$	1,42	0	**16,82**	8,384	4,736	0,392	3,521	5,696	0,023
R_4	$E_{9,1}$	1,58	0	**16,94**	0,357	3,418	5,853	0,033	8,273	4,778
R_5	$E_{6,2}$	1,92	0	**17,22**	8,033	4,848	0,308	3,199	6,334	0,082
R_6	*$E_{7,2}$*	*4,4*	*0*	***18,22***	*5,71*	*5*	*1,043*	*0,828*	*9,192*	*1,103*
R_7	$E_{10,1}$	4,58	0	**18,2**	1,136	0,727	9,278	1,204	5,54	5
R_8	A_2	6	0	**17,21**	9,708	2,359	2,91	4,967	2,014	0,209
R_9	A_3	9	0	**16,28**	9,672	3,454	1,668	4,75	3,219	0,016
R_{10}	**$E_{11,1}$**	**9,07**	**0**	**16,25**	**3,292**	**0,011**	**9,65**	**3,505**	**1,606**	**4,726**
R_{11}	**$E_{12,1}$**				same as R10					
R_{12}	A_4	10	0	**16,45**	9,293	4,077	1,049	4,379	4,21	0

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