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Selecting Yard Cranes in Marine Container Terminals Using Analytical Hierarchy Process

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ABSTRACT

The time that container vessels and transportation trucks wait in a container terminal for loading and/or unloading of cargo is a real cost scenario which affects not only the smooth operation of ports, but may also the overall cost of the container trade. The main objective of this study is to provide a decision-making tool and also to introduce the concept of the Multiple Attribute Decision-Making (MADM) technique by using the Analytical Hierarchy Process (AHP) for solving the problem for selecting the best yard gantry crane among three alternatives including Straddle Carriers (SCs), Rubber Tyred Gantry Cranes (RTGs) and Rail Mounted Gantry Cranes (RMGs) by integrating the quantitative and the qualitative decision attributes into a hierarchical process.

1. Introduction

Maritime container terminals are now facing with a higher volume of traffic, limited land, larger vessel sizes and lower profit margins. The container port industry is very competitive and users such as shipping lines, transportation companies, and agents select a port based on the criteria offered such as low tariffs, safety, ease of access, minimum turn around times, lesser waiting, dwell and administration times to deal with the processing of their container ships and cargoes. In this context it is natural for port operators to expect high efficiency and productivity with a minimum cost from the operating systems in their terminals.

Most terminals are taking measures to increase their throughput and capacity by:

- Introducing new technology,
- Optimizing equipment dwell-times,
- Increasing storage density,
- Optimizing ship turn-around times, and
- Optimizing truck turn-around times,

The time that a ship and transportation trucks spend at a terminal for loading/unloading of cargo (truck turn-around time) is a real cost scenario which affects the overall cost of the container trade. There are two common measures that terminal operators are looking at to optimize their container terminal throughput. First, adding more yard cranes; and second, employing the aid of automated technologies such as automated yard cranes and the truck appointment systems (Huynh and Walton 2005).

Giulianio and O'Brien (2007) evaluated the outcomes of ports of Los Angeles and Long Beach after adopting the gate appointment system and off-peak operating hours as a means of reducing truck queues at gates. Han *et al.* (2008) have studied a storage yard management problem in a transhipment hub where the loading and unloading activities are both heavy and concentrated with the aim of reducing traffic. Jinxin *et al.* (2008) have proposed an integer programming model for containers handling, truck scheduling and storage allocation as a whole. Namboothiri and Erera (2008) studied the management of a fleet of trucks providing container pickup and delivery services to a port with an appointment based access control system. Lau and Zhao (2008) formulated a mixed-integer programming model, which considered various constraints related to the integrated operations between different types of

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container handling equipments. Guan and Liu (2009) applied a multi-server queuing model to analyze marine terminal gate congestion and quantifying truck waiting cost.

Development of decision support frameworks based on the conflicting objectives with different weights emerging from quantitative and qualitative nature of attributes are often difficult to make and require a comprehensive decision making technique. The Multiple Criteria Decision Making (MCDM) and MADM methods have been successfully applied to the marine, offshore and port environments to solve safety, risk, human error, design and decision-making problems for the last two decades. The applicability of such OR methods to maritime disciplines has been examined in the studies conducted by Kim (2005), Ung *et al.* (2006), Chou (2007), Stahlbock and Vob (2008), Mennis *et al.* (2008), and Bierwirth and Meisel (2010).

Saaty (1977) introduced the AHP technique for the first time. Nowadays, the AHP is applied in many studies as an accurate solving tool for the MCDM and MADM problems, e.g. those have been done by Fukuda and Matsura (1993), Zone and Chu (1996), Dym *et al.* (2002), See (2005) and Ishizaka and Lusti (2006).

It is worthwhile to examine the applicability of the MADM and AHP methodologies in marine container terminals as a decision-making tool for selecting the best yard gantry crane system. The challenging issues inherent this problem and the limitation of existing research motivate this study.

2. The AHP Technique

Perhaps the most creative task in making a decision is to choose the factors that are important for that decision. In the AHP we arrange these factors, once selected, in a hierarchic structure descending from an overall goal to criteria, sub-criteria and alternatives in successive levels (Saaty 1990). As stated by Cheng *et al.* (1999), the AHP enables the decision-makers to structure a complex problem in the form of a simple hierarchy and to evaluate a large number of quantitative and qualitative factors in a systematic manner under multiple criteria environment in confliction.

Solving a MADM problem with the AHP involves four main to do steps (Cheng *et al.* 1999):

- Break down the complex problem into a number of small constituent elements and then structure the elements in a hierarchical form.
- Make a series of pair wise comparisons among the elements according to a ratio scale.
- Use the eigenvalue method to estimate the relative weights of the elements.
- Aggregate these relative weights and synthesize them for the final measurement of given decision alternatives.

The AHP is categorised as an additive weighting method. The method proposed in this study involves the principal eigenvector weighting technique that utilizes the experts' opinions for both qualitative and qualitative attributes. In the process of the analysis, the basic logic of the additive weighting methods, and hence the AHP is characterized and distinguished by the following principles:

2.1 Hierarchy of the Problem

The first logic of every AHP analysis is to define the structure of hierarchy of the study. The structuring of a MADM hierarchy to solve the selection of the best yard gantry crane through the AHP method may be defined as the division of the series of levels of attributes in which each attribute represents a number of small sets of inter-related sub-attributes.

2.2 Matrix of Pair-wise Comparison

Decision-makers often find it difficult to accurately determine the corresponding weights for a set of attributes simultaneously. An AHP helps the decision-makers to derive relative values using their judgements or data from a standard scale. The professionals' and experts' judgements are normally tabulated in a matrix often called the Matrix of Pair-wise Comparison (MPC). In the MPC the decision-maker specifies a judgement by inserting the entry a_{ij} ($a_{ij} > 0$) stating that how much more important attribute "i" is than attribute "j" (Anderson *et al.* 2003). To simplify the analysis of a MADM problem, the experts' judgements in an AHP are reflected in a MPC. These judgments are generally expressed in cardinal values rather than ordinal numerals. A MPC can be defined as:

$$A = (a_{ij}) = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \qquad (1)$$

where:
a_{ij} = Relative importance of attributes a_i and a_j.

In this respect the MPC would be a square matrix, "A", embracing "n" number of attributes whose relative weights are "$w_1, \dots, w_n$", respectively. In this matrix the weights of all attributes are measured with respect to each other in terms of multiples of that unit. The comparison of the values is expressed in equation (2).

$$a_{ij} = \frac{w_i}{w_j} \qquad (2)$$

where:
$w = [w_1, w_2, \dots, w_n]^T$.
i,j = 1,2, …, n.
T = Transpose matrix.

3.2 Weighting the Attributes

Additive weighting methods consider cardinal numerical values that characterise the overall preference of each defined alternative. In this context, the linguistics judgements of the pair of qualitative or quantitative attributes may require ordinal values to be translated into equivalent cardinal numbers. Saaty (2004) has recommended equivalent scores from 1 to 9 as shown in Table 1 that will be used as a basis to solve the problem in this study.

Relative Importance of Attribute (Scale)	Definition
1	Equal importance.
3	Moderate importance of one over another.
5	Essential or strong importance.
7	Very strong importance.
9	Extreme importance.
2, 4, 6, 8	Intermediate values between the two adjacent judgments.
Reciprocals	When activity "i" compared with "j" is assigned one of the above numbers, then activity "j" compared with "i" is assigned its reciprocal.

Table 1: Comparison scale for the MPC in the AHP method (Saaty 2004).

4.2. Principal Eigenvector Approach for Calculating the Relative Weights

The relative weighting vector for each attribute of a comparison matrix is required to be calculated. The weights of attributes are calculated in the process of averaging over the normalised columns.

The priority matrix representing the estimation of the eigenvalues of the matrix is required to provide the best fit for the attributes in order to make the sum of the weights equal to 1. This can be achieved by dividing the relative weights of each individual attribute by the column-sum of the obtained weights. This approach is called the "Division by Sum" (DBS) method. The DBS is used in the AHP analysis when selection of the highest ranked alternative is the goal of the analysis (Saaty 1990).

In general terms, the weights (priority vectors) for w_1, w_2, w_3, ..., w_n can be calculated using equation (3) introduced by Pillay and Wang (2003).

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}}\right) \tag{3}$$

where:
k = 1, 2, …, n.
n = Size of the comparison matrix.

5.2 The Problem of Consistency

The decision-maker may require to make trade-offs within the attribute values in a compensatory way if the inconsistencies calculated exceed 10% (2004). This is possible when the values of the attributes to be traded-off are numerically comparable with all of the attributes assigned to a particular alternative. In a perfectly consistent matrix it is assumed that the rules of transitivity and reciprocity are complied with.

The calculated priorities are plausible only if the comparison matrices are consistent or near consistent. The approximate ratio of consistency can be obtained using equation (4).

$$CR = \frac{CI}{RI} \tag{4}$$

where:
CR = Consistency ratio.
CI = Consistency index.
RI = Random index for the matrix size, "n".

The value of "RI" would depend on the number of attributes under comparison. This can be taken from Table 2 given by Saaty (1990).

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 2: Average random index values (Saaty 1990).

The consistency index, "CI", may be calculated from the following equation:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{5}$$

where:
λ_{max} = The principal eigenvalue of an "n x n" comparison matrix "A".

6.2 Calculation of Performance Scores

In order to obtain the final priority scores, first it is necessary to calculate the performance values for each attribute. This will require bringing the qualitative values defined in the linguistic forms and the quantitative values into a common denominator. This can be achieved by defining a value function for each attribute that translates the corresponding parameter to a performance value. The values are assigned on the scale from 0 to 9 wherein 0 is assigned to the least and 9 to the most favourable calculated value amongst all. The conversion of the parameter values is accomplished using the equality function (6) proposed by Spasovic (2004).

$$\frac{y_{max} - y_0}{y_i - y_0} = \frac{x_b - x_w}{x_i - x_w} \tag{6}$$

where:
x_w = Least value of a parameter.
x_b = Highest value of a parameter.
y_0 = Lowest score on the scale for an attribute.
y_{max} = Highest score on the scale for an attribute.
x_i = Calculated value of parameter "i".
y_i = Value of performance measure for parameter "i".

3. Statement of the Problem

The analysis of this study is conducted on a case study using a SC system capable of stacking 4 containers high (1 over 3), an RTG system with a span of seven containers in a row (6+1) capable of stacking six containers high (1 over 5) and also an electrical powered RMG system with a span of fourteen containers in a row (12+2) with a similar vertical stacking capability to the RTG system. The data from container terminal of Shahid Rejaee Port Complex (SRPC) is used for evaluation of test cases since it represents the major Iranian container terminals.

Even though the case study is unique and distinctive of its kind, the general processes and characteristics are similar to a typical container terminal as shown in Figure 1.

4. Implementing AHP for Problem Solving

There are many main and sub-attributes to be considered for the analysis. For the MADM analysis in this study, the selection of the best yard gantry crane is identified and will be based on the following important criteria:

- **Operations:** Operational Attributes (OA) are represented in terms of Flexibility (FL), Land Utility (LU), Cycle Time (CT), and Container Movement (CM).
- **Cost:** The Economical cost Attributes (EA) are considered in terms of Purchase Cost (PC), Maintenance Cost (MC), Labour Cost (LC), Operational Cost (OC), Container Transfer Cost (CTC), and Depreciation Cost (DC).
- **Management:** Economic Life (EL) and Equipment Safety (ES) are included to represent the Management Attributes (MA).

Figure 2 illustrates the decision tree for this study which is defined in four levels. It shows three alternatives and three main attributes and their corresponding sub-attributes. The study will analyse and measure the weights of each attribute and their corresponding sub-attributes with respect to each alternative to obtain the final rankings.

Based on the expert's knowledge and the goal of this study, the importance of comparison criteria for the main attributes is assessed as extreme, essential and moderate for operations, costs and managements attributes, respectively.

1.4 Calculating the Performance Scores

The performance scores obtained and assigned by the decision-maker to other attributes are given in Tables 3, 4, and 5.

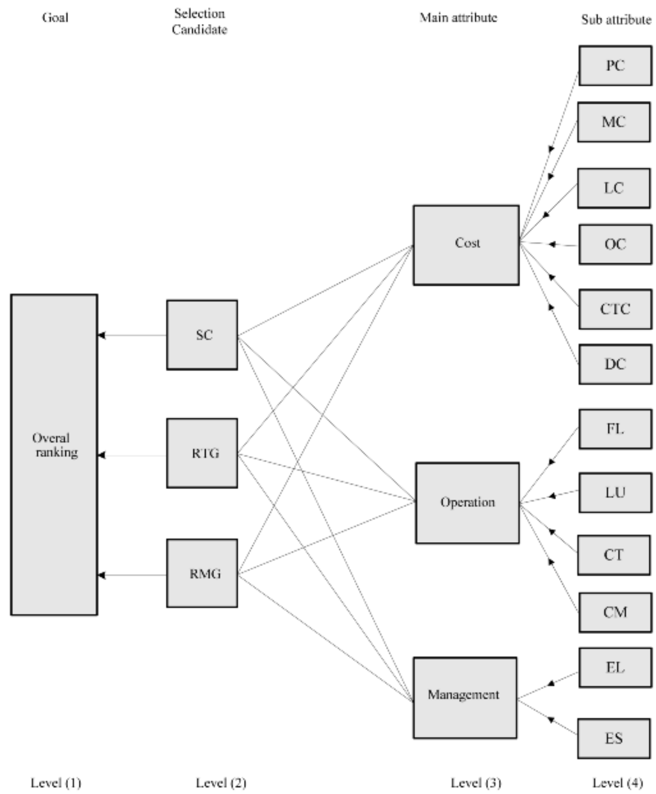

Figure 2: Container yard operating crane decision tree.

	FL	LU	CT	CM
SC	$\frac{9}{9}$=1.0000	$\frac{2}{9}$=0.2222	$\frac{2}{9}$=0.2222	$\frac{2}{9}$=0.2222
RTG	$\frac{7}{9}$=0.7777	$\frac{7}{9}$=0.7777	$\frac{7}{9}$=0.7777	$\frac{8}{9}$=0.8888
RMG	$\frac{4}{9}$=0.4444	$\frac{9}{9}$=1.0000	$\frac{9}{9}$=1.0000	$\frac{9}{9}$=1.0000

Table 3: Performance scores of operation attributes.

	PC	OC	MC	LC	CTC	DC
SC	$\frac{2}{9}$=0.2222	$\frac{2}{9}$=0.2222	$\frac{2}{9}$=0.2222	$\frac{2}{9}$=0.2222	$\frac{9}{9}$=1.0000	$\frac{2}{9}$=0.2222
RTG	$\frac{9}{9}$=1.0000	$\frac{4}{9}$=0.4444	$\frac{5}{9}$=0.5555	$\frac{4}{9}$=0.4444	$\frac{2}{9}$=0.2222	$\frac{9}{9}$=1.0000
RMG	$\frac{8}{9}$=0.8888	$\frac{9}{9}$=1.0000	$\frac{9}{9}$=1.0000	$\frac{9}{9}$=1.0000	$\frac{3}{9}$=0.3333	$\frac{4}{9}$=0.4444

Table 4: Performance scores of cost attributes

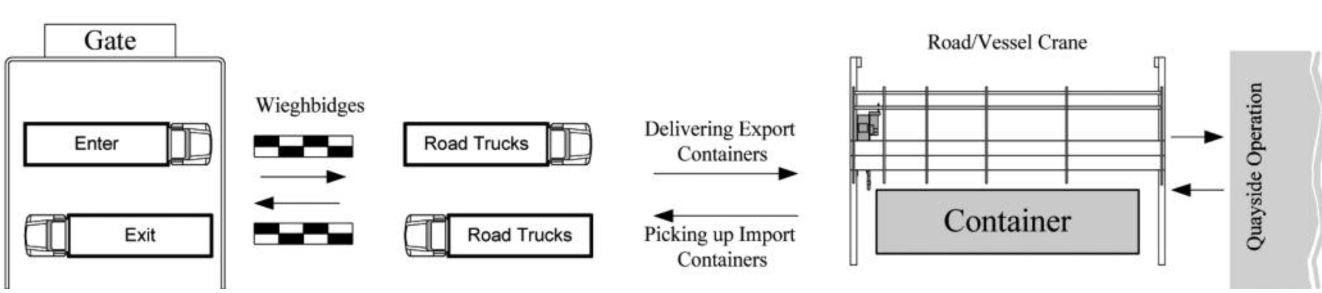

Figure 1: Process of loading/discharging operation in marine container terminals.

After finding the performance scores, this section follows with the evaluation of weighing vector, along with the consistency ratio.

	EL	ES
SC	$\frac{2}{9}$ =0.2222	$\frac{3}{9}$ =0.3333
RTG	$\frac{3}{9}$ =0.3333	$\frac{8}{9}$ =0.8888
RMG	$\frac{9}{9}$ =1.0000	$\frac{8}{9}$ =0.8888

Table 5: Performance scores of management attributes.

2.4 Calculating the Weighting Vectors

Table 6 represents the matrix of pair-wise comparison for the main attributes as defined by the decision-maker. The consistency ratio and weighting vector are also shown in this table.

	MA	EA	OA	Weighting vector
MA	1	$\frac{4}{7}$	$\frac{4}{8}$	0.2106
EA	$\frac{7}{4}$	1	$\frac{7}{8}$	0.3687
OA	$\frac{8}{4}$	$\frac{8}{7}$	1	0.4207
CI	$4.3\times10^{-4}<\%10$			

Table 6: Weighting vector of main attributes.

Weighting vectors of operation, cost, and management attributes are shown in Tables 7, 8, and 9, respectively. The normalized weights are the product of weighting vectors of sub-attributes and the main attributes.

	CT	FL	LU	CM	Weighting vector	Normal weight
CT	1	$\frac{4}{6}$	$\frac{4}{7}$	$\frac{4}{8}$	0.1587	0.0668
FL	$\frac{6}{4}$	1	$\frac{6}{7}$	$\frac{6}{8}$	0.2186	0.0920
LU	$\frac{7}{4}$	$\frac{7}{6}$	1	$\frac{7}{8}$	0.3054	0.1285
CM	$\frac{8}{4}$	$\frac{8}{6}$	$\frac{8}{7}$	1	0.3171	0.1334
CI	0.005374<%10					

Table 7: Weighting vector of operation attributes.

	CTC	LC	MC	DC	PC	OC	Weighting vector	Normal weight
CTC	1	$\frac{3}{4}$	$\frac{3}{5}$	$\frac{3}{6}$	$\frac{3}{7}$	$\frac{3}{8}$	0.0909	0.0335
LC	$\frac{4}{3}$	1	$\frac{4}{5}$	$\frac{4}{6}$	$\frac{4}{7}$	$\frac{4}{8}$	0.1212	0.0447
MC	$\frac{5}{3}$	$\frac{5}{4}$	1	$\frac{5}{6}$	$\frac{5}{7}$	$\frac{5}{8}$	0.1516	0.0558
DC	$\frac{6}{3}$	$\frac{6}{4}$	$\frac{6}{5}$	1	$\frac{6}{7}$	$\frac{6}{8}$	0.1821	0.0671
PC	$\frac{7}{3}$	$\frac{7}{4}$	$\frac{7}{5}$	$\frac{7}{6}$	1	$\frac{7}{8}$	0.2120	0.0781
OC	$\frac{8}{3}$	$\frac{8}{4}$	$\frac{8}{5}$	$\frac{8}{6}$	$\frac{8}{7}$	1	0.2423	0.0893
CI	$1.339310\times10^{-6}<\%10$							

Table 8: Weighting vector of cost attributes.

	EL	ES	Weighting vector	Normal weight
EL	1	$\frac{6}{8}$	0.4292	0.0904
ES	$\frac{8}{6}$	1	0.5708	0.1202
CI	0<%10			

Table 9: Weighting vector of management attributes.

As illustrated in Tables 6 to 9, the values of CI are less than 10%, which represents that the pair-wise comparisons are consistent and no extra trade-offs would be needed.

3.4 Setting up the Decision Matrix

The summary of the performance scores is given in the Table 10.

The normalized weights of sub-attributes are multiplied by their corresponding performance scores and the results are summed-up and indicated in the decision matrix in Table 11.

4.4 Selecting the Best Alternative

As shown in the Table 11, the final priority rankings are obtained by calculating the row-sum of the results for each indi-

	EA						OA				MA	
	PC	LC	MC	OC	CTC	DC	FL	LU	CT	CM	EL	ES
SC	0.2222	0.2222	0.2222	0.2222	1.0000	0.2222	1.0000	0.2222	0.2222	0.2222	0.2222	0.3333
RTG	1.0000	0.4444	0.5555	0.4444	0.2222	1.0000	0.7777	0.7777	0.7777	0.8888	0.3333	0.8888
RMG	0.8888	1.0000	1.0000	1.0000	0.3333	0.4444	1.0000	1.0000	1.0000	1.0000	1.0000	0.8888

Table 10: Summary of the performance scores.

	EA (0.3687)						OA (0.4207)				MA (0.2106)		Sum	Rank
	PC	LC	MC	OC	CTC	DC	FL	LU	CT	CM	EL	ES		
SC	0.0173	0.0093	0.0124	0.0198	0.0335	0.0149	0.0920	0.0285	0.0148	0.0296	0.0201	0.0401	0.3323	0.1747
RTG	0.0781	0.0198	0.0309	0.0397	0.0074	0.0671	0.0715	0.0910	0.0519	0.1186	0.0301	0.1068	0.7129	0.3748
RM G	0.0694	0.0447	0.0558	0.0893	0.0012	0.0298	0.0409	0.1285	0.0668	0.1234	0.0904	0.1068	0.8570	0.4505
											Total		1.9022	1.0000

Table 11: The decision matrix.

vidual alternative. Figure 3 represents the final ranking and selection of the three alternatives.

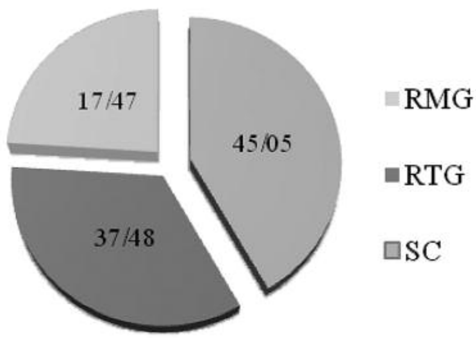

Figure 3: Final ranking of alternatives.

The AHP analysis in this study has shown that the RMG system with an under portal span of 12 + 2 container rows and capable of stacking 6 containers high (1 over 5) has obtained the highest priority with a ratio of 45.05%. The second best alternative will be the RTG system with a span of 6 + 1 container rows, capable of stacking 6 containers high (1 over 5) which has gained a priority ratio of 37.48%. The least priority is given to the SC system capable of stacking 4 containers high (1 over 3). The SC system has gained only 17.47% of the priority ratio.

5. Conclusion

This study has suggested selecting the best marine container yard gantry crane for loading/unloading trucks, using Multiple Attribute Decision Making (MADM) method along with the Analytical Hierarchy Process (AHP). The AHP analysis implies that the RMG system examined in this study is the most desirable yard operating system amongst others.

Based on the results, RTG and RMG cranes have been the best candidates for new terminal developments owing to their high stacking capabilities. The SC system may be preferred over other systems in many container terminals due to its versatility and relatively low purchasing cost per unit of equipment, smaller marshalling yard development and operation costs. On the other hand, yard gantry cranes such as RTG and RMG cranes are more space efficient, more accurate and faster in operation and are more suitable for development and instalment of automated technologies.

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