Cost Function Modelling for Semi-automated SC, RTG and Automated and Semi-automated RMG Container Yard Operating Systems

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Abstract

This study analyses the concept of cost functions for semi-automated Straddle Carrier (SC), Rubber Tyred Gantry (RTG) and automated Rail Mounted Gantry (RMG) container yard operating cranes. It develops a generic cost based model for a pair-wise comparison, analysis and evaluation of economic efficiency and effectiveness of container yard equipment to be used for decision-making by terminal planners and designers. The cost function analysis of this study incorporates major cost attributes used in modern container terminal operations and discussed in the literature. They play a determining role over the total cost of advanced operating systems in a container terminal. The cost model in this study enables the planner and designer of container terminals to make a pair-wise comparison of handling systems to help determine the most appropriate container yard operating system for a port, based on the required technological capabilities and functions. The sensitivity analysis proposed in this study compares and demonstrates the magnitude and intensity of the selected attributes which determine preference of one system over another. The analysis assists a terminal planner in decision-making and selecting a container yard operating system with a minimum operating cost and a maximum annual throughput.

Keywords: Container terminal, Cost Function Modelling, Sensitivity Analysis.

1. Introduction

The operation of advanced technologies including automated and semi-automated equipment in container terminals has reduced the time

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of transferring, stacking and retrieving of containers in marshalling yards. The adoption of automated devices has increased the efficiency of the shipside, quayside, marshalling yard, gate and transfer operations. This in turn has reduced the loading and discharging time, dwell-time, cycle-time of container and transfer vehicle movements and consequently the total turnaround-time of containerships in ports. A variety of advanced systems such as semi-automated Straddle Carriers (SCs) capable of transferring and stacking containers to a height of 1 over 3 or more, Automated Guided Vehicles (AGVs) and shuttles capable of automatically transferring containers without human intervention have been involved in the operation of container terminals during the last two decades. At the stack-yard, semi-automated Rubber Tyred Gantry cranes (RTGs) and fully automated Rail Mounted Gantry cranes (RMGs) have been deployed for operation in today's modern container terminals.

This analysis identifies cost factors associated with the above container yard operating systems and provides a method of measuring the cost effectiveness of the systems involved. Factors that determine the adoption and investment in any container yard operating system are the availability of land, initial cost of investment in any operating system, capacity of transfer and stack-yard operating system and the operational costs. The cost of transfer, the stacking capacity and the operation costs are directly dependent on the availability of the land and the type of equipment to be employed. In some container terminals particularly in the Asian ports, due to the difficulties in expanding the availability and the high cost of land, there has been an attempt to stack containers higher in order to increase the capacity of container terminals (Watanabe, 2001). RTG and RMG cranes have been the best candidates for new terminal developments owing to their high stacking capabilities. In some other terminals where there is a piece of land available for expansion of the stack-yard, SC systems are more popular (Chen, 1998 and 1999 and Agerschou, 2004). Examples of these terminals are Southampton Container Terminals and the Europe Combined Terminals (ECT) in Rotterdam that have preferred to utilise the flexibility of SC systems even though their annual throughputs could be increased by employment of other systems. Some hub centres such as

Medecentre Tauro in Italy and Hutchinson Freeport in Bahamas with a high capacity which are considered as the container terminals with a high transhipment ratio have successfully employed SC as their main transfer and stacking system (Avery, 1999). The SC system is 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. However, there are some drawbacks with SC operating systems. The SC systems utilise less space in terms of m^2 / TEU, lower stacking ability, require more area for receipt and delivery operations, require higher maintenance and greater down-times and are less suitable for automation. 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 (Watanabe, 2001). The yard gantry cranes however require a higher development and land preparation costs than SC systems due to their high wheel load and body weight. RTGs are more flexible and more economic to purchase and install, but more expensive to operate than RMGs (Containerisation International, 1996).

2. Literature review

The productivity of the container stacking operation in container terminals has been viewed from economic scales particularly the cost efficiency in many studies. Hatzitheodoroue (1983) has compared the total cost of stacking over the cost of transfer operation in a container terminal under a Top Loader (ToL) yard operating system. Hee and Wijbrands (1988) have proposed a model that measures the performance of the Reach Stackers (RSs) in a terminal. The sensitivity analysis developed in their studies has compared the associated cost components of real cases in the port industry. Nahavandi (1996), Chu and Huang (2002-a, 2002-b and 2003) have carried out different studies to formulate the required number of containers for container terminals based on different container yard handling systems. They have discussed various cost parameters involved in their analysis. Kap and Hong (1998) have suggested a conceptual cost model to determine the optimum space and the number of yard cranes for import stacks. Kim and Kim (1998 and

2002) have developed a cost model for different space layouts and transfer systems and included different cost variables in their analysis. They have suggested a cost model which incorporates the fixed investment and variable operations costs to be used to help decision-making. Two objectives have been suggested to be met in their analysis. These objectives are the minimisation of the total cost of terminal operations and the costs associated with customers using a terminal. Zhow *et al*. (2001) have proposed a cost comparison model for various container stacking and handling systems. Their model provides comprehensive methods to calculate the maximum throughput and the optimum total cost of the operating system and revenues derived from the operations in container terminals.

Nam and Ha (2001) have investigated different aspects of adoption of advanced technologies such as intelligent planning, operation and automatic handling systems for container terminals. Their studies have set different criteria for evaluation of different stacking and handling systems and have been applied to the Korean terminal environment. However, their results illustrate that the application of automatic equipment should not violate the basic concept of a total cost minimisation policy in container terminals. Liu *et al*. (2002) have evaluated four different types of automated container terminal design models using a simulation model. They have provided detailed cost analysis of the models in which the performance of the systems has been discussed from the operational viewpoint of the terminal. The cost model developed in their studies evaluates the associated cost factors for each automated terminal concept. The results imply that automation could improve the performance of conventional container terminals at a considerably lower cost. Saanen *et al*. (2003 and 2006) have developed a cost model to evaluate the cost values of different segments and equipment to be installed at a container terminal. The test cases analysed in their studies have compared the productivity values and cost effectiveness of a SC system over AGVs and Automated Loading Vehicles (ALVs). Amongst other things, they have concluded that a designer of a container terminal should know the threshold limit of the number of AGVs and ALVs to allocate and assign for operation beyond which the productivity of a terminal diminishes with increased cost. In

different studies carried out by Yang *et al*. (2004) and Vis and Harika (2004), the optimum productivity of automated container terminals with minimum possible costs has been discussed. It has been argued that ALVs including automated SCs provide higher productivity and cost effectiveness principally because they can eliminate the waiting-times of the transfer vehicles at the stack-yard. In different studies conducted by Kiani *et al* (2006-a, 2006-b, 2009) the economic feasibility of automated quayside cranes has been evaluated and in the later research a break-even model has been formulated to evaluate the cost of containerships' waiting-times and berth unproductive-times in automated quayside operations. Kiani *et al* (2009) have also developed a concrete decision tool to show the viability and applicability of multiple attribute decision-making (MADM) and analytical hierarchy process (AHP) methods in the selection decisions for a container yard operating system.

3. Analysis of cost parameters and variables

The productivity and efficiency of a container terminal is dependent not only on the effective automated and semi-automated container yard operating systems, but also on employing an efficient cost model. The basic parameters and variables that play a determining role in a cost function model for container terminal operating systems needs to be identified and analysed. Data for different cost parameters of this study have collectively been obtained from different sources particularly the Bandar Abbas Container Terminals (BACT), Bandar Imam Container Terminals (BICT) and Chabahar Container Terminals (CCT) of Iran, Containerisation International (1990-2005), World Port Development International (1990-2006), United Nations Conferences on Trade and Development (UNCTAD) (1990-2005), Bahrani (2004) and Watanabe (2001) and from different container terminals and equipment manufacturers. The average values of costs will be reflected in the appropriate tables in this study. The cost parameters and their individual variables are related to the direct cost of capital investment and indirect costs such as maintenance, repair and manning costs. Other cost concepts such as container yard management costs, cost associated with administration, management and processing of containers, internal yard equipment and external trucks that may be attributed to revenue are

beyond the scope of this study. The parameters and variables may be categorised and defined into three groups as follows:

3.1 Container yard development and maintenance costs

For different ports situated in different geographical and political locations, there are different factors that may affect the volume of investment and consequently the development and maintenance of the purchased or leased land. These factors may range from subsidies, loans and borrowings to the physical features of a container terminal site such as costs involved in civil engineering, hydrography, topography, meteorological and oceanography influences, coastal hydraulics and environmental issues (UNCTAD, 1985). However, factors and issues such as those mentioned above are considered beyond the scope of this study. In this study, four major factors related to the land investment, development, maintenance and depreciations are considered. For almost all of the Iranian ports such as the BACT, BICT and CCT, the land within the port area has been retained as the property of government. Therefore, the initial cost of investment in land in the examples of the Iranian ports may differ significantly from European countries and many Asian countries such as Japan, Singapore and Hong Kong. This study includes the following factors in the proposed cost model:

▪ **Cost of investment in land**

The Port and Shipping Organisation of Iran (PSO) have leased out some part of the land in its port environment to private sectors operating the terminals. The values are approximate and are contracted for about 40 to 50 years. These values are stated in Table (1).

Table (1) Average annual cost of investment in land

Port	Cost of Investment in Land £ / m² / Year		
	1990-1994	1995-1999	2000-2004
BACT	23.60	25.00	27.20
BICT	19.50	28.40	31.30
CCT	17.30	21.50	34.50

(Source: Bahrani, 2004)

▪ Container yard development cost

The cost of container yard development may vary from terminal to terminal due to the variations in the site construction and conditions. One may devote a considerable budget for preparation of the container yard surface, turning areas, road and passageway accesses, ducting and cable laying preparations, drainage, light stands, etc. It should be noted that the surface of the container yard and its receipt and delivery areas, turning areas and the junctions of the road and passageways must be prepared to withstand loads of about 80-120 tonnes (Nahavandi, 1996). The terminal operator in BACT has considered a cost of £20 to £23 / m² in land preparation in 2004 for SCs operating system. In mid-2003 in BICT, an average of £52 / m² was spent on the preparation of stacking areas for the new modern 12+2 RMG system (Zahiri, 2005). This study considers a cost of £23 to £52 / m² which is used for the preparation of the container yard for CCT.

▪ Container yard development depreciation cost

The facilities used in the development of a container yard stated in the previous section will wear out over time. This may require the operator of container terminals to consider an annual depreciation cost for development of facilities in their calculations. This study uses the depreciation method recommended by UNCTAD and proposed by Constantinides (1990). Generally the annual depreciation of a system is obtained by subtracting the salvage value of the equipment from the initial cost of investment and dividing the results by the expected project life of the system. In this study a salvage value proportional to about 20% of the initial cost of investment in the container yard development is considered.

▪ Container yard maintenance cost

The annual maintenance cost of container yard is usually taken as a percentage of its initial cost of investment in one meter of land multiplied by total land area. UNCTAD (1985) has suggested a fraction of 0.1% to 0.5% of capital cost of container yard investment for a concrete container yard, apron, roads, and asphalt surfaces. In BACT an extra fraction of 0.05% has been included for auxiliary facilities, lighting, ducts, pipes and cables, markings, drainage, insurance etc., (Bahrani,

2004). In this study, a fraction of 0.15% of the initial cost of investment is considered for the analysis.

It should be noted that in calculating the maintenance costs of a system, one should consider the wear and tear of the assets (particularly equipment) which would increase over time. As the economic life of the container yard and equipment increases the annual maintenance cost increases at an exponential rate (Guthrie and Lemon, 2004). This implies that the annual maintenance cost of a system is minimum in year one and would be maximum at the end of its project life. For the purpose of this study, the Future Worth Factor (FWF) method recommended by UNCTAD (Constantinides, 1990), Nahavandi (1996), UNCTAD (2002) and Guthrie and Lemon (2004) will be used for calculation of the annual maintenance costs for container yard development and yard cranes.

3.2. Crane investment, manning and maintenance costs

The costs and attributed factors related to the investment, operation and maintenance of a container yard operating system might be categorised as follows:

▪ **Crane procurement cost**

The purchasing price of container yard operating systems depends on factors such as:

i) Order time.

ii) Order size.

iii) Place and location of manufacturer from the purchaser.

iv) Equipment specification (type, capacity, size, degree of automation, crane lateral speed, number, type and speed of trolley and hoist, etc.).

v) Variations in market prices.

The prices have been averaged from variety of purchase prices detailed for each modern SCs, RTGs and RMG cranes and are summarised in Table (2). The values include the cost of about 150 meters of rails and corresponding fittings per unit of equipment.

Table (2) Average procurement cost of container yard operating systems, £/equipment

Year	SC			RTG				RMG			
				5 + 1		6 + 1		11 + 2		12 + 2	
	1 over 2	1 over 3	1 over 4	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5	1 over 4	1 over 5
1990-1994	175,300	190,550	-	217,250	228,570	230,350	247,500	522,320	566,320	587,140	604,450
1995-1999	191,750	212,310	-	321,200	330,240	385,870	407,760	612,550	633,540	609,240	614,250
2000-2004	232,450	260,870	290,780	394,200	419,150	440,400	471,550	640,100	667,140	610,320	623,200

(Source: Compiled by author)

▪ **Annual cost of capital investment in cranes**

The cost of capital investment in any container yard operating system may depend on the number, procurement cost, average economic life of cranes and the average interest rate expected during such a period.

▪ **Economic life of cranes (t)**

The theoretical economic life of container yard equipment is usually given by the manufacturer as the number of full cycles, movements and/or travels performed by the equipment. In practice, these values may differ from terminal to terminal under different operational and climatic conditions. The actual economic life of the equipment may, however, depend on the extent of utilisation, maintenance efficiency, skill of operators and the magnitude of hazards affecting the equipment. UNCTAD, (1990), Containerisation International, (1996) and some terminal operators have proposed different values of economic life. The average economic life of container yard operating systems has been compiled from different sources and tabulated in Table (3). The practical economic life of equipment for BACT may be considered shorter than the theoretical values recommended by UNCTAD. This is due to the fact that most Iranian ports are located in a tropical climate and are more vulnerable to corrosion, wear and tear in a temperate climate.

Table (3) Average economic life of QSCs, SC, RTG and RMG cranes, years

Recommending Body	QSCs	SC	RTG	RMG
UNCTAD	10-12	6-10	15-18	-
Containerisation International	10-14	15-20	15-20	20-22
Manufacturers	12-15	10-16	12-16	18-22
Port Operators	12-15	10-15	12-15	15-20

(Source: Compiled by author)

▪ Crane depreciation cost

The depreciation of yard cranes may be considered as a process by which a container terminal gradually loses the fixed value of its investment in the equipment. The purpose of including crane depreciation cost is to spread the initial purchase price of the equipment over its useful life. It may be defined as the difference between the initial cost of investment and the salvage value of the equipment expressed as present values divided by its economic life. UNCTAD (1985) and Constantinides (1990) have proposed a fraction of about 20% of the initial cost of investment as a salvage value for SC, RTG and RMG systems after their economic lives are over. In this study the fraction recommended by UNCTAD will be considered for yard cranes.

▪ Crane maintenance costs

The maintenance cost of SC, RTG and RMG systems is considered in this study. The maintenance cost varies from equipment to equipment depending on the mobility, speed, type of fuel, number of moves etc. The annual maintenance cost of yard cranes is normally taken as a percentage of the initial cost of investment over the economic life of the cranes. UNCTAD (1985) and Constantinides (1990) have proposed 1.0% to 1.2% and 1.8% of capital cost of investment for a SC system respectively. Their proposed percentage includes the cost of fuel, consumables such as lubricating oil, tyres, spare parts, etc. Watanabe (1995) has proposed 1.5% of initial investment and has included cost of fuel and spare parts too.

In a container terminal using a `direct SC system`, the containers can be stacked end to end and laid vertical or parallel to the quay face in rows. In this system a SC directly and independently accesses containers from the shipside. Where containers are generally transferred to and from the quayside to the roadways and interchange area by other modes of transfer systems such as Tractor-Trailers (T-Ts) or Front-end Lift trucks (FLs), the system is called the `relay system`. One may consider about 0.2% extra for a SC operating under a direct system where, a direct system would require the SCs to travel on longer routes than those operating under a relay system thus requiring higher maintenance. In a relay system, costs associated with the extra number of vehicles fulfilling the transfer operation is required to be included. UNCTAD

(1985) and Constantinides (1990) have suggested that about 1.0% of the initial cost of investment to be considered for RTG and RMG systems. In BACT, the maintenance cost of a SC system is about 0.8% whereas, in BICT the value for electrical power driven RMGs is between 0.3% to 0.4% and diesel RMGs is between 0.5% to 0.6% of the initial cost of investment (Bahrani, 2004). Wear and tear of the road and passageways for RTGs particularly at the junctions and turning areas may be more than that of a SC system therefore, it may be reasonable to consider a higher percentage for the cost of maintenance for an RTG system. It should be noted that some terminals having four wheel RTGs have concrete beams to reduce wear and tear (Watanabe, 2001). This study uses the method proposed by UNCTAD (Constantinides, 1990) and Nahavandi (1996) for calculation of the equipment annual maintenance cost.

▪ **Inter-yard operation cost of cranes**

An attribute that may be used as a performance indicator between different systems is the average Cost Per Container (CPC) movement in a terminal. This value would be dependent on the annual throughput of a terminal. The annual capacity for container terminals with different sizes operating under SC, RTG and RMG systems with different container dwell-times, transhipment ratio and stacking height has been calculated in different studies during this research and will be used in this study. The average value for the direct SC system in BACT is about £0.4/move. The value for the electrically driven RMGs in BICT is about £0.2/move and £0.3 / move for the diesel driven equipment (Bahrani, 2004). Conservatively, one may consider about £0.6 /move for an RTG system.

▪ **Crane manning cost and coordinating container yard foreman cost**

The minimum manpower required for each of the advanced SC, RTG and RMG cranes is about 3 operators per day that is one for every shift / day. In addition to the crane drivers, a coordinating foreman on each shift would be required to supervise the interactive and interdependent operation of the yard cranes, transfer vehicles (SC, AGVs, internal trucks, etc.) with the Quayside Cranes (QSCs). The manpower cost for other personnel who are not involved in the crane operation is left outside the scope of this study. The approximate salary

of a competent crane driver and a container yard foreman including insurance, training, bonuses, incentives, etc. is about £13,440 / year (£1,120 / month) to £16,500 / year (£1,375 / month) (Bahrani, 2004).

3.3 Container transfer cost

The average annual cost of container transfer to and from the quayside to the stack-yard may be expressed as an average cost of handling operation fulfilled by AGVs in RMG or RTG systems, SCs in a SC direct system, internal trucks or T-Ts in the SC relay system or other means of transferring and marshalling containers between the quayside and the stacking area. The calculated average cost may include the cost of fuel, maintenance, insurance, etc. In both BACT and BICT, the transfer operation has been contracted out to the private sector. A fixed cost has been agreed to be paid to the private operator according to the number of containers handled. A total amount of about £0.10, £0.20 and £0.25/container/move may be considered for SC, RTG and RMG systems respectively (Bahrani, 2004).

4. Cost function modelling

One of the most difficult decisions at the planning stage of the container terminals is to make a decision on the most suitable container yard operating system for a terminal. Decisions should be made strategically for a long-term run of terminals. It is also difficult to indicate as to where and to what point in the time the terminal is going to stand in the future. Is the terminal going to develop the present Origin-Destination (O-D) stage into a Hub-Port (HP) status at some time in the future? Is it likely that land becomes less expensive and more available for future expansion of the terminal? What would be the cost of the development of a specific operating system in the terminal? There would be many questions that should be clearly answered before the final decision is made.

There are other cost related attributes, some of which are qualitatively expressed, that play a determining role and affect the layout, design and final selection decision of container yard equipment in a terminal. They can be categorised as follows:
▪ Land size, shape and condition.

- Calculated annual throughput.
- Under portal span and vertical lifting capacity of the container yard equipment.
- Type, number and level of technology of container yard equipment.
- Ease of maintenance and repair.
- Strength of the container yard construction.
- Economic life of the equipment.
- Environmental and social considerations.

This study only considers SC, RTG and RMG systems. The cost model developed in this study comprises the following elements:

1) Land cost and container yard development and maintenance cost.
2) Cost of equipment, maintenance and manning for a specific container yard operating system.
3) Transfer cost.

There will be more cost elements such as administration costs, cost of inflation, possible rise in the price of land, fuel consumption, and spare parts etc., which are out of the scope of this study. It should be noted that different container yard operation systems require different facility, preparation and installation and training costs etc. These may affect the total annual cost of the system. A trade-off can be made between the cost of the land and equipment and operation costs for the container yard system to be employed. This study develops a cost based method with the steps indicated in Figure (1) and the process as follows:
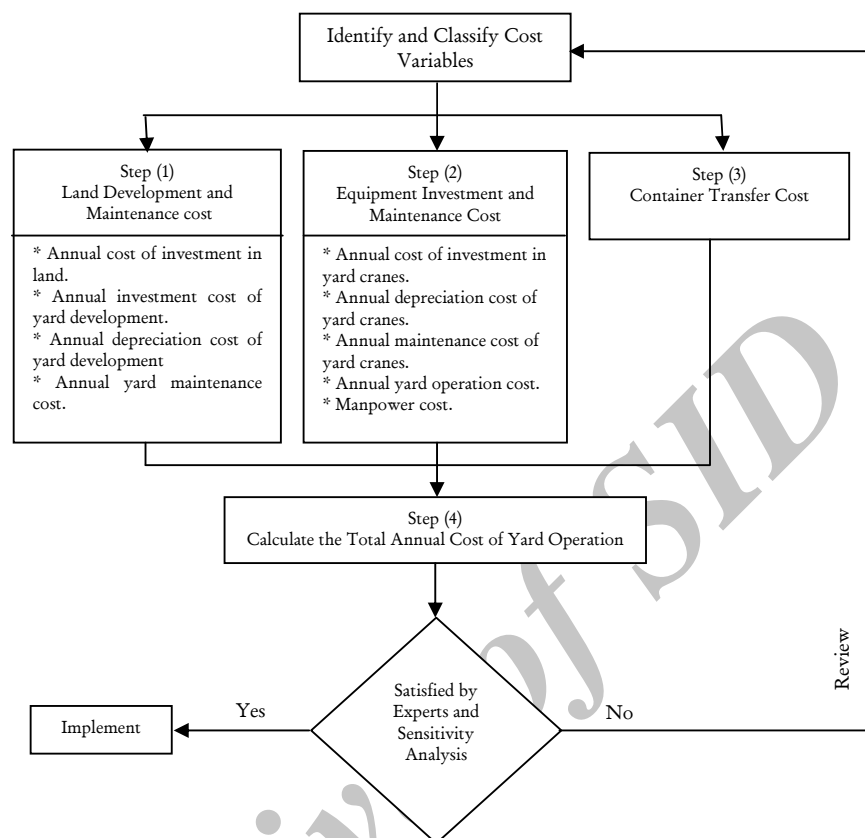
Figure (1) Cost function process

(Source: Author)

Step (1) Land development and maintenance costs

Steiner (1992), Thuesen and Fabrycky (1993), UNCTAD (2002) and Guthrie and Lemon (2004) have proposed applying a Capital Recovery Factor (CRF) to calculate the annual cost of investment for `t` years of a project life [see Appendix (1)]. The cost of land for a container yard operating under a specific operating system can be defined in the following process:

▪ **Annual cost of capital investment in land**

LC = CL x AT x CRF   (1)

where:

LC = Annual cost of investment in land in ₤ / year.

CL = Average cost of one square metre of land in ₤ / m².

AT = Total area of container terminal for a specific container yard operating system (including stack-yard + gate, CFS, workshop area, rail and transhipment buffers + Interchange area, if appropriate, roadways, *etc.*) in m².

CRF = Capital recovery factor which converts the initial investment into an equivalent average annual cost of equal series calculated as follows:

$$CRF = \frac{i \times (1+i)^t}{(1+i)^t - 1}$$ (2)

t = Economic life of the terminal in years.

i = Average annual interest rate.

▪ **Annual container yard development cost**

YDC = CD x AT x CRF   (3)

where:

YDC = Annual container yard development cost in ₤ / year.

CD = Development cost of one square metre of land for a specific container yard operating system in ₤ / m².

▪ **Annual depreciation cost of container yard development**

$$Y_{dep}C = \frac{(CD \times AT) - S_{yard}}{t}$$ (4)

where:

$Y_{dep}C$ = Annual depreciation cost of container yard development in ₤ / year.

S_{yard} = Salvage value of facilities in ₤.

▪ **Annual container yard maintenance cost**

This study uses the FWF method recommended by UNCTAD (Constantinides, 1990) and UNCTAD (2002) [see Appendix (1)] as follows:

YMC = CYM x FWF   (5)

where:

YMC = Annual cost of container yard maintenance in £ / year.

CYM = Average annual maintenance cost of a specific container yard operating system in £.

$FWF = (1+i)^{t-1}$

where:

t = Economic life of the terminal in years.

i = Average annual interest rate.

Step (2) Crane investment, manning and maintenance costs

This study assumes that only one type of operating system such as SC, RTG or RMG would be operating in the terminal. Although a combination of the above systems with other modes of operation is possible, the analysis of their effect is not considered in this study. The costs involved in any specific operating system may be defined in the following process:

▪ **Annual cost of investment in yard cranes**

$$IC = PC \times NC \times CRF \qquad (6)$$

where:

IC = Annual cost of capital investment in container yard operating system in £ / year.

PC = Procurement cost of a yard crane in £.

NC = Average number of RMGs, RTGs or SCs (adopted from previous studies conducted by authors).

▪ **Annual depreciation cost of yard cranes**

$$DC = \frac{PC - S_{crane}}{t} \qquad (7)$$

where:

DC = Annual depreciation cost of yard cranes in £ / year.

S_{crane} = Salvage value of a specific container yard operating system.

t = Average economic life of the cranes in years.

▪ **Annual maintenance cost of yard cranes**

The cost of maintenance may include the cost to cover spare parts, repairs and fuel (energy), *etc*. It should be noted that as the economic life of the yard cranes increases, the cost of maintenance increases. This study uses the recommended method proposed by UNCTAD

(Constantinides, 1990), Nahavandi (1996) and UNCTAD (2002). This can be formulated as:

$$MCC = PC \times FWF \tag{8}$$

where:

MCC = Annual maintenance cost of a container yard operating system in £ / year.

PC = Average annual maintenance cost of equipment in £.

$FWF = (1+i)^{t-1}$

where:

t = Average economic life of the cranes in years.

i = Average annual interest rate.

▪ **In-yard operation cost**

$$OC = HC_{TEU} \times C_Y \times CRF \tag{9}$$

where:

OC = Annual cost of in-yard-handling operation of containers in £ / year.

HC_{TEU} = Cost of handling of one container in £ / container (An average cost for one TEU and / or 2 x TEU may be taken).

C_Y = Annual throughput of a terminal in TEUs (adopted from previous studies conducted by the authors).

▪ **Manning cost**

Two types of workers are normally involved in the daily operation of a container yard. They are the yard gantry drivers and foremen who coordinate the operation of container transfer from the quayside to container stack-yard and *vice versa*. Where the container yard operation is fully automated, then there would not be such a work force. Instead, a few automation technicians would be available at all times to support yard cranes. The average salary of technicians is expected to be high in today's container terminals. In this contest, the cost of crane operator and container yard foremen therefore can be defined as:

i) **Crane operators cost**

$$LC_{driver} = NL_{shift}^{driver} \times N_{shift} \times AS_{CD} \tag{10}$$

where:

LC_{driver} = Annual cost of work force for all cranes (including stack-yards, gate, rail and transhipment buffers, empty and refer stacks, *etc.*) in £ / year.

NL_{shift}^{driver} = Number of crane divers in each shift.

N_{shift} = Number of shifts in 24 hours.

AS_{CD} = Average annual salary of a crane driver including taxes, insurance, incentives, *etc.* in £ / year / person.

ii) Coordinating foremen cost

$$LC_{YFM} = NYF_{day} \ x \ N_{shift} \ x \ AS_{YF} \tag{11}$$

where:

LC_{YFM} = Annual cost of all container yard foremen in £ / year.

NYF_{day} = Number of container yard foremen for the coordination of the QSCs and yard cranes in each day.

AS_{YF} = Average annual salary of a container yard foreman including taxes and all other benefits in £ / year / person.

Step (3) Container transfer cost

Depending on the type of container yard system employed in a terminal, the transfer of containers between the quayside and the container yard, and *vice versa*, may be carried out by a SCs, T-Ts, AGVs, *etc.* The cost of container transfer by SC relay system and other modes of transfer such as AGV, lift trucks, T-Ts *etc.*, may be higher than a SC direct system. The total cost of container transfer excluding the costs of transfer equipment such as maintenance, depreciation and cost of investment can be defined as:

$$C_{transfer} = C_{TEU} \ x \ C_Y \ x \ N_{moves} \tag{12}$$

where:

$C_{transfer}$ = Annual cost of container transfer operation in £ / year.

C_{TEU} = Average cost of handling one container in £ / container.

C_Y = Annual throughput of the corresponding container terminal in TEUs.

N_{moves} = Average number of moves per container performed by a specific transfer vehicle within the terminal (at least 2 moves are usually considered for import and export jobs).

Step (4) Total container yard operation cost

The Total Cost (TC) of a container yard operating system will be the summation of all costs involved in Steps (1) to (3). The equation can therefore be defined as follows:

$$TC = LC + YDC + Y_{dep}C + YMC + IC + DC + MCC + OC + LC_{driver} + LC_{YFM} + C_{transfer} \qquad (13)$$

This study introduces the concept of a `cost comparison indicator` that will help a port designer to measure the percentage of cost effectiveness of one container yard operating system over another.

5. Sensitivity analysis

To help the terminal operator in making decisions, this study introduces the concept of a cost comparison process for the sensitivity analysis. The `cost comparison indicator` analyses the cost effectiveness of one-container yard operating system over another in terms of investment, maintenance, operation, depreciation, *etc*. The `Variable Intensity Factor` (VIF) method analyses the cost effectiveness of the selected parameters by demonstrating the magnitudes of the parameters with each other.

5.1 Cost comparison indicator

The selection of a cost effective operating system may be done by comparison of similar cost parameters, for example, the annual costs obtained for each container yard operating system (TCY) in Step (4). Where the annual cost of a system is considered as a criterion, a semi-automated SC operating system may be preferred over a semi-automated RTG or an automated RMG system from a cost effective standpoint when $TCY_{SC} < TCY_{RTG}$ and $TCY_{SC} < TCY_{RMG}$. A semi-automated RTG system may be preferred over a SC or an automated RMG system when $TCY_{RTG} < TCY_{SC}$ and $TCY_{RTG} < TCY_{RMG}$. This study denotes variables `j`, `k` and `m` to represent semi-automated SC, semi-automated RTG and automated RMG systems respectively. Therefore, the cost comparison indicator to compare the cost effectiveness of a SC over an RTG and RMG and on RMG over an RTG system may be defined as follows:

$$R_{j/k} = \frac{TCY_j}{TCY_k} \tag{14}$$

$$R_{j/m} = \frac{TCY_j}{TCY_m} \tag{15}$$

$$R_{m/k} = \frac{TCY_m}{TCY_k} \tag{16}$$

Other combinations are possible. In this process and under the lowest-cost-preference policy, for example, if $R_{j/k} < 1$ the `j` container yard operating system is preferred over `k` system. There would be of course no preference of a system over another if $R_{k/j} = 1$. Therefore, a sensitivity analysis would be required to indicate each case comparison by indicating the value of $R_{j/k} = 1$ as a benchmark to help better indicate such a relation.

5.2 Variable Intensity Factor (VIF)

The variables and parameters identified in the development of the cost model may vary significantly from each other, from port to port and from time to time. Therefore, a further sensitivity analysis is required to represent the magnitude of a preference of a container yard operating system over another by taking the individual cost parameter in the analysis. A terminal designer and or a port operator may vary the value of any of the cost parameters and keep others unchanged to observe the impact of cost changes under the new condition. The operator may consider one or more particular cost parameters as the important and / or governing cost factors to be analysed. For example, a terminal planner may be interested in purchasing a SC rather than a semi-automated RTG system or switching from a SC to a semi-automated RTG system. Therefore, the operator can calculate the magnitude of his / her preference of SC over RTG using specific cost parameters, cost intensity factor (R) and Variable Intensity Factor (VIF). ^{Hee} and ^{Wijbrands} ([1988]) have defined the VIF as:

$$VIF_{j/k} = \frac{CP_j \times R_{j/k}}{CP_k - CP_j} \tag{17}$$

where:
$VIF_{j/k}$ = Variable intensity factor of `j` operating system over `k`
$R_{j/k}$ = Comparison indicator of `j` operating system over `k`.

CP_k = Value of cost parameter `k`.
CP_j = Value of cost parameter `j`.
$CP_k \neq CP_j$

The value of `VIF` will indicate the relative degree of preference of one system over another. The higher the positive value becomes the higher the desire to employ a system will be. When the value of `VIF` of a system, for example `j` system over `k` system, becomes negative, that is to say $VIF_{j/k} < 0$, it may indicate that `j` system is no longer desirable over `k` system. This undesirability of course will be based on the specific cost component considered in the analysis. Depending on the magnitude and the sign of the value (being of a positive or a negative value) calculated for different combinations of cost factors, it may be argued that `j` system may or may not be considered preferable over `k` system. When the value of $VIF_{j/k}$ becomes negative, it is valid to assume that the `k` system possesses more preferability over `j`. In this case the value of $VIF_{k/j}$ may not be equal to the $VIF_{j/k}$ value even with a different sign and polarity. This means that the exact value of $VIF_{k/j}$ requires to be calculated in the same way. It should be noted that when the values of CP_k and CP_j are close to each other, then the VIF result produced may be very high and therefore unreliable. To avoid uncertainties in calculating the value of VIF, it would be better to select cost factors with unequal values and preferably with a high difference between the values of the pairs.

6. Test case

The Port and Shipping Organisation of Iran that owns most of the active ports in Iran is transforming the former Kalantry Port in Chabahar into a modern automated container terminal to facilitate the transfer of containers through land modes of transport to Europe *via* Turkey at a lower cost than sea transport from the Suez Canal. The data from the CCT and BACT are used for evaluation of test cases since they represent a typical terminal of the Persian Gulf and many others in the region. This study uses the cost model and different variables developed to evaluate the viability of the proposed model. The majority of cost values are from Iranian and other ports in the Persian Gulf region obtained from the BACT and the port operators (Bahrani, 2004) and are

converted to Pounds Sterling equivalent for the purpose of this study. The following assumptions are made:

a) Size of the container yard is assumed to be 350m x 400m (14 hectares) similar to the BACT.

b) Average interest rate of about 8% to be considered.

c) An estimated cost of £38 / m^2 for a long-time rent (usually 50 years for Iranian ports and renewable) for land investment has been assumed.

d) Cost of development of about £23, £38 and £52 / m^2 for SC, RTG and RMG systems has been considered respectively.

e) Container yard maintenance cost of about £7,980 [0.15% x £38 x 350m x 400m (14 hectares)] for SC, RTG and RMG systems to be considered.

f) The economic life (t) of container terminal is about 50 years.

g) Procurement cost of SC (1 over 3) = £260,870 / equipment, RTG 6+1 (1 over 5) = £471,550 / crane and RMG 12+2 (1 over 5) = £623,200 / crane.

h) Number of yard cranes taken from previous studies by the authors is about 63 for SC, 30 (2 RTG x 15 blocks) for RTG and 24 RMG (2 RMG x 12 blocks) for RMG systems (Kiani, 2007).

i) Average economic life (t) of a SC = 15 years, RTG = 15 years and RMG = 20 years.

j) This study considers about 20% of the initial investment cost of container yard development and 10%, 20% and 30% of the initial investment cost of SC, RTG and RMG cranes as salvage values in Iran after their economic life is over.

k) An average of 1.0%, 0.8% and 0.4% of the initial procurement cost of SC, RTG and RMG would be considered for the annual maintenance cost of the cranes respectively. Therefore, the average annual maintenance cost of yard cranes would be as follows:
  - SC = £260,870 x 63 x 1.0% ≈ £164,348
  - RTG = £471,550 x 30 x 0.8% = £113,172
  - RMG = £623,200 x 24 x 0.4% ≈ £59,827

l) In-yard operation cost of containers is assumed to be £0.4 / container for SC, £0.5 / container for RTG and £0.3 / container for any RMG systems (Section 6.2.2).

m) Maximum annual throughput of SC (1 over 3) = 1,379,876 TEUs / year, RTG 6+1 (1 over 5) = 1,972,196 TEUs / year and RMG 12 +2 (1 over 5) = 2,113,168 TEUs / year (obtained from previous studies conducted by the authors).

n) Average salary of a competent driver and a container yard foreman is considered about £15,000 and £17,500 / year respectively. There would be 3 shifts a day where the terminal is considered to be operating 24 hours / day and 365 days a year.

o) Number of crane drivers in each shift is assumed to be 40 persons for SC, 20 persons for RTG and 15 persons for RMG systems.

p) Number of container yard foremen for SC = 4, RTG = 3 and RMG = 2 persons.

q) Transfer costs of about of £0.10, £0.20 and £0.25 / container are considered for SC, RTG and RMG systems respectively. Transfer vehicles are considered to perform at least two continuous moves in each job assignment.

The calculation of the values and a summary of the parameters are illustrated in Tables (4) and (5). In addition to the cost parameters stated in this study, a Cost Per Container (CPC) parameter which indicates the cost efficiency of one system over other is also included. CPC is found by dividing the Total Cost (TC) of a particular system by the annual throughput (C_Y) of the corresponding container terminal.

Table (1) Average annual values of parameters of the cost model, £

	Cost Parameter	SC (1 over 3)	RTG 6+1 (1 over 5)	RMG 12 +2 (1 over 5)
Step (1)	LC	$38 \times (350 \times 400) \times \dfrac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 434{,}872$	$38 \times (350 \times 400) \times \dfrac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 434{,}872$	$38 \times (350 \times 400) \times \dfrac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 434{,}872$
	YDC	$23 \times (350 \times 400) \times \dfrac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 263{,}212$	$38 \times (350 \times 400) \times \dfrac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 434{,}872$	$52 \times (350 \times 400) \times \dfrac{0.08 \times (1+0.08)^{50}}{(1+0.08)^{50} - 1} = 595{,}088$
	$Y_{dep}C$	$\dfrac{23 \times (350 \times 400) - 0.2 \times 23 \times (350 \times 400)}{50} = 51{,}520$	$\dfrac{38 \times (350 \times 400) - 0.2 \times 23 \times (350 \times 400)}{50} = 85{,}120$	$\dfrac{52 \times (350 \times 400) - 0.2 \times 23 \times (350 \times 400)}{50} = 116{,}480$
Step (2)	YMC	$7{,}980 \times (1+0.08)^{50-1} \approx 346{,}551$	$7{,}980 \times (1+0.08)^{50-1} \approx 346{,}551$	$7{,}980 \times (1+0.08)^{50-1} \approx 346{,}551$
	IC	$260{,}870 \times 63 \times \dfrac{0.08 \times (1+0.08)^{15}}{(1+0.08)^{15} - 1} = 1{,}920{,}071$	$471{,}550 \times 30 \times \dfrac{0.08 \times (1+0.08)^{15}}{(1+0.08)^{15} - 1} = 1{,}652{,}729$	$623{,}200 \times 24 \times \dfrac{0.08 \times (1+0.08)^{20}}{(1+0.08)^{20} - 1} = 1{,}523{,}383$
	DC	$\dfrac{63 \times (260{,}870 - 0.1 \times 260{,}870)}{15} \approx 986{,}089$	$\dfrac{30 \times (471{,}550 - 0.2 \times 471{,}550)}{15} = 754{,}480$	$\dfrac{24 \times (623{,}200 - 0.3 \times 753{,}200)}{20} = 523{,}488$
	MCC	$164{,}348 \times (1+0.08)^{14} = 482{,}722$	$113{,}172 \times (1+0.08)^{14} = 332{,}408$	$59{,}827 \times (1+0.08)^{19} \approx 258{,}195$
	OC	$0.4 \times 1{,}379{,}876 \approx 551{,}950$	$0.5 \times 1{,}972{,}196 = 986{,}098$	$0.3 \times 2{,}113{,}158 \approx 633{,}947$
	LC_{driver}	$40 \times 3 \times 15{,}000 = 1{,}800{,}000$	$20 \times 3 \times 15{,}000 = 900{,}000$	$15 \times 3 \times 15{,}000 = 775{,}000$
	LC_{YFM}	$4 \times 3 \times 17{,}500 = 210{,}000$	$3 \times 3 \times 17{,}500 = 157{,}000$	$2 \times 3 \times 17{,}500 = 105{,}000$
Step (3)	$C_{transfer}$	$0.1 \times 1{,}379{,}876 \times 2 \approx 275{,}975$	$0.2 \times 1{,}972{,}196 \times 2 = 788{,}878$	$0.25 \times 2{,}113{,}158 \times 2 = 1{,}056{,}579$

Table (4) Summary of the cost parameters

Step	Cost Parameter	SC (1 over 3) / £	RTG 6+1 (1 over 5) / £	RMG 12 +2 (1 over 5) / £
	`CP`	`j`	`k`	`m`
Step (1)	LC	434,872	434,872	434,872
	YDC	263,212	434,872	595,088
	$Y_{dep}C$	51,520	85,120	116,480
	YMC	346,551	346,551	346,551
Step (2)	IC	1,920,071	1,652,729	1,523,383
	DC	986,089	754,480	523,488
	MCC	482,722	332,408	258,195
	OC	551,950	986,098	633,947
	LC_{driver}	1,800,000	900,000	675,000
	LC_{YFM}	210,000	157,500	105,000
Step (3)	$C_{transfer}$	275,975	788,878	1,056,579
Step (4), TC		7,322,962	6,873,508	6,268,583
Cost Per Container (CPC)		5.3	3.5	3.0

6.1 Cost comparison and sensitivity analysis using `R` values

The values of cost comparison indicator (R) for different parameters are calculated and summarised in the second, third and fourth columns in Table 6.6 (second, third and fourth columns). The attributed cost factors indicated in the table show that from a minimum cost policy standpoint, a SC system may be preferred over a semi-automated RTG system where it produces a lower value of `R` (R < 1) for cost factors such as `$C_{transfer}$`, `OC`, `$Y_{dep}C$` and `YDC`. In cases where the value of `R = 1`, then there would be no preference of one system over another. For R > 1 values such as `$LC_{driver}$`, `CPC`, `MCC`, `TC`, `DC` and `IC`, a SC system is no longer preferred over an RTG system. A SC may be preferred over an automated RMG system only where the cost parameters such as `$C_{transfer}$`, `YDC`, `OC` and `$Y_{dep}C$` have produced a lower `R` value than `1`. However, the comparison indicator implies that for the rest of cost parameters such as `$LC_{driver}$`, `CPC`, `$LC_{YFM}$`, `TC`, `MCC`, `DC`, and `IC` and except `LC` and `YMC` an automated RMG may be preferred over a SC system. The cost comparison indicator shows that for most of the cost

parameters except `C$_{transfer}$`, `YDC` and `Y$_{dep}$C`, the other parameters promise a lower cost ratio to prefer an automated RMG to a semi-automated RTG system. There is no preference of one system over another in `LC` and `YMC` cost parameters.

For an easier concept, the results of the three columns are illustrated in Figures (2), (3) and (4). The horizontal line drawn at `R = 1` indicates an indifference level above / below which other systems may be preferred.

Table (5) Cost comparison indicator

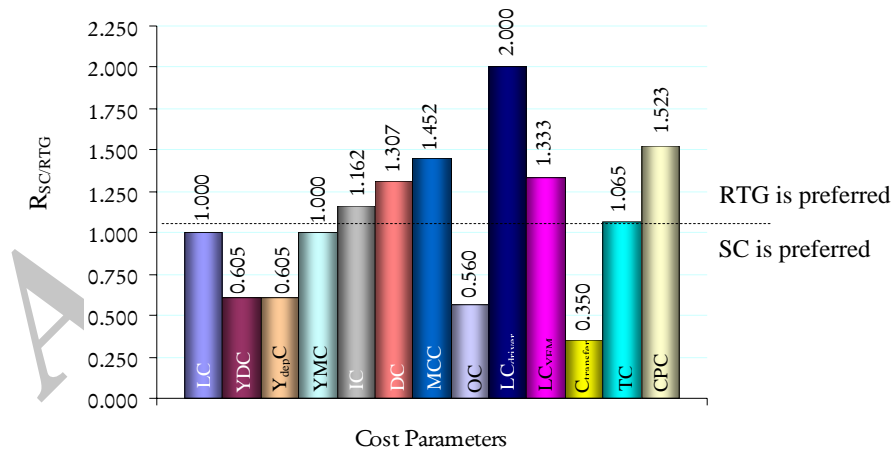| Cost Parameter	R$_{SC/RTG}$	R$_{SC/RMG}$	R$_{RMG/RTG}$
LC	1.000	1.000	1.000
YDC	0.605	0.442	1.368
Y$_{dep}$C	0.605	0.442	1.368
YMC	1.000	1.000	1.000
IC	1.162	1.260	0.922
DC	1.307	1.884	0.694
MCC	1.452	1.870	0.777
OC	0.560	0.871	0.643
LC$_{driver}$	2.000	2.667	0.750
LC$_{YFM}$	1.333	2.000	0.667
C$_{transfer}$	0.350	0.261	1.339
TC	1.065	1.168	0.912
CPC	1.523	1.789	0.851

Figure (2) Relationships between R$_{SC/RTG}$ and cost parameters
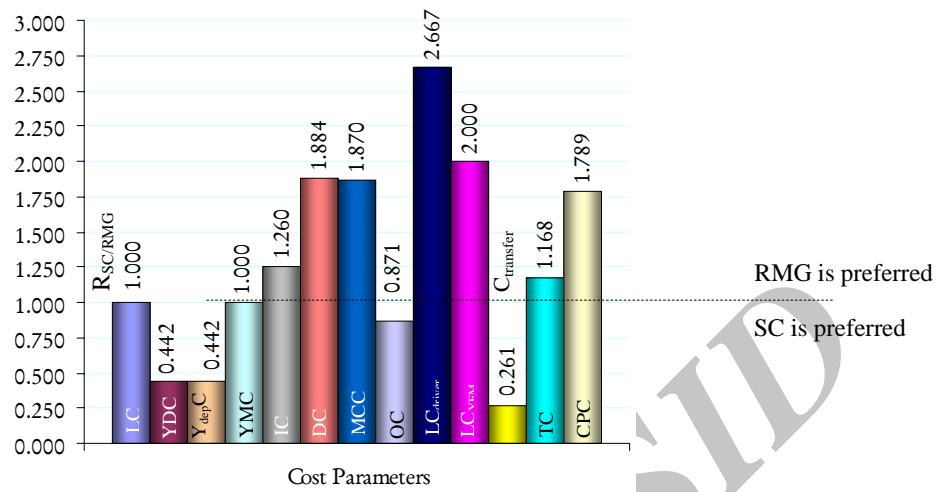
Figure (3) Relationship between R_{SC/RMG} and cost parameters
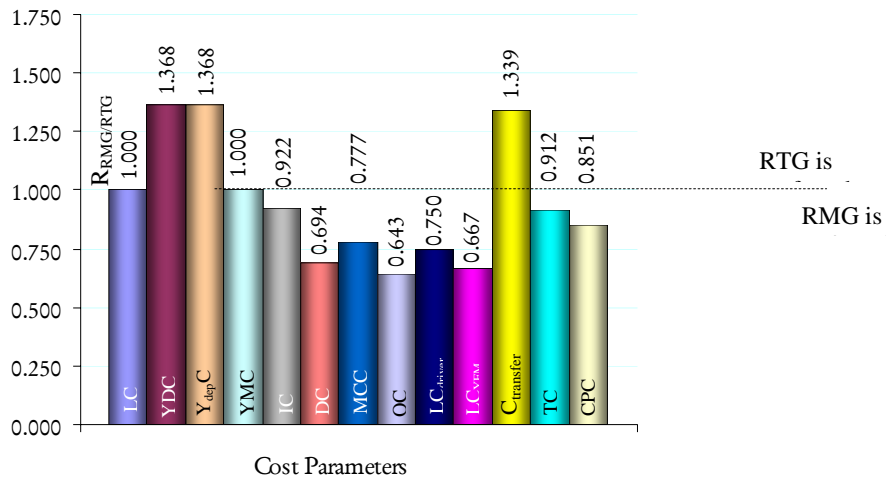

Figure (4) Relationship between R_{RMG/RTG} and cost parameters

6.2 Cost comparison and sensitivity analysis using `VIF` values

The values of cost comparison indicator, `R`, given in Table (6) have been used for calculation of `VIF` in this study. The following example demonstrates how the value of the variable intensity factors that favour a SC system over a semi-automated RTG system for different cost parameters, has been obtained. Consider that the initial cost of container yard equipment, `IC`, is the cost parameter that has been chosen as a preference attribute of comparison by a port operator. Then the `VIF` for a SC system over an RTG system with regard to the annual investment cost of both systems [Table (5)] which has been reflected by the `R` value ($R_{SC/RTG}$ = 1.162) obtained in Table 6.6 would be:

$$VIF_{SC/RTG} = \frac{1,920,071 \times 1.162}{1,652,729 - 1,920,071} \approx -8.346$$

The `VIF` for an RMG over an RTG system, where `$R_{RMG/RTG}$ = 0.750` with regard to the `$LC_{driver}$` would be:

$$VIF_{RMG/RTG} = \frac{675,000 \times 0.750}{900,000 - 675,000} = 2.250$$

The `VIF` values for the SC over the semi automated RTG, the SC over the automated RMG and the automated RMG over the semi automated RTG have been calculated and summarised in Table (7).

Table (6) Variable intensity factor

Cost Parameter	$VIF_{SC/RTG}$	$VIF_{SC/RMG}$	$VIF_{RMG/RTG}$
LC	-	-	-
YDC	0.928	0.351	-5.081
$Y_{dep}C$	0.928	0.351	-5.081
YMC	-	-	-
IC	-8.346	-6.099	9.859
DC	-5.565	-5.401	1.573
MCC	-4.663	-4.020	2.703
OC	0.712	5.863	1.158
LC_{driver}	-4.000	-4.267	2.250
LC_{YFM}	-5.332	-4.000	1.334
$C_{transfer}$	0.188	0.092	-5.285
TC	-8.352	-8.112	9.451
CPC	-4.484	-4.122	5.106

Table (7) illustrates the `VIF` values of the systems discussed with the same sequence of preferences as indicated in `R` values. In the second column of the table, the $VIF_{SC/RTG}$ where a SC is considered to be preferred over a semi-automated RTG system with regards to the `R` value and different cost parameters, it is evident that cost parameters for SC system such as `IC`, `DC`, `TC`, `LC_{driver}`, `LC_{YFM}`, `MCC` and `CPC` produce negative and the least values of `VIF`. They imply that a semi-automated RTG may be preferred over a SC system. In contrast `YDC`, `Y_{dep}C`, `OC` and `C_{transfer}` cost factors have produced positive values that may indicate the preferability and magnitude of `VIF` of a SC system over an RTG system. Figure (5) demonstrates the above statement where a SC system has not gained sufficient positive `VIF` values to override or even balance the negative values of `VIF` that imply the preference of an RTG over a SC system when the whole scenario is considered.
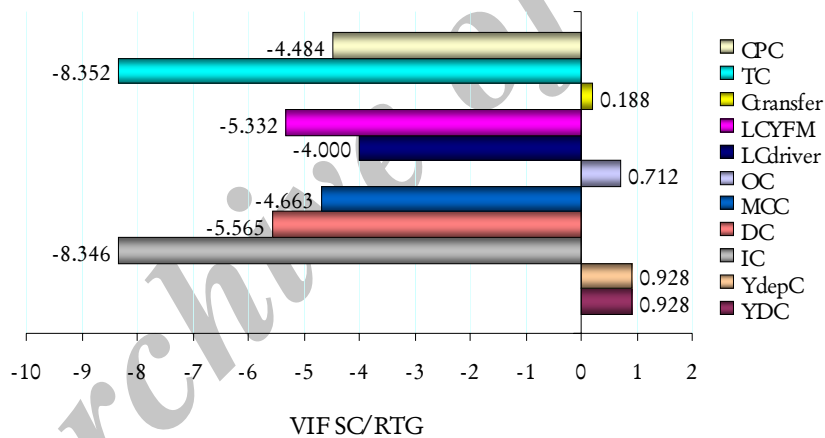

Figure (5) Magnitude of VIF_{SC/RTG}

In the third column of Table (7) and the corresponding illustration in Figure (6), it is demonstrated that `OC` has provided the highest positive `VIF` value for a SC system over an automated RMG system. Even though `YDC`, `$Y_{dep}C$` and `$C_{transfer}$` cost attributes have also provided additional positive values but the total positive value of the above parameters does not balance the total negative `VIF` value of `IC`,`DC`, `MCC`, `LC_{driver}`, `LC_{YFM}`, `TC` and `CPC` parameters. This implies the preferability of an automated RMG over SC system in this particular case.
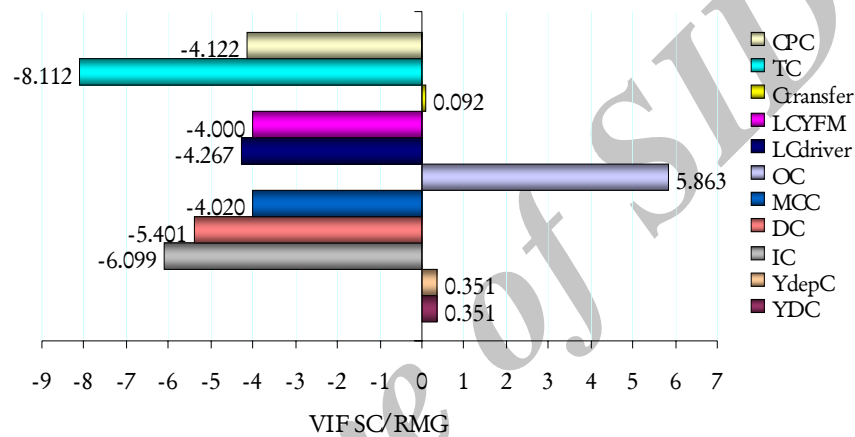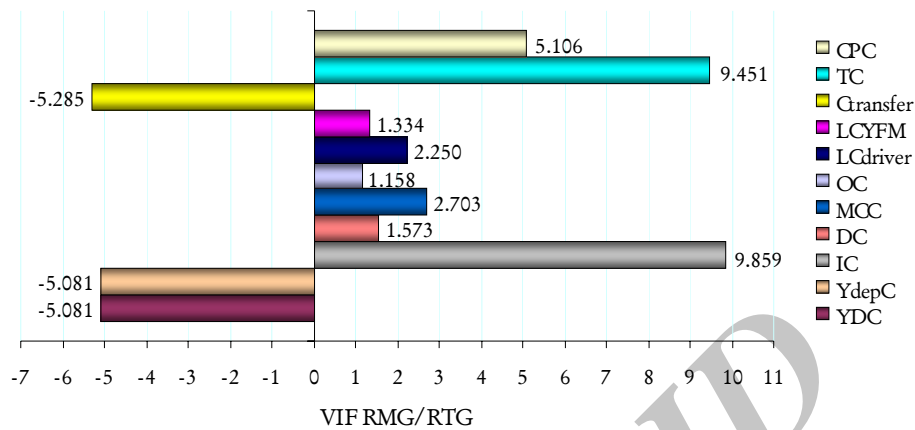

Figure (6) Magnitude of VIF$_{SC/RMG}$

From the forth column of Table (7) and the produced graph in Figure 6.7, it is evident that an automated RMG system has gained high positive `VIF` values in `TC`, `IC`, `CPC`, `LC_{driver}`, `MCC`, `LC_{YFM}`, `DC` and `OC` to favour an automated RMG over a semi-automated RTG operating system..

Figure (7) Magnitude of VIF$_{RMG/RTG}$

7. Discussion

This study has developed a conceptual cost function model for the design and capacity of container terminals. The analysis of the test case has revealed that the size of a container yard, total containers to be processed, type, number and size of stacking cranes and transfer fleet and the costs associated with the procurement and maintenance of the cranes play a major role in the total cost and cost per container processed in a container yard.

The sensitivity analysis has indicated that cost parameters such as the transfer, operation, container yard development and container yard depreciation costs may favour selection of a SC system over a semi-automated RTG system. However, the evaluation and analysis have shown that cost parameters such as the initial cost of investment in the container yard equipment, equipment depreciation, maintenance and labour including total cost per container processed in a terminal favour the selection of a semi-automated RTG over a SC system.

It has also been found that cost parameters such as container yard operation, development and depreciation and transfer costs are the only factors that may favour selection of a SC over an automated RMG system The pair-wise comparison implies that most of the cost attributes evaluated such as initial cost of investment, total cost, cost per container,

crane depreciation, operation and maintenance cost of yard cranes together with crane manning and container yard foremen costs strongly support selection of an automated RMG over a semi-automated RTG system. According to the sensitivity analysis of this study, a semi-automated RTG system may also be preferred over an RMG system where the analysis shows lower transfer, development and depreciation cost parameters.

8. Conclusions and recommendations

This study has developed a generic model that helps to analyse, evaluate and measure the cost efficiency and effectiveness of the container yard operating systems proposed in a pair-wise manner. It has considered different cost functions used in modern container terminals. The size, annual throughput and mode of operation, the size and stacking height of container yard equipment together with cost parameters such as land cost, development, maintenance, operation, depreciation and procurement costs of container yard equipment and transfer vehicles and labour costs which are normally affected by automation technologies have been incorporated in the model. The model developed may enable the designer, planner and operator of a container terminal to set-up a comparison analysis platform for decision-making and to measure the impact of different cost parameters involved on the total cost of container yard operating systems. This study has proposed a sensitivity analysis tool using a cost comparison indicator and cost intensity factors for the analysis of cost efficiency in container terminals. The cost based model of this study provides the basis for pair-wise comparisons of container yard operating systems which is the main contribution of this study. Using a case study, the sensitivity analysis has demonstrated that an automated RMG system promises a lower cost per container, crane procurement and maintenance and container yard total costs than both RTG and SC systems.

The model developed has a generic nature and may be used as a tool to set-up the basis for pair-wise comparisons of cost efficiency and effectiveness of equipment in other industries. This study has developed a cost based model only. Further studies may be required to evaluate the benefits gained in terms of revenue generated from the equipment or

operating systems. It should be noted that similar to the managers in the port industries, the managers and operators of other industries may resist revealing costs they have or are experiencing since high costs generally indicate the inefficiency and reduced productivity of systems.

9. Acknowledgments

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Appendix (1) CRF and FWF values

▪ **CRF**

A Capital Recovery Factor (CRF) is defined as the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Using an average interest rate `i` and number of annuities received `t`, the capital recovery factor converts a total amount of investment into an annuity amount of equal series. The CRF can be calculated from the following equation:

$$CRF = \frac{i \times (1+i)^t}{(1+i)^t - 1}$$

where:

t = Number of project life and

i = Average interest rate.

If `t = 1`, then CRF reduces to `1+i`. As `t` goes to infinity, the CRF goes to `i`. In this context, an annual cost of an investment can be expressed as follows:

P(IC) = IC x CRF

where:

P(IC) = Annual cost of investment.

IC = Initial cost of investment.

On the basis of the above statements, a total cost of an investment [TP(IC)] may be defined as:

TP(IC) = P(IC) x t.

▪ **FWF**

A Future Worth Factor (FWF) converts a present value of an investment into a future amount using an average interest rate `i` and number of economic life in years expected from a project `t`. The FWF = $(1+i)^{t-1}$. In this context `1/ $(1+i)^{t-1}$` would be a Present Worth Factor (PWF) that converts a future amount into a present value. If `t = 0`, then FWF reduces to `1`. As `t` goes to infinity, the CRF goes to infinity. The CRF and FWF values for an average annual interest rate of 8% are given in Table (A.1).

Table A.1 CRF and FWF values

Year	CRF	FWF	Year	CRF	FWF	Year	CRF	FWF
1	1.080	1.080	18	0.107	3.996	35	0.086	14.785
2	0.561	1.166	19	0.104	4.316	36	0.085	15.968
3	0.388	1.260	20	0.102	4.661	37	0.085	17.246
4	0.302	1.360	21	0.100	5.034	38	0.085	18.625
5	0.250	1.469	22	0.098	5.437	39	0.084	20.115
6	0.216	1.587	23	0.096	5.871	40	0.084	21.725
7	0.192	1.714	24	0.095	6.341	41	0.084	23.462
8	0.174	1.851	25	0.094	6.848	42	0.083	25.339
9	0.160	1.999	26	0.093	7.396	43	0.083	27.367
10	0.149	2.159	27	0.091	7.988	44	0.083	29.556
11	0.140	2.332	28	0.090	8.627	45	0.083	31.920
12	0.133	2.518	29	0.090	9.317	46	0.082	34.474
13	0.127	2.720	30	0.089	10.063	47	0.082	37.232
14	0.121	2.937	31	0.088	10.868	48	0.082	40.211
15	0.117	3.172	32	0.087	11.737	49	0.082	43.427
16	0.113	3.426	33	0.087	12.676	50	0.082	46.902
17	0.110	3.700	34	0.086	13.690			