# LAYOUT OPTIMIZATION OF CONTAINER TERMINALS USING MATHEMATICAL PROGRAMMING AND SIMULATION

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# ABSTRACT

Container terminal operators are under pressure to handle the increasing amount of container transfer in the global transportation network. To manage the growth, new container terminals are built or the capacity of existing ones is expanded using modern container handling technologies as well as automatic equipment. An efficient layout of the container terminal is crucial to obtain the maximum capacity.

In this paper we present an approach based on a mixed integer linear model to find promising layout configurations for container terminals. Means of simulation are used to validate and evaluate the attained layout configuration. In addition the adequacy of the mixed integer linear model for planning layouts of container terminals is evaluated using the developed simulation model.

Keywords: container terminal, layout optimization, simulation

# 1. INTRODUCTION

The layout of a container terminal is vital for an efficient operation of the terminal. The task of designing the layout is a strategic planning task arising when new terminals are built or existing ones are redesigned. Due to the continuing increase in the worldwide container turnover many container terminal providers have to extend their capacities to manage this growth. As a consequence new terminals like the Jade Weser Port in Germany are built and existing ones are expanded.

Planning the layout of a manufacturing facility is a well studied problem in the literature. Koopmans and Beckmann (1957) developed a quadratic assignment model which is the first model used to plan facility layouts. Until now the planning of facilities is an interesting field of research due to the complex combinatorial problem structure.

Current mixed integer formulations for the facility layout problem (Meller, Chen, and Sherali 2007; Xie and Sahinidis 2008) adopt the sequence pair concept introduced by Murata et al. (1996) for the related problem of the VSLI system design. An actual survey on the facility layout problem can be found in Drira, Pierreval and Hajri-Gabouj (2007) or Singh and Sharma (2006).

In comparison to the facility layout problem the design of container terminal layout is a less studied field. Mainly simulation studies have been carried out to compare different scenarios of possible terminal layout configurations.

Liu et al. (2004) evaluate the performance of two different layouts for the use of Automated Guided Vehicles. The results demonstrate that a higher performance can be gained using automated vehicles, and in addition that the yard layout has an impact on the number of vehicles needed as well as the terminal performance.

Yang, Choi, and Ha (2004) compare the performance of Automated Container Terminals using either AGV (Automated Guided Vehicles) or ALV (Automated Lifting Vehicles). Therefore they develop a simulation model considering a perpendicular yard layout. The simulation study shows that ALV configuration is superior to AGV configuration.

Yun and Choi (1999) develop a simulation model for a typical container terminal configuration with yard cranes and yard trucks. An object oriented simulation model for the terminal configuration is developed consisting of the subsystems gate, container yard and berth. Experiments are done considering a reduced configuration of a real container terminal in Pusan, Korea.

Brinkmann (2005) describes a simulation study in order to investigate the optimal capacities of a new container terminal for given expected container turnover. In consecutive simulation studies they determine the optimal number of quay cranes and the storage capacities needed.

Kim, Park, and Jin (2007) suggest a method for designing the layout of container yards regarding a configuration where terminal trucks are used as internal transport mean. They determine an optimal yard configuration using formulas to calculate the expected travel costs of trucks and the number of relocations for a container to pick up.

Steenken, Voß, and Stahlbock (2004) and Stahlbock and Voß (2008) give an extensive survey on different optimization methods for container terminal logistics.

# 2. LAYOUT PLANNING FOR CONTAINER TERMINALS

In terms of facility layout design the problem is to find an efficient arrangement of objects in a given area knowing the material flow between these objects. In general, the aim is to minimize the cost for transporting material. Transferring this concept to container terminal layout planning we have items to arrange on a container terminal and a flow of container among these items.

Items of a container terminal are quay cranes which are organized at berthing places, the storage blocks for intermediate storage of containers and additional buildings. Furthermore, depending on the regional characteristics, tracks might exist on the terminal. Trucks enter the container terminal through a gate to collect import or to deliver export containers. Besides these items driving lanes for transport equipment have to be considered on determining a feasible layout.

Regarding the list of items just mentioned we have to consider that not all of them have full flexibility to be positioned on the terminal area: The quay cranes are bound to the quay and, furthermore, they are moveable during daily operation. In addition the land side connections to external roads and train tracks necessitate that the gate and tracks are restricted to subsections of the available terminal area. As a result a model for container terminal layout design needs the ability to restrict elements to a subset of possible positions.

The most important remaining flexible items are storage blocks. Addressing storage blocks several observations can be made in the context of layout design. We assume that the storage capacity of the terminal for different types of container such as empty and reefer container is predetermined. Depending on the terminal equipment used, the dimensions of the blocks can be considered either as constant or as variable. For example when using yard cranes the width of a block is restricted to the given width of the used yard cranes. This is in contrast to a straddle carrier system where the width can be assumed to be flexible at least in a given range. In addition the length of a block is not restricted by any of the described equipment. To sum up we can make two observations: First, the used terminal equipment influences the design of the blocks, thus having an impact on the terminal layout. Second, the storage blocks can be variable in their dimensions. Despite these observations we assume in the following that the terminal equipment is given for each scenario and that the block dimensions are fixed due to the inherent complexity of the problem when considering variable dimensions.

As mentioned before different types of containers are handled on a container terminal. With respect to the storage of these container types different conditions have to be considered. The most frequent containers are regular twenty- or forty-foot containers for which no special attributes addressing storage conditions have to be considered. On the contrary, for reefer containers, containers for hazardous goods and empty containers special storage conditions exist: Empty containers are normally stored separately and can be stacked higher than normal containers. Containers for hazardous goods have to be stored in sections of the yard which are specially prepared. Moreover a minimal distance between this type of containers and other types is defined by law. Reefer containers need a power supply and thus cannot be stored in a section for regular containers. As layout design is considered, these conditions have to be considered on building blocks and in particular on defining a container-flow among items. For instance, considering a block that solely stores reefer containers, a less intensive flow of containers to this block can be assumed compared to a block storing regular containers.

For the horizontal means of transport like yard trucks or straddle carriers driving lanes need to be considered on planning a terminal layout. In order to regard them we introduce minimal distances among blocks and among all other items.

For the model introduced in the present work we make the following assumptions:

- The number of quay cranes is given, each with a fixed position at the quay.
- The area of the container terminal is rectangular and its dimensions are given.
- The needed storage capacity is given and the number as well as each dimension of a storage block is predetermined.
- The gate can be positioned at a predetermined border of the terminal area.
- The container flow between the items is given and considers the ratio of container types.

To consider non-rectangular areas in the model it is possible to introduce virtual items with a fixed position on the non-useable segments of the area. Quay cranes operate flexibly on the quay and thus their position changes during daily operation. For the strategic decision on the layout we spread the quay cranes equally along the quay given each crane a fixed position.

# 2.1. Model Formulation

Based on these assumptions we are able to formulate a mixed integer model. To reduce the model complexity we use the sequence pair representation. Meller, Chen, and Sherali (2007) and Xie and Sahinidis (2008) successfully adopted this representation used in VLSI design for the facility layout problem. For sake of brevity we only describe our used variable representation and refer for a more detail description to the above mentioned publications. We introduce binary variables  $n_{ij}^a$  and  $n_{ij}^b$  to define a relationship of item *i* to item *j* with respect to their relative location in the layout:

- If  $n_{ij}^a = 1$  and  $n_{ij}^b = 1$ , then item *i* must follow item *j* in the x-direction.
- If  $n_{ij}^a = 0$  and  $n_{ij}^b = 0$ , then item *j* must follow item *i* in the x-direction.
- If  $n_{ij}^a = 0$  and  $n_{ij}^b = 1$ , then item *i* must follow item *j* in the y-direction.
- If  $n_{ij}^a = 1$  and  $n_{ij}^b = 0$ , then item *j* must follow item *i* in the y-direction.

Using this representation we formulate a mixed integer model to find a layout for a container terminal considering minimal distances between items and a set of quay cranes each having a fixed positions.

#### Parameters:

- sdirection indices  $(s = \{x, y\})$ vsequence pair variable indices  $(v = \{a, b\})$  $w_i$ width of item i $l_i$ length of item i
- $lb_i^s$  lower bound of s-position of item *i*
- $ub_i^s$  upper bound of s-position of item *i*
- $L^{s}$  length of container terminal in s-direction
- $pos_i^s$  s-position of item *i*
- $a_{ij}^s$  minimum distance in s-direction between items *i* and *j*
- $f_{ij}$  container flow between *i* and *j*
- *I* set of all items
- Q set of quay cranes ( $Q \subset I$ )

#### Variables:

- $d_{ij}^s$  Manhattan distance in s-direction between item *i* and item *j*
- $x_i$  x-coordinate of upper left corner of item *i*
- $y_i$  y-coordinate of upper left corner of item *i*
- $p_i$  binary variable for the orientation of item i
- $n_{ij}^{\nu}$  binary variable denotes the relative location to each other of item *i* and item *j*

Using the described variables and parameters we define the following model, which we refer to as CTLE:

$$z = \min \sum_{i,j \in I, i \neq j} \left( d_{ij}^{x} + d_{ij}^{y} \right) f_{ij}$$
(1)

s.t.

$$\begin{aligned} x_i &\geq x_j + p_j \, l_j + (1 - p_j) w_j + a_{ij}^x - \\ L^x \Big( 2 - n_{ij}^a - n_{ij}^b \Big) &\forall \, i, j \in I \ i \neq j \end{aligned} \tag{2}$$

$$y_{i} \geq y_{j} + (1 - p_{j})l_{j} + p_{j} w_{j} + a_{ij}^{y} - L^{y}(1 + n_{ij}^{a} - n_{ij}^{b}) \qquad \forall i, j \in I \ i \neq j$$
(3)

- $L^{x} \geq x_{i} + p_{i} l_{i} + (1 p_{i}) w_{i} \quad \forall i \in I$   $\tag{4}$
- $L^{y} \ge y_{i} + (1 p_{i})l_{i} + p_{i}w_{i} \quad \forall i \in I$ (5)
- $y_i = pos_i^y, x_i = pos_i^x \qquad \forall i \in Q \tag{6}$
- $p_i = 0 \qquad \forall i \in Q \tag{7}$
- $1 = n_{ij}^{\nu} + n_{ii}^{\nu} \qquad \forall i, j \in I, i < j, \forall \nu(8)$

$$\begin{split} n_{ik}^{\nu} &\geq n_{ij}^{\nu} + n_{jk}^{\nu} - 1 & \forall i, j, k \in I, i \neq j \neq k, \forall \nu \ (9) \\ d_{ij}^{x} &\geq \left( x_{i} + p_{i} \frac{l_{i}}{2} + (1 - p_{i}) \frac{w_{i}}{2} \right) - \\ & \left( x_{j} + p_{j} \frac{l_{j}}{2} + (1 - p_{j}) \frac{w_{j}}{2} \right) & \forall i, j \in I \quad i \neq j \ (10) \\ d_{ij}^{x} &\geq \left( x_{i} + p_{j} \frac{l_{j}}{2} + (1 - p_{j}) \frac{w_{j}}{2} \right) - \\ & \left( x_{i} + p_{i} \frac{l_{i}}{2} + (1 - p_{i}) \frac{w_{i}}{2} \right) & \forall i, j \in I \quad i \neq j \ (11) \\ d_{ij}^{y} &\geq \left( y_{i} + (1 - p_{i}) \frac{l_{i}}{2} + p_{i} \frac{w_{i}}{2} \right) - \end{split}$$

$$\begin{cases} y_{j} + (1 - p_{j})\frac{l_{j}}{2} + p_{j}\frac{w_{j}}{2} \\ (y_{j} + (1 - p_{j})\frac{l_{j}}{2} + p_{j}\frac{w_{j}}{2}) \\ \psi_{i,j} \geq \left( y_{j} + (1 - p_{j})\frac{l_{j}}{2} + p_{j}\frac{w_{j}}{2} \right) - \end{cases}$$

$$\begin{pmatrix} y_i + (1 - p_i)\frac{l_i}{2} + p_i\frac{w_i}{2} \end{pmatrix} \quad \forall i, j \in I \quad i \neq j \quad (13)$$

$$lh^x \leq x \leq uh^x \qquad \forall i \in I \quad (14)$$

$$\begin{aligned} lb_i^{\gamma} &\leq x_i \leq ub_i^{\gamma} & \forall i \in I & (14) \\ lb_i^{\gamma} &\leq y_i \leq ub_i^{\gamma} & \forall i \in I & (15) \\ x_i, y_i \in \mathbb{R}^+ & \forall i \in I & (16) \\ p_i \in \{0,1\} & \forall i \in I & (17) \\ n_{ij}^{\nu} \in \{0,1\} & \forall i, j \in I, \forall \nu & (18) \end{aligned}$$

The objective function (1) minimizes the travel distances needed to transport the given container flows. Constraints (2) and (3) in conjunction with constraints (8) and (9) prevent the overlapping of items and in addition force the existing of a minimum distance between items. Constraints (4) and (5) guarantee the limitation of item positions to the dimension of the terminal area  $(L^x \times L^y)$ . The quay cranes are fixed to a given positions with a fixed orientation ((6), (7)). Constraints (10)-(11) are used to calculate the rectangular distances between the items. Finally, constraints (14) and (15) define an upper and lower bound on the possible positions of the items upper left corner.

Additionally, we adopt valid inequalities presented in Meller, Chen, and Sherali (2007) to our formulation:

$$\begin{aligned} d_{ij}^{x} &\geq \min\left(\frac{l_{i}}{2}, \frac{w_{i}}{2}\right) + \min\left(\frac{l_{j}}{2}, \frac{w_{j}}{2}\right) + a_{ij}^{x} - \\ L^{x}\left(2 - n_{ij}^{a} - n_{ij}^{b}\right) &\forall i, j \in I \ i \neq j \quad (19) \\ d_{ij}^{y} &\geq \min\left(\frac{l_{i}}{2}, \frac{w_{i}}{2}\right) + \min\left(\frac{l_{j}}{2}, \frac{w_{j}}{2}\right) + a_{ij}^{y} - \\ L^{y}\left(1 + n_{ij}^{a} - n_{ij}^{b}\right) &\forall i, j \in I \ i \neq j \quad (20) \end{aligned}$$

These valid inequalities force the distances between items *i* and *j* to be at least as great as the sum of the following values: the minimum of the half length and width of item *i*, the minimum of the half length and width of item *j* plus the minimum distance  $a_{ij}^s$  depending on the relative location denoted by the  $n_{ij}^v$  variables.

### 2.2. Distance Correction

To model the distances between two items we choose the rectangular distance also known as Manhattan distance. This measure of distance is suitable for use in a mixed integer formulation. Nevertheless, it is an approximation of the actual distance needed for means of horizontal transport to travel between two items, for example having two items *i* and *j* with  $x_i = x_j$ . In this case  $d_{ij}^x = 0$ , even if an item *k* exits with  $y_i < y_k <$  $y_j \land x_j - p_k \frac{l_k}{2} + (1 - p_k) \frac{w_k}{2} < x_k < x_j$  (see Figure 1). We refer to item *k* as blocking item because in reality a horizontal mean of transport travel from item *i* to item *j* has to detour round the blocking item *k*.



Figure 1: Manhatten Distance

To consider those detours we implement a procedure which takes solutions of the CTLE model and searches for pairs of elements for which the distance has to be corrected. For those pairs we update their distances and finally a new objective value  $z^c$  is calculated.

For the above constellation of items *i*, *j* and *k*  $d_{ij}^x$  is updated by adding:

$$d_{ij}^{x} += 2 * \min\left(|x_{j} + p_{j}\frac{l_{j}}{2} + (1 - p_{j})\frac{w_{j}}{2} - x_{k}|, |x_{j} + p_{j}\frac{l_{j}}{2} + (1 - p_{j})\frac{w_{j}}{2} - (x_{k} + p_{k}l_{k} + (1 - p_{k})w_{k})|\right) (21)$$

Figure 2 illustrates the updated distance  $d_{ii}^{x}$ .



Figure 2: Corrected Distance

#### 2.3. Problem Instances

We develop two scenarios based on typical yard and equipment configuration of container terminals. Based on these two scenarios we build instances of different size. We consider one terminal configuration using a straddle carrier system like the CT4 in Bremerhaven, Germany, and a terminal with yard trucks and yard cranes which is typical for an Asian container terminal like the HIT 9 in Hong Kong.

For the straddle carrier scenario we use the available data described in Brinkmann (2005) to build a realistic instance: The CT4 container terminal has a quay length of 1750 m with four berths and a terminal depth of 650 m. The containers are stored in 22 blocks in the yard. They are divided in 15 blocks for storing regular containers (l = 117 m, w = 150 m), 3 blocks for storing reefer containers (l = 76 m, w = 175 m),one storage block for container containing hazardous goods (l = 117 m, w = 150 m) and one block for containers (l = 139 m, w = 117 m).empty The external trucks enter the terminal through a gate (l = 30 m, w = 30 m) and are serviced in a truck service area (l = 30 m, w = 79 m). Tracks with a length of 1430 m and a width of 45 m exists for the service of trains, and 16 quay cranes are used to service vessels. Based on this instance with four berths we build smaller instances with 1, 2 and 3 berth(s). These instances are built by scaling the values respectively to the number of berths. For example the scenario regarding three berths consists of 12 quay cranes. To determine the correct number of storage blocks needed we do not scale directly the number of blocks but the storage capacity needed. Based on the storage capacity the actual number of blocks is calculated. In particular considering the block for storage of hazardous container we scale the dimensions to avoid an unrealistic high storage capacity for hazardous container (B 14 8: l = 59 m, w = 122 m; B 12 4; l = 59 m, w =122 m). In Table 1 the instances are detailed.

Table 1: CT4 Instances

| ruble 1. CT ( Instances |      |       |       |      |      |     |                    |
|-------------------------|------|-------|-------|------|------|-----|--------------------|
| Instance                | Reg. | Reef. | Haza. | Emp. | Lx   | Гà  | l <sup>train</sup> |
| B25_16                  | 15   | 3     | 1     | 3    | 1750 | 650 | 1430               |
| B19_12                  | 11   | 2     | 1     | 2    | 1470 | 600 | 1073               |
| B14_8                   | 8    | 1     | 1     | 1    | 980  | 600 | 715                |
| B12_4                   | 6    | 1     | 1     | 1    | 784  | 600 | 572                |

For the layout instances based on a yard crane system we build instances in orientation to the terminal HIT 9 in Hong Kong having two berths with an overall quay length of 700 m. Due to a lack of available data we assume the following values: we use a typical block length for blocks operated by rubber tired gantry cranes of 176 m (Kim, Park, and Jin 2007). We assume a width of a block for reefer and regular container of 24 m. The block width for empty container is set to 29 m. Storage of hazardous containers is not considered. The depth of the terminal is assumed to be 450 m. For the instance having two berths 8 quay cranes operate at the quay. In the container yard 22 blocks are used for the storage of containers. The landside connection consists of a gate with additional waiting slots for trucks with a length of 170 m and a width of 45 m. No railway connection exits. Based on this instance with two berths we build additional instances regarding one or three berth(s). The instances for the yard crane scenario are described in Table 2.

| Instance | Reg. | Reef. | Emp. | Lx   | Гà  |
|----------|------|-------|------|------|-----|
| A34_12   | 28   | 3     | 2    | 1050 | 450 |
| A23_8    | 19   | 2     | 1    | 700  | 450 |
| A12_4    | 9    | 1     | 1    | 350  | 450 |

Table 2: HIT9 Instances

### 2.4. Container Flow

In short term daily operation of a container terminal the decision of where to place an export container is an essential task. The occurrence of rehandles has to be avoided and in addition the aim is to have short distances to the berth where the designated vessel is expected to be moored. In addition the workload of the equipment in the yard should be balanced to avoid bottlenecks. The same thoughts can be made for import containers.

For the strategic layout design these operational planning tasks for the flow of containers can be neglected. Regarding two blocks storing the same type of containers and having the same dimensions it is of no relevance which of the blocks is next to a specific berth. Hence we model the flow for equal container types by equally distributing the containers among the blocks of the same size.

In contrast the flows of different container types have to be considered. That is, containers of special type can only be routed to storage blocks meant for this type. Thus one building the flow matrix we distinguish different container types. Based on the statistical occurrence of the special container type we weight the corresponding flow of containers.

To show the complexity of the CTLE model with a non-equally distributed flow matrix we introduce a second method. This method adopts the equally distribution and randomly intensifies or reduces the flow between blocks. To ensure a nearly same overall flow a decrease is only allowed when the sum of decreases is less than the sum of increases and vice versa. In addition a ratio r is given which bounds the maximal possible increase or decrease of the flow  $f_{ij}$  value to a value lower than  $r * f_{ij}$ . For each of the described instances in section 2.3 we model one flow equally distributed and one with a randomly adjustment using a ratio of r = 0.3.

#### 2.5. Ordering of Items

As mentioned in the previous section it can be observed that pairs of identical items exits which have the same flow to all other items. With respect to a layout the positions of those items can be interchanged without a change of the solution value. To avoid the enumeration of identical solution we add a constraint to CTLE to order those items in advance. Let *ID* be the set of identical items pairs:

$$ID \coloneqq \{(k,m) | f_{ki} = f_{mi} \land f_{ik} = f_{im} \land w_k = w_m \land l_k = l_m \forall i \in I, i \neq k, i \neq m, k < m\}$$
(22)

We add the following constraint to CTLE:

$$n^a_{km} = 1 \qquad \forall (k,m) \in ID \tag{23}$$

This constraint forces item k to follow item m either in the x- or the y-direction.

### 2.6. Computational Results

The resulting mixed integer instances are solved using Cplex 11 (ILOG 2007) on an Intel Pentium 4 CPU 3.40GHz with 4 GB RAM. Table 3 shows results for the instances using the standard flow of containers. The described valid inequalities and constraint (23) are added to the CTLE model. The column #Nodes describes the number of nodes examined in the branch and bound process and Time depicts the time in minutes needed to solve the instances. We set a time limit of 12 hours to solve the instances. For instances with a higher gap than zero no optimal solution could be found due to restriction of time or memory. The column  $z^c$  shows the results by adjusting the distances as described in section 2.2. Values in columns  $z^c$  and z are given in kilometers. The last column Gap depicts the Gap between the current lower bound and the current best solution.

Table 3: Results with r = 0

| Tuble 5. Results with $r = 0$ |        |        |          |          |      |  |  |
|-------------------------------|--------|--------|----------|----------|------|--|--|
| Instance                      | #Nodes | Time   | Z        | $z^{c}$  | Gap  |  |  |
| B25_16                        | 2989   | 721.4  | 7827.60  | 7911.21  | 25.4 |  |  |
| B19_12                        | 84389  | 378.8  | 4879.47  | 4995.13  | 12.6 |  |  |
| B14_8                         | 565711 | 76.7   | 2507.92  | 2533.11  | 0    |  |  |
| B12_4                         | 200645 | 11.0   | 1737.77  | 1749.97  | 0    |  |  |
| A34_12                        | 661    | 720.0  | 4284.83  | 4352.54  | 38.0 |  |  |
| A23_8                         | 49361  | 484.7  | 2062.01  | 2188.10  | 23.9 |  |  |
| A12_4                         | 58312  | 4.5    | 788.96   | 883.95   | 0    |  |  |
| Sum                           | 962068 | 2397.0 | 24088.56 | 24614.03 |      |  |  |

Table 3 shows that about 40 hours are needed to solve all instances. The CT4 instances can be optimally solved until two berths. A higher proportion of berth to the number of blocks exists in HIT9 scenario. Just the one-berth-instance can be solved optimally for the HIT9 instances. Updating the distances by considering blocking elements increases the sum of the solution values by about 2.18%.

Table 4 shows results for the instances with a randomly adjusted flow using a ratio of r = 0.3.

Table 4: Results with r = 0.3

|          | 100001.1000000000000000000000000000000 |         |         |                |      |  |  |
|----------|--|---------|---------|----------------|------|--|--|
| Instance | #Nodes                                 | Time    | Z       | z <sup>c</sup> | Gap  |  |  |
| B25_16   | 2046                                   | 720.0   | 7359.27 | 7634.2         | 30.7 |  |  |
| B19_12   | 61501                                  | 177.87  | 4828.72 | 5050.1         | 26.8 |  |  |
| B14_8    | 1523117                                | 720.0   | 2469.63 | 2527.6         | 23.2 |  |  |
| B12_4    | 4263591                                | 718.53  | 1691.8  | 1780.1         | 12.5 |  |  |
| A34_12   | 16                                     | 720.0   | 3829.9  | 3928.2         | 37.9 |  |  |
| A23_8    | 21595                                  | 720.0   | 2039.0  | 2155.1         | 31.2 |  |  |
| A12_4    | 3676232                                | 720.0   | 762.6   | 858.6          | 20.6 |  |  |
| Sum      | 9548098                                | 4496.42 | 23161.1 | 23933.9        |      |  |  |

For those instances the constraint (23) is not relevant because of an empty set *ID*. The results show that none of the instances can be optimally solved when using a randomized flow matrix.

# 2.7. Discussion of Model

The assumption of fixed block dimensions restricts a possible important degree of freedom. The above results show that even without considering variable block dimensions the model is hard to solve. That is, why we first restrict this degree of freedom. The aim is to evaluate the adequacy of a layout model like the CTLE for planning container terminal layouts.

With respect to fixed block dimensions one can state that by knowing this information it is easily possible to construct manually an at least feasible solution. The main degrees of freedom remaining are:

- The placement of gate and tracks.
- The orientation of the blocks; either perpendicular or parallel to the quay.
- The placement of blocks considering different container types.

To evaluate the above discussed adequacy of the CTLE model for planning container terminal layouts we developed a simulation model. This simulation model is used to evaluate the resulting layouts in simulation studies. In addition to the layouts found by the CTLE model we manually constructs layout solutions that are additionally evaluated.

# 3. SIMULATION

A modular configurable discrete event-based simulation model has been designed in Plant Simulation 8.1 (UGS Tecnomatix 2007) to evaluate the performance of the layout configurations generated by the previous described solution method and to analyze the adequacy of the CTLE model.

As we have to cope with two different equipment scenarios we use a level of abstraction that gives us the ability to manage various scenarios. Moreover it is essential for evaluating the performance of a container terminal that the whole terminal operation is simulated.

### **3.1. Simulation Design**

We structure our simulation model in modules for each vital part of the terminal. Beginning at the seaside the first module consists of a berthing place and a fixed number of assigned quay cranes. The quay cranes at one berth are all either in discharging mode or (when all containers are unloaded) in charging mode. The sequence of the containers to unload and load for a vessel is defined in advance. For transporting containers between the seaside and the storage blocks as well as between storage blocks and landside facilities we use an abstract class of horizontal means of transport. Depending on the ability of the horizontal means of transport to hoist a container the process of unloading a container from a vessel is decoupled from the availability of horizontal means of transport at the corresponding apron. The container can be temporary stored on the apron until a horizontal transport mean arrives that is able to hoist the container. The needed transport times are calculated based on distance matrix

gained from the results of the layout optimizing procedure.

The stacking module either consists of a yard crane system or in case of the straddle carrier system is just a memory of stored containers. To determine the time needed for storing a container in a block or for taking a container out of a block a distribution is used which depends on the length of the block.

The landside connections are modeled by a module for tracks using a defined number of stacking cranes to manage the loading and unloading operations of trains. As for the vessels the sequence of containers to discharge and charge is given. The operation of external trucks on the terminal is modeled similar to the horizontal means of transport using a distance matrix to calculate the needed travel times. In case of external trucks the gate is either start or destination for each move of an external truck on the yard. For the straddle carrier system truck service lanes exit, where straddle carriers load or unload arriving external trucks.

The operational assignment of ships to berthing places is managed by a First Come First Serve procedure. The choice of a block to temporarily stack a container is done randomly by considering that non regular containers have to be stored in designated blocks. Transport jobs are randomly assigned among the currently available horizontal means of transport.

# **3.2. Simulation Scenarios**

For the generation of data we use a scenario generator based on the work of Hartmann (2004). The scenario generator computes information about vessel, truck and train arrivals. In addition the amount of containers delivered by each arriving carrier as well as the type of container is generated. Based on a dwell time distribution the containers are assigned to a carrier which picks it up. For a detailed description of the generation process and the configurable parameters we refer to Hartmann (2004).

For the scenario CT4 and HIT9 we assume a configuration with two berthing places. Thus the layout solutions for the instances B14\_8 and A23\_8 are relevant for the simulation. Arrival data is generated for a horizon of seven days with 6500 containers arriving by vessels, 4367 containers arriving by feeders, 225 containers arriving by truck and 490 containers arriving by train. The average dwell time of containers is 4.6 days. For the HIT9 scenario we assume the same values except that no containers arrive by train. The containers arriving by train are added to truck arrivals. Using different seed values we generate 10 datasets with different arrival data for each scenario. To achieve a relative high workload in the terminal for the last two days we let up to two vessels arrive on day two and the remaining three vessels on day six of the horizon. The collection of statistical data is started at the beginning of day six. For the HIT9 scenarios 20 trucks and for the CT4 scenario 22 straddle carriers are used as horizontal means of transport. Table 5 shows the average number of carriers arriving in the given horizon.

 Scenario
 Trucks
 Feeders
 Vessels
 Trains

 CT4
 651.5
 39.4
 4.6
 8.5

 HIT9
 1564.8
 39.4
 4.6
 0

Table 5: Average Carrier Arrivals

For both scenarios CT4 and HIT9 we evaluate the adequacy of the CTLE model by simulating different layout solutions found during the branch and bound process and manually constructed layout solutions. In addition solutions with corrected distances are simulated. The manual layout solutions are constructed by positioning the blocks perpendicular to the quay considering minimal distances. The blocks for non regular containers are positioned in the back of the yard as well as the truck service area and the tracks.

The layout solutions simulated for the CT4 scenario are displayed in Table 6. The columns z depict the corresponding solution value and columns  $z/\max(z)$ the proportion of the solution value compared to the worst solution. B\_Man is a manually constructed solution. Using the distance correction method the solutions in the forth column are computed based on the corresponding solution in the first column.

| Table | 6. | Simulated | Lav | vont | Solutions | for | CT4 |
|-------|----|-----------|-----|------|-----------|-----|-----|
| rabic | υ. | Simulateu | La  | your | Solutions | 101 | CIT |

| Lay. Sol. | z      | $\frac{z}{\max{(z)}}$ | Lay. Sol. | z      | $\frac{z}{\max{(z)}}$ |
|-----------|--------|-----------------------|-----------|--------|-----------------------|
| B_z1      | 2507.9 | 0.78                  | B_z1_C    | 2533.1 | 0.79                  |
| B_z2      | 2541.2 | 0.79                  | B_z2_C    | 2599.8 | 0.81                  |
| B_z3      | 2752.7 | 0.85                  | B_z3_C    | 2757.8 | 0.86                  |
| B_z4      | 3208.7 | 1.00                  | B_z4_C    | 3221.4 | 1.00                  |
| B_Man     | 2635.3 | 0.82                  | B_Man_C   | 2650.3 | 0.82                  |

Table 7 shows the layout solutions for the HIT9 scenario. A\_Man and A\_Man2 are manually constructed solutions, whereat A\_Man2 has been constructed with the aim to get a worse solution. In total 12 layout solutions are simulated for the HIT9 scenario with a different of 16 % of the best solution value (A\_z1) compared to the worst solution value (A\_Man\_c2).

 Table 7: Simulated Layout Solutions for HIT9

| Lay. Sol. | Z      | $\frac{Z}{max(z)}$ | Lay. Sol. | Z      | $\frac{Z}{max(z)}$ |
|-----------|--------|--------------------|-----------|--------|--------------------|
| A z1      | 2062.2 | 0.84               | A z1 C    | 2188.1 | 0.89               |
|           | 2099.9 | 0.85               | A_z2_C    | 2155.1 | 0.87               |
| A_z3      | 2117.6 | 0.86               | A_z3_C    | 2221.7 | 0.90               |
| A_z4      | 2151.6 | 0.87               | A_z4_C    | 2248.8 | 0.91               |
| A_Man     | 2154.3 | 0.87               | A_Man_C   | 2267.6 | 0.92               |
| A_Man2    | 2431.7 | 0.98               | A_Man2_C  | 2469.2 | 1.00               |

#### 3.3. Simulation Results

To quantify the efficiency of the terminal layout we use the following performance measures:

• Average turnaround time (TAT) of trucks and trains.

- Average quay crane moves per hour when a ship is moored at the corresponding berth.
- Average of the sums of travel distances of horizontal means of transport.

The values displayed are scaled either by dividing the maximal average value or in case of the quay crane moves per hour by the minimal average value.

Figure 1 shows the results for the CT4 scenario simulating each layout solution in Table 6. The sum of distances traveled by the horizontal means of transport is the lowest for the optimal solution B\_z1 found by the CTLE model. The second best value of average travel distance is achieved by B\_z2. Sorting the solutions by the solution values z would result in the same hierarchy than sorting by the average travel distances. Focusing on the average quay crane moves per hour a maximal difference of 1.8% occurs between B\_Man and B\_z3. The best value of train TAT is achieved by B\_z2 and the best value of truck TAT by B\_z1.

Comparing the manual constructed solutions B\_Man with B\_z1 a slightly higher value of about 2.7% occurs for the average travel distances. This results in a 0.5% lower value of quay crane moves and a 1.6% higher value of truck turnaround time for the manual solution. However the B\_Man solution achieves a 2.7% better result for the turnaround time of trains.

The horizontal means of transport in the CT4 scenario service quay crane jobs with a higher priority than truck and train jobs. As the results show this leads to higher differences in the corresponding performance measures (Truck TAT and Train TAT) compared to the quay crane moves performance measure.

Figure 2 shows the simulation results for the HIT9 scenario simulating the layout solutions in Table 7. The maximal difference in the average travel distances about 11.4% exits between the solutions A\_z1 and A\_Man2\_C. Regarding the performance measures average quay crane moves per hour and turnaround time of trucks just slightly differences occur. The best value of quay crane moves per hour is about 2% increased and the best value of turnaround time of trucks is 1.6% decreased compared to the worst solution. The manual constructed solution has the highest value of average quay crane moves and just a 0.3% higher value of average turnaround time of trucks.

The results for the solution with corrected distances shows that compared to the corresponding solutions with no correction the travel distances are increased by values between 2.6% and 3.3%. This leads to an average decrease in quay crane moves per hour of about 0.8% and an average increase of truck turnaround times of about 0.6%.









Figure 4: Simulation Results for HIT9 Scenario

# 4. CONCLUSION AND OUTLOOK

We presented a mixed integer formulation for the layout planning of container terminals. Based on two scenarios we build different instances and present computational results. The results show that instances of practical size are hard to solve. To analyze the rectangle distance measure we use a distance correction method. Considering blocking elements increases the distances in average by about 3.6%.

In section 2.7 we discuss the adequacy of the presented model (CTLE) for planning container terminal layouts. To analyze the adequacy we carry out a simulation study for different layout solutions. The results show that a higher performance is gained for solutions found by the CTLE with a low gap compared to worse solutions. Nevertheless the manual constructed

solutions show no significance difference in the performance compared to the solutions found by the CTLE. Promising layout solutions are found by the CTLE but manual planning achieves quite competitive solutions. For example the solution value z for A\_Man differs by 3% from the best solution found by the CTLE. The simulation results show that a small improvement in the solution value z not results in significantly higher terminal performance.

For further research it would be interesting to extend the model to consider variable block dimensions. In addition the influence of different types of equipment on the layout could by studied. Furthermore, the simulation model should be extended by implementing more detailed operational decisions such as the dispatching of horizontal means of transport.

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