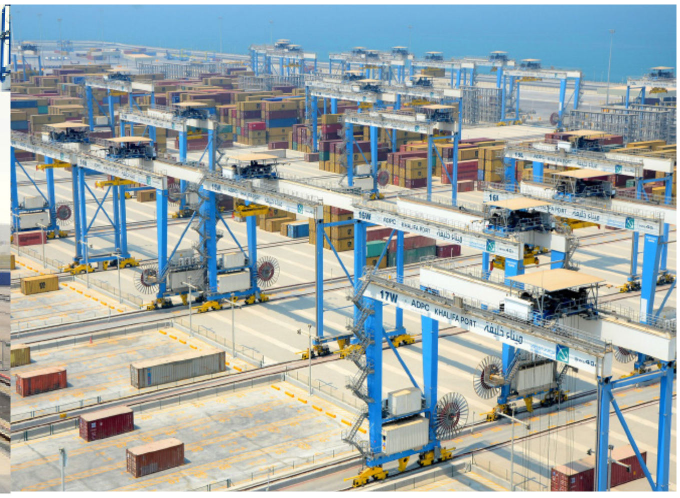
Automatic Stacking Crane Performance

A PEMA Information Paper



This information paper aims to improve understanding of the definition and measurement of Automatic Stacking Crane (ASC) performance in realistic scenarios for use in simulations and field testing.

The paper describes alternative ASC layouts, stack operation modes, interfaces, and environmental influences and how they affect performance.

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INTRODUCTION

DOCUMENT PURPOSE

This Information Paper aims to improve understanding of the definition and measurement of Automatic Stacking Crane (ASC) performance in realistic scenarios for use in simulations and field testing. Performance simulation data are often required by equipment buyers. In this document, the term ASC refers to any kind of gantry crane, (either rail mounted or rubber-tyred), that performs container stacking operations automatically.

The document describes alternative ASC layouts, stack operation modes, interfaces, and environmental influences and how they affect performance.

While the primary aim of this paper is to support understanding of the measurement and definition of the performance of an "isolated" ASC or ASC stack, TOS and horizontal transport and their effects on stack performance are also analysed to reflect integrated terminal operations. Guidelines and recommendations for defining KPIs and test scenarios provided in this document are intended to be informative and illustrate the best possible performance of the ASC system.

DEFINITIONS AND TERMINOLOGY

A list of terminology and acronyms used in this publication to describe technologies, applications and processes in relation to ASC is provided in Appendix 2.

ABOUT THIS DOCUMENT

This document is one of a series of Information Papers developed by the Automation and Control Technologies Committee (PEMA). The series is designed to inform those involved in port and terminal operations about the design and application of software, hardware, systems and other advanced technologies to help increase operational efficiency, improve safety and security, and drive environmental conservancy.
This document does not constitute professional advice, nor is it an exhaustive summary of the information available on the subject matter to which it refers.

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1 | EXECUTIVE SUMMARY

The first ASCs were introduced in Rotterdam in The Netherlands at the ECT Delta Terminal in 1993. By 2017, there were more than 1,200 ASCs in operation worldwide.

When driven manually by a driver, the performance of a container handling crane (cycle times) depends on the crane driver's skill as well as the performance of the crane itself. The introduction of unmanned robotized cranes (ASC), however, made cycle times more "deterministic". It thus became relevant to measure crane performance in terms of repeatable cycle times.

The crane tendering process typically includes a demonstration of automated cranes' performance in the form of simulations, or by defining some other performance figures.

The performance benchmark simulations attempt to imitate real operations, preferably at peak periods to show the maximum capacity of ASCs. ASC operation consists of different types of movements: container storage into the stack; container retrieval from stack; and house-keeping moves. House-keeping moves are typical for testing ASC performance in simulation, since they are completely automatic, (no remotely operated parts), and external vehicles do not affect performance, (no waiting time due to external vehicles).

Top speeds and acceleration of ASC gantry, trolley and hoist motions define the "raw" performance of an ASC crane. Cycle times are reduced by optimal moves, e.g. if trolley, gantry and hoist motions are executed in parallel, and "shortest path" trajectories are used.

Theoretically calculated cycle times based on top speeds and ramp times are typically not achieved because of various automation related delays, (e.g. scanning times and fine positioning), in operation. Furthermore, multiple crane synchronization on the same tracks, and, e.g. resolving "dead-lock" situations, cause additional delays.

It would be convenient to use simple numerical indices (KPI) to define performance because they are readily comparable and make trends easy to identify. KPIs are, however, more suited to identify trends in a given operation rather than comparing two completely different operations.

Predetermined scenarios instead of KPIs are therefore often defined by job-order lists of container moves. The performance of ASC or complete ASC stack is then defined based on, for example, the time needed to perform the scenario.

2 | BACKGROUND

2.1 THE CONCEPT OF CRANE PERFORMANCE

When driven manually by a driver, the performance of a container handling crane (cycle times) depends on the crane driver's skill as well as the performance of the crane itself. The introduction of unmanned robotized cranes (ASC), however, made cycle times more "deterministic" due to computer control and standardisation of sensors across crane fleets. It thus became relevant to measure crane performance in terms of repeatable cycle times, rather than purely by traditional gantry, trolley and hoist speeds.

It should be noted, however, that removing the drivers from cranes did not make container handling entirely deterministic or predictable, since there are still many environmental influences affecting the operation of cranes and sensors (for example, wind, rain and terrain inclines).

2.2 ASC HISTORY

The first ASCs were introduced in Rotterdam in The Netherlands at the ECT Delta Terminal in 1993. This installation operates with automated unmanned RMGs (ARMGs) and unmanned Automated Guided Vehicles (AGVs) for horizontal quay-yard container transfers. HHLA's CTA facility in Hamburg followed in 2002.

As of 2017 there were more than 1,200 ASCs in operation in Asia, Europe, US, the Middle East and Australia, handling tens of millions of containers per annum [1], [2]. The global deliveries of ASC cranes in recent years have varied between 60…120 units per year [2].

Today, while there are some automated straddle carrier terminals and some automated RTG operations (ARTGs) in use and in planning, automated RMGs, i.e. ARMGs, continue to dominate the current yard automation landscape and these will be the focus of this information paper.

2.3 ASC CRANE SPECIFICATIONS

Currently, the crane tendering process typically includes a demonstration of automated cranes' performance in the form of simulations or by defining some other performance figures. These simulations are typically defined by terminal operators. Crane vendors are required to provide results according to common benchmarks. It is the interest of all parties that these simulations and performance figures are realistic and clearly understood by all vendors, (and purchasers), so that results are comparable. This is the primary goal of this information paper. A secondary goal is to highlight the technical and operational aspects that might help to show the best performance of the ASC systems offered.

3 | ASC SYSTEM LAYOUTS AND INTERFACES

3.1 CHOICE OF ASC SYSTEM LAYOUT

One of the main factors considered when selecting ASC system layout is the trans-shipment ratio. This can range from below 15 per cent (especially in United States, in England and at the European continent) to nearly 100 per cent (for example Tanjung Pelepas, Singapore, Salalah, Port Said, Gioia Tauro, Malta Freeport, and Algeciras) [3]. In trans-shipment operations, containers are not moved all the way from quay cranes to the gate.

3.2 MAIN ASC LAYOUTS

The main ASC layouts today are:

- End-loaded ARMGs with blocks located perpendicular or parallel to the quay
- Side-loaded cantilever CARMGs with blocks laid out parallel to the quay

The parallel block layout with CARMGs has so far been favoured in Asia and Latin America, while the perpendicular design with ARMGs has been largely preferred in other areas. The layout of an automated RTG (ARTG) operation is similar to CARMGs, with the exception that ARTG has no cantilevers, but the trucks drive on lanes under the gantry.

Basic operational differences between the approaches are as follows:

- In end-loaded design "crane travels to the container" and in side-loaded design "the container is travelling to the crane" [5]
- An end-loaded perpendicular design separates waterside (WS) and landside (LS) operations.
- An end-loaded design tends to fix the handling capacity at either end, and provides less flexibility to handle peaks at one side. Exceptions to this are "cross-over" ASCs, where a smaller ARMG can pass underneath a larger ARMG in the same stack.
- A side-loading CARMG design allows capacity to be deployed more flexibly to WS/LS side, increasing peak production.

A combination of end-loaded and side-loaded designs has been employed in Thamesport in the UK and at the Rotterdam World Gateway (RWG) terminal.

3.3 ASC BASIC TECHNOLOGY

Rail-mounted ARMGs run on rails, fixed either to sleepers in gravel beds, or to concrete or steel bridge structures supported by pilings. Rubber tired ARTGs do not require rails, but typically produce lower gantry speeds.

Fig 1. A typical ARMG design where containers are moved along the gantry direction and transfer vehicles are served at block ends.

Fig 2. Remote operation of the ASC is performed from a remote operator desk

Crane sizing is a trade-off between handling and storage capacity. End-loading ARMGs usually span eight to ten containers. Side-loaded CARMGs are generally 10-14 containers wide.

Crane movements are performed automatically, based on instructions received from the TOS. When executing moves to and from a manned vehicle, such as an ITV or an external street truck, a remote operator is often required to perform or supervise the operation when the container is close to the target or is moved over a manned vehicle.

Fully automated street truck handling, (unloading and loading of trailers), has already been implemented in some terminals, thereby automating normal ASC work cycles entirely. The remote operator is then only needed for exceptional handling.

3.4 HORIZONTAL TRANSPORT

Yard blocks using ASCs are served by road trucks, ITVs, AGVs, SCs and ShCs. The choice of equipment deployed to serve the stacks is determined by several factors, including required investments, labour costs, technical capabilities etc. In addition to unmanned AGVs, unmanned shuttle carriers are used to move containers between the quay cranes and the ASC stack.

The horizontal transport system serving ASC cranes consists of two logistic operations:

- Landside (LS) transport: moving containers from the terminal truck gate or intermodal railhead to ASCs and vice versa
- Waterside (WS) transport: moving containers from quay cranes (QCs) to ASCs and vice versa

There are important design choices which affect the efficiency of ASC systems. These include:

- Synchronized or alternatively, de-coupled operation between horizontal transport systems, ASCs and QCs
- Manned or unmanned horizontal transport vehicles

3.5 LANDSIDE TRANSPORT

LS transport, such as external street trucks, will enter the yard via a truck gate and typically drive to one of the ASC LS transfer points for handling.

With side-loading CARMGs, external trucks typically drive under the cantilevers of the CARMGs. With ARTGs, external trucks drive on lanes under the gantry.

3.6 WATERSIDE TRANSPORT

WS transport can be conducted using several different equipment combinations including traditional tractor/trailer sets or ITVs, AGVs or manual/automated straddle-type carriers that lift and move containers from the ground.

ASC WS operation can be de-coupled, (i.e. buffered), by using SCs or lift-AGVs. SCs were originally developed as a self-contained transport/stacking system for container ports. Using SCs with a gantry crane system for WS transfer enables the operating cycles of the ASC and QC to be made independent of horizontal transport (i.e. decoupled). ASCs, QCs and SCs all place containers directly on the ground and use the ground interchange areas as "buffer zones" for containers.

De-coupling the operation cycles between horizontal transport and ASCs can also be achieved by using lifting platform vehicles. Here, special elevated interchange racks are built in ARMG WS transfer areas. Horizontal transport vehicles and ARMGs independently pick and place containers on interchange racks, removing the need to synchronize work cycles between ARMGs and horizontal transport.

3.7 UNMANNED HORIZONTAL TRANSPORT

ASC terminals, where the WS transport system is entirely robotic, have operating driverless AGVs since the 1990s. Another unmanned solution is a fully automated ShC.

Fig 4. A "lift-AGV" de-couples the waterside interchange

Fig 3. Landside horizontal transport in the end-loading ARMG layout.

4 | TOS AND ECS

TOS software controls the logistics of a terminal, including key functions such as vessel planning, container inventory maintenance, job order creation, and gate operations.

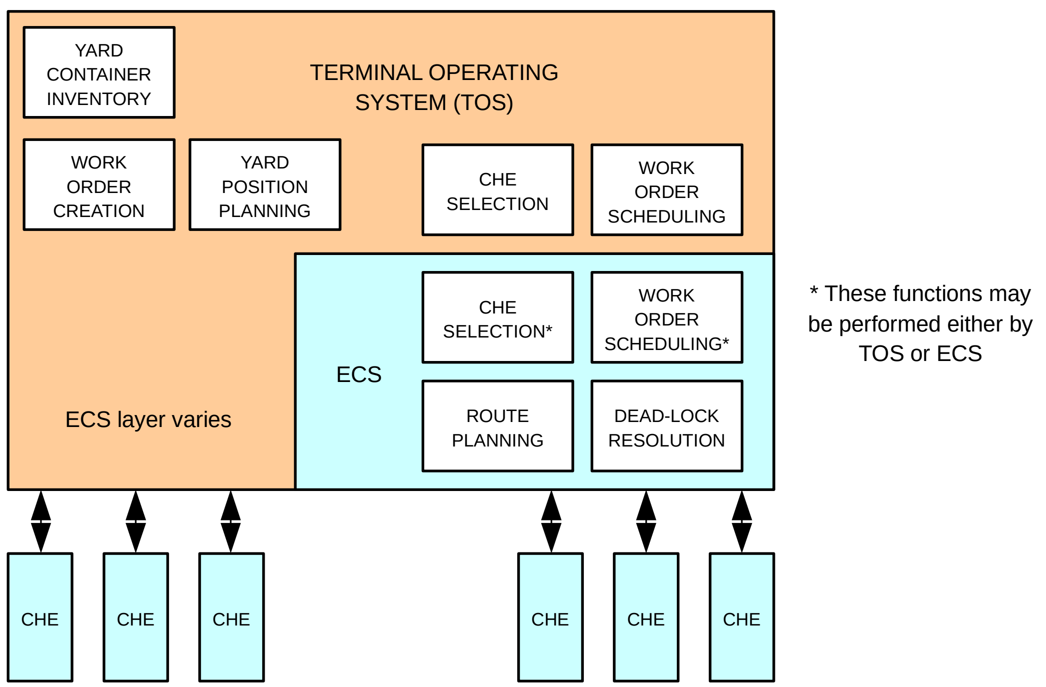
In an automated container terminal, some CHE controlled by a TOS may be unmanned, while part of them may be manually operated.

4.1 TOS AND EQUIPMENT CONTROL SYSTEM (ECS)

An unmanned crane or a group of unmanned vehicles may share a common software control module at equipment level, often referred to as the "Equipment Control System" (ECS) for handling, for example, safety features and intra-vehicle co-ordination. Typically, automated vehicles operating on the same tracks or pathways, such as ASCs, are co-ordinated by such software. When co-ordinating interactions between different types of automated equipment, an ECS is now an essential part of the terminal software landscape.

Figure 5 illustrates the concept of TOS and ECS. Due to the number of system providers and developers, there are differences between the functionalities of different TOS software and the standardization of interfaces is still developing [4]. Several functionalities can be implemented within TOS, in a separate ECS system or at CHE level.

Fig 5. Terminal operating system (TOS) and Equipment Control System (ECS)



Basically, TOS has two main functions from ASC system perspective:

- To maintain a correct container inventory i.e. record all container moves that are reported by the CHE
- To plan container storage locations in the terminal and provide job orders to CHE (or ECS).

Different kinds of optimisation can be achieved by TOS and ECS software. Functions typically performed by TOS include:

- Planning the optimal yard positions for containers, especially control of container distribution between blocks (to distribute crane workload)
- Control of transfer points (occupied, free, claimed)
- Creation of the primary transport orders

The following control functions are typically performed by ECS:

- Dead-lock resolution between the cranes ("high-level" collision avoidance between the cranes)

The following functions may be performed by the TOS, but could also be implemented by the ECS:

- Control of container positions in the blocks, (based upon attribute sets and assignment etc.). This kind of optimiser is sometimes also called a Block Management System (BMS)
- Scheduling the order and dispatch at the time of transport
- Selection of CHE to execute a transport orders
- CHE sequencing

The following control functions are typically performed at the crane level:

- Calculating and optimising crane path (gantry, trolley and hoist)
- Control of crane movements
- Collision avoidance for safety (containers, vehicles, obstacles, other cranes).

5 | TYPES OF CONTAINER MOVES IN ASC OPERATION

The performance benchmark simulations attempt to imitate real operations, preferably at peak periods to show the full performance of the ASCs. ASC operation consists of different types of movements, which are described here to explain the challenges detected in performance simulations.

5.1 CONTAINER STORAGE INTO THE STACK

In side-loaded ASC stack layout, container is moved from the transfer area under ASC cantilevers into the stack, (or from truck lane to stack with ARTGs).

In end-loaded layouts, containers are moved from one of the ASC stack transfer points (TP) to the container stack. In perpendicular design, there are separated transfer points for WS and LS.

In container storage operation, manned transfer vehicles such as road trucks, terminal tractors or SCs are still most often used. In these cases, there are typically remotely operated work phases in the ASC movement sequence for safety reasons and the cycle times are thus not deterministic. Because of this, many performance simulation scenarios ignore or simplify these moves.

5.1.1 WATERSIDE STORAGE

Containers may be brought to WS transfer points either by terminal tractors, SCs or AGVs. With SCs, containers are left on the ground in transfer point areas, and the operation of ASCs is typically totally automated, (no remote operation needed). In AGV operation, containers may be automatically picked from AGVs or AGVs leave containers on special racks, (lift-AGVs), where containers are automatically picked by ASCs. Handling of manned terminal tractors may require remote operation because of safety reasons.

5.1.2 LANDSIDE STORAGE

Containers are typically brought to landside transfer points by road trucks, but sometimes also by intermediate terminal vehicles, for example SCs. Handling of road trucks typically requires remote operation, although there are some sites where this part is also automatic, (and is then included in "ASC performance").

5.2 CONTAINER RETRIEVAL FROM THE STACK

Similar to container storage operation, some work phases are typically executed using remote control, thus cycle times are not deterministic. Many performance simulation scenarios ignore or simplify these moves.

In side-loaded ASC stack layouts, containers are moved from the stack to the transfer area under cantilevers, (or truck line with ARTGs).

In end-loaded ASC stack layouts, containers are moved from the stack into one of the transfer points (TP).

In container retrieval operations, the containers that need to be retrieved may be under other containers. These containers need to be relocated before the target container can be accessed. The total cycle time of container retrieval operations may thus be a sum of several individual container moves.

5.2.1 WATERSIDE RETRIEVAL

Similar to container storage operations, SC or AGV horizontal transport allows total automation of ASC operations at WS, and thus ASC performance can be defined deterministically in these cases.

5.2.2 LANDSIDE RETRIEVAL

Handling of road trucks typically requires remote operation, since loading containers to external trailers with varying shapes is considered to be one of the most difficult work phases to automate. In some sites this sub-process is also fully automated, in which case remote handling is only needed for exceptional handling requirements. The success rate of automatic operation depends also on human (truck driver) behaviour, (for example preparing twist-locks on trailers, using operator consoles, staying out of hazardous areas etc.).

5.3 SHUFFLING MOVES

Shuffling moves are conducted to remove containers located on top of target containers, allowing access to target containers. Shuffle moves are typically performed within one container bay, i.e. gantry motion is unnecessary, but trolley and hoist motions are active. The trolley-hoist position trajectories could be optimised to be as short possible, i.e. containers are not necessarily hoisted at the highest tier, but only to provide a collision-free path to target location.

Container moves per hour (cmph) typically mesures only "productive" container moves: container storage to stack container retrieval from stack
Performance decline 1: • Long move distances (trans-shipment vs. through-the-stack)
Performance decline 2: • "Shuffle" container moves (digging containers)
Performance decline 3: • Housekeeping moves

Table 1: Container moves per hour - concept

5.4 HOUSEKEEPING CONTAINER MOVES

Housekeeping container moves are internal moves inside the stack storage area to optimise stack configuration [6]. They are typically performed , for example, at night-time when the ASCs do not need to do serve external vehicles.

House-keeping moves are typical for testing the ASC performance in performance simulation, since they are completely automatic (no remote operated parts) and the external vehicles do not affect to the performance (no waiting time because of external vehicles). However, in typical configuration of two or more RMGs on the same rails, the ASCs may still have to wait for each other and some idle time is generated.

6 | CRANE PERFORMANCE FACTORS

6.1 TOP SPEEDS AND ACCELERATION RAMP TIMES

The top speeds of gantry, trolley and hoist motions have a significant effect on ASC performance when the distances to be moved are long. End-loaded ASC stack layouts require large amounts of gantry travelling, since each container is input and output to/from the stack via the ends of the stack. Typical end-loaded ASC gantry top speed may be , for example, 5 meters per second. Speed requirements are lower for side-loaded layouts [5].

Hoist lifting speed typically depends on container weight, (this should be specified in KPI measurement). Hoisting containers is typically the slowest part of work cycles. If containers are always lifted to the highest tier before trolley or gantry motion, a significant portion of cycle time is spent on hoisting.

When travelled distances are short, which is typically the case for , for example, trolley motion, acceleration ramps are more significant than top speeds. Trolley speed may not reach a maximum when, for example, shuffling containers from one row to another, (digging up a container located in the bottom of stack).

6.2 OPTIMISED TRAJECTORIES

Cycle times are reduced if trolley, gantry and hoist motions are executed in parallel and "shortest path" trajectories are used.

Typically, trolley travel can be executed in parallel during a long gantry move, however in some cases, the trolley is centered during long gantry moves for balance.

For shuffle moves, it is typical to execute hoist and trolley motion simultaneously if the container stack profile allows this. In this case, the container stack profile must be measured or known with considerable confidence to avoid collisions with stacked containers.

A great cycle time reduction is achieved if containers are not hoisted to the highest tier when, for example, shuffling containers from one row to another.

6.3 DELAYS CAUSED BY AUTOMATION

Theoretically calculated cycle times based on top speeds and ramp times may not be achieved because of various automation related delays in operation. One example is the anti-sway -function which may modify the speed profiles of trolley and gantry to dampen the sway of the spreader and container. There are designs, however, where anti-sway function does not affect to the speed profiles.

Other possible delays are related to the scanning times needed for certain sensors to, for example, locate containers or locate vehicles used for horizontal transport. Scanning may be necessary to form a 3D-data set or filter out noise in raw measurements. Some systems attempt to avoid scanning delays by trusting their internal container inventory at ECS level.

Finally, controlling the position of gantry, trolley and spreader accurately may require slowing speeds more gradually than theoretically required by ramp times. It may also be necessary to perform some slow-speed fine-tuning motion or feedback control near the target positions.

Although not directly caused by ASC automation, it is good to notice also the delays which may be caused by the horizontal transport system imprecisions. Especially, if the horizontal transport is performed by humans, their lack of accuracy when setting containers in, for example, water-side transfer areas may lead to exception handling or even to aborting work instructions.

Theoretical kinematic performance is defined by top speeds and acceleration ramps
Performance improvement 1: Optimized trajectories from A to B (simultaneous trolley, hoist, gantry moves. i.e. "shortest path" moves)
Performance decline 1: Automation delays (sensor scanning times, slow-speed approach, stacking re-tries).

Table 2: Crane performance

6.4 MULTIPLE CRANE SYNCHRONIZATION

When two or more ASC cranes operate on the same tracks, there may be situations where one crane has to wait for the other crane. This happens, for example, when the job order of one crane requires the crane to move to an area that is already occupied by another crane. Situations like this can only be solved by a higher-level block control (typically ECS) that synchronizes the operation of both cranes. A "dead-lock" situation arises, when , for example, two cranes are active at the same time, executing their individual work orders, but are on conflicting routes, so that one of the cranes should "back up" before either of them can finish their job orders. In this case, a block management software, ECS or TOS should decide the optimal execution order of the moves. It is natural that if conflicts like this occur often, the theoretical peak efficiencies of the single ASC cranes are reduced

6.5 REMOTELY OPERATED WORK PHASES

Most ASC operations still include manually remote operated (tele-operated) phases. A typical work phase is the loading of external street trucks, which is both technically challenging and may also include safety risks, because the driver of the street truck stays in close vicinity of the operation.

Since the execution time of a tele-operated work phase depends on the skills and training of the tele-operator, (and even on the behaviour of truck drivers), measuring pure crane performance during this part of the work cycle is challenging. On the other hand, there may be differences in the extent of automation that will accelerate the work of the tele-operator, so it would not be the advisable to entirely exclude these aspects from performance definition.

6.6 ENVIRONMENTAL EFFECTS

Environmental effects like terrain quality, wind and rain may have an effect on both stacking accuracy and cycle times.

Peak performance = Single ASC performance with no idle time
Performance decline 1: • Multiple ASC synchronization in stack (collision avoidance, dead-lock resolution)
Perfromance decline 2: • Synchronization with horizontal transport (i.e. waiting times)
Performance decline 3: • Teleoperated workphases (e.g. landside handling)

Table 3: Crane idle time

6.6.1 STACKING RE-TRIES

Strong winds may slow container stacking operations and force stacking re-tries, before an acceptable stacking accuracy is reached. Typically, a stacking accuracy of +/- 5cm is required. In strong winds, it may not be possible to completely stop the sideways oscillation of the container during hoist down motion. However, after placing the container on top of another container, (spreader still engaged), final accuracy could be verified and decided upon to perform a re-stacking, if needed. In this case, the cycle time will naturally increase.

6.6.2 STACKING ACCURACY

Terrain quality will have an effect on stacking accuracy and thus indirectly to cycle times. Stacking accuracy requirements are often given as the maximum admissible offset between successive containers in the vertical stack. However, there may also be a given offset limit between top and bottom containers. If terrain is not completely level, conflict may arise between these two requirements: on inclined surfaces it is necessary to allow some steps between successive containers, if the overall verticality of the container "tower" is desired (Fig. 6).

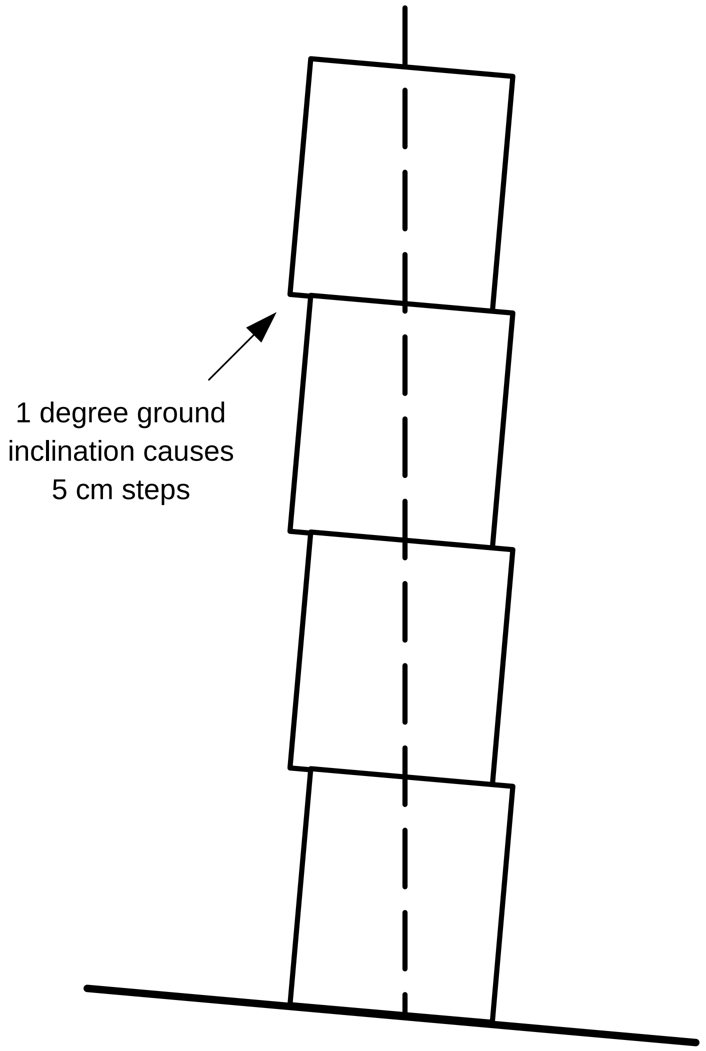


Fig 6. Terrain inclination effect on stacks, when vertical stacking required (inclination heavily exaggerated)

7 | KEY PERFORMANCE INEXES (KPI)

7.1 WHY KPIS?

It would be convenient to use simple numerical indices to define performance because they are easy to compare and their trends are easy to follow. However, over-simplification should be avoided due to the variety of container stacking operations. KPIs are thus more suited for following the trends in a particular operation than comparing two completely different operations.

Key performance indicators define a set of values against which to measure [7]. Some relevant KPI indicators are summarised in the following subsections:

7.2 SPEED AND ACCURACY

Speed, acceleration, and deceleration are typical values that can be easily checked during a performance test. However, to determine the performance of an ASC, it is also necessary to check positioning speeds and stacking accuracy. Stacking accuracy is typically a trade of between fast cycle times and minimum required space between two stacks.

7.3 MOVES PER HOUR

Container moves per hour (per crane or per ASC stack). This KPI is an important parameter to check the logistic concept of the terminal, since it is also affected by ASC stack integration to terminal operations. The concept of a "container move" has to be defined clearly for the KPI. For example, a move could include: 1) moving the empty spreader from its initial position at pick position; 2) picking up a container; 3) moving the container to its target position; 4) opening the twist-locks and raising the empty spreader at a height of, for example, 0.5m. Naturally, average travelling distances (influenced e.g. by transshipment ratio) affect to this KPI. Side-loaded cantilever cranes typically perform more moves per hour than end-loaded ASCs, since there is less gantry movement.

Depending on the type of interchange zone, ASC performance can also vary considerably. Fastest interchanges occur when containers are placed on the ground only, (typically at water-side transfer zone). Truck handling is due to its large variety of trailers more time consuming. This KPI could be split into separate KPIs, for example, for WS moves, LS moves and intra-stack moves.

7.4 CYCLE TIME

Cycle time could be defined as a full work cycle for one ASC crane without external or internal waiting times. Different crane cycles have to be defined and should represent crane use in the stack. These typical cycles should include 1) LS cycles combined with stacking, 2) WS cycles combined with stacking and 3) housekeeping cycles. Waiting times due to blocked transfer zones or other ASCs should be eliminated. The result of the checks of typical crane cycles represent a theoretical capacity of the crane within the stack.

Typical average cycle times are two to three minutes per crane including loading or offloading.

7.5 ASC CAPACITY/ STACK TROUGHPUT

One way to measure performance is to measure the maximum amount of work done in a defined amount of time. In this case, the ASC/ASC stack should be under full load and external waiting times eliminated. This demonstrates e.g. stacking capacity on ship arrival, which is an important factor in determining the number of stacks needed to meet a ship's capacity in a certain amount of time.

7.6 TRUCK SERVICE TIME

Another way to measure performance is to measure the ASC stack response time to an external event, for example, servicing a road truck. "Truck-service-time" could be defined as the total time that the truck is present on LS interchange area, and differs from "truck turn-around-time", which means the entire time a trucker is needed on site, (i.e. the time measured starts when the truck arrives at the terminal and ends when the truck leaves the terminal). To keep the truck service time and truck turn-around time low, a proper truck management is needed. Both KPIs are thus strongly linked to TOS configuration and yard strategy. Typical truck turn-around times in terminal are 30 to 45 minutes.

7.7 MMBF AND MTBF

MMBF = "Mean Moves Between Failure". MTBF = "Mean Time Between Failure". Both KPIs are representing typical reliability data. Where MMBF is taking the move as a measurement element, the MTBF is time orientated only. For practical reasons, it is recommended to use the MMBF measurement in a container terminal, since the usage of the cranes may vary significantly. MMBF could be calculated as an average over one month.

A failure should be defined clearly for this KPI. It could be defined, for example, as an event that causes a stop of the crane, excluding third party impacts, external factors, (for example, damaged containers, containers displaced by wind, wind speeds greater than specification), incorrect operation and such exceptions to remote operator that could be safely handled and reset without maintenance actions.

Furthermore, success rates (%) for automated WS and LS handling could be defined separately as KPIs, as they affect OPEX, (number of remote operators needed per shift).

A ramp up curve in MMBF is typical: for example, first month MMBF 500, after three months MMBF 1000 and so on. Today MMBF 2000 is common practice.

It is essential to monitor MMBF values as trends reveal, for example, poor maintenance and the service life of components. To evaluate MMBF values properly, knowledge of the entire equipment and measurement process is required.

7.8 AVAILABILITY

Equipment availability is essential in a container terminal. Availability can be defined according to ISO 11994:1997 or more practical as the crane ready to use (excluding planned stops such as maintenance) in ratio to the time of the crane where it is supposed to be in operation. Typical availability rates are 98 per cent.

8 | PERFORMANCE DEFINED BY SIMULATED SCENARIOS

8.1 WHY SCENARIOS?

Due to the large spectrum of different operations and moves in an ASC stack, it may be difficult to describe ASC stack performance with simple measures (KPIs) only. Predetermined scenarios are therefore often defined by given job-order lists of container moves. The performance of ASC or complete ASC stack is then defined based on, for example, the time needed to perform the scenario. It is typical that these scenarios are to be simulated by the equipment provider using a crane model as realistic as possible. After the installation of the site, these simulations are to be proven by field tests, i.e. to show that the simulation model was realistic.

8.2 MISSION TIME AS BENCHMARK

In case a job-list of container moves is given and there are no external timing constraints, the total time needed to execute the job-order list may be used as a performance criteria for ASC or ASC block. Alternatively, it may be sufficient to execute the given work-order list within a given time. Many factors affect the mission time, for example, how much decision freedom is given to the ASC cranes or Equipment Control System (ECS).

8.3 SIMULATION MODEL OF THE CRANE

A realistic simulation model shall first implement the crane dimensions, top speeds and acceleration and deceleration ramps. Any additional delays caused by, for example, sensor scanning times and automation shall also be modelled. When simulating several cranes on the same tracks, collisions of any parts of the cranes should be detected to avoid unrealistic simulations where the cranes could occupy the same space. It is typically necessary to include the ECS (Equipment Control System) also in simulation to model the delays caused by, for example, multi-crane coordination and dead-lock resolution. A simulation model normally does not include exception handling, since exceptions are typically random in nature.

8.4 FIELD TESTING

Field testing is typically used to verify simulated results and verify e.g. stacking accuracy. To be able to verify the simulated result, it is important that the scenarios are repeatable with real equipment. As an example, the scenario should then include a limited number of individual containers and horizontal transport vehicles.

8.5 SINGLE ASC SIMULATION

Single ASC simulation enables the ASC to operate with 100 per cent duty cycle (at least if horizontal transport is excluded), since the ASC does not have to synchronize with other ASCs, i.e. there is no idle waiting time. If the container move order in the job list is predetermined and fixed, then this kind of simulation is a "brute force" performance simulation with no testing of optimisation algorithms.

8.6 ASC STACK SIMULATION

Simulation of ASC stack with two or more ASCs brings more complexity to simulation, since the ASCs need to synchronize together to avoid collisions. Some idle times for ASCs are thus unavoidable. This kind of simulation will also test the low-level optimisation performance of the ECS, since the amount of idle time per crane depends on the logic of the ECS software. If synchronized horizontal transport is included in the simulation, more waiting times for ASCs are generated.

8.7 SIMULATION DEFINITION

The following chapters describe the necessary information to be provided as basis for a well-defined simulation scenario.

8.7.1 INITIAL STATE OF THE STACK

Each simulation shall start with a clear definition of stack initial state, i.e. the container population of the stack, including exchange areas: number of stacked containers in each container slot along with the lengths, heights and weights of the containers. The initial locations of the cranes shall be defined.

8.7.2 WORK-ORDER LIST DESCRIPTION

A specified work list is often given to simulate crane performance without TOS software. Alternatively, "on-line" work order sequencing during the scenario could be done by "TOS emulation".

The work order list shall be defined by giving the pick- and place positions for each container. Pick- and place-positons could either be inside the stack or in exchange areas. Pick- or place position in an exchange area could be ground slots or rack positions, but could also involve e.g. an AGV, which is located on that position.

When the container to be picked is under other containers, "shuffle" moves are required. Shuffle moves are typically also included in the job list (however not mandatory).

The order of the container moves may be specified, however in this case it is important that the top container in the job list is always moved before the containers under the top container. If the order of the container moves is not fixed, some other parameters like "priority", "latest finish time", "earliest start time" may be assigned to a job in the list.

Finally, the crane id executing the move could be specified, or alternatively it could be left open.

8.7.3 EXTERNAL EVENTS DURING SCENARIO

Performance simulations are frequently conducted without external events that require synchronization, (for example, only using housekeeping moves or buffer areas for feeding in new containers and delivering containers out). Typical external events that require synchronization are , for example, road trucks, which need to be served in a given time frame. If such external events are included, it is advisable to allow freedom for the ECS layer for job order and crane selection, since it is difficult to predict in advance how the simulation is proceeding and thus select the job order or crane accordingly.

8.7.4 FORCED OR FREE WORK ORDER SEQUENCE

Optimal sequencing of container moves is a mathematically "sensitive" problem, where one single sequencing change can entirely alter the subsequent optimal sequence. Fixing the order of the moves in the work list by definition could thus degrade the best possible performance of the ASC stack.

When stacking containers on top of each other, the work order of those containers is implicitly defined, (without explicit ordering).

8.7.5 FORCED OR FREE CRANE SELECTION

As stated before, optimal sequencing of container moves is a mathematically "sensitive" problem, thus fixing the crane selection for a particular move in the work list may also degrade the best possible ASC stack performance.

8.8 PERFORMANCE DOCUMENTATION

At the least, simulation documentation should include the actual order of performed moves with start and finishing times for each crane. Idle times are documented along with the reason for idle time. Graphical presentation of the gantry, trolley and hoist trajectories may be required.

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APPENDIX 1: A SIMULATED TEST SCENARIO EXAMPLE

A small part of a simulated test scenario is shown here as an example. In this scenario, there are two RMG cranes on the same tracks. Crane 1 services land-side trucks and crane 2 services water-side. The horizontal transport system on the water-side is straddle carriers, so containers on water-side transfer zone are picked and placed on ground slots. The moves are numbered in the first column. However, the actual order of the moves is given in the second column. Please note that since there are two cranes operating in parallel, an explicit move order specification, especially between the cranes may slow down the operation since in many cases this is not necessary. On the other hand, the move order is often implicitly defined, for example, when "digging" containers.

The crane number to perform the move is optionally given, but often implicitly defined, for example, when handling containers in transfer zones. The moves are specified by giving the "From-slot" (the pick position) and the "To-slot" (the place position). The following naming convention is used in this example:

- ST: a storage slot in the stacking area
- LS: a transfer slot on the land-side truck handling area.
- WS: a transfer slot on the water-side exchange area.

The ST/LS/WS-indicator is followed by the bay-row-height index of the storage slot in this order. The index numbering is according to 20-foot size container slots. For 40-foot containers the container occupies also the next higher bay index.

- Different move types are demonstrated in this example, although not typically executed in parallel:
- Moves from truck into the stack.
- Moves from stack to truck, including also some necessary shuffle moves.
- Moves from water-side exchange into the stack.
- Moves from the stack to water-side exchange area.House-keeping moves for the containers that travel "through" the stack. (Transshipment container do not travel through the stack)

The total number of moves in this kind of test scenario is typically several hundred.

Move number	Sequence number (optional)	Container id	Container size	Weight	Crane number (optional)	From-slot	To-slot	Note
1	1	c1	20	2.0t	1	LS-02	ST-35-07-02	From truck to stack
2	3	c2	40	10.0t	1	LS-04	ST-38-09-01	From truck to stack
3	5	c3	40	10.0t	1	ST-20-01-02	ST-20-05-03	Shuffle move
4	7	c4	40	4.0t	1	ST-20-01-01	LS-01	From stack to truck (remote operated phase assumed constant duration)
5	9	c5	20	2.0t	1	ST-13-03-04	ST-13-04-02	Shuffle move
6	11	c6	40	10.0t	1	ST-13-03-03	ST-13-04-03	Shuffle move
7	13	c7	40	4.0t	1	ST-13-03-02	LS-03	From stack to truck (remote operated phase assumed constant duration)
8	15	c2	40	10.t	1	ST-38-09-01	ST-12-03-01	House-keeping
9	17	c1	20	2.0t	1	ST-35-07-02	ST-13-02-02	House-keeping
10	2	c8	20	2.0t	2	WS-01-01	ST-10-07-02	Waterside to stack (transshipment)
11	4	c9	40	10.0t	2	WS-04-01	ST-4-04-01	Waterside to stack
12	6	c10	20	2.0t	2	ST-09-04-02	ST-09-05-03	Shuffle move
13	8	c11	40	10.0t	2	ST-09-04-01	WS-07-01	From stack to waterside ground slot (SC horizontal transport)
14	10	c12	40	4.0t	2	ST-11-04-03	ST-11-05-02	Shuffle move
15	12	c13	20	2.0t	2	ST-11-04-02	ST-11-05-03	Shuffle move
16	14	c14	40	10.0t	2	ST-11-04-01	WS-03-03	From stack to waterside ground slot (SC horizontal transport)
17	16	c9	40	10.0t	2	ST-4-04-01	ST-30-07-01	House-keeping

APPENDIX 2: DOCUMENT TERMINOLOGY[1]

AGV	Abbreviation for automated guided vehicle, a robotic vehicle for horizontal transport of containers between quay and yard
ASC	Abbreviation for automated stacking crane, a driverless gantry crane (in this document either rail mounted or rubber tyred) for container yard handling operations
AShC	Abbreviation for automated shuttle carrier, a driverless 1-over-1 straddle carrier (ShC) for horizontal transport of containers between yard and quay
AutoSC	Abbreviation for automated straddle carrier, a driverless straddle carrier (SC) for transporting and stacking containers in terminals
ARMG	Abbreviation for automated rail mounted gantry crane (RMG)
ARTG	Abbreviation for automated rubber tyred gantry crane (RTG)
CARMG	Abbreviation for side-loading cantilever automated stacking crane, an ARMG designed for operation in stacking blocks laid out parallel to the quay
DGPS	Abbreviation for differential global positioning system, a technology for automated identification and tracking
ITV	Abbreviation for internal transport vehicle, a generic term denoting vehicles used for container transport within terminals
OCR	Abbreviation for optical character recognition, a technology for automated identification and tracking
OHBC	Abbreviation for overhead bridge crane
PDS	Abbreviation for position detection system, a system for automatically detecting container and crane location in the yard stacks
QC	Abbreviation for quay crane, also known as ship-to-shore crane, a type of crane for moving containers between ships and terminal berths
RFID	Abbreviation for radio frequency identification, a technology for automated identification and tracking
RTLS	Abbreviation for real time locating system, a solution for determining RFID tag location by triangulation
RMG	Abbreviation for rail mounted gantry crane
RTG	Abbreviation for rubber tyred gantry crane
ShC	Abbreviation for shuttle carrier, a 1-over-1 straddle carrier designed for horizontal transport of containers between yard and quay
SC	Abbreviation for straddle carrier, a type of equipment for transporting and stacking containers in terminals
TOS	Abbreviation for terminal operating system, specialist software used to plan and manage container terminal operations
Note 1:	Other terminology also exists on the market

ABOUT THE AUTHORS & PEMA

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