New Approach for the Cross-Dock Door Assignment Problem

Article

4 authors, including:

Yi-Rong Zhu
University of Pennsylvania
8 PUBLICATIONS **256** CITATIONS

SEE PROFILE

Peter M. Hahn
University of Pennsylvania
46 PUBLICATIONS **2,176** CITATIONS

SEE PROFILE

Monique Guignard
University of Pennsylvania
102 PUBLICATIONS **3,231** CITATIONS

SEE PROFILE

New Approach for the Cross-Dock Door Assignment Problem

Yi-Rong Zhu
Electrical and Systems Engineering, University of Pennsylvania
Philadelphia, PA 19104-6314, USA
yrzhu@seas.upenn.edu

Peter M. Hahn
Electrical and Systems Engineering, University of Pennsylvania
Philadelphia, PA 19104-6314, USA
hahn@seas.upenn.edu

Ying Liu
Electrical and Systems Engineering, University of Pennsylvania
Philadelphia, PA 19104-6314, USA
liuying1@seas.upenn.edu

Monique Guignard-Spielberg
Operations and Information Management, University of Pennsylvania
Philadelphia, PA 19104, USA
guignard@wharton.upenn.edu

Abstract: In a cross-dock facility goods are moved by forklift from incoming truck platforms (strip doors) to temporary holding areas and then to platforms (stack doors) for outgoing trucks or directly from incoming truck strip doors to stack doors for outgoing trucks. Costs within the cross-dock may be minimized by appropriate assignment of strip doors to incoming trucks and stack doors to outgoing trucks. We present in this paper a formulation of this problem as a Generalized Quadratic 3-dimensional Assignment Problem and describe a methodology for generating practical Cross-dock Door Assignment Problem (CDAP) test cases. For our presentation at XLI SBPO, we will generate a range of CDAP test cases (from easy to very difficult) and attempt to solve these, using an exact and an approximate solution method.

Keywords: cross-dock, door assignment, quadratic assignment

Main area: optimization

1. Introduction

1.1 Background and literature review

Cross-docking is a logistics technique used in the retail and trucking industries to rapidly consolidate shipments from disparate sources and realize economies of scale in outbound transportation. Cross-docking essentially eliminates the costly inventory-holding functions of a warehouse, while still allowing it to serve its consolidation and shipping functions. The idea is to transfer shipments directly from incoming to outgoing truck trailers, without storage in between. Shipments typically spend less than 24 hours in a cross-dock, sometimes less than an hour. With the process of moving shipments from the receiving dock (strip door) to the shipping dock (stack door), bypassing storage, cross-docking reduces inventory carrying cost, transportation cost, and other costs associated with material handling. Research topics on the design and operational problems in cross-docking include the size of the cross-dock, the number of strip and stack doors, the width of the cross-dock, shapes for different cross-dock sizes, and assigning strip and stack doors to incoming and outgoing truck trailers, which is addressed here.

In a cross-dock facility, goods are moved by forklift from the incoming strip door to the appropriate outgoing stack door, for a specific destination. The dynamic nature of the flow patterns between origin-destination combinations makes the assignment of origins to strip doors and assignment of destinations to stack doors a difficult combinatorial optimization problem.

The cross-docking problem is a type of the assignment problems for which many studies have been reported in the literature. Peck (1983) developed a simulation for the integer programming model of the trailer-to-door assignments that minimizes the total transfer time. Tsui and Chang (1990, 1992) presented a general model of the dock door assignments and then developed a solution based on the branch and bound method. Kinnear (1997) introduced the definition of the cross-docking and explained the advantage of the cross-docking. Gue (1999) addressed the cross-dock "layout" as of the arrangement of strip/stack doors and the assignment of destination to stack doors. Gue proposed a look-ahead scheduling algorithm to reduce more labor cost compared to first-come first-served policy. Bartholdi and Gue (2000) described models that guide a local search routine in cross-dock door assignment so as to minimize the total labor cost. Their layout models balanced the cost of moving freight from incoming trailer to outgoing trailers with the cost of delays due to different types of congestion. Bermudez (2002) developed a genetic algorithm for assigning doors in order to minimize the total weighted travel distance. Sung and Song (2003) designed an integrated service network for a cross-docking supply chain network. Bozer and Carlo (2008) proposed a simulated annealing heuristic to determine the door assignments in cross-docks which is formulated as a Quadratic Assignment Problem (QAP) with rectilinear distances.

In this paper, we address an extension of the cross-dock door assignment problem as first defined in Tsui and Chang (1990). The fundamental difference is that our model handles the situation where the strip door serves more than one origin and the stack door serves more than one destination. Unlike previous study combining several origins or destinations with a "larger" one, we apply the formulation of the Generalized Quadratic 3-dimensional Assignment Problem (GQ3AP) to consider the multiple-to-one assignment as a knapsack constraint on the dock's capacity.

1.2 Tsui and Chang's Cross-dock Door Assignment Problem

Here is Tsui and Chang's mathematical model of the Cross-dock Door Assignment Problem (TS-CDAP),

Parameters:

M number of origins,

N number of destinations,

I number of strip doors,

J number of stack doors,

w_{mn} represents the number of trips required by the material handling equipment to move items originating from m to the cross-dock door where freight destined for n is being consolidated,

d_{ij} represents the distance between strip door i and stack door j.

Decision Variables:

$x_{mi} = 1$ if origin m is assigned to strip door i, $x_{mi} = 0$ otherwise,

$y_{nj} = 1$ if destination n is assigned to stack door j, $y_{nj} = 0$ otherwise.

Formulation:

$$\text{Minimize:} \quad \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{n=1}^{N} d_{ij} w_{mn} x_{mi} y_{nj} \tag{1}$$

Subject to:

$$\sum_{m=1}^{M} x_{mi} = 1 \qquad i = 1,2,...,I\,, \tag{2}$$

$$\sum_{i=1}^{I} x_{mi} = 1 \qquad m = 1,2,...,M\,, \tag{3}$$

$$\sum_{n=1}^{N} y_{nj} = 1 \qquad j = 1,2,...,J\,, \tag{4}$$

$$\sum_{j=1}^{J} y_{nj} = 1 \qquad n = 1,2,...,N\,, \tag{5}$$

$$x_{mi} = 0 \text{ or } 1 \qquad m = 1,2,...,M\,, \ i = 1,2,...,I\,,$$

$$y_{nj} = 0 \text{ or } 1 \qquad n = 1,2,...,N\,, \ j = 1,2,...,J\,.$$

Here, (2) makes sure that each strip door is assigned to only one origin, (3) makes sure that each origin gets assigned only one strip door, (4) makes sure that each stack door is assigned to only one destination, and (5) makes sure that each destination is assigned only one stack door (Tsui and Chang, 1990).

But, there are errors in this definition of the TS-CDAP. Namely, for both assignment constraints (2) and (3) to hold, M must be equal to I. Similarly for (4) and (5) to hold, N must be equal to J. Tsui and Chang saw the TS-CDAP as a Quadratic Assignment Problem. But, here too they were wrong. The QAP has just one permutation matrix solution variable. Whereas, the TS-CDAP has two sets of permutation matrix solution variables $\boldsymbol{x}$ and $\boldsymbol{y}$, which are indeed independent.

Follow the previous argument that M must be equal to I and N must be equal to J in the TS-CDAP model, we make a few observations. Solution matrices X of size $M \times M$ and Y of size $N \times N$ are necessarily square. But the flow matrix W and the distance matrix D are not. The 'squareness' of X and Y is a serious deficiency. In no practical situation would each strip door serve only one origin and each stack door serve only one destination. We tried first to relate the TS-CDAP to the Quadratic 3-dimensional Assignment Problem (Q3AP). The Q3AP has application in the design of symbol mapping diversity for the improvement of wireless communications in noisy and fading environments (Hahn, et al., 2008a).

In Zhu (2007), we manipulated the formulation Q3AP to look just like the TS-CDAP, making the TS-CDAP a special case of the Q3AP. The Q3AP solves the CDAP problem when the number of origins equals the number of strip doors equals the number of stack doors equals the number of destinations. We also showed that the 3-dimensional Assignment Problem (3AP) is a special case of the TS-CDAP. The 3AP is NP-hard. So, the TS-CDAP is proven to be NP-hard. Unfortunately, the restrictions that each strip door would serve only one origin and each stack door would serve only one destination remained. Thus, it was necessary to develop a more general algorithm, i.e., the Generalized Quadratic 3-dimensional Assignment Problem (GQ3AP), which is covered in the next Section.

2. A New CDAP and its relationship with the GQ3AP

We define a much more useful Cross-dock Door Assignment Problem (CDAP) and attempt to relate it to a Generalized Quadratic 3-dimensional Assignment Problem (GQ3AP). With the same setting for the TS-CDAP and additional parameters,

Additional Parameters:

s_m	volume of goods from origin m,
S_i	capacity of strip door i,
r_n	demand from destination n,
R_j	capacity of stack door j.

A new and generalized formulation of the CDAP is:

$$\text{Minimize: } \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{n=1}^{N} d_{ij} w_{mn} x_{mi} y_{nj} \tag{6}$$

Subject to:

$$\sum_{m=1}^{M} s_m x_{mi} \leq S_i \quad i=1,2,...,I, \tag{7}$$

$$\sum_{i=1}^{I} x_{mi} = 1 \quad m=1,2,...,M, \tag{8}$$

$$\sum_{n=1}^{N} r_n y_{nj} \leq R_j \quad j=1,2,...,J, \tag{9}$$

$$\sum_{j=1}^{J} y_{nj} = 1 \quad n=1,2,...,N, \tag{10}$$

$$x_{mi} = 0 \text{ or } 1 \quad m=1,2,...,M, i=1,2,...,I,$$

$$y_{nj} = 0 \text{ or } 1 \qquad n = 1, 2, ..., N, \, j = 1, 2, ..., J.$$

Here, (7) makes sure that the capacity of each strip door S_i is not exceeded, (8) makes sure that each origin gets assigned only one receiving (strip) door, (9) makes sure that the capacity of each outbound (stack) door R_j is not exceeded, and (10) makes sure that each destination is assigned only one stack door. With this new model we are able to assign multiple origins to a single strip door, as long as its capacity S_i could accommodate them. And, it is also possible to assign multiple destinations to one stack door, as long as its capacity R_j could accommodate them.

The GQ3AP model as first defined in Guignard, et al. (2006) is:

$$\text{Minimize:} \quad \sum_{i=1}^{K} \sum_{j=1}^{I} \sum_{p=1}^{J} \sum_{k=1}^{K} \sum_{n=1}^{I} \sum_{q=1}^{J} c_{ijpknq} u_{ij} u_{kn} t_{ip} t_{kq} \quad , \tag{11}$$

subject to the following constraints on $\boldsymbol{u}$:

$$\sum_{i=1}^{K} s_{ij} u_{ij} \le S_j \qquad j = 1, 2, ..., I, \tag{12}$$

$$\sum_{j=1}^{I} u_{ij} = 1 \qquad i = 1, 2, ..., K, \tag{13}$$

$$u_{ij} = 0 \text{ or } 1 \qquad i = 1, 2, ..., K, \, j = 1, 2, ..., I,$$

where s_{ij} is the resource requirement of equipment i and S_j is the available resource at location j, and subject to the following constraints on $\boldsymbol{t}$:

$$\sum_{k=1}^{K} r_{kq} t_{kq} \le R_q \qquad q = 1, 2, ..., J, \tag{14}$$

$$\sum_{q=1}^{J} t_{kq} = 1 \qquad k = 1, 2, ..., K, \tag{15}$$

$$t_{kq} = 0 \text{ or } 1 \qquad k = 1, 2, ..., K, \, q = 1, 2, ..., J,$$

where r_{kq} is the resource requirement of equipment k and R_q is the available resource at location q. Here, we purposely leave out the linear terms with coefficients b_{ijp}, as these terms have nothing to do with this analysis. Observe that the constraints in both models are essentially same, considering they are different only in variable subscripts.

The GQ3AP is a newly defined assignment problem, which is the generalization of both the Generalized Quadratic Assignment Problem (GQAP) and the Quadratic 3-dimensional Assignment Problem (Q3AP). This GQ3AP arises in many applications such as multi-story evacuation design and cross-dock layout design. Zhu (2007) describes a Lagrangian dual for the GQ3AP based on a level-1 reformulation-linearization technique (RLT) dual-ascent procedure similar to those successfully used for the GQAP and Q3AP. In Hahn, et al. (2008b) experimental results show the branch-and-bound algorithm embedded with the dual-ascent procedure has solved several instances of multi-story space assignment problem (MSAP) for the first time.

Now, if the six-dimensional cost matrix C can be written as:

$$C_{ijpknq} = w_{ik}d_{jq},$$ (16)

where $W = [w_{ik}]$ is $K \times K$ and $D = [d_{jq}]$ is $I \times J$, and D are the strip/stack distances in cross-docking facility and W are the number of moving trips of goods, just as before. The difference is that now in (16) the number of strip doors is equal to the number of stack doors (a perhaps serious limitation).

Then the objective function to be minimized becomes $\sum_{i=1}^{K}\sum_{j=1}^{I}\sum_{p=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{I}\sum_{q=1}^{J} w_{ik}d_{jq}u_{ij}u_{kn}t_{ip}t_{kq}$, which can be simplified based on the equality constraints shown in (13) and (15) as:

$$\sum_{i=1}^{K}\sum_{j=1}^{I}\sum_{p=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{I}\sum_{q=1}^{J} w_{ik}d_{jq}u_{ij}u_{kn}t_{ip}t_{kq} = \sum_{i=1}^{K}\sum_{j=1}^{I}\sum_{p=1}^{J}\sum_{k=1}^{K}\sum_{q=1}^{J} w_{ik}d_{jq}u_{ij}\sum_{n=1}^{I} u_{kn}t_{ip}t_{kq}$$
$$= \sum_{i=1}^{K}\sum_{j=1}^{I}\sum_{k=1}^{K}\sum_{q=1}^{J} w_{ik}d_{jq}u_{ij}\sum_{p=1}^{J} t_{ip}t_{kq} = \sum_{i=1}^{K}\sum_{j=1}^{I}\sum_{k=1}^{K}\sum_{q=1}^{J} w_{ik}d_{jq}u_{ij}t_{kq}.$$ (17)

Then (11) can be rewritten as:

$$\text{Minimize: } \sum_{i=1}^{K}\sum_{j=1}^{I}\sum_{k=1}^{K}\sum_{q=1}^{J} w_{ik}d_{jq}u_{ij}t_{kq}.$$ (18)

Now come a tricky step, which permits us to use the GQ3AP to solve a CDAP where the number of origins is not equal to the number of destinations. The GQ3AP formulation insists that this is the case. To fool the GQ3AP to solve a CDAP, we play with the product $w_{ik}d_{jq}$ in such a way that forces the solution of the GQ3AP to be a solution of a CDAP whose x and y matrices are of different size. To accomplish this, we set W such that:

$$w_{ik} = 0 \text{ if } i > M \text{ or } k > N \text{ and } M, N \leq K,$$ (19)

Then, substituting x with u and y with t, we have $\sum_{i=1}^{M}\sum_{j=1}^{I}\sum_{k=1}^{N}\sum_{q=1}^{J} w_{ik}d_{jq}x_{ij}y_{kq}$. With further variable subscript replacement, the objective function finally becomes:

$$\text{Minimize: } \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{n=1}^{N} d_{ij}w_{mn}x_{mi}y_{nj},$$ (20)

which is exactly the same as that in CDAP.

In conclusion, we manipulated the GQ3AP formulation to look like the CDAP, making the CDAP a special case of the GQ3AP. The model of GQ3AP, i.e., equations (11)-(15), solves the CDAP problem when the number of origins equals the number of destinations. Furthermore,

$u_{ij} = 1$ if strip door j is assigned to origin i, $u_{ij} = 0$ otherwise,

$t_{kq} = 1$ if stack door q is assigned to destination k, $t_{kq} = 0$ otherwise.

But, if we play the trick in between (19) and (20), we can solve the CDAP of equations (6)-(10).

One extra note for using the GQ3AP model to solve a CDAP arises when there are goods transferred from origin i to destination i. This produces a non-zero value in the flow matrix, which incorrectly moves quadratic costs in the objective function to the linear cost terms. In the GQ3AP, the quadratic expression in the objective function (11) does not include any terms for which $i = k$, unless $i = k$ and $j = n$ and $p = q$. Here we use the decision variables $x_{ijp} = u_{ij}t_{ip}$ and $x_{knq} = u_{kn}t_{kq}$. So if $i = k$ and $j = n$ and $p = q$, then $x_{ijp}x_{knq} = x_{ijp}$, which becomes associated with the linear cost only. If $i = k$ and either $j \neq n$ or $p \neq q$, then $x_{ijp}x_{knq} = 0$. Thus, we run into trouble with solving the CDAP is goods are sent from origin i to destination i. Fortunately, there is a simple solution.

We put zeros on the diagonal of the flow matrix W, by permuting the rows (columns) of the flow matrix so that zeros fall on the diagonal and correcting the resulting solution vectors to compensate for the permutation. If a row (or column) of the flow matrix has no zero, we will add a dummy destination (or origin).

Now, let's get to the question of whether or not the CDAP is an NP-hard problem. Take (18), which is really a special case of the CDAP, set $K = N, I = N, J = N$ and make matrix W a diagonal matrix. We get:

$$\min\left\{\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{N}\sum_{q=1}^{N}w_{ii}d_{jq}u_{ij}t_{kq}\right\} = \min\left\{N\sum_{j=1}^{N}\sum_{k=1}^{N}\sum_{q=1}^{N}w_{ii}d_{jq}u_{ij}t_{kq}\right\}, \qquad (21)$$

which is the formulation for a 3-dimensional Assignment Problem (3AP). Thus, the 3AP is a special case of the CDAP. The 3AP is NP-hard. So, the CDAP is proven to be NP-hard.

3. Generating test examples

Generating test examples requires generating origin/destination matrices and sample cross-dock floor plans (layouts).

3.1 Generating origin/destination matrices

In order to have realistic shipping volumes for testing our CDAP solution algorithms, we consulted a number of authors who had been involved in cross-dock design. While we were unable to get complete origin/destination volumes, Professor Kevin Gue of Auburn University was able to provide a set of destination volumes for a less-than-truckload (LTL) trucking example in which goods were sent to 56 destinations in the U.S. Thus, we used this list of volumes as the basis for generating origin/destination matrices. Thus, in all our experiments, the destinations have been given pre-determined volumes of goods as their demands.

The procedure for generating origin/destination matrices is that, for each destination, decide from which origin it will receive goods, and how much it will receive. It can be done by following the two steps below:

Step 1. Toss a fair coin M times (M is the number of origins) and record the results of the experiment as Heads = 1, Tails = 0. If it is a head then the origin corresponding to the outcome number is chosen to send goods to the destination (e.g. if, for the 7th destination, the outcome of the 4th coin toss is head, then the 4th origin sends a certain amount of goods to the 7th destination).

Step 2. This experiment is repeated for all N destinations. For each destination, the demand from the corresponding origin is given by a random integer number, and make sure the sum of these random numbers is equal to the total demand of that destination.

Table 1 is an example of flow matrix derived from this method.

Origin / Dest.		O1 65572	O2 29944	O3 7371	O4 22404	O5 9421	O6 26756	O7 11108	O8 2229
D1	39751	0	144	0	14729	0	24163	0	715
D2	21390	0	16608	0	0	4782	0	0	0
D3	20842	0	13192	1744	2236	1633	2037	0	0
D4	20758	10640	0	0	3701	2906	343	1691	1477
D5	19372	19108	0	0	0	76	0	174	14
D6	18073	9011	0	0	0	0	0	9062	0
D7	17790	14069	0	1686	1738	0	213	61	23
D8	16829	12744	0	3941	0	24	0	120	0

Table 1 – Origin/Destination Matrix of Flow of Goods

3.2 Cross-dock shapes to be considered

We start with a simple layout of the cross-dock, which has the long rectangular shape, with strip (receiving) doors on one side of the building and stack (outbound) doors on the other side. And we use rectilinear distances to simulate corridors or safety isles, so that there are clearly marked lanes for the forklifts, and they would not collide in this way. The distance between i-th strip door and j-th stack door is $d_{ij} = 3 + |i - i|$. See Figure 1.
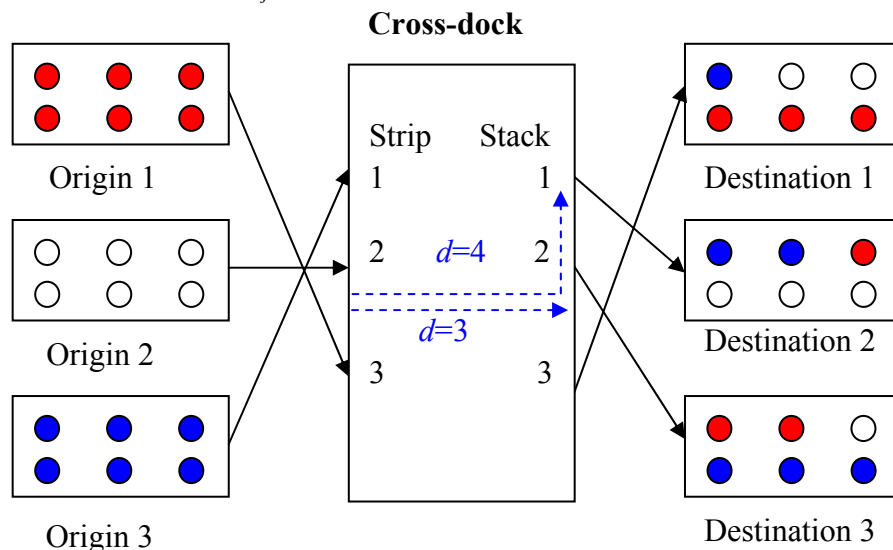

Cross-dock

Figure 1 – Typical Cross-dock Layout

Figure 1 gives an impression how the transfer of goods taking place. In the figure, each origin has exactly six goods to transfer. Each destination receives six goods. But, the goods received by the three destinations do not have the same mix of origins. The figure also gives strip door to stack door distances. For instance, the distance of 4 units from strip door 2 to stack door 1 comes

from 3 units to cross the space from the strip door side to the stack door side plus another 1 unit to get to stack door 1.

4. Experimental results

We have tested the 8×8×4×4 CDAP model with 8 origins, 8 destinations, 4 strip doors and 4 stack doors. The flow matrix is generated as above (see Table 1). In order to fit into the GQ3AP algorithm, we permute the columns of flow matrix, so that all diagonal entries are equal to 0. This is because in GQ3AP the i-th origin and i-th destination are the same entity, and there is no flow between them.

Table 2 is the flow matrix generated from Table 1 after permutation.

|	Origin	O1	O3	O7	O2	O4	O6	O5	O8
Dest.		65572	7371	11108	29944	22404	26756	9421	2229
D1	39751	**0**	0	0	144	14729	24163	0	715
D2	21390	0	**0**	0	16608	0	0	4782	0
D3	20842	0	1744	**0**	13192	2236	2037	1633	0
D4	20758	10640	0	1691	**0**	3701	343	2906	1477
D5	19372	19108	0	174	0	**0**	0	76	14
D6	18073	9011	0	9062	0	0	**0**	0	0
D7	17790	14069	1686	61	0	1738	213	**0**	23
D8	16829	12744	3941	120	0	0	0	24	**0**

Table 2 – Flow Matrix Generated from Table 1 after Permutation

After testing the model with different door capacities, we have the following results. Here the minimal cost came from implementing the GQ3AP solver proposed in Hahn, et al. (2008b).

Door Capacity	**1**	**7/8**	**6/8**	**5/8**	**4/8**
Minimal Cost	524415	533582	535875	535876	549745

Table 3 – Door Capacity vs. Minimal Cost

If each door capacity is equal to the total volume of all demands, where 'percentage of total volume' = 1, we can get the least cost, i.e. 524415. However, there is only one strip door assigned, as well as only one stack door assigned, which is a huge waste in door utility. As percentage of total volume decreases, the minimum cost gets larger. When each door capacity reduces to half of the total volume, the minimum cost is 549745, but it starts to use 3 different strip (and stack) doors. So we should really make decisions based on balancing between the minimum cost and the door usage. When each door capacity reduces to 3/8 of total volume or below, there is no feasible solution then.
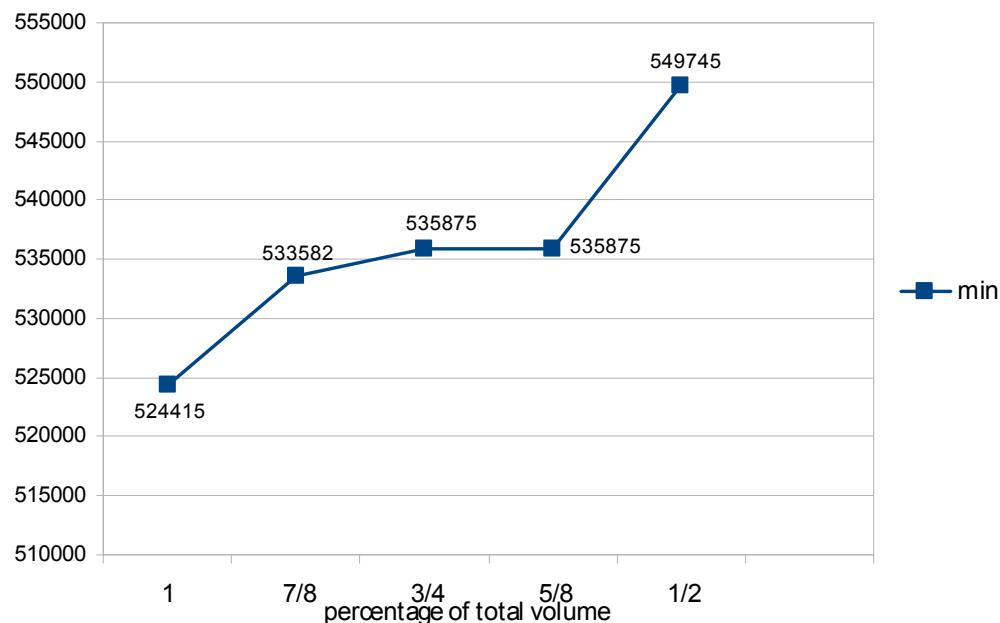
5. Conclusion and planned experimental work

In this paper, we propose a new formulation for the Cross-dock Door Assignment Problem, which concerns assigning origins to receiving (strip) doors and destinations to outbound (stack) doors such that costs within the cross-dock are minimized. The form could be presented as a Generalized Quadratic 3-dimensional Assignment Problem. We also propose a method for generating realistic test cases of the Cross-dock Door Assignment Problem.

For our presentation at XLI SBPO, we plan to generate a variety of test examples for several sizes of origin/destination volume situations and to draw appropriate cross-dock layouts to serve the volume of goods that need to be handled by the cross-dock for these origin/destination examples. Then, we will attempt to solve these with following CDAP solvers:

1. The GQ3AP exact solution solver described in this paper.
2. A heuristic solver for the GQ3AP developed by Bum-Jin Kim.

References

Bartholdi, J.J., and Gue, K.R. (2000) Reducing labor costs in an LTL crossdocking terminal. *Operations Research*, **48**(6), 823-832.

Bermudez, R.A. (2002) A genetic algorithm approach to LTL breakbulk terminal door assignment. MS Thesis, University of Arkansas, Fayetteville, AR 72701.

Bozer, Y.A., and Carlo, H.J. (2008) Optimizing inbound and outbound door assignments in less-than-truckload crossdocks. *IIE Transactions*, **40**(11), 1007-1018.

Gue, K.R. (1999) The effects of trailer scheduling on the layout of freight terminals. *Transportation Science*, **33**(4), 419-428.

Guignard, M., Hahn, P.M., Ding, Z., Kim, B.-J., and Zhu, Y.-R. (2006) Extensions and variations on quadratic assignment problems including the quadratic 3-dimensional assignment problem

(Q3AP). *Proceedings of 2006 NSF Design, Service, and Manufacturing Grantees and Research Conference*, St. Louis, MO.

Hahn, P.M., Kim, B.-J., Stützle, T., Kanthak, S., Hightower, W.L., Samra, H., Ding, Z., and Guignard, M., (2008a) The quadratic three-dimensional assignment problem: exact and approximate solution methods. *The European Journal of Operational Research*, **184**(2), 416-428.

Hahn, P., Smith, J.M., and Zhu, Y.-R., (2008b) The Multi-Story Space Assignment Problem. Accepted for publication to *The Annals of Operations Research*.

Kinnear, E. (1997) Is there any magic in cross-docking? *Supply Chain Management. An International Journal*, **2**(2), 49–52.

Peck, K.E. (1983) Operational analysis of freight terminals handling less than container load shipments. PhD Dissertation, University of Illinois at Urbana-Champaign, Urbana, IL 61801.

Sung, C.S., and Song, S.H. (2003). Integrated service network design for a cross-docking supply chain network. *The Journal of the Operational Research Society*, **54**(12), 1283–1295.

Tsui, L.Y., and Chang, C.-H. (1990) A microcomputer based decision support tool for assigning dock doors in freight yards. *Computers and Industrial Engineering*, **19**(1-4), 309-312.

Tsui, L.Y., and Chang, C.-H. (1992) An optimal solution to a dock door assignment problem. *Computers and Industrial Engineering*, **23**(1-4), 283-286.

Zhu, Y.-R. (2007) Recent advances and challenges in quadratic assignment and related problems. PhD Dissertation, University of Pennsylvania, Philadelphia, PA 19104.