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Dangerous Goods in Maritime Transport: Assessment of Container Scanning as Means of Risk Mitigation

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Maritime accidents caused by misdeclared dangerous goods have resulted in significant losses over recent years. We study if the amount of these accidents could be reduced by scanning the cargo containers in a port before they are loaded to ship. A combination of methods was used to address this question. We present a summary of findings for our review of accidents caused by dangerous goods. We used this review as a basis for a risk assessment that consisted of risk identification and a failure mode and effect analysis. The operational implications of a scanner were further assessed using a single server queue model. This study considers a novel muon scanner technology that could mitigate the risk of accidental radiation exposure. The exact operational parameters of these scanners are not public. So, we performed a sensitivity analysis with different scanning parameters. Our results and conducted expert interviews show that scanning the containers can reduce the risk. However, this practice may create new operational challenges regarding managing detected misdeclared containers.

Keywords: Dangerous goods, Maritime transport, Container scanning, Risk assessment, FMEA, Single Server Queue Model.

1. Introduction

There have been over 70 reported fires on board container ships alone in the past five years AGCS (2022). Poor practices related to dangerous goods, such as misdeclaring or undeclaring them are major causes of these accidents Gonzalez-Aregall et al. (2021). Although shipping companies have implemented strategies to avoid misdeclaration TT Club (2017); CINS (2023), it is estimated that 1/3 of the dangerous goods are undeclared AGCS (2022). This issue is significant, as about 1/10 of all shipped containers contain declared dangerous goods.

This study examines if scanning the containers before they are loaded onto ships could prevent these accidents. In the past, similar studies have been conducted to assess the feasibility of scanning 100% of outbound containers in ports Alix et al. (2010); Bakshi et al. (2011). These were prompted by U.S. legislation demanding such action. Today, scanners are mainly used by customs to detect illicit goods Visser et al. (2016). This study was conducted as a part of a research project that focuses on a new scanning technology based on cosmic ray muons Barnes et al. (2023). Therefore, we gave special consideration to this technology.

We combine different methods to assess the potential of these scanners, as illustrated by Fig. 1. Mind map approach and accident review were used for risk identification and providing historical data about dangerous goods accidents. These risks were then analyzed using the FMEA method Carlson (2012). We validated the results using semi-structured expert interviews Adams (2015). Congestion in a port was one of the identified risks that also identified in the expert interviews. The impact of a scanner in a port was studied with a Single Server Queue (SSQ) model Cohen (1992). As the exact scanning time and accuracy are uncertain, we further performed a sensitivity analysis.

Section 2 presents the results of the accident review, and section 3 the risk assessment with a mind map and FMEA methods. In section 4, the impact of a scanner in a port is discussed based on

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simulation results from the SSQ model. Section 5 summarizes the findings gathered from expert interviews, and section 6 draws our conclusions, which suggest that scanning the containers can reduce the risk but introduces operational challenges.

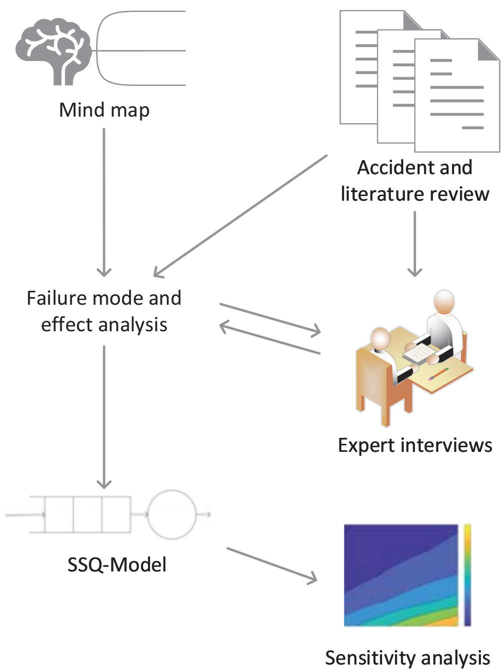

Fig. 1. Joint use of methods to assess the feasibility of mitigating dangerous goods risks with container scanning.

2. Accident Review

This review combines information from past studies Ellis (2011), Callesen et al. (2021), and Krmek et al. (2022) with news articles to identify the main causes of accidents due to dangerous goods. In total, we identified 53 dangerous goods accidents during the years 2005-2022. This subset consisted of accidents occurring mostly in Europe and Asia. Notably, accidents that occurred due to technical reasons, such as the collision of the cranes, are not considered, unless dangerous goods aggravated the accident.

Fig. 2 shows the identified main attributes of dangerous goods accidents. An accident can be in many categories, for example, if a container fire was caused by undeclared dangerous goods. Based on our study, calcium hypochlorite, charcoal, and lithium-ion batteries are the most commonly misdeclared dangerous goods involved in accidents. All these goods are flammable.

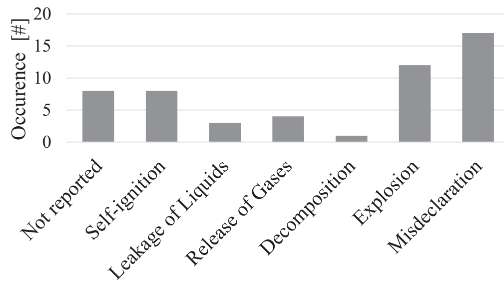

Fig. 2. Frequency of selected attributes in dangerous goods accidents.

3. Risk Assessment

Our study uses the risk management process defined by ISO 31000 standard ISO (2018) as guidance for our risk assessment. This standard defines risk assessment to consist of risk identification, risk analysis, and risk evaluation. Section 3.1 presents the findings from our risk identification, and section 3.2 presents risk analysis based on the FMEA method Carlson (2012). Risk evaluation was not performed as this is an academic study. The purpose is only to provide input on a potential evaluation of which risks need treatment.

3.1. *Risk Identification*

We performed the risk identification based on the accident review and an assessment of port processes illustrated in Fig. 3. However, we mainly used an earlier work by Bakshi et al. (2011) as a reference for the process. A mind map is used as a method to organize the identified risks. This method has been used for example in the past for identifying cyber risks Hristova et al. (2014) and Saad et al. (2016).

Fig. 4 shows a mind map that arranges the identified risks under four activities: 1) Arrival at the terminal, 2) Scanning at landside operations

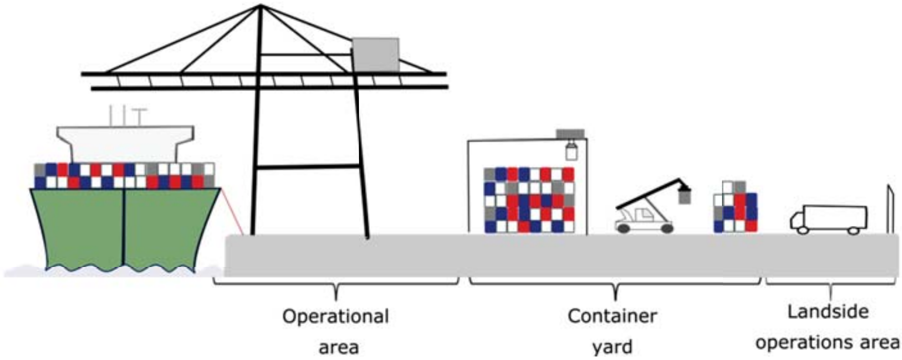

Fig. 3. Illustration of a container terminal showing the three main zones: operational area, container yard, and landside operations area Hervás-Peralta et al. (2019) (CC BY).

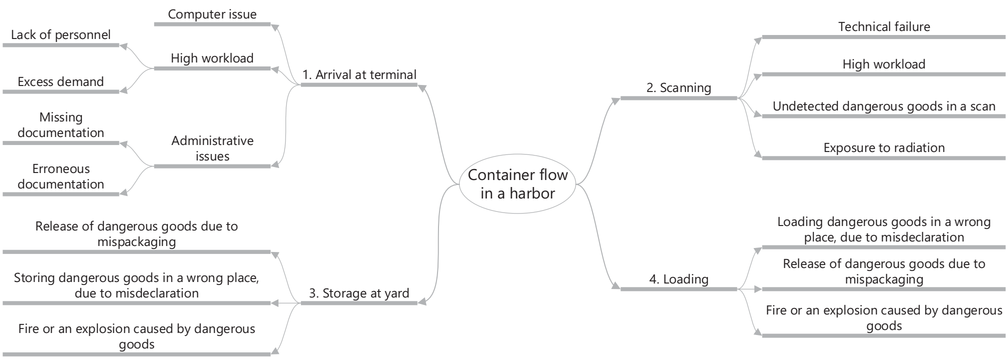

Fig. 4. Mind map of risks identified in the container flow process.

area, 3) Storage at the yard, and 4) Loading. This activity is similar to brainstorming. Thus, the map combines risks with different causes and consequences. These include risks from minor administrative issues to severe accidents in ships.

3.2. *Risk Analysis with FMEA*

We conducted a Failure Mode and Effect Analysis (FMEA) Carlson (2012) for the identified risks. This method ranks the risks based on Risk Priority Number (RPN). It is calculated with the following equation

$$\mathrm{RPN} = \mathrm{S} * \mathrm{O} * \mathrm{D}, \tag{1}$$

where S is the severity, O occurrence, and D detectability. Ideally, the RPN should be as low as possible. We used the method qualitatively and evaluated the risks against the criteria in Table 1.

We performed an evaluation both for the initial risks and also considering a mitigating action. Table 2 presents the evaluation of dangerous goods related risks and Table 3 of scanning system related risks. In both tables, the subscript ”M” denotes the evaluation considering the mitigation. The initial numbers were revised based on our expert interviews. Especially the risk of leakage of dangerous goods was understood to occur much more frequently than what we considered.

Both the leakage and gas release have high occurrence ratings. The identified main cause for these issues is the lack of adequate packaging, which is often difficult to detect since cargo is stowed in sealed containers. Practically, the easiest ways to detect these issues are by detecting a smell or leaking liquid. The released dangerous goods can damage other cargo through chemical reactions, or in the worst case lead to a fire or an

Table 1. Rating criteria for FMEA.

Rating	Severity	Occurrence	Detectability
2	Minor financial loss	At most annually	Very easy to detect
4	Significant loss	Multiple times per year	Easy to detect
6	Limited threat to health	Multiple times per month	Detectable
8	Increased threat to health	Multiple times per week	Hard to detect
10	Acute threat to health	Multiple times per day	Undetectable

Table 2. FMEA for dangerous goods related risks.

Failure mode	Effects	Causes	S	O	D	RPN	Mitigation	S_M	O_M	D_M	RPN_M
Misdeclared dangerous goods	Container wrongly loaded to ship	Incorrect labeling due to negligence or criminal intent	8	10	8	640	Manifest verification	8	5	4	160
——”——	——”——	———”———	–”–	–”–	–”–	–”–	Container weighing and **scanning**	8	2	4	64
——”——	Issue noticed causing a delay	———”———	4	10	1	40	Manifest verification	4	5	1	20
——”——	——”——	———”———	–”–	–”–	–”–	–”–	Container weighing and **scanning**	4	2	1	8
Explosion	Explosion in a terminal	Overheating or leakage causing chemical reaction	10	2	8	160	-	-	-	-	-
——”——	Explosion in a ship	———”———	10	2	8	160	Temperature control in a ship	10	1	1	10
Self-ignition	Start a fire	———”———	10	2	8	160	Firefighting system	9	2	1	18
Decomposition	Damage to cargo	———”———	4	8	10	320	-	-	-	-	-
Gas release	Potential to cause fire	Incorrect or damaged packaging	8	8	9	576	Inspection with gas detector	8	4	2	64
Leakage	Potential to cause fire or damage other cargo	———”———	8	8	10	640	Visual inspection	8	8	9	576

explosion.

The FMEA approach is inconvenient for assessing conditional risks, as the method is usually used in cases where each contributor is considered separately Carlson (2012). Here the issue is that a misdeclaration can either lead to a finan-

Table 3. FMEA for scanning system related risks.

Failure mode	Effects	Causes	S	O	D	RPN	Mitigation	S_M	O_M	D_M	RPN_M
Lack of personnel to conduct scans	Increased queuing time for a scan	Financial or hiring issues	2	4	1	8	-	-	-	-	-
——"——	More limited number of scans	——"——	6	4	2	48	-	-	-	-	-
Human error in depicting scan results	Container wrongly loaded to a ship	Insufficient training or hard to interpret results	8	4	8	256	Regular training, or accessible documentation	8	2	6	96
Scanner unavailable due to a fault	Scanner does not work	Component related failures	6	4	1	24	Maintenance plan	6	3	1	18
Sudden increase of workload	Increased queuing time for a scan	More incoming containers than expected	2	8	1	16	Setup an arrival schedule	2	4	1	8
——"——	More limited number of scans	——"——	6	8	1	48	——"——	6	4	1	24
Blackout	No electricity for scanner	Fault in electricity distribution	6	2	1	12	Uninterruptable power sources	6	1	1	6
Missing manifest	Minor process delay	Error by a shipper	4	4	1	16	Papers in advance principle	4	2	1	8
Scan image incomprehensible	Re-scan or physical inspection	Erroneous container placement, or scanner shortcoming	4	3	1	12	Technical development	4	2	1	8
Human exposure to X-ray radiation	Potential long term health issue	Accident or a stowaway hiding in container	4	1	8	32	Provide **muon scanner**	0	1	1	0

cial impact on the container shipment (delay) or improper stowage, with the potential to lead to severe accidents. Due to this accident potential, the current assessment yields a rather high RPN for the misdeclaration. When one considers only the risk of fire or explosion, the occurrence rate is significantly lower than the risk of misdeclaring dangerous goods resulting in lower RPNs.

Our proposed mitigation measures intend to reduce the severity and likelihood or to increase the chances to detect the risk. Most of these measures are from International Maritime Organization guidelines and best practice documents published by CINS and TT Club. When muon scanners are considered, the risk of a person being exposed to X-ray radiation is eliminated, as the technology relies on naturally occurring cosmic rays Barnes et al. (2023).

4. Container Scanning Assessment with an SSQ Model

4.1. *Methodology*

An operational assessment of container scanning is done with a Single-Server-Queuing (SSQ) model Cohen (1992). Fig. 5 illustrates how an SSQ model can represent the scanning process in a port.

An SSQ model is based on the first-in-first-out principle with containers arriving at random times at the terminal. The arrival time (t_n) is defined as a Poisson process as follows:

$$t_n = \max(1, 1 - \bar{A} * \ln(1 - r)), \qquad (2)$$

where $\bar{A}$ is the average interarrival time and r is a random value between 0 and 1. The arriving containers are waiting in a queue to be scanned. The server is frequently modeled with an exponential distribution. However, here we assume that the scan time μ is constant.

4.2. *Sensitivity Analysis*

The exact performance of scanning is uncertain. For the existing scanners, the exact chance to detect incorrect cargo is not public information. For a muon scanner, both the scanning time and the detection rates are uncertain due to the novelty of the technology. Therefore, we performed a sensitivity analysis to understand how these uncertain inputs affect the SSQ model output. We consider that the Overall Equipment Effectiveness (OEE) Stamatis (2011) concept is useful for assessing the scanning process. It is measured as

$$\text{OEE} = \text{Availability} * \text{Performance} * \text{Quality}. \qquad (3)$$

We assume that the availability is 100% and consider first how the performance varies with different scanning times between one to five minutes. Table 4 shows these results. The performance reduction with scanning time can be interpreted as the process being affected by small delays in container arrival times. This feature is caused by the fact that a shorter scan time allows more containers to be scanned, which leads to more chances for delays to occur.

Table 4. Resulting equipment effectiveness with different scanning times in simulations.

Time [min]	Average daily scans [#]	OEE [%]
1	1036	72
2	633	88
3	442	92
4	328	91
5	269	93

Next, the detection rate was varied between 50% to 100%. In the OEE concept, this can be understood to be the quality in terms of a failed scan. In this analysis, we only consider false negative scans where a container had misdeclared dangerous goods, but the scan failed to detect them. In a more thorough assessment, one could also consider the operational delays caused by false positive detections.

We consider that achieving 100% performance requires scanning 1440 containers per day, i.e. scanning one container per minute[a]. We assume that the containers that a scanner did not have time to scan will be passed through without scanning them. Fig. 6 combines the performance values from Table 4 to the varying detection rate. It shows that in this scenario, the performance is more strongly linked to the scanning time. When a large number of containers that are not scanned are loaded onto a vessel, the improvement to the present situation is small.

One can draw two conclusions from this result. Firstly, it motivates the 100% container scanning schema that has been considered in the USA Alix et al. (2010); Bakshi et al. (2011) and explains why airport security scans all the passengers. It also motivates the practice where the customs use so-called targeting algorithms to choose which

[a]In the port of Hamburg, there are on average 11389 outbound containers per dayPort of Hamburg (2023) and they operate 24/7 on 360 days per year.

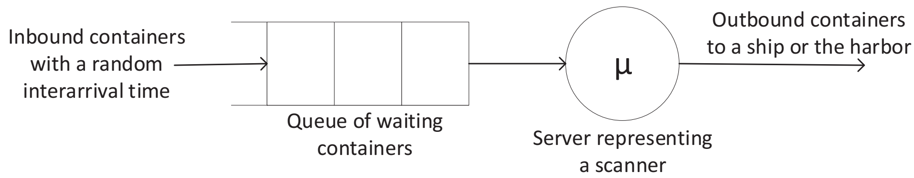

Fig. 5. SSQ model of the container scanning process.

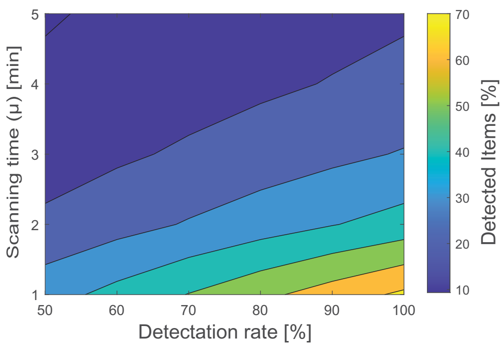

Fig. 6. Sensitivity analysis that shows the number of detected items as a function of scanning time μ, and detection rate. Shorter μ results in more detected items, as the number of scanned containers increases.

arriving containers to scan for detecting illicit goods Vanhoeyveld et al. (2020).

5. Summary of Expert Interviews

We conducted semi-structured interviews Adams (2015) with three experts working in the maritime field whose work involves dangerous goods. Experts worked as a consultant in safety management, a director of the dangerous goods department, and a principal engineer in a classification society, which gives certificates to carry dangerous goods.

All of them agreed that leakages are the most common type of incident for dangerous goods and they are quite unreported. Correct stowage of these goods is a crucial aspect during transport and failing to do it can result in severe accidents. Experts mentioned examples of bad stowage including a lack of load securing that allows the cargo to move, incorrect packaging, or a failure to respect the quantity limits for dangerous goods in individual containers. Misdeclaring the goods can also lead to bad stowage as the goods are treated as normal cargo. The experts named several reasons that can cause the misdeclaration of dangerous goods. These can be a lack of knowledge, lack of incentive, loss of information within the logistics chain, or seeking cost savings.

All participants highlighted that some Asian and developing countries may have poor training on dangerous goods handling. Experts stated that the regulations and training are less accessible in countries that lack their own regulations. One expert estimated that the amount of these goods can be lower than 0.05% of the cargo, which is much less than the 5% value that was given in AGCS (2022). However, the expert stressed that even this low percentage is significant considering the large volumes of cargo.

Regarding the scanning of the containers, the experts thought that having a scanner may act as a deterrent and discourage criminal acts and misdeclaration. They were also curious if a scanner could detect bad stowage of the goods. Yet, having a scanner may lead to new issues with container flow. It is an additional step in the process, which might cause congestion. Experts also noted the limited experience in dealing with containers caught in a check. If the number of these containers is large, it may cause logistical issues.

6. Conclusions

This work began with the question if scanning the containers in a port can reduce the risk of misdeclared dangerous goods. We conducted an accident review, risk analyses, operational assessment with a single server queue model, and expert interviews to address this question. The main conclusion of our work is that this practice can reduce the risks caused by misdeclared dangerous goods. Our study also gave ideas on potential future research topics. Misdeclaration is not the sole issue linked to dangerous goods. Bad stowage of these goods is a risk factor. Therefore, it would be useful to have a non-intrusive way to inspect cargo stowing within a container.

The sensitivity assessment in section 4.2, reaffirmed the current security practices where all the items or a selected set of items are inspected. It is more realistic to assume that a scanner would be used selectively based on a targeting algorithm Vanhoeyveld et al. (2020). The legislation requiring 100% container scanning was passed in the USA more than ten years ago Alix et al. (2010); Bakshi et al. (2011), but it has not been implemented. Therefore, efficient scanning of the outbound containers depends on having inspection targeting algorithms. Ideally, these should detect containers with safety issues concerning dangerous goods, as well as criminal cases that interest customs.

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