Comparing Manned and Automated Horizontal Handling Equipment at Container Terminals. A Productivity and Economical Analysis

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Comparing manned and automated horizontal handling equipment at container terminals. A productivity and economical analysis

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ABSTRACT

The choice of horizontal handling transport in automated container terminals is not fully consistent in comparison with the automation of stacking cranes at the storage yard. Often the decision of automated system that connects the berth with the yard area is not clear and terminal operators tend to use not automated systems (straddle-carrier systems). The goal of this paper is providing an economical analysis to figure out under which conditions an automated horizontal transport is more efficient than a straddle-carrier. The study provided several simulation models to calculate the optimal equipment necessary to connect storage and berth subsystems in a maritime container terminal in fully automated and semi-automated scenarios. For that purpose, the data from the semi automated container terminal at Port of Barcelona has been used. After a cost analysis, some guidelines on what might be the best alternative considering labor costs, throughput movements per quay crane and year and different quay cranes productivities are provided.

1 INTRODUCTION

Although the international maritime transport of containers is a relatively recent activity, having begun barely fifty years ago, its growth rate has been stunning. Over the last two decades, container traffic grew at an average annual rate of around 10.0 per cent and, according to Clarkson Research Services, total container trade volumes amounted to 151 million TEUs and world total port throughput grew to 573 million TEUs in 2011 *(1)*. This steady growth is explained by several factors, such as reduced transit time, reduced shipping costs, increased reliability and security, and multi-modality.

The process of containerization and its continuous traffic increase has forced technological innovations in the size of containerships. Nonetheless, one of the consequences of increasing vessel size is that inefficiencies are simply moved elsewhere in the logistics chain.

As a consequence container terminals are making efforts to increase productivity in container handling by introducing, on one hand, significant improvements in operational planning, and, on the other hand, technological innovations in terminal equipment like robotization. An efficient terminal must therefore guarantee that container ships are unloaded and loaded quickly and assure an optimum cooperation between different types of handling equipment.

The application of information technologies, optimization techniques and improvement of management are considered efficient-solutions that do not require significant investment in physical facilities *(2, 3)*. In the same way, an advanced control technology is a necessary condition in order to achieve an improvement of productivity and a reduction in investment costs *(4)*.

Complementarily, a cost-efficient solution for high-density terminals with a capacity exceeding 1 million TEU in countries with high labor costs is robotization of the terminal equipment, that is, the design of automated container terminals *(5)*.

In general terms, two types of automated container terminals may be considered: semi-automated and fully automated terminals. The difference is that, whereas stacking operations are automated in both cases, the transportation from/to yard to/from berth is manned (i.e.: operated by traditional straddle carriers) in semi-automated terminals while is made by means of automated guided vehicles (firstly used for manufacturing systems in 1955) *(6)* in fully automated terminals.

Several container terminals with varying degrees of automation currently exist, mainly in Europe and Asia. During the 90s, Europe Container Terminal in Rotterdam was the first fully automated terminal using automated guided vehicles (AGVs) and automated stacking cranes (ASCs) for vertical transport in the storage area. Similar concepts were applied in the Port of Singapore, in the terminal of HHLA's Altenwerder (CTA) from the Port of Hamburg and in the port of Brisbane, where automated lifting vehicles (ALVs) systems were introduced in December 2005. Nonetheless, not all new configurations of automated container terminals consider the horizontal transport automation between quay and storage yard, as occurs in the new automated container terminal operated by HPH in the port of Barcelona.

From all those experiences, Angeloudis and Bell *(7)* stated that ASCs are increasingly perceived as a successful technology, but this is not the case with horizontal handling equipment. Horizontal handling is, in fact, still seen as a risky option, since manned equipment outperforms automated machines in terms of reaction to unplanned situations. Moreover, interactions between automated and manned operations may lead to less unpredictable situations to be managed by automated equipment. Because of that, terminal operators often do not see full automation as a clear investment and, consequently, tend to semi-automated terminals.

Therefore, in order to assure an optimal coordination between stacking and quay cranes, this paper answers whether horizontal handling equipment should be manned or automated regarding productivity and operating costs. This is one of the main planning issues to be analyzed in automated container terminals. In fact, yard-shore connection is one of the main consecutive operational processes (subsystems) of a container terminal that are required to work a smoothly and well synchronized in order to reach a good overall performance *(8).*

Consequently, to ensure that operations are carried out quickly and efficiently, both at the terminal shore and at the terminal yard, it must be ensured that there are enough vehicles, either automated or manned, to transport all containers from/to shore to/from yard.

In the light of all this, this paper focuses on the berth-yard transfer subsystem at automated container terminals, and particularly on the choice of manned or automated horizontal handling equipment between quay and stacking areas. The choice will depend on the feasibility and economic analysis of the required number of straddle carriers vs. automated guided vehicles. The necessary equipment will be quantified by means of a model simulation that reproduces the real functioning of an automated container terminal, whose layout is similar to that recently designed in the Port of Barcelona.

The paper is structured as follows: first an overview of literature is done. Then, the description of the problem is formulated and afterwards the simulation model employed is described. In section 4, simulation scenarios are defined and calculated and the results are analyzed economically in section 5. Finally, conclusions and suggestions for further research are given.

2 LITERATURE REVIEW

A comprehensive literature review regarding container operations and logistics problems at terminals can be found in *(9), (10), (11).* Additionally, Luo et al., *(12)* focused principally on storage and stacking logistics problems and Günther and Kim's book *(13)* discussed logistics control issues of container terminals and automated transportation systems providing quantitative decisions support for design, operational planning and real time control problems.

Regarding automated transportation systems such as AGVs or ALVs and their corresponding issues, Vis *(14)* analyzed AGVs in depth under different environments such as manufacturing, distribution, transshipment and transportation. As a result he provided design guidelines for AGV systems including path layout, traffic management -focused on prediction and avoidance of collisions and deadlocks-, location of pick-up and delivery points, AGVs control system including dispatching, routing and scheduling problems, positioning of idle vehicles and, finally, technological aspects such as battery management. All those issues were not applied specifically to automated container terminals but their concepts and methodologies can be adapted.

Complementarily, there are many research studies on AGVs and ALVs applied to container terminals and their optimization. In general terms studies focus in a specific AGV (or ALV) issue (e.g., dispatching or traffic management) either individually (regarding only one piece of equipment) or globally (integrated scheduling). For instance, the assignment of AGVs to transportation jobs (dispatching problem) has been analyzed by several authors such as (*15*), (*16*) or Kim and Bae (*17*) -who presented a dispatching method to minimize delays during container ship operations-, (*18*), (*19*) and more recently by Angeloudis and Bell (*7*) ,whose main contribution was the utilization of known but unreliable information from Terminal Operating Systems in a dispatching algorithm operating under uncertain conditions within a detailed container terminal model.

Because individual equipment optimization can cause low performance and deadlocks and mutual cooperation between handling equipments in terminals is essential to improve the productivity, a new optimization alternative has been considered in the literature: integrated scheduling, which was firstly suggested by (*20*).

Later on, B.J. Park et al. (*21*) proposed an event-oriented methodology based on a dispatching rule in order to reduce delay time and minimizing the makespan through simulation models. Similarly, Lau and Zhao (*22*) analyzed the problem suggesting an integrated approach by developing a mixed-integer programming model. This model was solved by defining a heuristic algorithm, namely a multi-layer genetic algorithm.

The former studies and investigations have been really useful for developing the simulation model employed in this paper and its equipment processes such as quay cranes (QC), ASC, AGV and SC transportation process.

Literature not only includes papers studying the optimization of automated horizontal transport methods in a container terminal context. Some authors even compare transportation handling equipments at container terminals and their feasibility such as:

Liu et al., (*3*), for example, analyzed and evaluated four different transportation concepts in automated container terminals with a microscopic simulation model: AGV system, linear motor conveyance system (LMCS), overhead grid rail (GR) and a high-rise automated storage and retrieval structure (AS/RS). Their comparison and evaluation was made through a cost model and results found that the AGV system is the most effective in terms of performance and cost. Next, Yang et al. (*23*) compared through simulation an AGV system and an ALV system for transporting containers from ship to yard in a container terminal with a perpendicular layout. Their study demonstrated that ALVs are superior to AGVs in both productivity and efficiency because ALVs eliminate the waiting time in the buffer zone. Moreover, ALV systems need fewer vehicles than AGV systems.

AGV and ALV transportation systems were also simulated and compared in terms of cost modeling by Saanen et al. (*5*). Furthermore, both automated transportation concepts were compared with manually operated shuttle carriers (SCs). The results demonstrated that AGVs are less costly than ALVs because of the decoupling between RMGs (YC) and ALVs and despite it requires fewer vehicles to achieve the same QC productivity. Additionally, automated alternatives are found cheaper than shuttle carriers. Despite that, automation is still considered a risky option for its smaller adaptability.

Similarly, Vis and Harika (*24*) simulated the effects from using AGVs and ALVs on vessel unloading performance. More specifically they compared unloading times, crane waiting times, QC occupancy degree and vehicle fleet necessary. They concluded that the AGVs fleet had to be 38% larger than its counterpart made up by ALVs. Then, cost-wise, ALVs are a better option than AGVs.

The comparison of transportation systems for inter-terminal transport was applied at the Maasvlakte container terminals by Duinkerken et al. (*25*). This time the cost-comparison was done between multi-trailers (MTS), AGVs and ALVs. The study concluded with considerations such: the MTS option requires a great deal of effort into the control and planning of vehicles, a large fleet of MTSs is required because they are also used as buffers on wheels but, however, MTS are idle around 50% of the time. In contrast, the number of

ALVs needed is less than half the number of AGVs, and idle only 15% (ALVs) and 30% of the time (actually values vary from 50 –quiet case- to 0 percent –peak scenario-).

The same case was analyzed by Bae et al. (*26*), where the productivities of the two types of abovementioned vehicles were compared when combined with quay cranes of various performances. As assumptions they considered that vehicles could move almost freely in any vertical and horizontal directions (flexible path layout) and introduced traffic control schemes to avoid deadlocks and minimize routing times. The results revealed that the ALVs system could reach the same productivity than the AGVs using almost 70% less number of vehicles and that are preferable with high performance QC. The numbers could vary, however, when the yard cranes reach high performances as well.

Finally, it should be remarked the contribution of Zhen et al., (*27*), who compared the new designs observed in China to transport containers between quay and yard: frame bridges (system based on multistory frame bridges and rails, on which electric trolleys transport containers) and rail mounted trolleys. Nonetheless, this new system presents some limitations regarding operational processes.

The choice of horizontal handling transport in automated container terminals is not fully consistent in comparison with the automation of stacking cranes at the storage yard. This paper provides supplementary conclusions in addition to those presented in the literature review to facilitate the choice of manned vs. automated equipment during the design process and in terms of economic cost.

3 PROBLEM DESCRIPTION

The convenience of AGV or SC for the berth-storage connection is evaluated by simulating (using the commercial software Witness) a terminal lay-out resembling the new automated container terminal operated by HPH in the port of Barcelona. The terminal layout being considered consists of three main physical elements (and terminal subsystems), namely Yard (storage) blocks and cranes (YC), Quay (berth) cranes (QC) system and Interconnection between both of them. Particularly, it is considered a loading and unloading representative operation, with 3 QC and 6 yard blocks.

Both crane systems (QC and YC) are considered to have the same input/output capacity. This allows simulating the berth-storage transportation system without restriction on the amount of time simulated since 'birth and dead effects' are avoided. That is, the simulation can run for long time periods and the values obtained belong to a stationary situation.

A detailed description of the problem simulated is indicated as follows:

Quay cranes (QC)

This paper deals with a 3 QC system because of the loop size used in the simulation of the AGV system (see Figure 2). Bigger loops would mean inefficient use of the automated equipment. This approach is similar to the one taken by Yang et al. *(23)* and Vis and Harika *(24)*. There are papers, however, that aim to optimize AGVs routing, considering a smaller circulation grid and the whole AGV fleet at once *(7), (15)*. A 3QC system is considered to be sufficient to micro-simulate the transportation equipment without altering the final results.

Real terminals with an intensive use of the berth line enough to justify automation of the storage-yard connection will be, indeed, bigger. In fact, multiple papers have addressed the direct relationship between berth length and occupancy to maintain certain quality standards (i.e. avoid excessive ship waiting times) *(28), (29), (30)*. Those berth occupancy values will be considered in the economic analysis, in the next section.

QC performance is far from constant *(10), (24)*. This paper considers the service time distribution observed in the Port of Barcelona (BEST terminal), similar to a lognormal function. The distribution has been slightly modified to give the same total productivity to both yard and quay (in this case, underperformance will only be attributable to the rolling stock and the decoupling between YC and QC performances). See Figure 1. Two YC performances (corresponding to scenarios E1 and E2, explained in the results section) were considered: 40 movements/hour (close to the peak values observed in Barcelona) and 30 movements/hour (average value).

Each QC is considered to have a buffer area for both import and export movements. When interconnection is handled with SC, the crane will pick up and deliver containers directly to the ground from where the SC will leave/pick up them. However, in AGV import systems, the crane will need at least one free AGV in the buffer in order to deliver a container; whereas the export AGVs will have to wait the crane picking up the container they are carrying in order to keep working.

Yard cranes (YC)

The storage area is composed by blocks perpendicular to the berth line with automatic cranes handling import and export containers (Figure 2). The yard is considered to be handled using two YC per block, one focusing on the operations that take place at the block's land side and the other on the sea side.

Even with a given yard layout, the YC productivity can heavily vary depending on the stacking algorithm used, the traffic composition (percentage of import export and transshipment containers), the yard occupancy, etc. As established beforehand, and in order to maintain the YC capacity equal to QC, two blocks (yard cranes) are considered per crane with half the QC productivity. The YC service time is considered to follow a lognormal distribution (Figure 1).

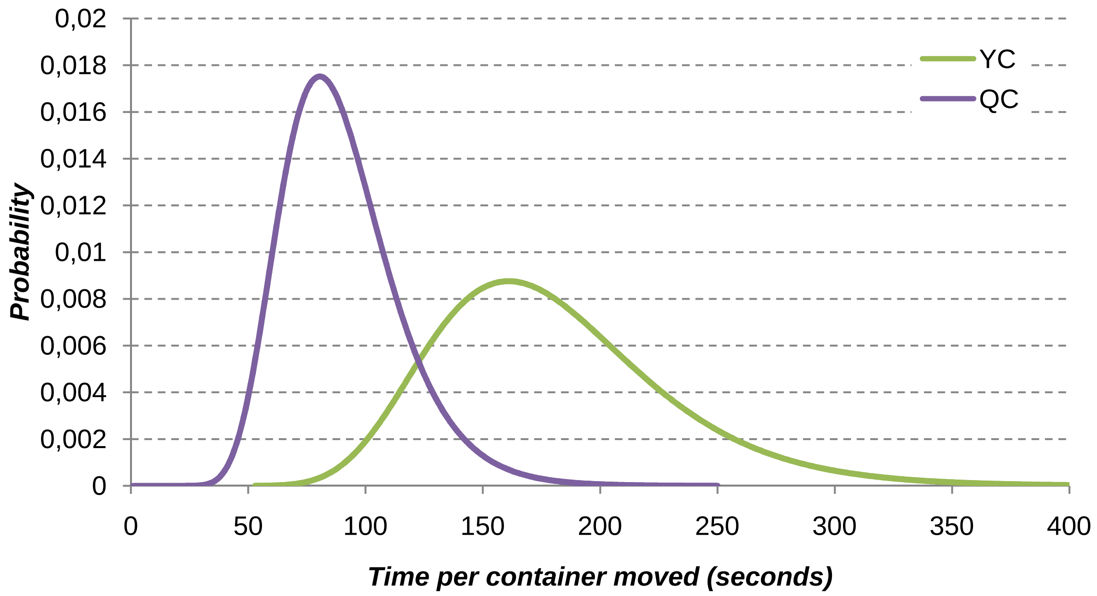

FIGURE 1 Service time distribution for Quay Cranes and Yard Cranes (peak, E1 scenario)

Transfer Point (TP)

Transfer from/to yard to/from the interconnection system is produced at the berth's closest end for each yard block.

The Transfer Point in a SC system is considered to be made up of 4 rows (2 for import and 2 for export containers) with 5 grounding slots each (Barcelona's BEST system). SCs will pick up export or deliver import containers in the corresponding lanes assigned to them through the simulation system.

The TP in the AGV system is considered to be made up of 5 lanes (can fit 5 AGVs) that will be used both for import and export movements. No extra rows will be considered since AGVs, unlike SC, cannot overtake ground obstacles.

Interconnection – AGV system

The AGVs rail system simulated follows a loop made up of a variable number of lanes as shown in Figure 2. To reduce the disruptions among different AGVs 3 different track lanes have been considered in the berth area (one lane per QC), and 6 lanes next to the yard area (one track per YC). All AGVs leaving a yard TP exit through the closest lane to the yard, in order to avoid further disruptions with AGVs going to the yard's TP. As a result of this layout, two different AGVs can only overlap at three different points: 1) when switching from the 3 lanes to the 6 lanes system; 2) when approaching crossing other lanes in order to enter any block TP and; 3) when leaving the yard area (crossing with AGVs accessing a block). AGVs from the last scenario (3)) (leaving the yard) have priority to allow a sooner arrival at the QC (see the zoomed area from Figure 2). In any other scenario, the latter AGV entering a conflict area will stop and wait until the area is emptied.

AGVs loaded with import or export containers are sent (assigned) the emptiest destination available from all the existing ones (block TP or QC buffer, respectively).

In import movements once an AGV has been emptied at the yard TP it is sent to the emptier QC buffer since QCs cannot produce containers if no AGV is present at their buffer area. On the other hand, in export movements, empty AGVs are sent to the yard TP with the smallest amount of AGVs because the YC will need at least one AGV in their TP in order to produce an export container.

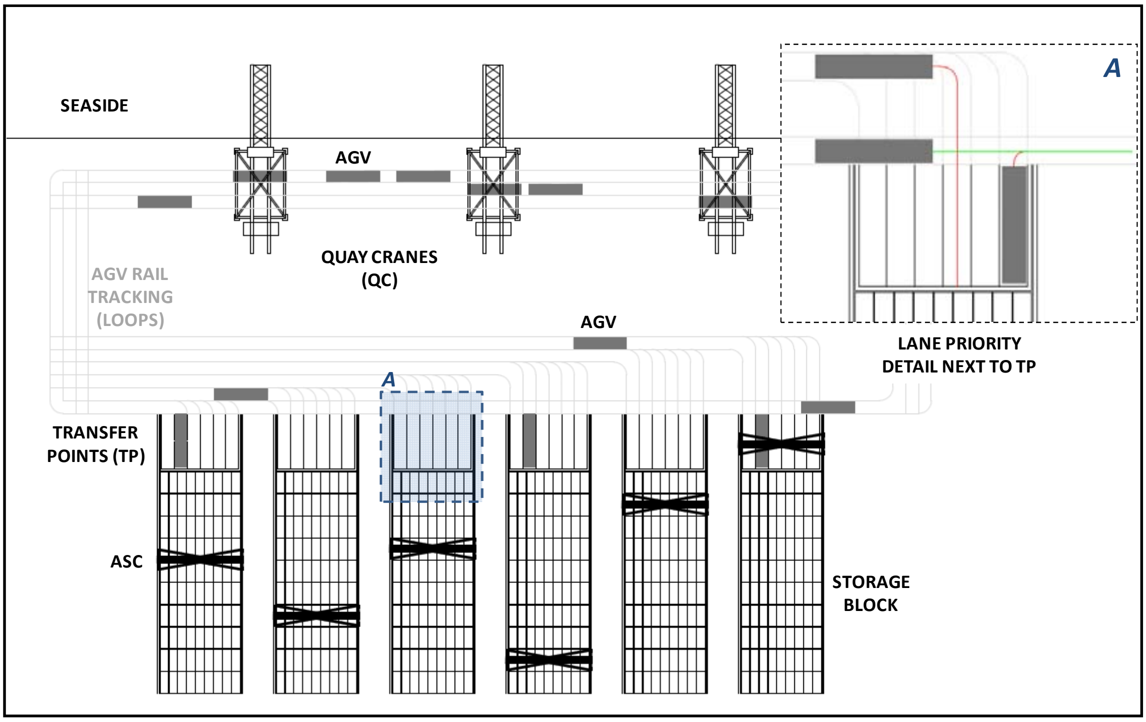

FIGURE 2 Sketch of the simulated AGVs loop rail system and detail showing lane priority next to a yard TP. The green movement has priority over the red ones.

Interconnection – SC system

All SCs are shared by all QC and YC. However, SCs first check available movements involving the QC and YC next to their current position in order optimize the distance travelled by container moved.

Import containers are assigned a destination block depending only on distance and block TP occupancy: the model estimates how long it will take each YC to pick up the container based on the remaining movements to be done –containers in transit are accounted for too– and how long it will take the container to get to that block's TP. The block registering a smaller value will be the block assigned to the container. Parameters usually considered like slot availability or block occupancy are not taken into account in the simulation.

Export containers are moved from their origin block to a random QC. Distance to be travelled is not taken into account in this scenario. In fact, at the terminal studied at Barcelona, all containers to be loaded to a specific ship are stored in usually 6 adjacent blocks regardless of their final destination inside the ship, i.e. regardless of the QC.

Other hypothesis considered

All containers have the same characteristics. That is other parameters such container size, weight, ownership or any other specific characteristic (reefer, open top, tank or dangerous goods containers) are not taken into account.

Import and export processes do not overlap. In real terminals overlapping usually happens at the transition from unloading to loading containers to the ship. Considering a stationary situation, overlapping situations lose their sense and, as stated by *(23)* and *(26)* do not add significant improvements in crane performance.

4 SIMULATION RESULTS

Two main scenarios have been considered: a) one with high QC capacity (40 mov/h-QC); and b) another with normal QC capacity (30 mov/h-QC). In both cases it is calculated how many SCs and AGVs are required to achieve performances over 99% of the QC capacity. With the fleet requirements known, the next section will consist on calculating and comparing the economic performances of both interconnection systems being considered: automated (AGV) vs. manned (SC).

Additionally, two slightly different simulation models have been produced per each kind of interconnection system (import vs. export operation). Over 20,000 containers have been moved using each simulation model and scenario and with different numbers of rolling stock available. Figure 3 shows the results obtained in terms of average QC productivity.

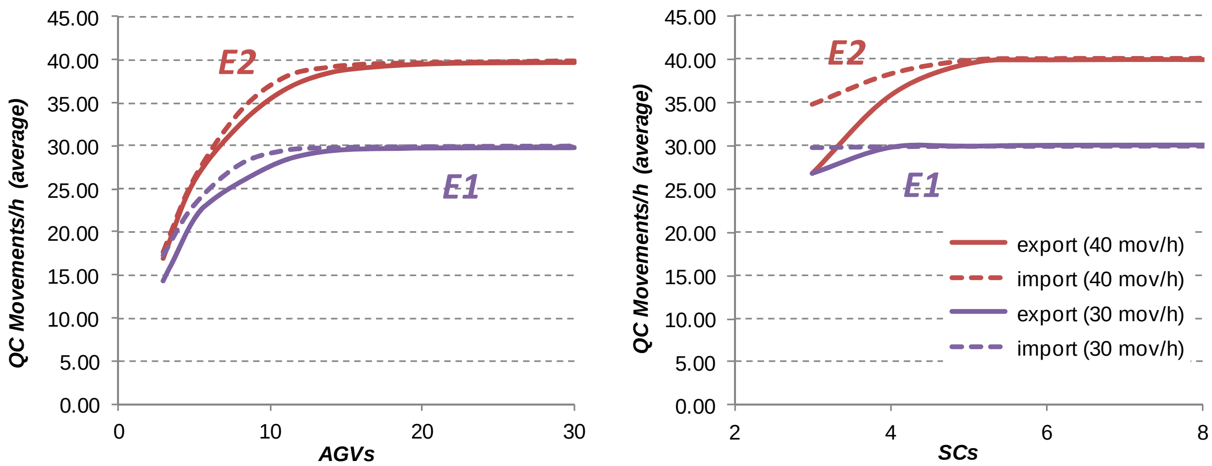

FIGURE 3 QC productivity related to size of AGV and SC fleets (scenarios E1 and E2)

As it can be observed from Figure 3, to reach QC productivity values next to their average capacity it is necessary to be served by 5 SCs (QC productivity reaches values over 99%) or, alternatively, 20 AGVs (when QC reaches 99% of its preset productivity) for the peak scenario (E1) and 4 SCs or 16 AVGs to keep the same service quality at the average scenario (E2).

Figure 3 also shows how import scenarios perform worse than their export counterpart. In the SC case this phenomenon is easily explained since the algorithms used to assign block (import) and QC (export) assignment are slightly different (the import algorithm takes into account the distance with origin and destination while the export algorithm assigns the destination QC on a random basis). In fact, the average distance per movement travelled per each SC is a 30% longer in the export case.

5 COST ANALYSIS OF AGV-SC SYSTEMS

Cost model

In order to compare economically both transportation systems and to figure out when an automated horizontal transport works better (that is, when going from semi automated terminal to full automated is better economically), a cost model for both systems is developed. The model developed takes into account the initial investment and operating costs. Moreover, it considers QC productivities and the number of equipment needed as obtained previously for each scenario.

In general terms, the cost analysis is based on the following components:

- Investment cost: Number of vehicles, acquisition cost, lifespan and financing costs (interests) are considered. The analytical expression to calculate the unitary investment cost (c_i) per TEU is:

$$c_i = \left(\frac{N_{(SC,AGV)}}{t_d} + I\right) \cdot \frac{P_{(SC,AGV)}}{q} \qquad [1]$$

  Where $N_{(SC,AGV)}$ is the required number of vehicles (SC or AGVs) per QC (from the simulation), $P_{(SC,AGV)}$ is the acquisition cost (SC or AGVs), q is the total throughput per QC, t_d is the depreciation time (lifespan) and I is the financing interest rate.

- Operating costs (c_o): Maintenance and operating costs (fuel consumption mainly). To calculate them, travel distance per vehicle and average consumption must be known.

$$c_o = \left(M \cdot \frac{P_{(SC,AGV)}}{q}\right) + \left(\frac{t_{(SC,AGV)} \cdot C_{f(SC,AGV)} \cdot p_f}{q}\right) \qquad [2]$$

  Where M is the percentage of the initial investment corresponding to annual maintenance, t is the total vehicle operating time per year (from the simulation), C_f is vehicle fuel consumption per hour (l/h) and p_f is the fuel price (€/l).

- Labor cost (c_l): Salary cost (labor cost per hour). They depend on vehicle operating time per year (from QC yearly throughput). This cost is only applied to the SC system.

$$c_l = \frac{t_{(SC,AGV)} \cdot S}{q} \qquad [3]$$

  Where S is the average labor cost per hour (€/h), $t_{(SC,AGV)}$ is the vehicle operating time per year (SC or AGV) and q is the total yearly throughput per QC (TEU/QC-year). The variable $t_{(SC,ASC)}$ is obtained through QC productivity (input from the simulation) and by the number of vehicles per QC.

Finally, total unitary variable cost per year (€/TEU) will be obtained adding up the three cost components.

As for the simulation, two scenarios are estimated: high QC performance (E1) and normal QC performance (E2). That is:

- Scenario E1: The automated container terminal design (transport and handling equipment) will be made considering a QC productivity of 40 containers/hour. However, the cost estimation will be done assuming an average gross productivity of 35 containers/hour, which is the current situation of the studied container terminal (beginning and end of stevedoring operations are considered).
- Scenario E2: The design of the automated container terminal (transport and handling equipment) will be made considering a QC productivity of 30 containers/hour, but cost estimation will be done according to an average gross productivity of 25

containers/hour. In fact, this is the current situation of many not automated container terminals.

The number of vehicles required per QC (per scenario and type of vehicle) was obtained in the previous section after executing the simulation model. According to the simulation results, 5 SCs or 20 AGVs will be needed at scenario E1 and 4 SCs or 16 AGVs at scenario E2.

The main cost components and assumptions are introduced in Table 1. All data was obtained either empirically or from interviewing the main stakeholders at the analyzed container terminal. In addition, it should be highlighted that those assumptions were contrasted with *(5)*.

	Manned system (SC)	Automated system (AGV)
1) Investment costs		
Gross QC productivity (E1)	35 box/hour	35 box/hour
Gross QC productivity (E2)	25 box/hour	25 box/hour
Operational vehicles per QC (E1)	1.67	6.67
Operational vehicles per QC (E2)	1.33	5.33
Additional vehicles per QC (maintenance and repair)	0.5	0.5
Investment per vehicle (€)	€550,000	€350,000
Depreciation (expected life) (n)	10 years	10 years
Financing costs (interests)	4% of investment	4% of investment
2) Operating costs		
Maintenance cost	10% of investment	8% of investment
Average consumption per vehicle (l/h)	20 l/h	10 l/h
3) Labor costs		
Average cost per hour	€75	Not required
Working hours per year	1,440 hours	Not required

TABLE 1 Main data and assumptions considered in the cost analysis

A comparative analysis

Results from the cost analysis are depicted in Figures 4 and 5, where the total cost per TEU is calculated for different annual QC throughput levels (TEU/QC-year) and different labor costs per hour (€/h), In fact those two are the main variables affecting the decision of using AGV or SC. As a baseline scenario, c_l= 75€/h and q=100,000TEU/QC.

From the simulation results and Figures 4 to 6 it can be stated that, regarding the cost differences between both systems:

Scenario E1:

- Each QC needs 1.67 SCs and 6.67 AGVs on average. That is, the interconnection berth-yard system requires 4 times more AGVs than SCs to keep the high productivity of the QC.
- The AGV system is the most economical system for throughput ratios higher than 125,000 TEUs/QC per year and assuming an average labor cost per hour

over 75.00€/hr. Otherwise SCs are better. Nonetheless, Figure 4 shows how between 80,000-170,000 TEU/QC-year the cost of both systems are very close (i.e.: in Figure 4, there is a difference of only 10 € cents per TEU) and, therefore, the choice of the best interconnection equipment is not clear. In such cases, the risk from the investment in automation and the higher resiliency of the SCs in case of disruptions make SCs preferred option for many terminal operators.

- Assuming an annual throughput per QC around 100,000 TEU/QC-year the AGV becomes better economically only when labor cost is over 76.75€/h.

Scenario E2:

- Each QC needs 1.33 SCs and 5.33 AGVs in order to maintain the QC productivity over 99% of its preset value.
- Regarding costs, the AGV system is the cheapest choice for throughput ratios over 75,000 TEUs/QC-year given an average labor cost over 75.00€/h. Cost reductions from using AGVs when faced with SCs ranges from 10% (100.000 containers/QC-year) to 48% (300.000 containers/QC). The range with similar costs goes from 50,000-80,000 TEU/QC-year. From the values obtained, SC is only appropriate when labor costs are very small.
- Assuming an annual throughput of 100,000TEU/QC, the SC is better if the labor cost per hour is less than 61.30€ per hour.

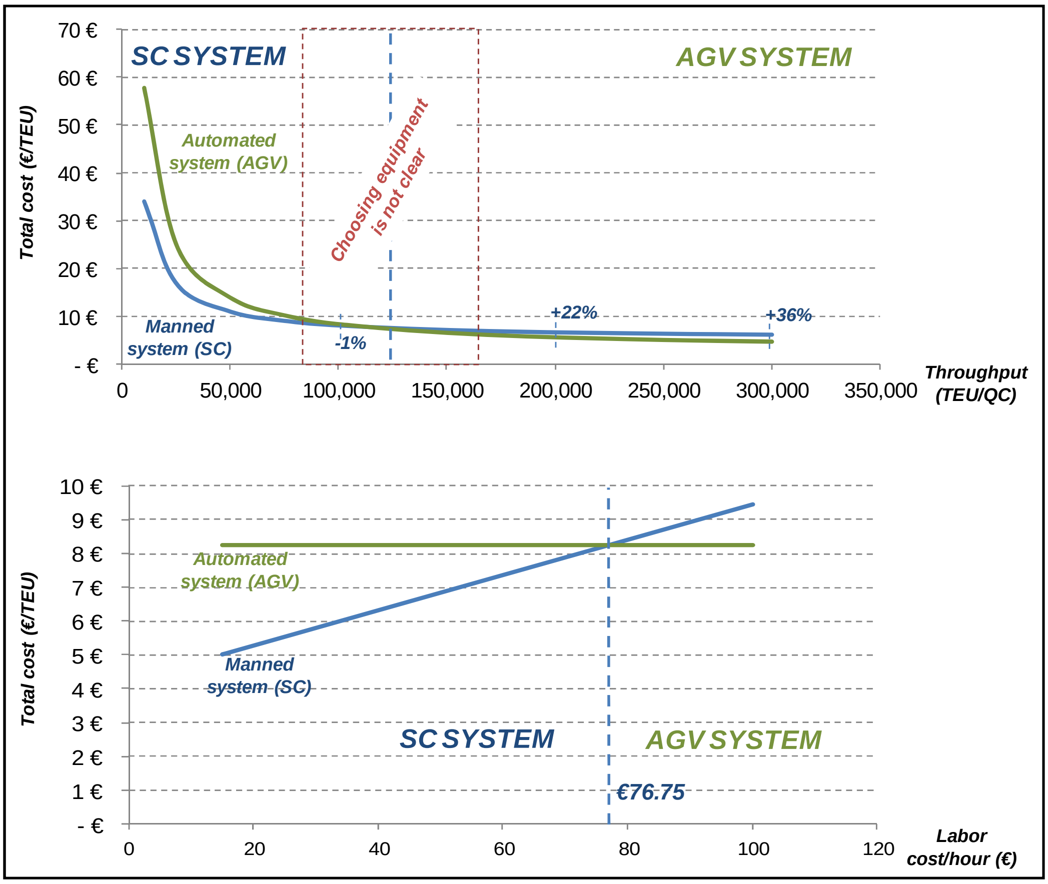

FIGURE 4 SC vs. AGV costs in Scenario E1 (40 containers/hour)

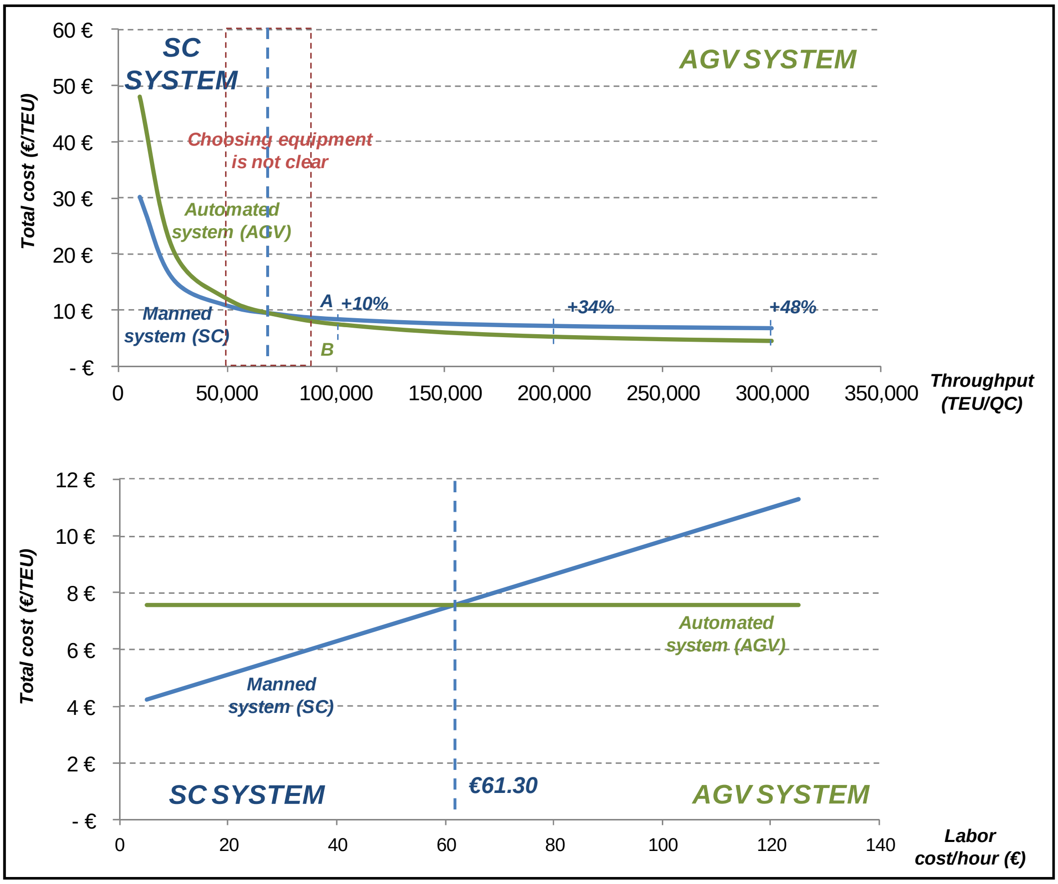

FIGURE 5 SC vs. AGV costs in Scenario E2 (30 containers/hour)

Figure 6 exemplifies the importance of labor costs in the final choice between manned or automated systems representing over 50% of all costs in the S2 scenario with 100.000 movenents/year-QC and a salary cost of 75€/h. More specifically the cost composition from the figure corresponds to the points A and B from Figure 5.

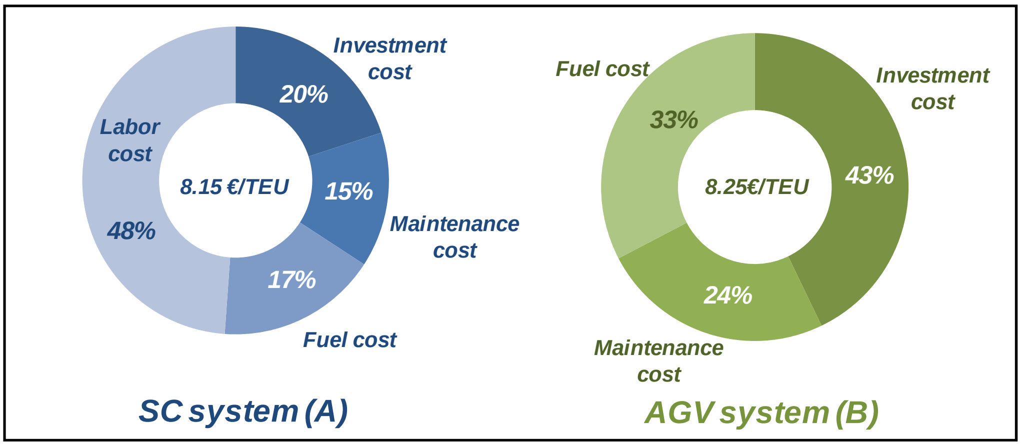

FIGURE 6 Cost components for SC and AGV systems assuming an annual throughput of 100,000 boxes per quay crane and labor cost equal to 75€/h in Scenario E2 (30 containers/hour)

6 CONCLUSIONS

Internal transport of containers from the ship to the storage yard can be done by manned or automated vehicles. Depending on the system used terminals are considered to be either semi automated or fully automated, respectively. This paper studies the economical cost of a manned system operated by Shuttle Carriers (SC) vs. an automated one consisting of automated guided vehicles (AGVs). For that purpose, knowledge and data from the new semi automated container terminal from Port of Barcelona has been used to build a microsimulation model of a representative part of the terminal, consisting of the interconnection system between 6 yard blocks and 3 quay cranes.

The simulation points out that 1.67 SCs or 6.67 AGVs are necessary per quay crane (QC) if they have high capacity (40 mov/h), while 1.33 SCs and 5.33 AGVs are needed in order to ensure that average QC work at full capacity (30 mov/h).

According to the assumptions and the data used for the economical analysis AGV systems are preferable in ports with high labor costs and a throughput over 100,000 containers/QC-year (depending on labor costs). SC systems, however, are advisable in terminals with lower annual throughput (less than 100,000 containers per QC) and lower labor costs. Both interconnection systems register similar unitary cost for wide ranges of annual throughput (80,000-170,000 TEU/QC-year for the 40 mov/h scenario and 50,000-80,000 TEU/QC-year for the 30 mov/QC scenario). In this case, SCs are considered to be less risky since a smaller investment is needed and have more adaptability to operating changes.

The highest cost for the SC system is labor, which represents almost 50 per cent of total costs. Investment costs, including financing interests, is the second main cost for the manned system and the first one for the automated system, representing the 43% of total average cost.

REFERENCES

[1] UNCTAD. *Review of Maritime Transport 2012*. United Nations Publications, Geneva, 2012.

[2] Wan, T.B., Wah, E.L.C., Meng, L.C. The use of information technology by the port of Singapore authority. *World Development*, Vol. 20, 1992, pp. 1785-1795.

[3] Liu, C-I., Jula, H., Ioannou, P.A. Design, simulation, and evaluation of Automated Container Terminals. *IEEE Transactions on intelligent transportation systems*, Vol. 3, 2002, pp. 12-26.

[4] Leeper, J.H. Integrated automated terminal operations. *Transportation Research Circular*, Vol. 33, 1988, pp. 23-28.

[5] Saanen, Y., Van Meel, J., Verbraeck, A. The design and assessment of next generation automated container terminals. *Proceedings 15th European Simulation Symposium*. Alexander Verbraeck, Vlatka Hlupic (Eds.), SCS European Council, 2003.

[6] Müller, T. *Automated Guided Vehicles*. IFS publications, Springer-Verlag, UK/Berlin, 1983.

[7] Angeloudis, P., Bell, M. An uncertainty-aware AGV assignment algorithm for automated container terminals. *Transportation Research Part E*, Vol. 46, 2010, pp. 354-366.

[8] Henesey, L., Wernstedt, F., Davidsson, P. A market-based approach to container port terminal management. In: *Proceedings of the 15th European Conference on Artificial Intelligence, Workshop-Agent Technologies in Logistics*, Lyon, 2002.

[9] Vis, I.F.A., and De Koster, R. Transshipment of containers at a container terminal: An overview. *European Journal Operation Research*, Vol. 147, 2003, pp. 1-16.

[10] Steenken, D., Voβ, S., Stahlbock, R. Container terminal operation and operations research – a classification and literature review. *OR Spectrum*, Vol.26, 2004, pp. 3-49.

[11] Stahlbock, R., Voss, S. Operations research at container terminals: a literature update. *OR Spectrum*, Vol. 30, 2008, pp. 1–52.

[12] Luo, J., Wu, Y., Halldorsson, A and Song, X. Storage and Stacking Logistics Problems in Container Terminals. *OR Insight*, Vol. 24, 2011, pp. 256-275.

[13] Günther, H.O. Kim, K.H. Container terminals and terminal operations. *OR Spectrum*, Vol. 28, pp. 437-445 (2006).

[14] Vis, I.F.A. Survey of research in the design and control of automated guided vehicle systems. *European Journal of Operational Research*, Vol. 170, 2006, pp. 677-709.

[15] Bae, J.W., Kim, K.H. A pooled dispatching strategy for automated guided vehicles in port container terminals. *International Journal of Management Science*, Vol. 6, 2000, pp. 47-67.

[16] Koo, P.H., Lee, W.S., Koh, S.H. Vehicle dispatching for container transportation in seaport container terminals. *Proceedings of the 7th International conference on computers and industrial engineering*, Jeju, Korea, 2004.

[17] Kim K.H., Bae J.W. A look-ahead dispatching method for automated guided vehicles in automated port container terminals. *Transportation Science*, Vol. 38, 2004, pp. 224–234.

[18] Grunow, M., Günther, H-O., Lehmann, M. Strategies for dispatching AGVs at automated seaport container terminals. *OR Spectrum*, Vol. 28, 2006, pp. 587-610.

[19] Gujjula, R., Günther, H.O. The impact of storage block assignment for import containers on AGV dispatching in highly automated seaport container terminals. *Proceedings of the 2008 IEEE International Conference on Industrial Engineering and Engineering Management*, 2008, pp. 1739-1743.

[20] Meersmans, P.J.M., Wagelmans, A.P.M. *Effective algorithms for integrated scheduling of handling equipment at automated container terminals*. Erasmus Research Institute of Management, 2001, pp. 1-20.

[21] Park, B.J., Choi, H.R., Kwon, H.K. Kang, M.H. *Simulation analysis on effective operation of handling equipments in automated container terminal*. A. Sattar and B.H. Kang, Springer-Verlag Berlin Heidelberg, 2006, pp. 1231-1238.

[22] Lau, H. Y.K., Zhao, Y. Integrated scheduling of handling equipment at automated container terminals. *Annals of Operations Research*, Vol. 159, 2008, pp. 373-394.

[23] Yang, C.H., Choi, Y.S., Ha, T.Y. Simulation-based performance evaluation of transport vehicles at automated container terminals. *OR Spectrum*, Vol. 26, 2004, pp. 149-170.

[24] Vis, I.F.A., Harika, I. Comparison of vehicle types at an automated container terminal. *OR Spectrum*, Vol. 26, 2004, pp. 117-143.

[25] Duinkerken, M.B., Dekker, R., Kurstjens, S., Ottjes, J.A., Dellaert, N.P. Comparing transportation systems for inter-terminal transport at the Maasvlakte container terminals. *OR Spectrum*, Vol. 28, 2006, pp. 469-493.

[26] Bae, H.Y., Choe, R., Park, T., Ryu, K.R. Comparison of operations of AGVs and ALVs in an automated container terminal. *Journal of Intelligent Manufacturing*, Vol. 22, 2011, pp. 413-426.

[27] Zhen, L., Lee, L.H., Chew, E.P., Chang, D-F., Xu, Z-X. A comparative study on two types of automated container terminal systems. *IEEE Transactions on intelligent transportation systems*, Vol. 9, 2012, pp. 56-69.

[28] Agerschou, H. Facilities Requirements. In *Planning and Design of Ports and Marine Terminals*, 2nd Ed. (H. Agerschou, eds), Thomas Telford Ltd., London, 2004, pp. 5-20.

[29] Dai, J., Lin, W., Moorthy, R., Teo, C-P. Berth allocation planning optimization in container terminals. *In:* C. S. Tang, C.-P. Teo and K. K. Wei eds. *Supply chain analysis. A handbook on the interaction of information, system and optimization.* Springer Science+Business Media, New York. 2008, pp. 69–104.

[30] Aguilar, J., Obrer, R., 2009. *Consideraciones sobre la oferta y la demanda del servicio de atraque, en relación con la capacidad de las terminales de contenedores. In: X Jornadas Españolas de Costas y Puertos* 2009. 27–28 May 2009 Santander, Spain.

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