Container Terminal Automation: Assessment of Drivers and Benefits

Geraldine Knatz 1 , Theo Notteboom 2,3,4, Athanasios A. Pallis5*

1 USC Sol Price School of Public Policy, USC Viterbi School of Engineering, University of Southern California; knatz@usc.edu
2 Maritime Institute, Faculty of Law and Criminology, Ghent University, Belgium; theo.notteboom@ugent.be
3 Faculty of Sciences, Antwerp Maritime Academy, Belgium
4 Faculty of Business and Economics, University of Antwerp, Belgium
5 Department of Maritime Studies, University of Piraeus, Greece; apallis@unipi.gr

(*) Corresponding author

Geraldine Knatz ORCID No: 0000-0001-8966-5102
Theo Notteboom: ORCID No: 0000-0003-1203-2571
Athanasios A. Pallis ORCID No: 0000-0003-3242-5081

ABSTRACT

This study identifies and analyzes the relative importance of the multi-faceted factors that drive the decision to automate container terminals and the realized benefits, thus establishing how accurately terminal operators predicted the benefits of automation. The empirical analysis relies on a survey-based approach and the input of senior representatives of terminal operating entities in charge of the fully and semi-automated container terminals. The analysis of the findings, using statistical tools (i.e., descriptive statistics, Pearson correlations, ANOVA, Kruskal-Wallis), reveals that most of the benefits assumed by an individual terminal operator materialized once the automated terminal was in operation. It also concludes that expectations often exceed benefits and *vice versa.* A stepwise regression analysis enables the search of causal relationships between and realized benefits with key characteristics of automated container terminals, such as their organizational features, technical dimensions, and the maritime and urban markets they serve.

1 INTRODUCTION

Three decades ago, in 1993, the first automated container port terminal opened at Maasvlakte 1 in Rotterdam. Seven more automated container terminals were in operation when the global financial crisis of 2008/9 hit the port industry. Since then, and especially since 2012, there has been a push towards automation, with ports seeking to take advantage of technological advancements and improve their competitiveness. A distinction can be made between fully-automated and semi-automated container terminals. In line with earlier works (cf. Drewry 2018; McKinsey, 2018; Moody’s 2019;

Rodrigue and Notteboom 2021), a semi-automated terminal has manned vehicles to move the containers from the berth to the yard with automated stacking equipment. A fully-automated terminal is a terminal where both the horizontal movement of containers from the berth to the yard and the vertical movement of containers in the yard is automated (unmanned). Today the number of semi- and fully-automated ports around the world is considerable and growing. At the end of 2021, 63 fully or partially (semi) automated container terminals were identified worldwide, with 62 operating by early 2022 (see Knatz et al., 2022 for a full list).

Compared to the 1,300 full container terminal facilities worldwide (Drewry 2018), container terminal automation remains the exception; leading scholars to the conclusion that '*despite the wave of investments in automation, the port industry remains conservative to structural modifications*" (Ghiara & Tei, 2021, p. 717). Automation is a capital-intensive and complex process that takes place at different scales, paces, and locations. Temporal, institutional and spatial factors might play a role in the decision to automate, next to more operational and economic drivers. The same factors, or others, might undermine the benefits realized by implementing automation.

Complementing studies that have reported on the progressive global spread of terminal automation and listed some of the drivers of the ongoing spread (Section 2), this research provides an in-depth analysis of the drivers of the decision to automate a container terminal, the realized benefits, and the associated gaps between the respective drivers and benefits. It also reveals the variations of the relative importance of these factors (drivers and realized benefits) among terminals based on their organizational features, technical dimensions, and the maritime and urban markets they serve.

The first step was the review of the related literature on container terminals. This review provides a list of the expected benefits and, thus, drivers toward automation. It will be demonstrated that extant literature does not provide insights on the relative importance of the identified drivers from a terminal operator's managerial perspective. Notably, the empirical analysis and discussion of the relevant managerial perspectives have been absent. In the second step, the actual relevance of the potential drivers is tested following a survey-based approach targeting senior representatives of companies operating automated terminals. This survey has secured input from 32 fully-automated container terminals. The survey results allow for establishing how accurately terminal operators predicted the benefits of automation once the terminal automation was in operation. This "within terminal" analysis is key to answering whether the benefits assumed by an individual terminal operator materialized once the automated terminal is in operation.

An analysis focusing on the gap between drivers (benefits expected) and benefits realized, adds an additional layer to the survey findings. Descriptive statistics and statistical tests are applied to reveal any regional differences in terminal automation processes and attitudes, as well as of differences between fully-automated and semi-automated terminals. A stepwise regression analysis is applied to identify correlations between a set of terminal features and drivers or benefits of automation.

As highlighted in the concluding section, the analysis shows the most important drivers to automate include *increased safety*, *reducing the unit cost of container handling, reducing variabilities in* *performance,* and reducing *labor costs*. The findings also reveal several correlations between specific drivers (i.e., between drivers related to cost and performance), variances between drivers of semi-automation and those of full automation, and some regional differences in terminal operators' perspectives. Terminal managers typically overestimate the potential *reduction of the unit costs of container handling*, and *air/GHG emissions* and underestimate the benefits of automation on *increasing land productivity* and *improving truck turn time.* Beyond informing future managerial decisions, the findings of this first-of-its-kind study of a managerial perspective to terminal automation deepen our understanding of the drivers and benefits of terminal automation. This study also paves the way for future extended analyses as automation, which is fairly new in practice, expands in other terminals.

2 DRIVERS AND PERCEIVED BENEFITS OF AUTOMATION: A LITERATURE REVIEW

The decision to automate usually results from a complex interplay between multiple possible drivers (expected benefits) and realized benefits. Scholars examining business process redesigns related to the technology domain call for studies about the specific implications of the adoption of automation technologies on seaports (see: Ferretti and Schiavon, 2016). Extant literature on terminal automation refers to a wide array of possible factors influencing the decision to automate. The identification and review of potential drivers of terminal automation most commonly referred to in previous studies form the basis of this research and a key input for the drafting of a survey among terminal managers (see section 3 on methodology). The potential drivers are summarized in Table 1 and are discussed in detail by each driver category. Notably, this discussion uncovers the ambiguity of existing studies as regards the actual benefits of automation, and their potential as drivers for automation. In this context, the present study offers an integrated examination of all potential benefits of automation and the managerial perspectives of the relative importance and hierarchy of these benefits as potential drivers towards container terminal automation.

Insert: Table 1. Potential Drivers Towards Container Terminal Automation: A Literature review

2.1 Increase operational efficiency

Automated terminals purport to be more productive and lead to increased quay use and yard densities, resulting in better use of available space and improved facility capacity (Monfort-Mulinas 2012). Kon et al. (2020) suggest that automated container terminal technology could increase terminal efficiency and productivity, leading to cost reduction and improving environmental sustainability. According to a survey by Navis, most terminal operators expect productivity increases between 25 and 50% when opting for automation (Port Technology International, 2018). The operational efficiency gains would mainly result from eliminating uncertainty and more organized and methodological operations (Martin-Soberon et al. 2014). Wang et al (2019) note that terminals expect to benefit from the speed and reliability of operations (i.e. improved truck time) brought by automation (also: Yang and Shen, 2013). Thus, automation could improve workforce safety, ensure business continuity in port and terminal operation processes and vessel visits, and reduce processing times (ITF 2021).

Terminal productivity figures are generally not publicly available. Anecdotal evidence presented by terminal operators, equipment manufacturers, and relevant trade press suggests that automation might present better terminal productivity figures than manual terminals in some cases, while in others, traditional terminals still outperform automated terminals such as in net crane productivity. For example, initial performance data for the TraPac automated terminal in Los Angeles had planned targets of 27 moves per hour for ship to shore cranes but only achieved 20 moves per hour. Additional equipment was anticipated to improve this performance (Moody's, 2019). McKinsey (2017) concluded that, for a specific sample of automated ports, the productivity is 7 to 15% lower than conventional terminals. Ghiara and Tei (2021) found that automation has a reduced impact on the overall terminal productivity, advocating that automation alone cannot be considered to have a highly significant impact on port terminal performance but should always be linked to the general port context. Harsh outdoor conditions, poor information availability and accuracy, and a high degree of dynamics in vessel arrival times make productivity improvements through automation more difficult to achieve than in factory or warehouse environments (Miller, 2017). Limited information exchanges between supply chain actors (terminal operators, shippers, logistics service providers, and carriers) or bad/faulty information reduce operational productivity and increase overall handling costs, leading to a high level of avoidable re-handles in the yard.

The trade press provides some indications on the performance profile of automated vs. conventional terminals. For example, APM Terminals in Rotterdam declared that their fully-automated container terminal at Maasvlakte 2 did not reach the productivity level of the older conventional facility at Maasvlakte 1 (sold to Hutchison Ports in mid-2021). APM Terminals argued the Maasvlakte 2 facility was too small to fully reap the benefits automation can bring as "[*T]he high degree of automation only comes into its own when large volumes can be rotated, and these are insufficient at this time. Sometimes, processes are still carried out manually, which should actually be automated. If the terminal is expanded, with the same staffing, more volume is processed, and productivity goes to the intended level*" (Mackor, 2021). The specific facility will be expanded from 86 hectares in 2021 to 180 hectares by 2026. A terminal manager, who preferred to remain anonymous, revealed that fully-automated quay cranes with operators who sit in a remote-control room have cycle times that are 20 to 30% longer than manned ship-to-shore cranes.

Davidson (2016) argues that the actual operational efficiency gains of automation do not lie in the field of faster handling. It is more about achieving stability, predictability, and consistency of operational performance, which reduces downtime due to external factors (e.g., weather conditions) and allows continuous operations. Such operational conditions are easier to achieve when the cargo demand at the given terminal is consistent throughout the year, and only standardized boxes are used (thus, no open-top containers or oversized cargo units). When no ship is berthed at the terminal, the equipment can be used for other activities such as the reshuffling/restacking of containers or loading/discharging inland transport modes. Along the same lines, Martin-Soberon et al. (2014) point to the loss of flexibility linked to the standardization of automation processes. In other words, automated terminals have difficulties dealing with unique scenarios and exceptions, such as open top containers or non-standard container weights. When these exceptions occur, manual intervention is usually required, thus interrupting normal operations at the automated facility.

Existing literature is not clear on the productivity gains brought by **automation on the landside**. Supply chain disruptions at Los Angeles/Long Beach ports during 2021 indicate how landside constraints, such as insufficient warehousing, which drastically increased container dwell time and chassis street time, can undermine the efficient operations at the port terminals. For an automated terminal to achieve its fullest potential, the entire supply chain must have a certain level of reliability and efficiency to make the investment in automation worthwhile.

A last operational efficiency driver relates to improved **land productivity**. Commonly used yard automation configurations are assumed to result in denser yard stacking. The primary land productivity gains associated with automation are not necessarily related to the equipment itself , but rather the result of the implementation of associated IT systems leading to more efficient use of the stacks (i.e., higher utilization degree of available slots) and a more efficient container flow throughout the terminal system. Still, automation might bring significant land productivity gains in terminal retrofitting or reconversion, improving safety, security and environmental sustainability.

2.2 Reduce cost

Automation is often claimed to reduce generalized costs of terminal operations per unit handled. McKinsey (2017) concluded that automation could cut operating expenses (OPEX) by 25 to 55%. However, not all automation projects might realize savings in overall costs. Oliveira and Varela (2017) concluded that the reductions in handling costs are likely to be lower than expected. If a high degree of repetition and predictability and low volatility in cargo volumes cannot be achieved, the cargo handling cost per unit increases above conventional container terminals. As more knowledge and expertise are available, automation costs are being driven down, reducing risks and increasing benefits. Still, realizing cost savings through automation remains a challenge for at least four reasons.

First, automation requires *high up-front capital investments* (CAPEX) in rather new technologies and involves large bespoke and customized terminal capacities that lack flexibility. Once fixed, the layout is challenging to change. Therefore, automated terminals carry greater risk and are harder to implement than traditional container terminals, which have been tested and improved over many decades. This uncertainty could imply that the expected cost savings per unit handled are not fully realized.

Another factor that could weigh on the possibility of realizing cost savings per unit handled is the *complex interaction between different – potentially untested - technologies*. Terminal automation requires advanced approaches to integrated scheduling of handling equipment (Lau and Zhao 2008) to optimize and synchronize the quay, intra-terminal transport, yard, and gate operations (cf. Stahlbock and Voß 2008; Sha et al. 2021). Also, when an existing conventional terminal is retrofitted to an automated terminal, the *operational complications during the transition phase* could negatively affect the potential to realize cost savings. Upgrading a operating conventional terminal to an automated facility can be quite painstaking. The operator will temporarily have to give up some of its terminal capacity (and thus revenue generation) and will face running two systems (automated and conventional) concomitantly in the transition period.

Among the terminal operating costs, high direct labor costs (i.e., wages, bonuses, benefits) can be a driver for automation. Even in the capital-intensive container handling industry, the share of dock labor costs in total operating costs of a conventional terminal can be as high as 50% (Notteboom, 2018). Automation typically results in lower labor costs (PEMA, 2016). It also reduces the uncertainty that manual labor can bring. Risks such as the availability of dockworkers and labor actions are some of the factors that can bring uncertainty and can have detrimental long-term effects on a terminal's reputation. For example, the recent global COVID pandemic impacted the availability of the workforce at many terminals around the world (Notteboom and Pallis, 2021; Notteboom et al. 2022b). Elimination of human factors is a consideration in the automation of terminals and may become more important in the future as a result of the global pandemic. In some cases, local governance practices in terms of regulation and labor unions complicate the automation path to such an extent that a risk-averse terminal operator instead opts for the status quo.[1] An unmanned operation also avoids idle time caused by breaks and shift changes. ITF (2021) claims that terminal automation attractiveness depends on the local labor costs (i.e., low labor costs mean fewer financial incentives to automate) and the terminal profile (i.e., terminals that face a relatively stable market with guaranteed throughput volume would be more suitable for high levels of automation). Thus, there might be a robust regional dimension at play. Automated operations might provide one way to counter the high price of labor in the U.S., Europe, and Australia, with unions having various degrees of impact on decisions to automate. In many developing countries, where most new terminals are being constructed, dockworker wages are relatively low. Chinese terminals face a high worker turnover, which implies that automation can be a way to avoid having to invest in skill development of dockworkers who, on average, do not stay long with the terminal operating company. Nonetheless, the fact that some inter-regional differences in labor conditions and costs exist does not imply that all ports in a region follow the same logic when it comes to automation.

The willingness of terminal operators to invest in automation is partly related to the expected cost savings at the level of dock labor (Notteboom and Vitellaro, 2019). If automation allows reducing gang labor (or, in the case of full automation, even eliminating it), then the terminal operator will only benefit from the labor cost savings if the gangs are indeed reduced in number and/or size. If this reduction is not possible within the contours of the existing dock labor employment system, then the stevedoring company may be far less eager to introduce technological innovation.

2.3 Enhance safety and security

Automation can improve safety and security, particularly if automation results in increased density and productivity in the yard and quayside.

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[1] An example of these trade-offs surfaced in a dispute between labor unions and APMT, with several weeks of labor union action at APMT terminals in Rotterdam in 2013 before a compromise and the opening of the APMT terminal at Maasvlakte 2 that features remotely controlled ship-to-shore cranes. In another example of dockworkers trying to obtain a fair share of the benefits that can result when new technology is adopted, carriers calling at US ports manned by ILA members (east coast and gulf ports) pay royalties to ILA workers based on the tons of container cargo that move through the port, and, more than once, the pay-out amount formed a cornerstone in a social dialogue between dockworkers and port operators (see: Scheyder, 2013).

Concerning the safety issue, a fundamental safety challenge in container terminals is that accidents can be extremely serious due to the heavy equipment and large workloads involved. Unmanned terminal equipment requires fewer dockworkers and, thus a lower overall exposure to safety risks and human error. Risks are not eliminated, as one of the main sources of accidents, i.e., lashing and securing activities onboard ship, still require human intervention. Still, automated terminals enable near-zero accidents simply by separating people from container handling equipment (Kaunonen, 2017). Sisson (2012) attempted to quantify potential reductions of injury rates by automating terminals on the US west coast, but the evidence provided is somewhat ambiguous. Grau (2014) found that a reduction of the injury rate by 40% could be achieved when converting to full automation. Lower accident rates at terminals also have financial implications for lower insurance premiums and compensation costs.

Concerning the safety issue, investments in automation often go hand in hand with full integration with security systems. A terminal's better safety and security profile has positive financial repercussions, such as lower insurance premiums. However, automation brings specific cybersecurity risks. The management of such cyber risks typically focuses on the system or network availability, integrity, and confidentiality (Fenrich, 2008; Samonas and Coss, 2014).

2.4 Enhance environmental sustainability

Automation offers possibilities to reduce the environmental footprint of the terminal by reducing energy consumption and CO_2 emissions per terminal accurately (cf. Geerlings and Van Duin, 2011; Spengler and Wilmsmeier, 2016). Energy savings are typically achieved by optimizing container moves and horizontal transfers, reducing crane time per unit handled and distances covered, or using electric or hybrid power sources. Container handling equipment with high operating efficiency will accomplish their work assignments rapidly and lessen the berthing time of ships in the port, while saving energy and reducing CO_2 emissions. Yang (2017) found that electric ASCs can be considered green cargo handling equipment due to their significant contributions to working efficiency, energy savings, and CO_2 reduction. An optimal terminal layout can also reduce energy consumption and CO2 emissions in container terminals (Budiyanto et al. 2021).

2.5 Other drivers

Other drivers that have been identified in this study include the efficiency to handle larger ships, the ability to operate 24 hours a day and the ability to meet KPIs imposed on terminal operations by the ocean carriers. These drivers also enhance operational efficiencies in the terminal but may also address location-specific terminal constraints. For example, a carrier may impose KPIs at one of the terminals where its ships call to address an issue that may be specific to that terminal.

Some terminal automation projects have been developed in countries or regions that wanted to demonstrate their technological know-how or showcase specific technological innovations. For example, the pioneering Delta SeaLand Terminal in Rotterdam was developed with the nearby Delft University of Technology, a leading technology and engineering university. Phase 4 of the Yang Shan terminal complex in Shanghai can be considered a demonstration project of Shanghai port and Shanghai-based leading equipment manufacturer ZPMC. Such technological showcases are real-life test-beds and learning opportunities for developing next-generation automation solutions.

Port authorities and governments might embrace terminal automation projects to promote the ‘smart port’ status or spotlight the innovation capabilities of the maritime cluster. However, some policymakers might be quite reluctant to communicate intensely on these technological achievements to the public, as they fear this might trigger a social debate on potential job losses. For example, Van Den Driessche et al. (2019) did not find strong arguments to explain the automation differences between Rotterdam (many automated terminals) and Antwerp (only one semi-automated terminal) based on the differences in labor intensity and costs in both ports. Instead, they argue that the differences in automation might be more associated with the technological absorptive capacity and the first mover innovation advantage of Rotterdam versus Antwerp’s imbedded dock labor capability and performance.

3 METHODOLOGY

A review of port and terminal company information and existing studies shed light on the precise number and geographical distribution of semi- and fully-automated container terminals, and their characteristics (see Knatz et al., 2022 for a detailed analysis).

Once all automated terminals were identified (62 operating and an additional one under construction), a survey of their operators was conducted to analyze the combination of factors likely to influence or challenge the decision-making process to automate a conventional terminal and to document whether anticipated benefits of automation were realized once the terminal was in operation. Recognizing the proprietary nature of specific terminal operating data and the challenge in getting sufficient data to make global comparisons of terminals productivity, the study relied on a survey-based approach of senior executive perceptions of whether or not they had achieved their efficiency goals by automating the terminal.

Summarizing the literature review (Table 1) a set of 12 potential drivers/ benefits of automation was deduced:

1. Improve efficiency to handle larger vessels;
2. Reduce variability in performance (more consistency);
3. 24/7 hours of operation;
4. Meet KPI’s required by ocean carrier;
5. Improve truck turn time;
6. Reduce unit cost of container handling;
7. Reduce labor cost;
8. Eliminate human factors (illness, risk of labor disruption, etc.);
9. Cope with limited land for expansion;
10. Reduce air/greenhouse gas emissions;
11. Increase safety;
12. Test-bed for new technologies/showcase technological expertise of local terminal and/or research community

Automation projects also need to consider the demand characteristics for container handling, including the competition with and strategies of competing terminal operators. The governance and user profile of the terminal and the availability of funding or subsidies might also be at play. Therefore, two more potential drivers were added:

13. Competitive forces from other terminal operators who opted for automation;
14. The availability of financial incentives/subsidies by public entities or port authorities.

Terminal operators were asked to evaluate on a Likert scale from 0 (no importance) to 7 (maximum importance) the importance of the 14 factors in deciding whether to automate their container yard. Another question focused on the perceived benefits of automation. Terminal operators were also asked other questions that are used to discern benefits realized, such as the levels of stakeholders' support/opposition for automation. Inherent in the design was to create a survey form terminal operators would not immediately reject by asking for what might be considered proprietary information. The survey was also designed to be completed using an editable pdf format.

The survey was sent out by email in the period February – July 2021 to senior representatives of the terminal operating companies that manage the respective automated terminals. The initial distribution of surveys was followed by reminders, personalized follow-up initiatives by phone or other communication means. In quite a few cases, we received assistance to outreach to key persons in automated terminals from the global headquarters of the terminal operating company, branch associations and expert organizations (i.e., International Association of Ports and Harbors (IAPH), the Asia Pacific Economic Cooperation (APEC) Port Services Network (APSN), the Federation of Private Companies and Port Operators (FEPORT)), and international organizations (the United Nations Committee for the Caribbean and Latin America - CEPAL). No port authorities completed the surveys, only terminal operators. The survey explicitly stated that all the individual information will be strictly confidential, and the reader will not be able to identify any port terminal response. This approach was deemed necessary to increase the willingness of terminal operators in completing the survey. However, this stipulation implies that we present aggregated survey results, avoiding presentations and comparisons of individual terminals.

More than half of the world's operating automated terminals participated in the study (32 terminals, or 51.6%) by returning valid and usable filled-out surveys. Responses came from all automated terminals in the USA, China, Germany, and Ireland, along with terminals in Europe, Korea, Japan, and the Middle East. **Table 2** provides information on which terminals replied, the regional distribution and the number of semi- and fully-automated terminals that contributed by region.

In most cases, the CEO, COO, or managing director of the terminal filled out the survey. In a few cases, an automation project manager or a CIO (Chief Innovation Officer) responded. The survey had a temporal element, in that the person filling out the survey had to have knowledge of the initial drivers to automate the terminal, as well as see the results after automation was implemented. This often involved tracking down people who had moved from one terminal to another or had retired. The response time between sending out the survey and receiving the filled-out form ranged from immediate to up to a few months. In some cases, lengthy internal review and approval processes at the level of the terminal operating company prevented a fast response.

Insert: Table 1. List of Automated Terminals that completed surveys, by region and by type of terminal automation

Descriptive statistics facilitated an analysis of the hierarchy of the assessed factors, the variances of perspectives and experiences that exist between operators and between automation strategies, and the sensitivity that might be produced due to local perspectives. Three regions provided enough data for regional analysis: North America (replies by all six terminals); Pacific Asia (12 terminals representing over 57% of all); and, Europe (10 replies from North Europe and the Mediterranean combined or 50% of all automated terminals in these regions). The number of replies (32) is at the lower limit when considering the application of advanced statistical methods. While being aware of the potential limitations brought by the sample size, the dataset has been subjected to several statistical tests.

The one-way Analysis of Variance (ANOVA) has been applied to determine any statistically significant variations between groups of replies. ANOVA enables statistically testing for significant differences per each criterion, and between the perspectives expressed by a group of respondents (i.e., regional perspectives, fully versus semi-automated terminals). The independent variable is the group of respondents and as a dependent variable each one of the criteria under examination.

To strengthen the ANOVA results, we run a Kruskal-Wallis non-parametric analysis of independent samples such as (a) regional groups of respondents and (b) semi-automated versus fully-automated terminals. Kruskal-Wallis testing of pairwise comparisons was selected as (a) the dependent variable is measured at the ordinal or continuous level (i.e., the Likert scale we used), and (b) the independent variable consists of two or more independent groups, whereas, in our case, there are groups offering a number of independent observations.

The calculation of Pearson coefficients determined whether and how the researched variables are linearly related. Pearson coefficients range from +1 (perfect positive correlation) to -1 (perfect negative correlation), and 0 meaning no relationship. If the correlation coefficient is greater than zero, it is a positive relationship. Conversely, if the value is less than zero, it is a negative relationship.

Finally, a stepwise regression analysis identifies possible predictors of the drivers and the realized benefits. This technique uses an algorithm to select the best grouping of predictor variables that account for the most variance in an outcome (R-squared). The default elimination criterion is a p-value > 0.1. At each step, the variable X that has the lowest correlation with the outcome Y_i was removed from the model if it satisfied the elimination criterion. The procedure stopped when there are no variables left in the model that satisfy the elimination. The MATLAB software has been used for the stepwise regression analysis and SPPS for other statistical testing.

4 EMPIRICAL FINDINGS

We identified 63 automated container terminals, 62 in operation and one under development, in 23 countries, in Asia, the Americas, Europe, and Oceania Knatz et al. (2022) present a detailed analysis of the characteristics and operating parameters of all 63 terminals. Pacific Asia (22 terminals) and North Europe (11) are the hotspots in terms of terminal numbers. Eighteen terminals, located in the US, Oceania, Pacific Asia, and North Europe, are fully-automated. Stevedoring companies operate 39 automated terminals, carriers operate 14, financial holding companies operate six, and joint ventures or consortiums of multiple types of partners operate four. Most automated terminals handle between 2 and 3 million TEU. The terminal sizes vary significantly for both fully and semi-automated terminals, with 24 being less than 50 hectares. The average size of fully automated terminals is 98.6 hectares, while the average size of semi-automated terminals is 84.1 hectares. The average berth length is 1,497 meters without a significant difference between full and semi-automated terminals. All but one terminal have drafts over 14 meters, with the maximum draft being 16 meters. Finally, there is no strong relationship between transshipment incidence and automation; one fully-automated terminal is in a transshipment hub, while semi-automated terminals can be found in pure transshipment ports, ports with a mixed cargo mix, and gateway ports.

4.1 Drivers and Realized Benefits

The survey results reveal a wide range of factors contributing to the decision to automate a terminal. Next to purely economic and technical factors, more institutional factors and dynamics in stakeholder relations impact terminal automation. The most important factor driving the decision to automate among survey respondents was *increased safety* (**Table 3).** Three other primary factors driving the decision making were: *reducing the unit cost of container handling*, *reducing variability in performance,* and *reducing labor cost*.

Four terminals identified *improved truck turn-time* of maximum importance in driving their decision to automate. Only one of these four, a semi-automated terminal, did not realize the benefit of improved truck turn-time. The three that realized their anticipated benefits of reduced truck turn-times were all fully-automated terminals. Two additional semi-automated terminals realized benefits to truck turn-times that were not anticipated.

Insert: Table 2. Importance of drivers in deciding whether to automate container terminals

Nearly the same factors were recognized as benefits by the terminal operators once automation was implemented (**Table 4**). *Improved safety* was the most important benefit realized with *reduced unit cost of container handling*, *reduced variability in performance*, and *reduced labor cost*. In addition, the *elimination of human factors that could cause disruption to operations* was also a realized benefit that was ranked somewhat lower as a driver to decision-making.

Insert: Table 3. Benefits realized from the introduction of automation

Secondary factors, ranked slightly lower in importance, that drove the decision to automate include: *24/7 hours of operation*, *eliminate human factors*, *improve efficiency to handle larger vessels*, *reduce air pollution and greenhouse gases,* and *improve truck turn-time*. Terminals in China did not rank *24/7 hours of operation* as a key factor driving automation because their terminals already operate 24/7. Although every terminal noted *improved truck turn time* as a driver in deciding to automate, it was generally not among the most highly rated factors in the decision-making. Terminal operators had an opportunity to indicate other drivers not on the survey form. In one case, a terminal indicated that automating their terminal was part of an overall strategy of digitization.

The data for the drivers, which many terminals rated of greatest importance, was negatively skewed, meaning that for most of the terminal operators, their view of the importance of these drivers was very high, greater than the average score for those same factors across all terminals. In contrast, only a smaller number of terminals ranked these same factors of much lesser importance. Eighteen terminals ranked *increased safe*ty of maximum importance in their decision-making to automate their terminals, meaning these terminal operators scored this factor a 7. The high value of negative skewness implies that most terminals scored this value over the average value of 6.28, while only a few had much lower scores.

All terminal operators, except for one, rated the importance of *increasing safety* as a driver towards automation with a 'score' of at least 5 (97%). A single operator that assigned no importance at all to safety when deciding to advance automation. Conversely, for 18 terminal operators (56%), this has been a factor of major importance in deciding to automate the terminal.

The number of operators that realized the maximum benefits of *increased safety* is even higher, as 19 terminal operators ranked these benefits as 'maximum.' Only one automated terminal did not realize any increase in safety due to automation, while all the rest rated the benefits 4 or higher.

The second most important factor in driving automation was *reduced unit cost in container handling*. *Reduced unit cost* was also the second-highest ranked benefit realized by the terminal operators after automation. *Reducing costs of unit handling* is closely aligned with *reducing labor cost.* Despite the observation that reduced labor costs often drive the decision to automate, reduction in labor costs is only one of the primary factors driving the decision and not the most significant factor for many terminals. This observation is in line with the findings of the literature review, which already pointed to the mixed importance of labor cost as a driver for automation. Thirteen of the 32 terminals identified *reduced labor cost* as a driver of maximum importance. Of those 13 terminals, only 11 received the benefit of labor cost reduction they anticipated. Two terminals, one in the USA and one in Europe, did not realize the labor cost savings anticipated. One was a fully-automated and the other a semi-automated terminal. Twelve terminals identified reduced labor costs as a benefit of automation once implemented, 11 had anticipated those benefits, and an additional terminal in China realized benefits not anticipated.

All terminals realized some benefit in *reduced unit costs*, assigning a score of at least 3 out of 7 or higher with ten terminals realizing maximum benefits in *reduced unit costs*. All but one terminal realized savings in reduced labor costs. Twelve terminals realized maximum benefits in *reduced labor costs* while seven terminals realized benefits of minor importance and one realized no benefits. Six of the seven terminals that realized only minor importance in *reduced labor costs* (scores 1 to 4) were semi-automated terminals in the USA and Europe. The terminal that realized no benefits from reduced labor costs was in the Pacific Asia region.

Seven terminals ranked *improved efficiency to handle larger ships* of maximum importance in driving their decision to automate. These seven terminals were scattered around the globe. Eight terminals realized benefits in *handling larger ships*, seven of those that anticipated improved efficiencies, and two additional terminals that had ranked this as a slightly lower driver.

Five of the 32 terminals ranked *elimination of human factors*, such as illness or risk of a labor disruption, as a driver of maximum importance. Three of these same terminals also ranked *reduced labor costs* as a primary driver. Eleven terminal operators indicated benefits related to the *elimination of human factors*, including the five who identified this factor as a primary driver. Five additional semi-automated terminals and one fully-automated terminal indicated that *elimination of human factors* was a benefit after automation. Note that the surveys were completed during the COVID period, after terminals around the world had to deal with lower dockworker availability due to the illness. Operators of automated terminals may have recognized that automation provided some protection against the virus spreading among their dockworkers. However, this factor had not been a driver when these terminal operators decided to automate.

Six terminals ranked *the reduction in air emissions and greenhouse gases* of maximum importance in driving their decision to automate, i.e., four fully-automated terminals and two semi-automated terminals. Eight terminals ranked the benefits in a *reduction in air emissions and greenhouse gases* of maximum importance once the terminal was automated; four of them are terminals that had anticipated those benefits. One fully-automated terminal did not realize the benefits in emission reduction they anticipated, however, the reason for this response was not explained. Two additional semi-automated and fully-automated terminals ranked *reduction in air emissions and greenhouse gases* of maximum importance as an outcome but not a driver.

Subsidies can affect investment by boosting internal and external (credit market) financial sources and increasing firms' financial capacity. Interestingly, a total of 17 respondents indicates that *financial incentives/subsidies by public entities or port authority* are not a factor at all when deciding to automate (score 0). This factor achieved the lowest average score of all the drivers considered. This observation can be interpreted in two ways: no financial incentives and subsidies were given or the provided financial incentives or subsidies did not alter the business case for automation. Four respondents, i.e., two from China and two from Japan, gave a score of 6 or 7 (maximum) on this factor, implying that they consider the awarded subsidies a key contributing factor in the decision to automate.

The data for benefits rated of greatest importance for most terminals was negatively skewed meaning that the majority of the terminal operators realized more benefits than the mean value of benefits averaged across all terminals, while a few terminals achieved significantly lower benefits for these same factors.

4.2 Differences between decision-making drivers and benefits realized

Table 5 presents the differences between the drivers for decision-making and the benefits realized from automation averaged for all 32 surveyed terminals. **Table 6** presents a regional comparison of the results. A positive difference means that the achieved benefits were greater than the anticipated benefits; a negative number indicates that the achieved benefits were less than expected. *Reduced labor costs, reduced air emission, improved truck turn-time, elimination of human factors* along with terminals having *limited land for expansion* and the opportunity to *serve as a test-bed for new technologies* were all factors where benefits exceeded expectations. However, in the case of the *reduced labor cost* the difference between expectations and realized benefits is marginal (slightly negative for the U.S. and Europe and slightly positive for Pacific Asia). The high observed difference for the factor *test-bed for new technologies* reveals that the learning curve and innovation trajectory linked to an automated terminal project led to a much stronger positive outcome than initially anticipated by the developer. This is particularly the case for European and Pacific Asian terminals. The high positive difference between driver and benefits realized for the factor *increased land productivity* only relates to terminals in the U.S. and Pacific Asia. On average, automated terminals in Europe did not reveal any difference between benefits and expectations for this factor.

Insert: Table 4. Differences between benefits realized and decision-making drivers

Insert: Table 5. Differences between benefits realized and decision-making drivers per terminal, per region

Reduced cost of unit handling, the *ability to handle larger ships,* the *ability to operate 24/7*, and the *need to meet KPIs required by ocean carriers* were all factors where expectations were not met. When examining the entire data set (**Figure 1**), it is clear that a relatively significant percentage of terminal operators (38%) have slightly overestimated the benefits of automation from *reducing the unit cost of container handling*. A third of those terminals were fully automated, while 2/3rds were semi-automated. Thus, yard automation may not solve all of a terminal's inefficiency problems, especially if the systems are not integrated. The literature review already hinted at this issue which is now confirmed by the survey results. For an automated terminal to achieve its greatest potential in terms of productivity, all facets of the terminal operation have to be in sync.[2] This often requires a period of trial and error to smooth out any inconsistencies in cargo flows within the terminal. The high percentage of terminals (59%) that saw no benefit from as a *test bed for new technologies* is related to the fact that their terminals may not have served as a manufacturers' testing site for new equipment, or their automation journey may not have been part of a research study.

[2] For example, the TraPac terminal in Los Angeles initially experienced a reduction in ship to shore crane productivity (moves per hour) because there were too few shuttle carriers to move containers to the yard.

Insert: Figure 1. Percentage of operators that over/underestimated the benefits of automation

Terminal operators were identified as stevedoring companies, ocean carriers or financial holding companies. An ANOVA analysis returned no statistically significant variance in either the drivers, or benefits realized from terminal automation, based on the type of terminal operator.

4.3 Correlation between drivers to automate

Table 7 identifies the correlations of the importance of factors in deciding whether to automate container yard operation. Pearson coefficient calculations indicate a strong positive relationship between *reduced unit cost* and *reduced labor costs*, as might be expected because labor costs are a key factor in the unit cost of handling a container. Other strong relationships were found between *increased safety* and *elimination of human factors*, indicating that terminal operators view the human factor as a fundamental factor in overall terminal safety. These findings underline one of the outcomes of the literature review: terminal operators embrace automation to reduce the impact of potential accidents by creating a physical gap between people and the area where operations are physically being carried out.

Meeting the key performance indicators (KPIs) established by ocean carriers for terminal operators showed a high correlation with *efficiency to handle larger vessels* and *competitive forces from other terminals*. Key performance indicators were not correlated with cost factors, but they were correlated with *reduced variability in performance* and *elimination of human factors*. This correlation indicates terminal performance and reliability are of greater importance to the ocean carriers than cost. Only two factors were negatively correlated with each other: *reduced unit cost* and *limited land for expansion*. These appear to be unrelated in the view of the terminal operators, although operational costs for terminals currently constrained with insufficient land would likely be reflected in unit costs. If there is limited land for expansion, then the opportunity to reduce unit costs by adding additional land to the terminal would not be available.

Insert: Table 6. Correlations between the importance of drivers to automate container yard operations

4.4 Correlation between realized benefits

The strongest correlation among benefits realized was the relationship between *improved efficiency to handle larger vessels* and *reduced variability in performance with meeting KPIs required by ocean carriers* (**Table 8**). *Reduced variability in performance* was also highly correlated with *increased safety*, while *increased safety* was also highly correlated with the *elimination of human factors*. The tendency of the terminal operators to focus on the reliability of performance and all aspects of the terminal operation that could impact reliability was clearly visible over purely cost factors. This finding confirms one of the points presented in the literature review: the operational efficiency gains of automation are mainly found in achieving stability, predictability, and consistency of operational performance, which allows continuous operations.

Insert: Table 7. Correlations of benefits realized from automation

4.5 Predictors of Drivers to automate

A stepwise linear regression identified possible predictors of the drivers towards automation out of the following qualitative variables:

X_1 = Fully- or semi-automated terminal
X_2 = Year of terminal opening
X_3 = Year of the first automation
X_4 = Operator type (i.e., stevedoring companies, shipping companies, financial institutions)
X_5 = Terminal acreage (hectares)
X_6 = Length of Berths (meters)
X_7 = Max draft (meters)
X_8 = Maximum Ship Size called (the port) (2020)
X_9 = Liner Shipping Connectivity Index (LSCI) of the port (2020)
X_{10}= Listed in the top-100 Container ports (2019)
X_{11}= Rank in top-700 Cities of the world in terms of population (2019)

The findings suggest that three out of the 14 drivers examined are associated at statistically significant levels with some of the qualitative variables examined (**Table 9**).

- The first one is the *limited land for expansion* (Y_5). This driver is negatively linked with *the year of opening of the terminal* (X_2). Scarcity or other land-related limitations tend to be less significant drivers for the more recent automation projects. The limitation of land became a more significant driver towards automation the higher *the traffic of the port* (X_{10}= Listed in the top-100 Container ports), and the higher the *maximum ship size calling at the port* (X_8).
- The *competitive forces from other terminal operators who opted for automation* (Y_{13}) was found to be a less significant driver *the larger the terminal acreage* (X_5) , and a more significant driver the larger the *ship size calling the port* (X_8). When a terminal has enough space to develop its activities, the less important the pressure from competitors. When a terminal handles larger vessels, competition seems to generate motivation to automate the terminal.
- The presence of *financial incentives/subsidies by public entities or port authorities* (Y_{14}) is negatively related to *the larger-sized terminals* (X_5), and *the size of the port-city in terms of population* (X_{11} = rank of the city in the top-700 cities in terms of population), and positively related to the maximum draft (X_7) of the berth.

Insert: Table 8. Predictors of the importance of the drivers towards automation

4.6 Predictors of Realized Benefits

The stepwise linear regression was also used to identify possible predictors of the realized benefits from automation. In this case, we estimated the relationship out of 20 variables to the 11 variables examined in the case of the regression analysis of the determinants of the drivers towards automation. Seven additional variables were included, following the reply of the survey by terminal operators:

X_{12}=How many years has it taken to realize a return on investment for the automated system?
X_{13}=Number of suppliers that implemented automation

X_{14} = Level of support of automation of the terminal by the government (strong-moderate-minimum opposition / neutral /minimum-moderate-strong support)
X_{15} = Level of support of automation of the terminal by the Community
X_{16} = Level of support of automation of the terminal by the Port Authority
X_{17} = Level of support of automation of the terminal by dockworkers
X_{18} = Level of support of automation of the terminal by carriers
X_{19} = Level of support of automation of the terminal by shippers
X_{20} = Level of support of automation of the terminal by logistics service providers

For five of the 12 benefits, the scale of the benefits realized following automation is not related at a significant statistical level with any of the 20 examined variables (**Table 10**). For the other seven benefits, the stepwise regression analysis identifies specific determinants:

- The *increase of land productivity* (Y_5) is more significant than the length of the berths (X_6).
- The *reduction of labor costs* (Y_1), the consistency of performance variability (Y_9), and *increased safety* (Y_{17}) are positively related to the *time taken to realize a return on investments for automation* (X_{12}).
- The benefits *of 24/7 operations* are linked with the year of the first automation (X_3), the max draft (X_7), and the levels of support of automation by governments (X_{14}) and the community (X_{15}).
- Meeting KPIs required by ocean carrier (Y_{11}) benefits are higher the deeper the maximum draft of the terminal (X_7) and the higher the level of support of automation of the terminal by the community (X_{15}).
- A more significant boost for technological and operational innovation by terminal operator (Y_{12}) is positively linked with the levels of liner shipping connectivity of the port (X_9) and the level of support of automation of the terminal by the community (X_{15}).

Insert: Table 9. Predictors of the realized benefits of automation

4.7 Drivers vs Benefits: Fully vs Semi-automated terminal

For fully-automated terminals, drivers of importance were *increased safety*, *reducing unit costs of container handling*, *reducing labor cost*, *reducing variability in performance*, and *reducing air emissions and greenhouse gas production* (**Table 11)**. For semi-automated terminals, *reducing labor costs*, and *reducing air emissions* were ranked of less importance compared to fully-automated terminals, while *24/7 hours of ope*ration and *eliminating human factors* were ranked of higher importance.

Given the sample size (n=32), variations in the replies might be spontaneous or biased. An ANOVA test was performed to identify any statistically significant differences of the anticipated benefits by the operators who opted for fully automating the container terminal compared to those who opted to develop a semi-automated terminal. The results are not significantly different, with one exemption – the significance assigned to *elimination of the human factors* (P-value <0.05; Mean Square 18.923, F 5.116; Sig .031). A Kruskal–Wallis non-parametric analysis confirmed these ANOVA findings: the importance of *eliminating human factors (illness, risk of labor disruption, etc.)* is not the same across fully or semi-automated terminals (F: .037).

Insert: Table 10. Importance of drivers in deciding whether to automate container terminals: Fully vs Semi-automated containers

In short, the *elimination of human factors* was identified as a greater benefit for semi-automated terminals than fully-automated terminals. This is not expected as semi-automated terminals would have more dockworkers on a terminal than fully-automated terminals (**Table 12**). One explanation may be that terminal operators completed the surveys during the global pandemic. Only six of the 32 terminals that completed the survey indicated that the *elimination of human factors* was a driver of maximum importance. However, 11 terminals indicated *elimination of human factors* as a benefit of maximum importance; nine of these 11 terminals were semi-automated. It may be that semi-automated terminal operators, who recognized the risks to their dockworkers during the pandemic, also recognized that their risks were minimized to a large extent by the presence of automation. Whereas, fully-automated terminals operators might not have seen impacts on their workforce and may not have been influenced to rank *elimination of human factors* of maximum importance as a benefit when completing the survey. Only one automated terminal ranked *elimination of human factors* as a maximum driver when deciding to automate. Only one fully-automated terminal (different from the prior terminal) ranked *elimination of human factors* as a primary benefit. In the case of all other benefits, the findings were similar, irrespective of the level of automation that is endorsed.

Insert: Table 11. Benefits realized from the introduction of automation: Semi vs Fully-automated terminals

The gap between decision-making drivers and benefits realized indicate that operators of fully-automated terminals were more successful in meeting expectations overall than operators of semi-automated terminals, particularly in the areas of *reducing the unit cost of container handling, improved efficiency to handle larger ships, 24/7 hours of operation* and *meeting KPIs required by ocean carriers (***Table 13***).* The most significant difference between fully vs. semi-automated terminals is for the factor *eliminating human factors*. Semi-automated terminals realized more benefits of *eliminating human factors* than fully automated terminals; however, semi-automated terminals generally saw more benefits in this same factor than they initially expected. See earlier sections for further discussion of how survey results for the factor elimination of human factors might have been influenced by the pandemic.

Insert: Table 12. Differences between benefits realized from automation and decision-making drivers and benefits realized from automation: Fully vs Semi-automated terminals

5 FINDINGS AND CONCLUSIONS

This study identified the multi-faceted array of factors that drive the decision to automate a container terminal and analyzed the variation of the relative importance of these factors by several parameters, such as terminal operator and locality. This study is the first of its kind using terminal operators' survey inputs to deepen our understanding of the drivers and benefits of terminal automation, going beyond the mere description of terminal facts and figures and anecdotal evidence. The results show that the most important driver motivating terminal operators to automate was *increased safety*. Three other primary factors driving the automation decision were *reducing the unit cost of container handling, reducing variability in performance,* and *reducing labor costs*.

The research also established how accurate terminal operators predicted the benefits of automation once the terminal automation was in operation. The findings show that most of the benefits assumed by an individual terminal operator materialized once the automated terminal was in operation. Nearly the same factors were recognized as benefits by the terminal operators once automation was implemented. Globally, the terminal operators identified the most important benefit of automation as *increased safety* along with *reduced unit cost of container handling*, r*educed variability in performance* and *reduced labor cost. Elimination of human factors* was a benefit realized by terminals operators who did not consider this an important driver. This could be because the survey was filled out during the pandemic and terminal operators may have realized that the automated operation provided some protection against the virus spreading among their workers. Correlation was high among factors that related to cost and performance. For example, among drivers, *reduced labor cost* is correlated with *reduced unit cost of container handling*. Similarly, the strongest correlation among benefits was *improved efficiency to handle larger vessels* and *reduced variability in performance*. *Reduced variability in performance* was also highly correlated with *increased safety*, while *increased safety* was also highly correlated with *elimination of human factors*.

For fully automated terminals, drivers of importance were *increased safety*, *reduced unit cost of container handling*, *reduced labor costs, reduced variability in performance* and *reduced air emissions*. For semi-automated terminals, *reducing labor costs* and *air emissions* were ranked of less importance compared to fully-automated terminals while *24/7 hours of operation* and *elimination of human factors* were ranked more important for semi-automated terminals. This latter point would not be expected since semi-automated terminals would have more dockworkers but could be a result of terminal operators completing the survey during the pandemic.

An analysis of the gaps between decision-making drivers and benefits realized revealed that *reduced labor cos*ts, *reduced air emissions*, *improved truck-turn times*, *elimination of human factors* along with terminals having *limited land for expansio*n and the opportunity to *serve as a test-bed for new t*echnologies were all factors where benefits exceeded expectations. In the case of *reduced labor costs*, the differences between expectations and benefits realized is marginal, slightly negative for USA and Europe and slightly positive for Pacific Asia.

Reduced cost of unit handling, *ability to handle larger ships*, the ability to *operate 24/7*, and the need to *meet KPIs required by ocean carriers* were all factors where the expectations were not met. Thirty-eight percent of the terminals slightly overestimated the benefits of automation for reducing the unit cost of container handling (1/3rd fully automated, 2/3rds semi-automated). Thus, yard automation may not solve all a terminal's efficiency problems nor provide the cost savings expected, especially if the systems are not fully integrated.

The study also provides a regional comparison of the findings covering three regions (i.e., USA, Europe, and Pacific Asia), aiming to understand better the sensitivity that might be produced due to local perspectives and culture. For all regions, the greatest benefits realized from automation was *increase*d *safety*. The Pacific Asia region realized the greatest benefit in *reduced labor costs*, followed by Europe and the USA. The difference may be due to the wage guarantees for workers displaced by automation. None of the USA terminals realized the level of benefits for *reduced labor costs* that they anticipated, and two overestimated the reduction in labor costs.

The findings have relevance to practitioners and policy-makers when engaging in decision-making processes regarding automation. There is much similarity in the drivers for automation on a global basis, with *increased safety* generally considered the most important driver. But whether or not terminal operators receive the level of benefits they anticipated varies. Despite some level of similarity across terminals at the level of the decision-making drivers and realized benefits at a global and regional level, the survey exercise demonstrates that every automation project is unique and embedded in its local spatial, economic, and social context. One example is the driver on *reducing labor costs*, which many terminals in Asia realized as expected but in the USA that did not happen, reflecting tradeoffs terminal operators have made to secure stakeholder support for automation. The successful implementation of a terminal automation project is not so much dependent on the technological solutions adopted, which are now widely available across the world. It is more a matter of demonstrating a high level of adaptive capacity of the terminal operator to respond adequately to the imperatives brought by the local market environment and customer base, the social dialogue, and the stance of public entities. All these factors are highly embedded in the local context and differ from one port to another. While terminal operators can learn from each other's' experiences and best practices, there is no 'one size fits all' approach possible to automation.

The presented research comes with some limitations. This study has demonstrated that most automated terminal projects are still fairly new, with limited years of operations. Therefore, some of the answers provided might not provide a complete picture of the long-term outcomes of automation, particularly at the level of the realized benefits and financial implications. While the sample size at over 51% is high, the dataset still contains some 'blind spots' preventing a more inclusive picture of the entire world. For instance, despite assistance from Ports Australia, no survey was completed by any of the six automated terminals in Australia. The regional comparison can be further extended in future research to examine potential aspects that would reflect some level of regional embeddedness of terminal automation processes.

There is ample room for further deepening the analysis where meaningful, for example, by applying more advanced methods to obtain cross analyses between survey questions, comparison of results per sub-group, etc. Exploring the relationships between the results with some economic or logistics indicators of the country, region, port or city in which the terminal is located could provide some greater insight. The World Bank, UNCTAD and other international and regional organizations publish a wide range of indicators that might be useful to consider. Future research needs also to explore whether only certain terminals might fit the profile where unmanned automated equipment brings added value, why, despite the potential/realized benefits several terminal operators show reluctance or hesitation towards automation, adopting a 'wait-and-see' approach, but also why in some cases, terminal automation plans were canceled or delayed.

An important distinction is between fully versus semi-automated container terminals. While beyond the scope of the present study, it is worth further exploring the difference between these two groups of terminals at the level of the actual benefits of automation. For example, semi-automated terminals might imply challenges on the interaction between automated and non-automated parts with no real separation between humans and machines, and this might potentially be detrimental to safety, a parameter that in our study is seen by those that decided to proceed with automation as the main benefit of it. This also highlights another issue, i.e., whether a distinction needs to be made between (recent) greenfield developments and older terminals that got "upgraded" to either semi- or fully automated terminals. This variable, i.e., the path of the terminals toward automation, is worth to be considered in future research.

Finally, the literature review section of this report provided some fragmented information on the actual performance of automated terminals compared to conventional terminals. Future studies can attempt to develop a more systematic approach to terminal performance comparison based on hard data. Such data is available, but typically confidential in nature at the terminal operator level, or hidden behind 'high' paywalls in case one wants to rely on relevant information collected by advisory or data firms.

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Table 13. Potential Drivers towards Container Terminal Automation: A Literature Review

Driver category	Specific Drivers	Study
Increase operational efficiency	**Improve efficiency to handle larger vessels**	Monfort-Mulinas (2012); Kon et al. (2020); Moody's (2019); Ghiara and Tei (2021); Miller (2017); Davidson (2016)
	Reduce variability in performance (more consistency)	Yang and Shen, (2013); Martin-Soberon et al. (2014); Davidson (2016)
	24/7 hours of operation	Fenrich (2008); Samonas and Coss (2014)
	Meet KPI's required by ocean carrier	Lau and Zhao (2008); Stahlbock and Voß (2008); Sha et al. (2021)
	Improve truck turn time	Yang and Shen (2013) ; Martin-Soberon et al. (2014) ; Wang et al, (2019) ; ITF (2021)
	Improve land productivity and cope with limited land for expansion	Monfort-Mulinas (2012)
Reduce cost	**Reduce unit cost of container handling**	Oliveira and Varela (2017); McKinsey (2017); Kon et al. (2020)
	Reduce labor cost	PEMA (2016); Notteboom (2018); Notteboom and Vitellaro (2019); ITF (2021)
	Eliminate human factors (illness, risk of labor disruption, etc.)	Sisson (2012); Grau (2014); Notteboom and Vitellaro (2019);
Enhance safety and security, and environmental sustainability	**Increase safety**	ITF (2021); Kaunonen (2017)

	Reduce air/greenhouse gas emissions	Kon et al. (2020); Geerlings and Van Duin (2011); Spengler and Wilmsmeier (2016); Yang (2017); Budiyanto et al. (2021)
Other	**Test-bed for new technologies/showcase technological expertise of local terminal and/or research community**	Den Driessche et al. (2019)

Table 2. List of Automated Terminals that completed surveys, by region and by type of terminal automation

Region			Total Replies		Fully-Automated		Semi-Automated	
	Terminal (Port)	**Type of Automation**	**No**	**% of Total**	**No**	**% of Total**	**No**	**% of Total**
North America	APM Terminal Pier 400 (Los Angeles, US)	Full	6	100%	3	100%	3	100%
	Global Container Terminal, (New York/New Jersey, US)	Semi						
	Long Beach Container Terminal, (Long Beach, US)	Full						
	Norfolk International Terminal (Virginia, US)	Semi						
	TraPac, (Los Angeles, US, US)	Full						
	Virginia International Gateway (Virginia, US)	Semi						
Central America	APM Lazaro Cardenas (Lazaro Cardenas, Mexico)	Semi	3	75.0%	-	-	3	75.0%
	Manzanillo International Terminal, (Colon, Panama)	Semi						
	Tuxpan Port Terminal, (Veracruz, Mexico)	Semi						
North Europe / Atlantic	Belfast Container Terminal, (Belfast, Northern Ireland)	Semi	7	63.6%	2	20.0%	5	83.3%
	CTA Altenwerder, (Hamburg, Germany)	Full						
	CTB Burchardkai, (Hamburg, Germany)	Semi						
	Antwerp Gateway (Antwerp, Belgium)	Semi						
	Dublin Ferryport Terminal, (Dublin, Ireland)	Semi						
	London Gateway Port (Stanford, UK)	Semi						
	Rotterdam World Gateway b.v. (Rotterdam, Netherlads)	Full						
Mediterranean	Vado Gateway Spa (Vado Ligure, Italy)	Semi	3	50.0%	-	-	3	50,0%
	Bayport Haifa (Haifa, Israel)	Semi						
	Barcelona Europe South Terminal (BEST) (Barcelona, Spain)	Semi						
Pacific Asia	Busan South Korea (BNCT) (Busan, S. Korea)	Semi	12	57.1%	6	85.7%	6	42.9%
	Hong Kong International Terminals (Hong-Kong)	Semi						
	Oi Container Terminal (Berth 6) (Tokyo, Japan)	Semi						
	PSA Pasir Panjang Terminal, 1-2-3 (Singapore)	Semi						
	PSA Pasir Panjang Terminal, 4-5-6 (Singapore)	Semi						
	Pusan Newport International Terminal (PNIT) (Busan, S. Korea)	Semi						
	Qingdao New Qianwan Container Terminal (Qingdao, China)	Full						
	Tianjin Port Second Container Terminal (Tianjin, China)	Full						
	Tianjin Port Container Terminal (Tianjin, China)	Full						
	Tobishima Container Berth Co. Ltd. (Nagoya, Japan)	Full						
	Xiamen Ocean Gate Terminal (Xiamen, China)	Full						
	Yang Shan, Phase 4 (Shanghai, China)	Full						
South Asia / Middle East	DP World Jebel Ali (Dubai)	Semi	1	14.3%			1	14.3%
Total			**32**	**51.6%**	**11**	**61.1%**	**21**	**22.7%**

Table 3. Importance of drivers in deciding whether to automate container terminals

Driver	Mean	Std. Dev	Skewness	Kurtosis	Max Imp	No Imp
Increase safety	6.28	1.326	-3.659	16.593	18	1
Reduce unit cost of container handling	5.94	1.294	-1.403	1.786	14	1
Reduce variability in performance	5.62	1.641	-1.637	3.170	12	1
Reduce labor cost	5.37	1.930	-1.434	1.942	13	2
24/7 hours of operation	5.16	2.034	-1.159	.639	10	2
Eliminate human factors (illness, risk of labor disruption, etc.)	5.06	2.047	-1.534	1.252	5	2
Improve efficiency to handle larger vessels	4.97	1.823	-.940	.596	7	1
Reduce air/ GHG emissions	4.94	1.664	-.925	1.181	6	1
Improve truck turn time	4.66	1.450	-.231	.138	4	0
Meet KPIs required by ocean carrier	3.84	2.096	-.430	-.911	1	3
Limited land for expansion	3.63	2.406	-.105	-1.291	4	5
Test-bed for new technologies/ Showcase technological expertise of local terminal and/or research community	3.19	2.334	.148	-1.259	3	5
Competitive forces from other terminal operators who opted for automation	2.50	2.423	.501	-1.372	1	9
Financial incentives/subsidies by public entities or port authority	1.72	2.331	1.146	.045	2	17

** Notes: N=32 terminal operators; Scale: 1=limited importance; 7=Maximum importance; 0= Not a factor at all; Max Imp. = Number of terminals that ranked the specific factors as one of 'maximum importance'; No Imp. = Number of terminals that ranked the specific factors as 'not a factor at all'.*

Table 4. Benefits realized from the introduction of automation

Benefit	Mean	Std. Deviation	Skewness	Kurtosis	Max Ben	No Ben
Increased safety	6.28	1.373	-3.415	14.233	19	1
Reduce unit cost of container handling	5.63	1.314	-0.700	-0.592	10	0
Elimination of human factors (illness, risk of labor disruption, etc.)	5.59	1.829	-1.948	3.424	11	1
Reduce variability in performance	5.47	1.704	-1.342	2.108	12	1
Reduce labor cost	5.44	1.740	-1.279	1.698	12	1
Reduce air/GHG emissions	5.38	1.621	-1.771	4.015	8	1
Improve truck turn time	5.03	1.402	0.016	-1.365	6	5
24/7 hours of operation	4.88	2.612	-0.874	-0.577	14	5
Improve efficiency to handle larger vessels	4.72	1.971	-0.605	-0.301	8	1
Increase land productivity	4.59	2.298	-0.724	-0.620	8	3
Boost for technological and operational innovation by terminal operator	4.34	2.223	-0.652	-0.585	6	3
Meet KPIs required by ocean carrier	3.75	2.300	-0.403	-0.933	4	5

** Notes: N=32 terminal operators; Scale: 1=limited benefits; 7=Maximum benefits; 0= No benefit at all; Max Ben = Number of terminals that realized maximum; No Ben= Number of terminals that ranked the specific factors as 'not a factor at all'.*

Table 5. Differences between benefits realized and decision-making drivers

	Benefits realized	Decision-making drivers	Δ (Benefits-Expectations)
Test-bed for new technologies / Showcase technological expertise of local terminal and/or research community	4.34	3.19	1.25
Limited land for expansion	4.59	3.63	0.96
Eliminate human factors (illness, risk of labor disruption, etc.)	5.59	5.06	0.59
Reduced air/GHG emissions	5.38	4.94	0.44
Improve truck turn time	5.03	4.66	0.37
Reduced labor cost	5.44	5.38	0.06
Increase safety	6.28	6.28	-
Meet KPIs required by ocean carrier	3.75	3.84	-0.09
Reduce variability in performance	5.47	5.63	-0.16
Improved efficiency to handle larger vessels	4.72	4.97	-0.25
24/7 hours of operation	4.88	5.16	-0.28
Reduced unit cost of container handling	5.63	5.94	-0.31

* *Note: N=32 terminals; 1=limited significance; 7=Maximum significance*

Table 6. Differences between benefits realized and decision-making drivers per terminal, per region

	U.S. (n=6)	**Pacific Asia (n=12)**	**Europe Atlantic & Med (n-=13)**	**Total (n=32)**
Reduced labor cost	-3	4	-3	2
Reduced unit cost of container handling	-2	-1	-7	-10
Reduced air/GHG emissions	2	0	8	14
Improved efficiency to handle larger vessels	0	-1	-4	-8
Increased land productivity6	11	10	0	31
Improved truck turn time	4	4	6	12
Increased safety	-2	3	-1	0
24/7 hours of operation	-2	4	-15	-10
Reduced variability in performance (more consistency)	-3	-2	-2	-5
Elimination of human factors (illness, risk of labor disruption, etc.)	4	11	-2	17
Better meeting KPIs required by ocean carrier	1	2	-8	-3
Boost for technological and operational innovation by terminal operator	5	12	16	37
TOTAL	**15**	**46**	**-12**	**77**

** Note: Sum of Δ ((Benefits-Expectations) for terminals in the region.*

Figure 1. Percentage of operators that over/underestimated the benefits of automation

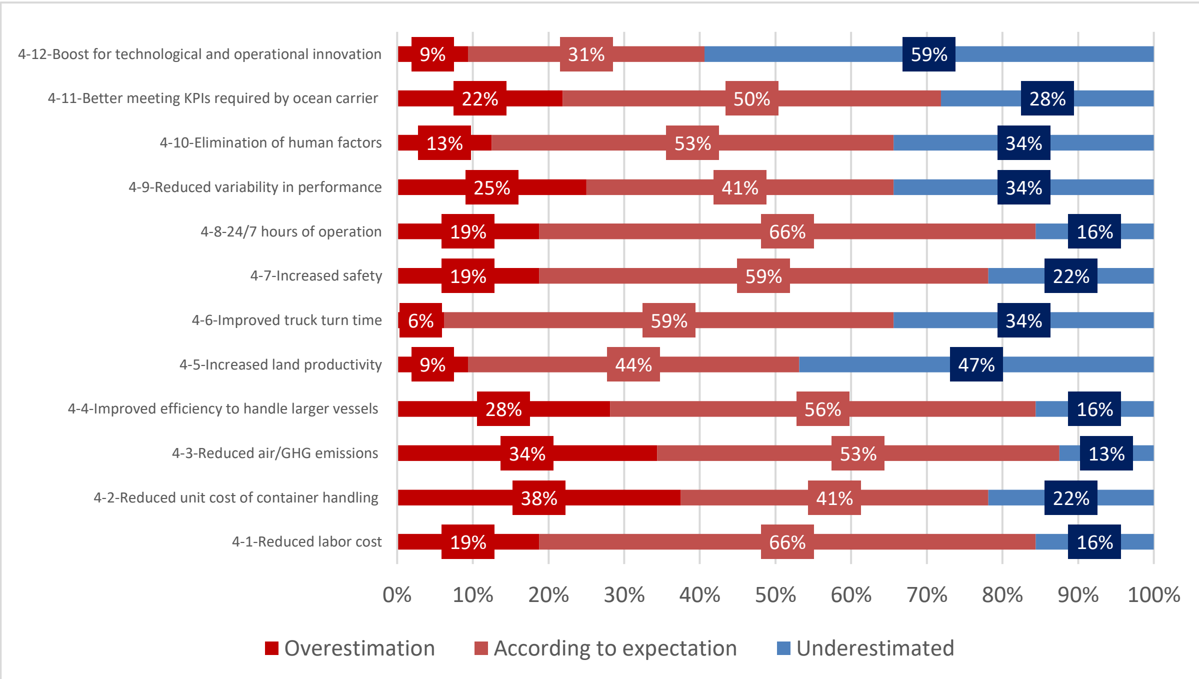

Table 7. Correlations between the importance of drivers to automate container yard operations

	High Correlation **	Correlation*
Reduce labor cost	• 24/7 hours of operation (.511) • Reduce unit cost of container handling (.462) • Increase safety (.575)	• Competitive forces from other terminal operators who opted for automation (.400) • Eliminate human factors (illness, risk of labor disruption, etc.) (.394)
Reduce unit cost of container handling	• Reduce labor cost (.462)	• Limited land for expansion (-.391)
Reduce air/ GHG emissions	• Financial incentives/subsidies by public entities or port authority (.511)	• Improve truck turn time (.365)
Improve efficiency to handle larger vessels	• Increase safety (.498) • Meet KPIs required by ocean carrier (.607)	• Reduce variability in performance (.438) • 24/7 hours of operation (.438) • Eliminate human factors (illness, risk of labor disruption, etc.) (.424)
Limited land for expansion		• Competitive forces from other terminal operators who opted for automation (.393) • Reduce unit cost of container handling (-.391)
Improve truck turn time		• Reduce air/ GHG emissions (.365)
Increase safety	• Reduce variability in performance (.643) • Reduce labor cost (.575) • 24/7 hours of operation (.593) • Eliminate human factors (illness, risk of labor disruption, etc.) (.600) • Improve efficiency to handle larger vessels (.498)	• Meet KPIs required by ocean carrier (.446)
24/7 hours of operation	• Eliminate human factors (illness, risk of labor disruption, etc.) (804) • Reduce labor cost (.511) • Increase safety (.593)	• Improve efficiency to handle larger vessels. (428) • Competitive forces from other terminal operators who opted for automation (.367)
Reduce variability in performance	• Increase safety (.643) • Eliminate human factors (illness, risk of labor disruption, etc.) (.459) • Meet KPIs required by ocean carrier (.620)	• Competitive forces from other terminal operators who opted for automation (.397) • 24/7 hours of operation (.424) • Improve efficiency to handle larger vessels (.438) • Reduce labor cost (.382)
Eliminate human factors (illness, risk of labor disruption, etc.)	• 24/7 hours of operation (.804) • Increase safety (.600) • Meet KPIs required by ocean carrier (.544) • Reduce variability in performance (.459)	• Reduce labor cost (.394) • Improve efficiency to handle larger vessels .424) • Competitive forces from other terminal operators who opted for automation (.351)
Meet KPIs required by ocean carrier	• Improve efficiency to handle larger vessels (.607) • Eliminate human factors (illness, risk of labor disruption, etc.) (.544) • Competitive forces from other terminal operators who opted for automation (.549)	• Increase safety (.446)
Competitive forces from other terminal operators who opted for automation	• Meet KPIs required by ocean carrier (.549)	• Reduce labor cost (.400) • Reduce variability in performance (.397) • 24/7 hours of operation (.357) • Eliminate human factors (illness, risk of labor disruption, etc.) (.351) • Financial incentives/subsidies by public entities or port authority (.403)
Test-bed for new technologies / Showcase technological expertise of local terminal and/or research community	• Financial incentives/subsidies by public entities or port authority (.455)	•
Financial incentives/subsidies by public entities or port authority	• Reduce air/ GHG emissions (.511) • Test-bed for new technologies / Showcase technological expertise of local terminal and/or research community (.455)	• Competitive forces from other terminal operators who opted for automation (.403)

** Correlation is significant at the 0.05 level (2-tailed); **. Correlation is significant at the 0.01 level (2-tailed).*

Table 8. Correlations of benefits realized from automation

	High Correlation **	Correlation*
Reduced labor cost	• Increased safety (.514**) • 24/7 hours of operation (.545**) • Better meeting KPIs required by ocean carrier (.494**) • Reduced variability in performance (more consistency) (.473**)	• Reduced unit cost of container handling (.370*) • Elimination of human factors (illness, risk of labor disruption, etc.) (.362*)
Reduced unit cost of container handling		• 24/7 hours of operation (.400*) • Reduced labor cost (.370*)
Reduced air/GHG emissions		• Improved efficiency to handle larger vessels (.418*)
Improved efficiency to handle larger vessels	• Better meeting KPIs required by ocean carrier (.731**) • Increased safety (.566**) • Reduced variability in performance (more consistency) (.559**)	• Reduced air/GHG emissions (.418*) • 24/7 hours of operation (.369*)
Increased land productivity	• Better meeting KPIs required by ocean carrier (.444*)	
Improved truck turn time		• Improved efficiency to handle larger vessels (.566**) • Better meeting KPIs required by ocean carrier (.517**)
Increased safety	• 4-10-Elimination of human factors (illness, risk of labor disruption, etc.) (.676**) • Better meeting KPIs required by ocean carrier (.544**) • Reduced labor cost (.514**) • 24/7 hours of operation (.505**)	
24/7 hours of operation	• Reduced variability in performance (more consistency) (.586**) • Elimination of human factors (illness, risk of labor disruption, etc.) (.576**) • Reduced labor cost (.545**) • Increased safety (.505**)	• Better meeting KPIs required by ocean carrier (.456**) • Reduced unit cost of container handling (.400*) • Improved efficiency to handle larger vessels (.369*)
Reduced variability in performance (more consistency)	• Increased safety (.797**) • Better meeting KPIs required by ocean carrier (.755**) • Improved efficiency to handle larger vessels (.559**) • 24/7 hours of operation (.586**) • Elimination of human factors (illness, risk of labor disruption, etc.) (.519**) • Reduced labor cost (.473**)	
Elimination of human factors (illness, risk of labor disruption, etc.)	• Increased safety (.676**) • 24/7 hours of operation (.576**) • Reduced variability in performance (more consistency) (.519**)	• Reduced labor cost (.362*) • Better meeting KPIs required by ocean carrier (.351*)
Better meeting KPIs required by ocean carrier	• Reduced variability in performance (more consistency) (.755**) • Improved efficiency to handle larger vessels (.731**) • Increased safety (.544**) • 24/7 hours of operation (.456**)	• Increased land productivity (.444*) • Elimination of human factors (illness, risk of labor disruption, etc.) (.351*)
4-12-Boost for technological and operational innovation by terminal operator	• Increased safety (.517**) • Reduced labor cost (.494**)	

** Correlation is significant at the 0.05 level (2-tailed); **. Correlation is significant at the 0.01 level (2-tailed)/*

Table 9. Predictors of the importance of the drivers towards automation

		Constant	X_2	X_5	X_6	X_7	X_8	X_{10}	X_{11}
Y_5 - Limited land for expansion	Estimate	33.65	-0.0157		0.0003			0.008	
	tStat	(3.067)	(-2.879)		(2.968)			(2.804)	
Y_{13}-Competitive forces from other terminal operators who opted for automation	Estimate	-0.288		-0.008			9.944		
	tStat	(-0.651)		(-3.358)			(4.528)		
Y_{14}-Financial incentives/subsidies by public entities or port authority	Estimate	-0.223		-0.016		0.292			-0.002
	tStat	(-0.136)		(-4.317)		(2.467)			(-3.072)

Table 10. Predictors of the realized benefits of automation

		Constant	X3	X6	X7	X9	X12	X14	X15	X19
Y_1-Reduced labor cost	Estimate	0.544					0.253			
	tStat	(0.1067)					(2.322)			
Y_5-Increased land productivity	Estimate	1.784		0.0001						
	tStat	(12.76)		(2.221)						
Y_7-Increased safety	Estimate	0.914					0.204			
	tStat	(2.028)					(2.108)			
Y_8-24/7 hours of operation	Estimate	80.603	-0.041		0.237			-0.159	0.339	
	tStat	(2.699)	(-2.761)		(3.997)			(-2.088)	(3.988)	
Y_9-Reduced variability in performance (more consistency)	Estimate	0.621					0.239			
	tStat	(1.245)					(2.234)			
Y_{11}-Better meeting KPIs required by ocean carrier	Estimate	1.146			0.153					1.146
	tStat	(-1.193)			(2.623)					(-1.193)
Y_{12}-Boost for technological and operational innovation by terminal operator	Estimate	1.202				0.004				1.202
	tStat	(6.559)				(1.970)				(6.559)

Table 11. Importance of drivers in deciding whether to automate container terminals: Fully vs Semi-automated containers

Drivers	**Fully-automated**		**Semi-automated**		**Δ (Full-Semi)**
	Average (1)	St. Dev	Average (2)	St. Dev	(1)–(2)
Increase safety	**6.18**	0.87	**6.33**	1.53	-0.15
Reduce unit cost of container handling	**5.91**	1.38	**5.95**	1.28	-0.04
Reduce labor cost	**5.82**	1.17	**5.14**	2.22	0.68
Reduce variability in performance	**5.73**	1.56	**5.57**	1.72	0.16
Reduce air/ GHG emissions	**5.45**	1.75	4.67	1.59	0.79
Improve efficiency to handle larger vessels	4.91	1.81	**5.00**	1.87	-0.09
Improve truck turn time	4.82	1.89	4.57	1.21	0.25
24/7 hours of operation	4.36	2.25	**5.57**	1.83	-1.21
Eliminate human factors (illness, risk of labor disruption, etc.)	4.00	2.49	**5.62**	1.56	-1.62
Test-bed for new technologies / Showcase technological expertise of local terminal and/or research community	4.00	2.79	2.76	2.00	1.24
Limited land for expansion	3.91	2.02	3.48	2.62	0.43
Meet KPIs required by ocean carrier	3.55	1.86	4.00	2.24	-0.45
Competitive forces from other terminal operators who opted for automation	2.73	2.49	2.38	2.44	0.35
Financial incentives/subsidies by public entities or port authority	2.45	2.94	1.33	1.91	1.12

Notes: N=32 terminal operators; Scale: 1=limited benefits; 7=Maximum benefits; 0= No benefit at all.

Table 12. Benefits realized from the introduction of automation: Semi vs Fully-automated terminals

Benefits	**Fully-automated**		**Semi-automated**		**Δ (Fully-Semi)**
	Average (1)	St. Dev	Average (2)	St. Dev	(1)–(2)
Increased safety	**6.27**	1.104	**6.29**	1.521	-0,01
Reduced labor cost	**6.09**	.944	**5.10**	1.740	1.00
Reduced unit cost of container handling	**5.64**	1.029	**5.62**	1.465	0.02
Reduced variability in performance (more consistency)	**5.64**	1.804	**5.38**	1.687	0.26
Reduced air/GHG emissions	**5.64**	1.804	**5.24**	1.546	0.40
Improved truck turn time	**5.27**	1.555	4.90	1.338	0.37
Increased land productivity	**5.09**	1.921	4.33	2.477	0.76
Elimination of human factors (illness, risk of labor disruption, etc.)	4.91	2.119	**5.95**	1.596	-1.04
Improved efficiency to handle larger vessels	4.91	2.071	4.62	1.962	0.29
Boost for technological and operational innovation by terminal operator	4.91	2.809	4.05	1.857	0.86
24/7 hours of operation	4.55	2.841	5.00	2.490	-0.50
Better meeting KPIs required by ocean carrier	3.82	2.272	3.71	2.369	0.10

Notes: N=32 terminal operators; Scale: 1=limited benefits; 7=Maximum benefits; 0= No benefit at all.

Table 13. Differences between benefits realized from automation and decision-making drivers and benefits realized from automation: Fully vs Semi-automated terminals

	Fully-automated **Δ** (Benefits-Expectations)*	Semi-automated **Δ** (Benefits-Expectations)*
Reduce labor cost	0.27	-0.04
Reduce unit cost of container handling	-0.27	-0.33
Reduce air/ GHG emissions	0.19	0.57
Improve efficiency to handle larger vessels	0.00	-0.38
Limited land for expansion	1.18	0.85
Improve truck turn time	0.45	0.33
Increase safety	0.09	-0.04
24/7 hours of operation	0.19	-0.52
Reduce variability in performance	-0.09	-0.19
Eliminate human factors (illness, risk of labor disruption, etc.)	0.91	0.33
Meet KPIs required by ocean carrier	0.27	-0.29
Test-bed for new technologies / Showcase technological expertise of local terminal and/or research community	0.91	1.29

** A positive difference indicates that the achieved benefits were greater than the benefits expected; a negative number indicates that the achieved benefits were less than the benefits expected; scale of importance of drivers from 1 to 7, 0= No benefit at all; scale of benefits realized from 1 to 7, 0= No benefit at all.*