The throughput capacity of most container terminals is determined by the throughput capacity of their container yards (CY), with the latter expressed by the formula:

**Throughput Yard Capacity (TEU/Year)**

\[
\text{Throughput Yard Capacity (TEU/Year)} = \text{Static Yard Capacity (TEU)} \times \frac{1}{\text{Dwell Time (day)}} \times 365
\]

With,

\[
\text{Static Yard Capacity (TEU)} = \text{Yard Area (ha)} \times \text{Storage Density (TEU/ha)}
\]

Accordingly, increasing static (holding) yard capacity mandates increasing yard area and/or storage density. Many ports in the era of big ships suffer from a shortage in developable waterfront area. To increase their terminal capacity then, they need to increase the storage density of their CYs – the subject of this paper.

**HIGH BAY SYSTEM (HBS)**

Increasing CY’s storage density, or densification, is also the prime objective of a highly innovative technology developed by High Bay System (HBS) [2, 3]; HBS’ second objective is increasing CY’s waterside productivity. The new system consists of three components: (a) An Automatic Storage & Retrieval System (ASRS), based on an 11-high, 50-metre rack structure, and automated 35-ton stacker cranes serving the waterside operations, or ship handling; (b) Automated Rail-Mounted Gantry (ARMG) cranes serving the landside operations, or truck handling; and (c) An internal, subterrain, rail-based horizontal transport system, connecting the stacker cranes and ARMGs. A potential expansion, not discussed here, includes a second set of ARMGs on the waterside for ship handling. ASRS common use is for cargoes that are not self-stackable and require covered storage, such as palletized cargo. HBS’ novelty is expanding the application of ASRS to marine containers that are self-stackable and do not require covered storage.

HBS’ main claim is an increase in CY’s storage density by 300% relative to common, manual Strad and RTG-based CYs; its secondary claim is an increase in waterside productivity, achieving 200 moves an hour per ship, or a total of 400 moves an hour when serving two ships. My intention in this short paper is to compare HBS with present CY’s storage systems in terms of density and productivity, examine its overall applicability, and comment on its prospects to ‘disrupt’ the container terminal industry.
The factor assumed for present yard re-handling (shuffling, shifting, digging) leaving empty slots in order to minimize factor reflects a common practice of calculation of module density for HBS. The upper section of Table 1 shows my calculation of relative storage density (%), taken from footnoted papers. HBS’ calculation is based on a detailed analysis of terminal layouts and operational simulations. There is a high correlation between HBS’ and my results for present Common ASCs and c-ARMGs. This correlation indicates that my admittedly rough method could be applied to compare HBS with future so-called Density ASCs and c-ARMGs.

DEVALUATION OF SELECTIVITY
The stacking height of marine containers is limited by the 192-ton overall stack weight, equivalent to six boxes laden to their maximum weight of about 30 tons. The actual stacks of boxes in ships and CYs can reach much higher since boxes are rarely laden to their maximum weight and some are empty. For example, the stowage plan of Maersk’s Triple E vessels (18,000 TEU) allows 11-high below deck and 10-high above deck. The future MSX24 vessels (24,000 TEU) are based on 12-high below deck and 12-high above deck. The CY stacks of Singapore’s Pasir Panjang (PPT1), based on overhead cranes, are 10-high. In contrast, present CY stacks served by Common ASCs and c-ARMGs, as shown in Figure 1, are only 5-high. The main reason for not going higher with present CY cranes is the concern of rapid decline in selectivity level resulting in respective increase in re-handling.

A high level of selectivity is not required, however, if boxes can be stored in “blocks”, meaning that the order in which they are stored and later on retrieved is not important. Block storage of import boxes is possible when a large chunk of them is destined to a single importer, usually a large shipper which has a large storage capacity at its warehouse. Following recent market concentration trends, the number of large shippers is on the rise. For example, in 2018, four US shippers, Walmart, Target, The Home Depot, and Lowe’s, collectively imported 2.3 million TEU, accounting for about 10% of total US imports. On some occasions, Walmart alone is reported to bring in several hundred boxes per ship-call. Block storage is common for rail-bound boxes, with blocks arranged accordingly to hinterland destination points. Block storage is also common for empty containers, with blocks arranged according to shipping lines, size and type. Stacks of empty boxes already reach 8-high when served by specially-fitted,
high-mast lift trucks (empty handler) and 15-high when served by overhead cranes. Selectivity is less critical for export boxes, since a ship’s stowage plan is prepared well in advance of a call, so boxes can be arranged according to their expected handling sequence.

Recent developments in TOS and truck appointment systems also allow for “intelligent” CY stowage plan to reduce shuffling for both import and export boxes. The most important development, however, is “peel-off” operations, a growing trend in US West Coast ports, which involves the storage of import boxes in temporary blocks immediately upon their discharge from a ship, after which they are sent en-block to nearby, off-dock CYs. The cost of re-handling in automated CYs is a fraction of that in manual CYs, especially the cost of “house-keeping”, a planned, total re-organization of stacks intended to minimize re-handling and shorten cranes’ service cycle. House-keeping is usually performed during night shifts, when the demand for landside operations is low. In manual CYs, ordering labour for night shifts is very costly, which is not the case in labour-less, automated yards. Altogether, the growing trends of block storage, peel-off operation, intelligent stowage planning and low-cost house-keeping suggest that storage selectivity is becoming substantially less important than in the past. The “devaluation of selectivity” is bound to trigger the deployment of denser versions of the present Common ASCs and c-ARMGs in the near future (5 – 10 years).

**DENSITY OF HBS VS. FUTURE YARD CRANES**

Figure 1 shows in its lower portion cross sections of Common ASCs and c-ARMGs, and in its upper portion Density ASCs and c-ARMGs. In Density ASCs, the stack width is increased from 8 to 11, one row wider than DP World’s London Gateway, and the height from 5 to 7, similar to COSCO/APMT’s Vado Gateway Terminal. In Density c-ARMGs, the width is increased from 12 to 14, similar to Haifa’s Carmel Terminal and the height from 5 to 8. The higher stack height considered for c-ARMGs is because the larger width allows more opportunities for placing re-handled boxes without resorting to traveling. Another way of increasing density without increasing stack height is to increase the width of future ASCs and c-ARMGs to 12 and 16 respectively.

The proposed increases in height and width of Density ASCs and c-ARMGs above are modest, but their impact on storage density is quite dramatic. The rightmost two columns of Table 1 indicate that HBS’s impressive density advantage of 300% over manual RTGs, and 200% over common ASCs and c-ARMGs, shrinks to a modest 30% over Density ASCs and c-ARMGs. Another problem of HBS, not elaborated here, is the substantial increase in travelling distance of shuttle Strads relative to perpendicular ASCs.

To recap, HBS’s main claim of a 300% increase in storage density relative to manual Strads and RTGs, as highlighted at the opening of this paper, is factually correct – but irrelevant. Conventional Strads and RTG terminals seeking to densify their CYs are likely to compare HBS to denser, automated yard systems expected in the near future, where HBS’s advantage is probably only around 30%. Likewise, terminals already operating ASCs and c-ARMGs seeking densification are likely to first raise legs of existing cranes and, eventually, consider replacing them with denser versions.

**HBS’ WATERSIDE PRODUCTIVITY**

The discussion thus far has only addressed HBS’s main component, the 11-high ASRS and its impact on storage density. Let’s turn now to HBS’ second and third components: ARMGs for landside operations and the internal rail transport system, connecting ARMGs to the ASRS. HBS claims that the unique, 3-component combination can produce waterside productivity of 200 moves an hour per ship, while not hurting landside productivity. However, such a level of productivity is within reach of existing yard systems by increasing the number of cranes and horizontal transport vehicles, and...
allocating them to serve the waterside. This is relatively simple with side-loaders and parallel stacks; with end-loaders it is a bit more complicated, requiring conversion to parallel stacks (Vado), or adding a third crane per block (HHLA/CTB). A Port Technology paper [4] summarizes a comprehensive simulation study on the performance of ASCs and ARMGs, demonstrating that 200 moves an hour per ship, or a total of 600 moves an hour for three ships, is achievable.

**HBS APPLICABILITY**
The foregoing discussion suggests that: (a) HBS has a modest advantage in storage-density relative to future Denser ASCs and c-RMGs; and (b) HBS has a limited or no advantage in waterside-productivity. In addition, HBS’s complicated system, based on 3-interrelated components, might have problems in coordination and reliability. Accordingly, I doubt that HBS would be a ‘disruptive’ technology ‘revolutionizing global port logistics’. HBS would probably be more of a niche technology applicable in special port situations, whereby even a modest increase in storage density is of critical importance.

I also doubt that Jebel Ali Terminal 4, where the first HBS is planned to be in operation by 2020, would fit the above definition of “special port situation”. First, transshipment, which HBS is not designed to handle, consists of about 50% of Jebel Ali’s traffic. Second, as illustrated in Figure 2, Terminal 4 appears to have ample expansion area, including additional waterfront land that can be acquired by low-cost reclamation.

**SHORT VS. LONG-TERM SOLUTIONS**
CY densification, either by using HBS or future and denser versions of existing yard systems, can do only so much for terminal capacity and therefore can only provide a short-term solution to the growing shortage in waterfront land. A long-term solution has to focus on the second term in the capacity formula presented at this paper’s outset: dwell time. A radical reduction in dwell time can be achieved by re-arranging the entire port system: detaching the waterside, ship handling operations from the landside, truck and rail handling operations. My vision of the re-arranged port system of the future will be the subject of a sequel paper.

**REFERENCES**
[1] The author would like to thank Frank Kho, formerly VP of Kalmar Global and presently Independent Consultant, for his insightful contribution.

[2] “BoxBay: The Future is Vertical”, PTI: Edition 84; and “DP World’s Terminal of the Future”, PTI, 16 April, 2019

[3] A previous, dolly-based, 7-high ASRS, designed by JFE Engineering and in operation since 2011 in Oi Pier, Tokyo, is not discussed here because of its relatively-low storage density. (See: https://www.jfe-holdings.co.jp/cgi-bin/jfe-eng/contact2.php)


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