TNO report

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Inventory of technologies for monitoring, tracking and identification of maritime containers and their cargo

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Samenvatting

Dit rapport is opgesteld in opdracht van het Ministerie van Infrastructuur en Waterstaat naar aanleiding van het incident met de MSC Zoe. Het bevat een inventarisatie van de technologische mogelijkheden voor het lokaliseren en het bepalen van de inhoud van containers.

Schepen verliezen soms containers op zee. Het gaat hierbij meestal om geringe aantallen. MSC Zoë verloor in de nacht van 2 januari 2019 342 containers ten noorden van de Waddeneilanden. Het duurde enige tijd om vast te stellen hoeveel containers er overboord gevallen waren.

Deze inventarisatie gaat ook over technologieën die helpen bij het bewaken van de integriteit van de stuwage van containers tijdens de reis. Dit is relevant omdat identificatie van het exacte tijdstip en locatie van een incident met overboord geslagen containers veelal het startpunt is voor effectieve opsporingstechnieken.

Voor de inventarisatie is gebruik gemaakt van desk research, interviews met tien domeinexperts binnen TNO en interviews met vijf externe experts. Daarmee is getracht een overzicht te bieden van huidige technologische mogelijkheden. Gezien de beperkte opdracht kan TNO de volledigheid van de inventarisatie niet garanderen.

Incident monitoring
Verschillende monitoringmethoden kunnen worden overwogen om te controleren of containers tijdens de reis nog aan dek staan. De beschreven toepassingen aan boord van schepen (visuele methoden en scheepssensoren) zijn, afhankelijk van investeringen door de sector schaalbare oplossingen die ook kosteneffectief kunnen zijn.

Intelligente beeldanalysetechnieken kunnen sommige van deze technologieën ondersteunen en zowel de efficiëntie als de effectiviteit verhogen. Als alternatief kunnen de containers worden uitgerust met sensoren die schokken, vallende bewegingen of snelle veranderingen in vochtigheid registreren. Dergelijke conditiemonitoringsmethoden kunnen ook worden ingezet om een mogelijke inbreuk op de stuwage integriteit te identificeren. Om een en ander kostenefficiënt uit te voeren zou ook alleen de buitenste en bovenste laag containers uitgerust kunnen worden met deze sensoren.

Lokaliseren containers
Voor het lokaliseren van containers zijn er verschillende scenario's waarmee rekening moet worden gehouden. Voor lokalisatie tijdens de reis en zolang containers drijven kunnen containertrackingtechnologieën zeer effectief zijn. Afhankelijk van het bereik en de bandbreedte, kunnen daarbij verschillende communicatietechnologieën worden overwogen. De inzet van LPWAN-oplossingen laat een snelle groei zien. Deze toepassingen kunnen zowel logistieke als commerciële functionaliteiten combineren.

Radar en Lidar zijn responsieve technologieën voor lokalisatie wanneer containers overboord gevallen zijn maar nog drijven. Voor onderwaterdetectie kunnen

verschillende sonartechnologieën worden overwogen. Sommige van deze technologieën kunnen ook fracties van containers lokaliseren. Dit is relevant omdat een groot aantal containers tijdens of na de val in stukken breekt. de kosten van inzet van sonartechnologie zijn hoog voor het lokaliseren van individuele containers.

Inhoud identificatie en detectie
Tenslotte zijn er technologische oplossingen om de inhoud van de container te achterhalen. Ten eerste kan het logistieke dataspoor worden gevolgd, ofwel via vervoerdersgegevens, die globale beschrijvingen van de containerinhoud bevatten, ofwel via visibility systemen, die transactiedata van verschillende order- en zendingstransacties combineren. Dat laatste is technisch mogelijk, maar praktisch lastig uitvoerbaar. Alleen als er een sterk commercieel belang is bij het combineren en vastleggen van verschillende transactiegegevens, kunnen verbindingen worden gelegd en is end-to-end zichtbaarheid c.q. beschikbaarheid voor de geautoriseerde gebruiker mogelijk.

Als alternatief kunnen visuele en niet-intrusieve inspectietechnologieën worden toegepast. Hierbij kan gedacht worden aan röntgen apparatuur zoals ook door de Inspectiediensten en Douane op terminals wordt gebruikt.

De inventarisatie laat zien dat er voor effectief incident management bij het verliezen van containers op zee geen standaardoplossing voorhanden is. Het identificeren van betrokken containers, het bepalen waar deze zijn verloren, lokaliseren op zee en wat de inhoud van verloren containers is (of kan zijn geweest) zal een combinatie van verschillende complementaire technologieën vereisen.

Summary

This report was carried out on behalf of the Dutch Ministry of Infrastructure and Water Management in response to the incident with the MSC Zoe. It contains an inventory of technological possibilities for container tracking and corresponding cargo identification.

Incidents with fallen containers occur, often involving a small number of containers. In the night of January 2nd in 2019, MSC Zoë lost 342 containers northwards of the Wadden Islands. It took quite a while to conclude how many and which particular containers were involved, and detailed information on the content of these containers appeared hard to track down.

This inventory also includes technologies to help monitoring the integrity of the stowage plan during the voyage. This is relevant since identification of the exact time and location of an incident with the stowage integrity, is the starting point for effective localization technologies.

The analysis is based on desk research, interviews with ten domain experts within TNO and five external experts. In this way, the report offers an extensive overview of possible technological solutions, though completeness cannot be guaranteed.

Incident monitoring
Several monitoring methods can be considered to check if containers are still onboard during transport. The ones applied on board of vessels (visual methods and ship sensors) are – depending on the sector investments - scalable solutions, and can be rather cost effective as well. Data science or intelligent imaging techniques can support some of these technologies and increase both efficiency and effectiveness. Alternatively, the containers can be equipped with sensors that register shocks, falling movements or quick changes in humidity. These condition monitoring methods can also identify a possible breach of the stowage integrity. A cost effective solution might be to equip only the top and outer layer containers in the stowage plan with these sensors.

Localizing containers
For container localization there are different scenarios to be considered.
For localization during voyage and containers floating above water, container tracking technologies can be highly effective. Depending on the range and bandwidth, several communication technologies could be considered. For the application of end-to-end container tracking, LPWAN solutions show rapid growth. They combine functionality to comply to both logistical and commercial requirements.

More responsive above water technologies include radar and lidar. For underwater detection, several sonar technologies can be considered. Some of these responsive technologies can also localize fractions of containers. This is relevant since quite a number of containers break in pieces during or after the fall.

Cargo identification and detection

Finally, there are technological solutions to track down the container contents. First, there is the logistics data trail, either via carrier data disclosing high-level descriptions of the cargo, or via visibility systems that combine different order and shipment transaction data. The latter is technically possible, but rather challenging to scale. Only if there is a strong commercial interest to capture and combine these different transaction data, the connections are also being captured and end-to-end visibility is available for the authorized user.

Alternatively, visual and non-intrusive inspection technologies could be applied. Think of röntgen equipment that Customs and inspection administrations use in sea terminals.

The inventory makes clear that there is no ‘one size fits all solution’ for effective incident management in case of lost containers during sea voyage. It would require a combination of different complementary technologies to identify which containers are involved in the incident, where and when the incident took place, where the lost containers are situated, and what the content of the involved containers exactly is (or was).

Contents

1 Introduction

Ships lose containers in the Dutch part of the North Sea almost every year. The last couple of years average about 25 containers per year. On the night of January 2nd, 2019, the ship MSC Zoe lost 342 containers - an exceptionally large number - north of the Wadden Islands. It is difficult to locate containers that have been fallen overboard. This has been demonstrated with the MSC Zoe, but also with other incidents. Moreover, it is also difficult to trace the detailed cargo details of the container that has been fallen overboard. In her letter of 15 January 2019 to the House of Representatives in response to the incident with MSC Zoe, the Minister of Infrastructure and Water Management indicated that she would make efforts to make it easier to detect containers in the event of incidents (she explicitly stated container chipping) and that she would explore the possibilities for this. In doing so, it was indicated that agreements to that effect can only be realized in an international context.

According to Drewry Maritime Research, the global container fleet reached 32.9 million TEU in 2012, mainly standard dry containers. Over 200 countries have ports open to container ships. Ports measure the volume of containers they handle in twenty-foot equivalent units (TEU). In 2014, containers handled by all ports world-wide (including empties, transhipments and port handling) are estimated at more than 680 million TEU. In 2016, the international liner shipping industry transported approximately 130 million containers packed with cargo (World Shipping Council).

The figure below shows the total losses of containers globally through the years, based on reported losses by carriers from 80% of the carrier capacity.

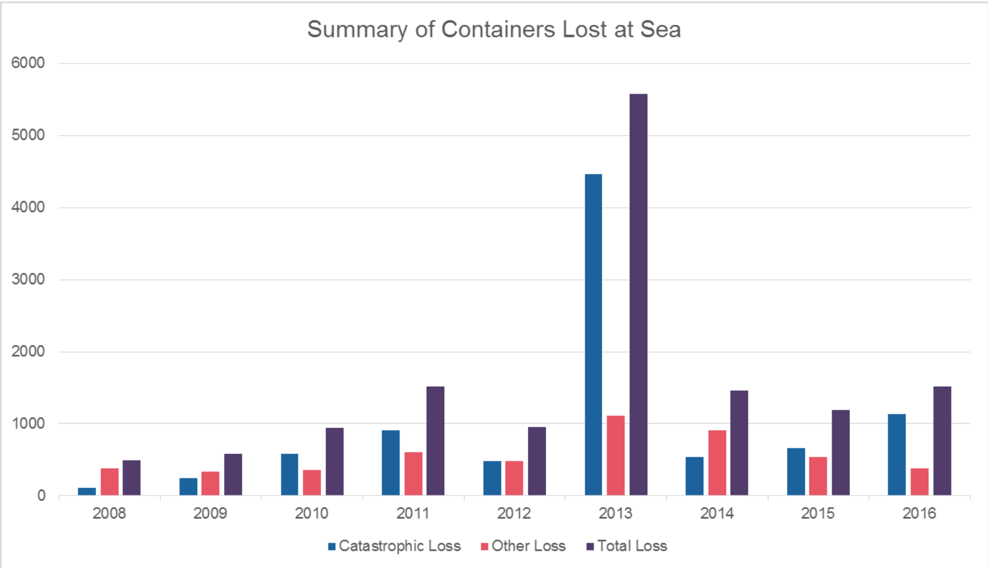

Figure 1: Worldwide containers lost at sea

Though this is just a fraction of the total number of transported containers, it may have a large impact on the environmental and ship safety.

1.1 The key questions

The Dutch Ministry of Infrastructure and Water Management asked TNO to provide a clear inventory of:

- The possibilities to track containers when they have fallen off the ship.
- The possibilities to know what the content of a found container is.

Within these two topics the following aspects should be highlighted:

1. Which technical solutions are currently available?
2. How effective are the solutions? This should be expressed in terms of reliability, precision, maturity and constraints.
3. How feasible is the solution? In which the feasibility should be measured in costs, current applications, future expectations and if the technology is complementary to other systems.
4. What can be achieved with regulations from international and national governments?

1.2 The problem scope

An incident in which a ship loses containers, can be described following certain phases. We have identified five phases to guide this report.
Figure 2 depicts the different stages of incident management related to the ocean carriage of containers, we use this to describe the different methods and corresponding technologies.

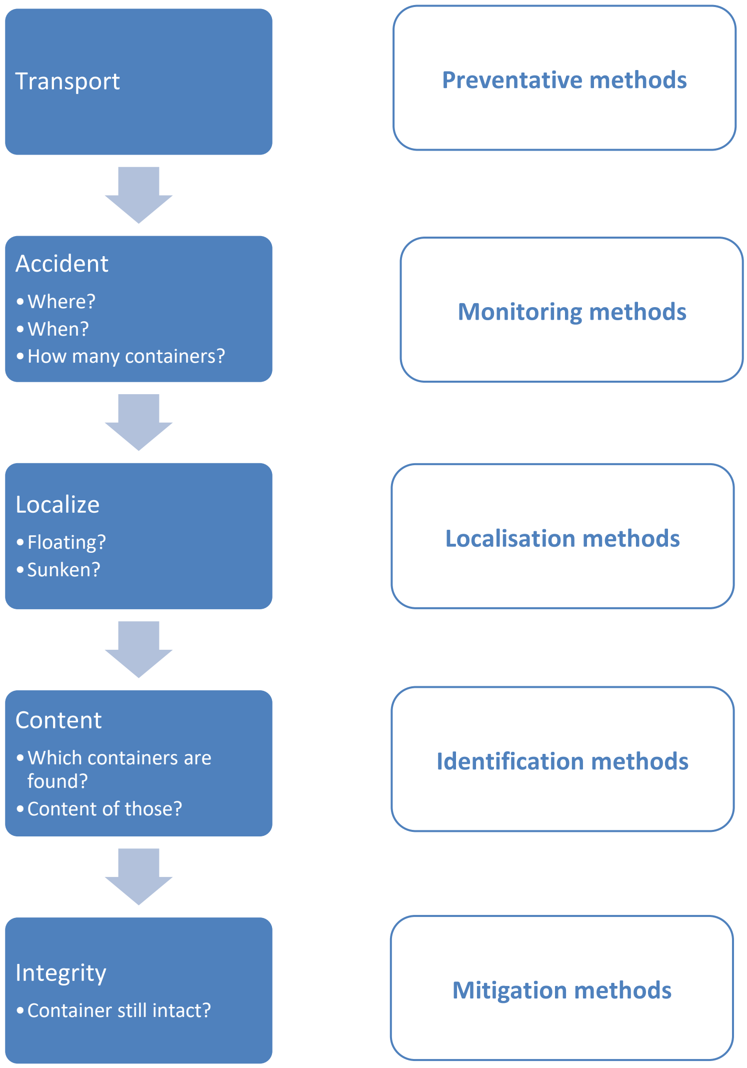

Figure 2: Diagram of different stages of incident management.

In the diagram five types of methods are identified:

1. **Preventative methods** to prevent the accident by, for example, focusing on lashing-techniques, locks, vessel stability and weight accuracy.
2. **Monitoring methods** to constantly monitor containers during transport in order to detect accidents immediately. Knowing where and when the accident occurs can be of valuable input to the localisation methods. Moreover, some of these methods are also capable of alerting exactly which container is lost.
3. **Localisation methods** are techniques to track the containers after they have fallen overboard.
4. **Identification methods** focus on the containers individually, so techniques to identify which container is found and what their individual content is.
5. **Mitigation methods** to limit damage, to ensure a safe way to recover containers and cargo lost overboard. These are methods that would benefit damage control, by – for example – techniques to check if the container is intact or by developing policies to equip dangerous goods with extra tracking devices.

In this study report, the inventory of possible techniques focusses on the monitoring, localisation and identification methods (2, 3 and 4).
So preventative methods and mitigation methods are out of scope.

1.3 Approach

In order to write this report, we performed desk research and interviews with experts.

The desk research involved a quick scan of relevant studies, articles and research reports related to the topic. This included TNOs Innovation Radar, which we used to identify possible relevant technologies such as Lidar and corresponding experts within the TNO organization for further in-depth interviews. This Innovation Radar was developed on behalf of the Ministry of Defense and includes an inventory of relevant Defense-related technologies and innovations, including technologies for tracking, detecting and localizing physical objects. The innovations include an analysis of the Technology Readiness Level (TRL). TRLs are a method for estimating the maturity of technologies during the acquisition phase of a program, developed at NASA during the 1970s. The European Commission advised EU-funded research and innovation projects to adopt the scale in 2010. TRLs were consequently used in 2014 in the EU Horizon 2020 program. We've filtered the technological solutions with TRL 7 or higher and selected the ones relevant for this study.

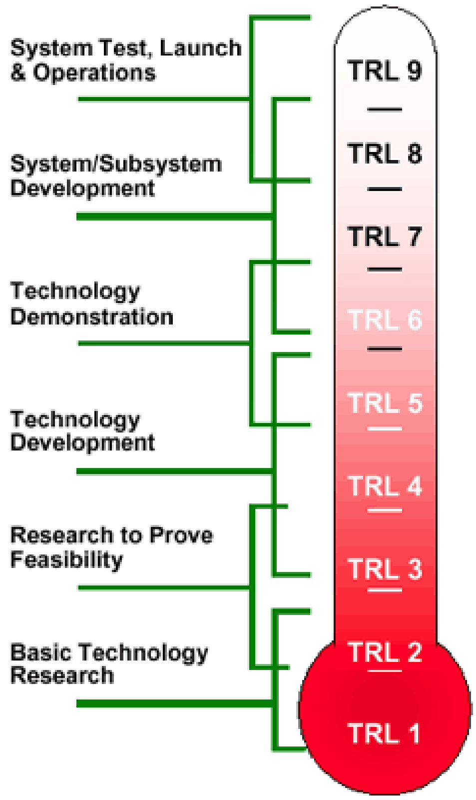

Figure 3: NASA Technology Readiness Levels

The desk research includes among others:
- Reports from SMART-CM: D1.1.1, D6.4.1, D7.3.1 (http://www.smart-cm.eu/)
- Reports from CASSANDRA (https://cordis.europa.eu/project/rcn/100060/results/en)
- Reports from CORE (http://www.coreproject.eu/ and http://www.coreproject.eu/media/16650/17-04-18-coreleaflet.pdf)
- Containers Lost at Sea Reports and studies from the World Shipping Council (https://worldmaritimenews.com/archives/tag/lost-at-sea/)
- Marine Sanctuaries Conservation Series ONMS-14-07: The Containerized Shipping Industry and the Phenomenon of Containers Lost at Sea (https://sanctuaries.noaa.gov/science/conservation/lostcontainers.html)
- Papers and documentation corresponding to the debate from May 14th 2019 about the incident with the MSC Zoe and the corresponding Hearing/Round Table procedure from April 10th 2019 (https://www.tweedekamer.nl/debat_en_vergadering/commissievergaderingen/details?id=2019A00440)
- Wikipedia for several technology descriptions (https://en.wikipedia.org/)

In-house interviews with nine subject matter experts were conducted in May 2019, representing the following domains: Sustainable Transport and Logistics, Acoustics and Sonar, Monitoring and Control Services, Networks, Radar, Structural Dynamics, Electronic Defense, Intelligent Imaging, Chemical, Biological, Radiological and Nuclear (CBRN) Protection, and Data Science.

In addition, interviews over the telephone with the following external experts were also held in May 2019 with: Wil van Heeswijk (EC DG Taxud), Jos Koning (Marin), Robin Puthli (Itude), Joris Tenhagen (Pharox), Henk van Unnik (Tosepo).

Based on the desk research findings and the interviews, we’ve drafted a quick scan assessment table of technologies and solutions for each application domain.
The tables, presented at the end of chapters 3, 4 and 5, include a quick qualitative assessment on effectiveness and (commercial) feasibility. The aspects reliability and costs contain a score on an ordinal scale between 1 and 5. A high score on reliability means the solution is more reliable in identifying an incident with fallen containers took place (Chapter 3), in correctly localizing where a container is (Chapter 4), or in determining what is exactly stuffed inside a container (Chapter 5). A high score on cost means the solution is rather cost effective. A low score corresponds to high costs.

1.4 Report structure

The report starts with an overview of wireless communication technologies (satellite and terrestrial), since there is a lot of attention for the subject of container tracking. Container tracking technologies can both be applied in the context of incident identification (monitoring methods) as well as localisation methods to localise the position of containers and identification methods to identify the contents of a container.

The chapters thereafter provide an inventory of the technologies per method, i.e. a chapter on monitoring methods, followed by localisation methods and identification methods. Each of these chapters describes the relevant applied technologies, highlighting the basic applicability, its effectiveness for the application under review, and its commercial feasibility. At the end of each chapter, all mentioned technologies are summarised in an assessment table, with the scores based on expert judgement and reviewed by the experts interviewed.

Finally, the report is concluded with a description of current container tracking applications and underlying technologies.

2 Wireless communication technologies

In the debates following the MSC Zoë incident, in January 2019, a lot of attention went out to the topic of container tracking. Most of existing container tracking technologies make use of wireless radio or satellite communication. Before we describe the applicability of these technologies for the use of monitoring, tracking or identifying containers, we start with a brief description of the basic characteristics of the different wireless communication technologies. In this chapter we frequently cited technology descriptions from Wikipedia, but did not include these references each time in the text for readability purposes.

The figure below plots the different wireless communication technologies on their bandwidth and range characteristics. High bandwidth generally means high power consumption.

We distinguish six groups, which we describe in the following sections:

1. Wireless Local Area Networks (WLAN), such as Wi-Fi (the 802.11 range);
2. Short range wireless technologies, such as Bluetooth and Zigbee;
3. Radio-Frequency Identification (RFID) and Near Field Communication (NFC);
4. Cellular communication networks, such as 2G, 3G, 4G and 5G;
5. Low Power Wide Area Networks (LPWAN), such as LoRa and Sigfox;
6. Satellite communication, such as VSAT.

After describing these technologies in the next sections, a section on network integration and mesh technologies is added followed by a summary of the communication technologies.

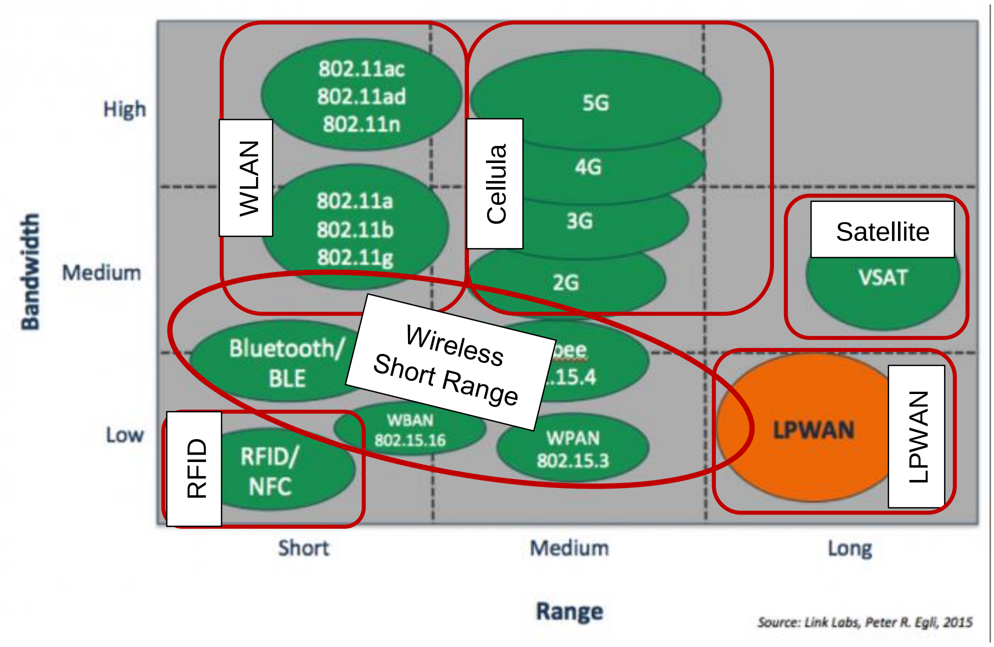

Figure 4: A portfolio map of the six groups of wireless communication technologies.

2.1 Wireless Local Area Networks

A Wireless Local Area Network (WLAN) is a wireless computer network that links two or more devices using wireless communication to form a Local Area Network (LAN) within a limited area such as a home, school, computer laboratory, campus, office building etc. This gives users the ability to move around within the area and yet still be connected to the network. Through a gateway, a WLAN can also provide a connection to the wider Internet. Consider the containers to be equipped with WLAN-devices and the vessel acting as gateway to offer connectivity to the internet.

WLANs are based on IEEE 802.11 standards and are marketed under the Wi-Fi brand name. Wireless LANs have become popular for use in the home and in the office, due to their ease of installation and use and due to the widespread adoption in end-user devices such as smartphones, tables, laptops etc. Wi-Fi supports a high bandwidth (>100 Mbs), has a reach up to 100 meters, and requires a wireless adapter onto the devices (containers) within the network. The configuration of hardware and software is relatively simple, and supports quite a large number of devices for Wi-Fi tracking purposes.

2.2 Short range wireless communication

The short-range communication cluster involves technologies such as Bluetooth, Zigbee, Wireless Body Area Networks, Wireless Person Area Networks and infrared communication.

2.2.1 Bluetooth

Bluetooth is a wireless technology standard for exchanging data between fixed and mobile devices over short distances using short-wavelength Ultra-high frequency (UHF) radio waves in the industrial, scientific and medical radio bands, from 2.400 to 2.485 GHz, and building Personal Area Networks (PANs). Bluetooth uses a lower bandwidth than Wi-Fi, has a reach up to 10 meters, allows for easy configuration, but supports only connectivity with a limited number of devices. This makes it less applicable for a ship-containers network application.

2.2.2 Zigbee

Zigbee is an IEEE 802.15.4-based specification suitable for high-level communication protocols used to create personal area networks with small, low-power digital radios, such as for home automation, medical device data collection, and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection. Hence, Zigbee is a low-power, low data rate, and close proximity (i.e. personal area) wireless ad hoc network. Its low power consumption limits transmission distances to 10–100 meters line-of-sight, depending on power output and environmental characteristics. Zigbee devices can transmit data over long distances by passing data through a mesh network of intermediate devices to reach more distant ones. Zigbee is typically used in low data rate applications that require long battery life and secure networking.

2.2.3 *Wireless Body Area Networks and Wireless Person Area Networks*

Wireless networks of wearable computing devices are referred to as Wireless Body Area Networks (WBAN), or Wireless Person Area Networks (WPAN), refer to communications applications on, near, and around the human body. These WBAN and WPAN use respectively the IEEE 802.15.3 and IEEE 802.15.16 communication protocols. They seem less applicable for both container tracking and ship-container monitoring.

2.2.4 *Infrared communication*

Infrared (IR) data transmission is employed in short-range communication among PDSs and handheld devices. Transmitting IR data from one device to another is sometimes referred to as ‘beaming’. Infrared is the most common way for remote controls to command appliances. IR does not penetrate walls and so does not interfere with other devices in adjoining rooms. It could be applicable for on-board monitoring applications, but does not seem applicable for container tracking.

2.3 Radio-Frequency Identification and Near Field Communication

This group contains Radio-Frequency Identification (RFID) and Near Field Communication (NFC).

2.3.1 *Radio-frequency Identification*

Radio-frequency Identification (RFID) uses electromagnetic fields to automatically identify and track tags attached to objects. The tags contain electronically stored information, for instance the unique container number (ISO 6346 International Shipping Container Standard Information reporting mark), eventually supported by cryptography and tag/reader authentication. Moreover, the tags can be either active or passive.

Active RFID tags have a local power source (e.g. battery) and may operate hundreds of meters from the RFID reader (using UHF frequency band: 433 MHz and 915 MHz). There are two kinds of active RFID tags: transponders and beacons. A transponder only communicates when it's in the immediate vicinity of a reader. These are commonly used in secure access control and in toll booth payment systems.

A beacon broadcasts constantly. Active RFID tags require low signal strength to communicate and can broadcast up to and even beyond a range of 100 meters. But this has consequences for the battery life. The cost per tag ranges anywhere from $15 to more than $100, depending on its capabilities. The high cost generally makes active RFID tags too expensive for simple inventory applications. They are more applicable for tracking high-value items like cargo.

Passive RFID systems use tags with no internal power source and instead are powered by the electromagnetic energy transmitted from an RFID reader. The low price per tag (starting from 5-20 cents per tag) makes employing passive RFID systems economical for many industries. A battery-assisted passive (BAP) has a small battery on board and is activated when in the presence of an RFID reader. This makes them more expensive.

Passive RFIDs are currently applied in mini-containers for waste collection: the tag is placed under the edge, whilst waste collection vehicles have an RFID reader in the lift-arm, able to identify the mini-container, and capturing the weight before and after emptying.

Figure 5: A passive RFID tag in a waste container

2.3.2 *Near-Field Communication*

Near-Field communication (NFC) is a set of communication protocols that enable two electronic devices, one of which is usually a portable device such as a smartphone. To establish communication, the devices need to be brought within 4 cm (11⁄2 in) of each other. NFC devices are used in contactless payment systems, similar to those used in credit cards and electronic ticket smart cards and allow mobile payment to replace or supplement these systems.

2.4 Cellular communication networks

Machine-to-machine connectivity using cellular communication standards 3G, 4G and in the near future 5G are characterised by high data rate and energy use, resulting in high operating costs to deploy on a large scale for tracking and localisation purposes. Additional functions are needed in a mobile network to support network-based localisation, e.g. via the mobile cell tower to which the device is connected, or more precise methods like triangulation of received signals via a minimum of three mobile cell towers.

To support machine-to-machine communication (M2M), specific versions are developed to support IoT with low power consumption, such as GPRS (2G) and improved versions in 4G such as Narrow-Band IoT (NB-IoT) and LTE-M. In 5G these versions are further improved to support low data rate communication of IoT devices.

2.4.1 *Narrow-Band Internet of Things*

Narrowband Internet of Things (NB-IoT) is a 4G radio technology to enable communication focusing on low cost, long battery life and high connection density. The narrowband refers to the bandwidth of the communication (200kHz). It is an operator managed network and operates on licensed spectrum.

The advantage of the narrowband channel width is the guarantee that all signals get delivered. So, the ship is guaranteed to receive signals from each container if they remain in range, varying from a few kilometres up until 10 km. The IoT sensors with battery can be attached to the containers to be tracked.

2.4.2 *Long Term Evolution, category M1*

Long Term Evolution category M1 (LTE-M) is an alternative 4G-based IoT solution, and standardised under the 3rd Generation Partnership Project (3GPP). LTE-M is a bit faster and data exchange is real-time, whereas NB-IoT is near real-time within intervals.

2.5 Low Power Wide Area Networks

In the Low Power Wide Area Network (LPWAN) technology space, there are quite a number of competing standards and vendors. We will elaborate on LoRa and Sigfox. Low Power protocols allow for sending and receiving limited amount of data using limited battery capacity. Coverage on land uses the network of radio masts, for coverage at open sea and peripheral regions it must fall back on satellite communication.

2.5.1 *LoRa*

An LPWAN technology is LoRa: a long range, low power internet of things technology. It has a range of 2.5-15 km per radio tower.

A difference with the NB-IoT solution is the channel width. The LoRa network operates on a free unlicensed frequency band, which means that it is not necessary to make deals with providers. LoRa’s dynamic open ecosystem is ideal for private networks with customized deployment. Nevertheless, this also gives rise to some disadvantages: other networks can use the same frequency, there is a fair-use policy and there is no guarantee that all signals will be delivered. The first in this list will be difficult in port areas, when other devices may also send signals on the same frequency causing noise in the network. However, this interference is not expected on the open sea. The second impediment is the fair-use policy in the telecom, which states that there is a maximum of ten times an hour to send a signal. So, the containers can only send signals that they are onboard at the maximum frequency of six minutes. Lastly, there is no guarantee that signals will arrive at the gateway. This all has the consequence that, on land, a quarter of the signals are lost. The expectation is that this number is less at sea, but there will be false alarms that the system will need to deal with.

In order to apply this technique on maritime container transport monitoring, containers are equipped with a LoRa-sensor and the ship has its own gateway (radio masts) and server. This technique is tested in the field and it is found that the signals of the sensors can travel through the steel of the containers if the antennas of the sensors are tuned. This even holds for the reefer containers. Moreover, when this technique is implemented on a ship, the network will send signals with a radius of ten kilometres around the ship as well.

An LPWAN container tracking example
An example is the smart container device from Traxens. It uses Tri-band frequencies (433MHz, 868MHz, 920MHz) and is adaptive to location to meet the local telecom regulations. The device is equipped with GPS, which will only be used if the mesh network is not functioning. The mesh network offers connectivity on the vessel and in container terminals. Moreover, the devices are permanently being attached, avoiding the problem of reverse logistics of the devices. In addition to the embedded sensors for monitoring temperature, shocks, GPS location, up to sixteen remote sensors can be integrated with the device (parent-box) using Near Field Communication.

CMA-CGM, MSC and Maersk each recently (May 2019) ordered 50,000 trackers from Traxens, and all obtained an equal share in the company. The smart devices can monitor GPS position, temperature fluctuations, shocks and container door openings. A mesh network was specifically designed to function in metallic and humid environments and communication reaches the deepest levels of the biggest container vessels.

Other solution providers, such as Globe Tracker or Semtech offer similar LPWAN based container tracking solutions to ports and container carriers.

2.5.2 Sigfox

Lastly, Sigfox is a French global network operator similar to LoRa. Just like LoRa, this technology is also proprietary. The costs of the sensors for this network are lower than of LoRa, but the network also provides a smaller range.

2.6 Satellite communication

Satellite communications use the very high-frequency range of 1–50 gigahertz to transmit and receive signals. A very small aperture terminal (VSAT) is a two-way satellite ground station with a dish antenna (around 1 meter). Data rates, in most cases, range from 4 kbit/s up to 16 Mbit/s. VSATs are used to transmit narrowband data (e.g., point-of-sale transactions using credit cards, polling or RFID data, or SCADA), or broadband data (for the provision of satellite Internet access to remote locations, VoIP or video). A maritime VSAT has features that allow it to be operated on a ship at sea. This enables it to transmit to and receive from the satellite while minimising losses and interference with adjacent satellites.

Satellite communication differs from satellite tracking, such as GPS tracking. The latter is a one-way communication, the satellite sends location, speed, time and direction data to the GPS device, see section 4.1.1.

Satellite communication uses relatively high power, which makes it a rather expensive way of communication. As such, it is does not seem a preferable mass application for container tracking.

2.7 Network integration technologies

This section elaborates on the communication techniques of the previous sections by combining technologies.

2.7.1 *Wireless Mesh Networks*

A Wireless Mesh Network (WMN) is a communications network made up of radio nodes organized in a mesh topology. The coverage area of all radio nodes working as a single network is sometimes called a mesh cloud. Access to this mesh cloud depends on the radio nodes working together to create a radio network. A mesh network is reliable and offers redundancy. When one node can no longer operate, the rest of the nodes can still communicate with each other, directly or through one or more intermediate nodes. Wireless mesh networks work with different wireless technologies including 802.11 (Wi-Fi), 802.15 (Zigbee), 802.16 (PWAN), cellular technologies (3G/4G) and need not be restricted to any one technology or protocol.

Mesh network solutions can combine the strengths of the different wireless communication technologies against reasonable costs, allowing for several applications in the end-to-end container logistics chain. See also the Traxens example elaborated in chapter 6.

2.7.2 *Wi-Fi Radio-Frequency Identification*

To combine active RFID in a network, a communication protocol is required. This could be Zigbee-enabled RFID networks or Wi-Fi enabled RFID networks. Wi-Fi-enabled RFID is commonly used for location-based services that track objects in a specific physical context, like children in a theme park, cars in a parking lot, equipment in a manufacturing plant, etc. It is considered a more accurate system than a traditional RFID network for determining the location of tagged objects. A regular RFID system can give what is called the “choke point” location, or zone-based location, meaning the location of the tag is known only in relation to the reader detecting its presence. A Wi-Fi network on the other hand can determine the precise coordinates of a tag using triangulation methods, similar to the workings of GPS.

2.8 Summary

This summary highlights the key features and restrictions in the application domain of maritime container transport.

WLAN technologies such as Wi-Fi require a rather complex configuration and have a relative high energy consumption. Specific configuration is needed to optimize this technology for tracking and tracing. Short range technologies such as Zigbee communicate only over a short distance up to 10 meters and scalability with many devices in a small geographic range is an issue. Passive RFID is cheap, but requires readers on very short distance, which makes it less feasible for the use case of maritime container monitoring. Active RFID uses a battery and signals can be received at distances up to 100 meters, but they are rather expensive. Cellular mobile communication uses high energy consumption and is expensive in use. NB-IoT is rather cheap, has good connectivity inside a vessel, but has no network coverage at sea. LoRa has lower energy use then NB-IoT, network coverage can be configured with radio masts on the vessel, but it is a proprietary standard.

In the next chapters, we will elaborate the different stages in an incident with fallen containers, describing relevant support technologies, starting with the technologies supporting monitoring methods.

3 Inventory of vessel monitoring methods

The monitoring techniques are based on checking if all containers are still onboard, so that it is immediately (real time) known if an incident occurs. Knowing where and when an incident occurs, increases the chances of finding and recovering the containers. In order to monitor stowage integrity during transport, these methods are categorized based on the perspective of incident identification. Generally, these approaches can be divided into three groups**:** visual, sensor and ship-container network.

The first group, *visual*, refers to the visual confirmation that containers have fallen overboard. Within this class the containers are observed from the ship in order to establish the when and where of an incident. The second group, *sensor methods*, includes sensors that can be added to the ship, container or cargo in order to detect the occurrence of an incident. These techniques require adding sensors and will not only detect an incident, but depending on the solution may also detect which container is involved in the incident. Lastly, the *network-group* describes the ship as its own network, in which the containers are all tagged and in communication with each other. In this group, like in the sensory-group, an incident will be detected, and it is known which containers are involved. After discussing the monitoring methods one by one, this chapter will end with an overall summary.

3.1 Visual monitoring methods

Each standard container carries its own unique ISO 6346 International Shipping Container Standard Information reporting mark, which can be tracked and monitored at every major freight terminal the cargo passes through. However, as this is not a live tracking system, the container’s location is unknown during the large amount of time it spends between terminals, such as when in transit via rail, road or sea. There are several techniques to check if containers are onboard by visual confirmation. The first methods would be by the human eye, either from the wheelhouse or from regular patrols along the containers. This human-manual approach is not further discussed here, but rather the technologies to support these observations.

One of the advantages of these visual methods is that they only need to be installed on the ship or on a drone, so no adjustments to the containers are needed. When attached to the ship itself, the devices can be placed strategically to connect them to the power supplies already onboard. The two drawbacks for these methods are that they depend on their line of sight - i.e. the specific placement (or flying route) will determine their effectiveness - and they depend on light waves, which means they can be blinded by dense fog. Fixed placed sensors should be mounted such that they cover all possible container locations, likely places include on top of masts of the vessel and on top of high structures such as the wheelhouse. Three possible techniques are identified: visual light cameras, lidar and infrared cameras. These three will be described here, followed by the addition of intelligent imaging which could be applied on all three techniques.

3.1.1 *Camera technology*

A visible light camera is an optical instrument to capture still images or to record moving images, which are stored in a physical medium such as in a digital system or on photographic film. When applying camera technology, depending on the ship, several cameras can be mounted on the ship to monitor the containers. Using cameras is the cheapest option of the three techniques in this section, but due to the light sensitivity, the effectiveness of this technique is very sensitive to weather conditions and the diurnal rhythm. In situations of bad weather, heavy fog and at night, the quality of the images does not allow for effective monitoring.

A solution to deal with darkness at night would be to periodically turn on the lights on the deck. These lights are already mounted on the ships, but turned off so that the crew can see the surroundings with other lights. It is an option though, to turn on the lights towards the deck every hour or two to check if all containers are still present. Alternatively, lighting can be added in the near-infrared, allowing ordinary cameras to work while not disturbing regular night sight of the ship crew as it is not visible by the human eye.

3.1.2 *Lidar technology*

Lidar is a surveying method that measures distance to a target by illuminating the target with pulsed laser light and measuring the reflected pulses with a sensor. This approach is now used in autonomous cars, in order to avoid accidents but also for incident detection on cruise vessels. By measuring the distances, this approach can also detect empty slots in a stowage plan that should have been filled. The lidar could measure how much lower a stack has become, upon which it can be calculated how many containers are involved in an incident and have possibly fallen overboard. As such, it is a more robust approach for monitoring vessel stowage integrity compared to camera technology. Another advantage over cameras is that lidar works in daylight as well as during the night. Moreover, lidar is less sensitive to weather conditions, though it should be noted that extreme weather conditions will also interfere with the lidar. Nonetheless, in order to pulse laser lights, lidar contains a rotating mirror. The rotation enables a 360-degree view, but at the same time the mirror and its monitoring platform are sensitive to the maritime environment including the salinity of the air.

3.1.3 *Infrared cameras*

An infrared camera (also called a thermographic camera, thermal imaging camera or infrared thermography) is a device that forms a heat zone image using infrared radiation, similar to a common camera that forms an image using visible light. Instead of the 400–700 nanometre range of the visible light camera, long-wave infrared cameras typically operate in wavelengths between 8,000 and 14,000 nm (8-14 µm). Because of that, this type of camera can still see well during the night, eliminating the diurnal disadvantage of a visible light camera. Besides, it returns more information than lidar and is less sensitive to weather conditions as it contains no moving parts. However, it is also the most expensive option of the three.

3.1.4 *Intelligent imaging*

Additional to each of these visual techniques, the captured images need to be processed to detect if a container falls overboard. This can be either done *manually or automatically*.

When the images are manually processed, it is possible to either do this *continuously* during the journey or only in *hindsight* when it has been determined that an incident occurred.

Continuous manual monitoring would be more labour intensive than hindsight monitoring, but can also call for immediate action, whereas hindsight monitoring would provide slower damage control. Nonetheless, when computer vision or artificial intelligence is applied to execute this task, the containers can be constantly monitored without it being labour intensive. Automatic processing can provide immediate alerts whenever an incident occurs. Yet, intelligent imaging models will still need to be developed to handle each type of weather and will still be dependent on the shortcomings of the visual method used. Building these models is feasible, but will still require configuration and testing time.

3.2 Sensor methods

With these methods sensor technology is being used on board to detect if slots are or have become empty or if containers are still onboard. In this definition, sensor refers to a device to detect changes or events in its environment. We distinguish two categories of sensor applications: *sensors that are applied to either (1) the ship, or (2) the containers*. It should be noted that some of the container sensor applications and network applications discussed under this section could also be used for localisation purposes.

3.2.1 Ship sensors

When the ship would be equipped with sensors, it is possible to monitor stowage integrity and detect if slots for containers are empty or not by the use of magnets. Slots on a container vessel are represented by a combination of bay number (2 digits), row number (2 digits) and tier number (2 digits): Slot number 530788 refers to Bay 53, row 07 and tier 88. Currently slot-sensors are used in bicycle storage to guide cyclists to empty slots. This could also be used for this use case, in which case the monitoring system could alert the crew if the slot suddenly changes states (i.e. change from occupied to empty or vice versa). Moreover, if this system is combined with the stowage plan and the GPS of the ship, it is possible to know exactly when and where a slot has become unoccupied, meaning that the corresponding container according to the stowage plan has been unloaded or has fallen (overboard). However, this option does entail that the entire ship needs to be adjusted to equip every slot with a sensor and power supply.

3.2.2 Container sensor devices

The other category is to equip the containers with sensors for monitoring stowage integrity. When it comes to sensors, there is a wide range of what could be measured, hence we concentrate on the application to monitor if a container is still on board or not. Note that sensor-enabled container tracking technologies are discussed in the chapter on localisation methods.

Shock sensors can detect physical shocks, that would indicate if a container is falling. This technique would hardly render false positive alerts, since the containers are very steady when they remain onboard. When a container is falling, a signal can be sent so the data can be combined with the ship's GPS.

Position sensors can also detect motion and displacement and can be used in combination with the right algorithms to identify the tilting of containers.

Temperature and humidity sensors are nowadays used to monitor the condition inside the container during transport for in perishable supply chains. Quick changes in the humidity level inside a container may be an indication that the container has fallen overboard and the container suffers from water ingress.

To monitor stowage integrity, we consider two approaches: (1) deploy all containers with sensors or (2) deploy only the top layer of containers. If only the top layer of the containers is tagged and these containers remain on the ship, we can assume there was no incident for any of the containers. But if an incident takes place, we cannot determine near real-time how many and which containers were involved in the incident. If all containers are tagged, it is possible to know exactly which containers are involved if an incident does occur.

Moreover, all sensors need to communicate the sensing data, requiring a communication module that can be activated. All these techniques use radio waves to communicate, but depending on the bandwidth, signals can travel further or have certain impediments (see chapter 2).
Next, we have to distinguish communication above and below water. Radio-signals do not travel well through water, so when a container is falling overboard, the ship can detect the container falling off, but the signal sent from the container will vanish when the container stops floating. This means that localisation of the container is aided by knowing when and where the sensor gave a signal, but not by a signal after being swept overboard and sunk.

3.2.3 Network monitoring methods

In the network methods, the ship is seen as its own computer network. A network is a way to overlay connections between the containers (nodes) and the ship (central node). This entails that each container device is a node that can exchange data using connections between each other and/or between the node and the central node. The central node functions as a gateway and provides wider connectivity to the internet via other communication methods.

NB-IoT seems less feasible for vessel network systems, since it does not use a gateway to the internet but directly connects to 4G networks. Though there are 4G-LTE offshore networks to provide connectivity for offshore platforms (e.g. Tampnet), full network coverage at open sea is lacking.

LoRa or Sigfox IoT devices on containers creating a network with a gateway on the vessel connecting to the internet could be combined with shock sensors in order to lower energy use. In a multisensory configuration, the device only communicates if triggered by the shock sensor. The application of container tracking in Chapter 6 provides an example of a mesh network typology of LWAN devices.

3.3 Effectiveness of policies

Policies or legislative measures to assure that container vessels have proper monitoring systems on board may be governed on international level under the IMO.

IMO has developed and adopted a number of requirements to ensure the safe carriage of containers and has also developed specific guidance for packing and securing of containers. IMO's International Convention for the Safety of Life at Sea (SOLAS) includes, in its chapter VI on carriage of cargoes, requirements for stowage and securing of cargo or cargo units (such as containers).
The International Convention for Safe Containers (CSC) provides test procedures and related strength requirements for containers.

The International Maritime Dangerous Goods (IMDG) Code is a mandatory international code for the maritime transport of dangerous goods in packaged form, in order to enhance and harmonize the safe carriage of dangerous goods and to prevent pollution to the environment. The Code sets out in detail the requirements applicable to each individual substance, material or article, covering matters such as packing, container traffic and stowage, with particular reference to the segregation of incompatible substances.

These requirements do not specify if or how integrity of the container stowage plan should be monitored. New requirements regarding container integrity monitoring could also be proposed at IMO.

3.4 Summary

In summary, the approaches of monitoring contains during transport to immediately be aware of an incident, are described by three groups**:** visual, sensory and networks.

Using visual methods it is possible to detect an incident using either cameras, lidar or infrared cameras. These methods require the lowest impact on the ship and containers, while they will suffice for detection of an incident. Furthermore, if intelligent models are trained to visually detect where containers are missing and combined with the stowage plan, it is possible to obtain which containers fall overboard at which locations and at what time.

When it comes to sensory methods, either slots, containers or cargo needs to be equipped with sensors. This either requires an investment in the ship’s design, in large numbers of sensors so containers can send a signal or in obligating clients into tagging the cargo.

Lastly, the ship can be viewed as a network, in which the option is to deploy all containers or a subset (for instance only the top layer in the stacks, and/or the dangerous goods containers.

The summary table below (Table 1) describes the mentioned technologies and includes a qualitative quick scan assessment of reliability and feasibility aspects.

Table 1: Overview of the monitoring methods. The effectiveness of the each technique is described in four columns: (1) reliability in terms of a star-rating (1-5 stars, in which more stars represent a more reliable method), (2) the coverage describes the scope of the method, (3) the automation level indicates if the technique is continuous or manual, and (4) the limitations provide a list of disadvantages to the method. The last three columns describe the feasibility of the technique, in terms of: (1) scalability defining the domain of the method, (2) costs in terms of a star-rating (1-5 stars, in which more stars represent a cheaper method) and (3) logistics value to describe the added value in end-to-end logistics.

	Effectiveness				Feasibility (Commercial)		
Technology	**Reliability**	**Coverage**	**Automation level**	**Limitations**	**Scalability**	**Costs**	**Logistics Value**
Camera, manual hindsight	★★★★	Deck of ship	Manual	- Quality is weather dependent - Needs light source - Manual observations - Passive response	All container vessels	★★★★★	N.A.
Camera, manual continuously	★★★	Deck of ship	Manual	- Quality is weather dependent - Needs light source - Manual observations - Manhours	All container vessels	★★	N.A.
Camera, automatic	★★	Deck of ship	Continuous	- Quality is weather dependent - Needs light source	All container vessels	★★★★	N.A.
Lidar, manual hindsight	★★	Deck of ship	Manual	- Heavy weather can obstruct - Mirror is sensitive - Manual observations - Passive response	All container vessels	★★★★	N.A.
Lidar, manual continuously	★★	Deck of ship	Manual	- Heavy weather can obstruct - Mirror is sensitive - Manual observations - Manhours	All container vessels	★★	N.A.
Lidar, automatic	★★★	Deck of ship	Continuous	- Heavy weather can obstruct - Mirror is sensitive	All container vessels	★★★	N.A.
Infrared camera, manual hindsight	★★★★	Deck of ship	Manual	- Quality is weather dependent - Manual observations - Passive response	All container vessels	★★	N.A.
Infrared camera, manual continuously	★★	Deck of ship	Manual	- Quality is weather dependent - Manual observations - Manhours	All container vessels	★	N.A.

Infrared camera, automatic	★★★★	Deck of ship	Continuous	- Quality is weather dependent	All container vessels	★(★)	N.A.
Slot-sensors	★★★★	Every slot	Continuous	- Affects design of the ship	All container vessels	★	N.A.
Shock sensors	★★★	Every container	Continuous	- Only detects movement	All containers	★★★★★	- Cargo insurance
Positioning sensors	★★★	Every container	Continuous	- Only detects movement	All containers	★★★★★	N.A.
Temperature/humidity sensors	★	Every container	Continuous	- No guarantee for incident detection	All containers	★★★★★	- Conditioned transport
RFID network	★★★	Every container	Continuous	- No network coverage when fallen overboard, so only for stowage integrity	All containers	★★	- Transhipment (container-crane) - Gate in/gate out
LoRa / Sigfox	★★	Every container	Continuous	- No guarantee of signal delivery - Interference from other devices - Fair-use policy	All containers	★★	- End-to-end container tracking and tracing
LoRa / Sigfox with shock sensor	★★★	Every container	Continuous	- No guarantee of signal delivery - Interference from other devices - Fair-use policy	All containers	★★★	- End-to-end container tracking and tracing - Cargo Insurance

4 Inventory of localisation methods for lost containers

These methods focus on finding containers after an incident has occurred. In this case there are two scenarios: the container communicates its whereabouts, or it is unknown where the container is. For a container to communicate its location, a container needs to be equipped with a communication-module. Based on the range of the communication, the container can be localized from a certain distance. On the other hand, when a container is not tagged with an active communication-module (or the module lies underwater and therefore not transmitting), the localisation of a container occurs either by accident or by a process consisting of two phases. In general, these two phases are: defining the search space and the actual localisation of a container.

The first phase, defining the search space, can be massively improved by knowing the exact location (where and when) of an incident, which would be obtained by a monitoring method. Without this information, containers can be lost along the entire route of the ship, rendering a huge search space. If it is known when and where the ship lost a container, and what the weight is of the particular container, drifting models can be used to calculate the probable current location of the container.

In the second phase, a container is found in a certain state: the container has washed ashore, is floating, is sinking, has sunk or is broken. The last three scenarios entail that the container can only be detected with techniques that work underwater, whereas this does not hold for the first two. Therefore, the methods here are split up into two groups: above water and underwater detection techniques. Of course, these techniques could still be combined in one vehicle with underwater as well as above water detection mechanisms.

This section will first describe which communication methods can aid the localisation of the containers. The second section will focus on above water detection methods and the last on under water detection methods.

Figure 6: Example of container rescue operation

4.1 Active container-based localisation and positioning

As discussed in the previous section on monitoring methods, it is possible to deploy the container with a smart (communication) device. This can be based on satellite systems (e.g. GPS or the next-generation Galileo), Wi-Fi access points and cellular networks (GSM, UMTS, LTE), Short Range Communication Systems and LPWAN systems, for indoor, outdoor land and sea application.

Localisation and positioning systems can be categorized as active and passive. In active systems the objects to localize collaborate to the positioning task (e.g. in the case of a tag transmitting some radio signals for its identification), whereas in passive systems the localisation targets are non-collaborative (e.g. in the case of anti-intruder multi-static radar systems). The passive radar technology will be discussed in the next section.

All active techniques use radio waves to communicate, which entails that communication under water is not possible. For instance, using GPS for underwater navigation is quite impossible because high-frequency signal penetrates only about 2 millimetres into the water.

For smart container localisation at sea, only Satellite and LPWAN devices (LoRa or Sigfox) offer a practical range to localise. These will be discussed in the next sections.

4.1.1 Global Positioning System tracking

A GPS tracking unit is a navigation device that uses the Global Positioning System (GPS) to track the device's movements and determine its location. The recorded location data can either be stored within the tracking unit or transmitted to an Internet-connected device using the cellular (GPRS or SMS), radio, or satellite modem embedded in the unit. There are three type of GPS-trackers: data loggers, data pushers and data pullers.

Data loggers allow downloading of the track log data for further computer analysis. This does not seem applicable for incident management in the case under consideration.

Data pushers are the most common type of GPS tracking unit, used for asset tracking, personal tracking and vehicle tracking systems. Also known as a GPS beacon, this kind of device pushes (i.e. sends), at regular intervals, the position of the device as well as other information like speed or altitude to a determined server, that can store and analyse the data instantly. They can also be configured to transmit location and telemetric input data when an event (door open/close, auxiliary equipment on/off, geofence border cross) triggers the unit to transmit data.
Data pullers are also known as GPS Transponders. Unlike data pushers that send the position of the devices at regular intervals (push technology), these devices are always on, and can be queried on demand as often as required (pull technology). These can often be used in the case where the location of the tracker will only need to be known occasionally e.g. placed in property that may be stolen, or that does not have a constant source of energy to send data on a regular basis, like freight or containers.

4.1.2 *LPWAN localisation*

As already described in section 3.2.3 on network monitoring methods, the same technology also allows for tracking and localisation as long as there is connectivity. If the device signals are no longer received by the vessel (acting as gateway, the vessel does not stop after an incident and continues its journey), and there is no coverage from land stations (about 10 km), a patrol boat with radio mast could act as gateway and be sent to the incident location to localise still floating fallen containers, as long as the antenna is above water levels.

4.1.3 *Device with floating radio antenna*

A solution to localise containers even if the container sinks is to equip the container with a radio antenna, which is connected to a self-inflatable balloon via a long fibre wire (e.g. 100 meters). Humidity & shock sensors should activate a helium pressure device that inflates the balloon when it falls and touches the water during voyage. Even if the container is (slowly) sinking, the balloon with the radio antenna - connected via the wire - will keep floating and able to communicate. This innovative application combines a number of proven technologies, but would need some development stages to be applied in an integrated way for this particular use case. Nevertheless, this solution could be considered for containers containing dangerous goods. Subject matter experts think such a system can be developed against a cost price of around €50.

4.2 Visual detection above water

Several techniques can aid the discovery of floating containers. When the container is not tagged (or the tag is under water, while the container still floats) or the remaining search space is still quite large, only visual methods for detection remain. To search for containers, two vehicles are commonly used: helicopters and boats. The techniques to support observations by the human eye are split into these two approaches.

4.2.1 *By helicopter*

If a helicopter is used, the observations can be aided by using visual light cameras. Embedding infrared cameras overcomes some limitations regarding the diurnal rhythm and weather conditions, as described in the visual monitoring methods. Moreover, coloured coatings could help in visual recognition. Reflecting coatings or dedicated colours for dangerous goods containers may be helpful in immediate recognition of floating dangerous goods containers. However, they make the global transport system also more vulnerable for terroristic attacks.
Currently search and rescue services use infrared cameras to detect drowning people during the night. Even more, artificial intelligence can also be used in this application. AI-models for this particular application do not exist yet, but it should be possible to recognize floating containers by looking for patterns in waves or colour. So, building an automatic system is technically feasible and the algorithms are available, but it would require some training and testing activity to have an automated solution running.

4.2.2 *By ship*

From a boat’s perspective, the most relevant technology is radar (radio detection and ranging). As the acronym says, radar is a detection system that uses radio waves to detect objects.

Ships are already supplied with a navigation-radar, but these are not sensitive enough to detect the containers. Therefore, the radar technology described here is a separate radar that is dedicated to the detection of floating containers. Further, this technology works better from a boat than a helicopter due to the stability of the vehicle. Depending on the height at which the radar is installed on the boat and the height of the waves, a radar can detect objects with a range of approximately a kilometre. However, a radar cannot detect if a container is undamaged, open or broken. Nowadays there are techniques under development (TLR 5/6) to detect the height of waves by radar, which could also be used for container detection.

For completeness, another visual technique mentioned before and could be used, is lidar. This technology cannot be used from a helicopter due to the angle to the water, but it can be used from a boat. With lidar, floating containers could be detected, provided that the waves are not too high.

4.3 Underwater detection

Once containers, or parts of containers start sinking, there is a need for specific underwater technologies. Three underwater techniques are found to help discover containers: laser, sonar and magnetometers.

4.3.1 Laser or lidar applications

Depending on the conditions of the water, laser or lidar technology can be applied to investigate the top layer of the water. This is not enough to find containers on the bottom of the sea, but the advantage of this technique - with respect to the other two - is that is can be used from a helicopter.

4.3.2 Active sonar applications

The primary detection technique used underwater is sonar. We can distinct active and passive sonar. In active sonar, the system emits a pulse of sound and an operator listens for echoes. Passive sonar is listening for the sound made by vessels, or a pinger. Containers could be equipped by similar transponders/pingers, but it would be much too expensive and unrealistic according to experts. Below, we elaborate on active sonar applications. A big advantage of sonar is that it does not have a restriction on depth. Based on the settings, sonar can be used on any depth. Moreover, parts of containers will still be detected by sonar. The disadvantages of sonar are the sensitivity to stability, temperature and salinity. As per the other visual methods above water, sonar is still being processed manually, but also has the potential to be supported by artificial intelligence.

Two types of sonar exist: hull mounted and side-scan. The first, hull mounted sonar, is incorporated into the hull of a ship and detects objects in front of the boat. The use of these sonars nowadays is mine hunting. But, because of the location in the hull, this sonar is sensitive to waves. Additionally, the temperature and salinity of the water differ more on the surface, leading to a lot of fine tuning to have a hull mounted sonar to detect floating containers.
The second type of sonar are the side-scan sonars. As the name implies, these detect objects to the side of the device. Furthermore, these are separate devices that are not incorporated into a boat, but rather attached to a boat by a clip-on system. This renders the advantage that they can be used by any boat.

Also, the side-scan sonars can be set to a certain depth, so they can be adapted to the depth of the sea. The only restriction for depth would be the length of the cable to the boat. An additional advantage of this is that, the deeper under water, the stability, temperature and salinity fluctuate less. Thus, this technique is very reliable under water.

Currently, a special sonar is in development to even detect a container that is buried under sand by using low frequencies. However, this sonar now works in test environments, but it is not fully developed to use on the open sea yet.

4.3.3 Magnetometer applications

An alternative to sonar is the magnetometer, which detects steel by using magnetic properties. These devices are also clip-on systems that need to be dragged behind a boat. Of course, the distance to the boat needs to be big enough so that the boat does not interfere with the signals of the magnetometer. This technology can be used to detect steel objects near the device and downwards from the device. Compared to sonar, magnetometers have a smaller range of detection and detection entails that the magnetometer returns blobs rather than images, so it is not possible to see if a container is intact or not. Another disadvantage of magnetometers is that the magnetic properties of containers can differ, so there is no guarantee of detection for all containers. Nevertheless, an advantage of magnetometers is that these devices can detect a container that is covered in sand.

4.4 Effectiveness of policies

Policies or legislative measures to support the localisation of maritime containers could be governed from the perspective of maritime safety or from the perspective of global supply chain security. For maritime safety policies, we refer to the IMO governance described in section 3.3. For Supply Chain Security, the governance lies within the European Union. Regulation about bringing containerised cargo into the European Union does not specify the tracking ability to localise where a container exactly is when in transit.

4.5 Summary

Either the container communicates its whereabouts, or it is unknown where the container is. For a container to communicate its location, a container needs to be equipped with a communication-module, using GPS or LPWAN. When unknown, finding a container starts with defining a search space. This can be estimated by drifting models and will become more accurate with more information.
The monitoring methods help in determine the exact location where the incident took place, drifting models provide an estimate of the search area.

While the containers remain above the surface, multiple visual methods can be used to search for them: cameras or infrared cameras from helicopters or, radar or lidar from a boat. Once the container has ceased to float, a laser from a helicopter could detect the container if the water is clear and not too deep.
As soon as the container has sunk deeper, a side-scan sonar or magnetometer can be clipped on to a boat or a transducer could localize a transponder fixed to the container.

Table 2: Overview of the localisation methods. The effectiveness of the each technique is described in four columns: (1) reliability in terms of a star-rating (in which more stars represent a more reliable method), (2) the coverage describes the scope of the method, (3) the signal frequency, and (4) the limitations provide a list of disadvantages to the method. The last three columns describe the feasibility of the technique, in terms of: (1) scalability defining the domain of the method, (2) costs in terms of a star-rating (in which more stars represent a cheaper method) and (3) logistics value to describe the added benefit to the end-to-end logistics.

	Effectiveness				Feasibility (Commercial)		
Technology	**Reliability**	**Coverage**	**Automation level**	**Limitations**	**Scalability**	**Costs**	**Logistics value**
Containers with GPS device	★★	All smart containers above water level	Periodic	- Only for intact containers above water - No guarantee of signal delivery - Interference from other devices - Fair-use policy	Global	★	- End-to-end container tracking
Containers with LPWAN device	★★	All smart containers above water level and in vicinity of gateway node	Periodic	- Only for intact containers above water - No guarantee of signal delivery - Interference from other devices - Fair-use policy	Global	★★	- End-to-end container tracking
Smart container with floating radio antenna	★★★(★★)	All smart containers	Automatic Activation	- Proven technology, but not this application - Wire length	Global	★	- End-to-end container tracking
Radar	★★	Floating containers	Continuous	- No signal reception guarantee - Manual observations - Wave height dependent	Search area	★★	N.A.
Laser	★	Floating containers and top layer under water surface	Continuous	- No signal reception guarantee - Manual observations - Clarity sea water	Search area	★★	N.A.
Camera	★	Floating containers	Continuous	- Quality is weather dependent - Manual observations - Needs light source	Search area	★★★(★)	N.A.
Lidar	★	Floating containers	Continuous	- Heavy weather can obstruct - Manual observations	Search area	★★★(★)	N.A.

Infrared camera	★★★	Floating containers	Continuous	- Quality is weather dependent - Manual observations	Search area	★★(★)	N.A.
Active sonar with transponder/pinger	****	Containers equipped with transponder	Continuous	- Also deep water detection, depending on the frequency of the transponder - Very expensive - Unreliable if container falls with transponder on the sea bottom - Multiple transponders cause interference of sound	Search area	★	N.A.
Sonar: hull-mounted	★★	Every container in water in front of hull	Continuous	- Only effective within beam area range - Manual observations - Embedded vessel installation - Not effective for containers hidden under sand layer	Search area	★★★	N.A.
Sonar: side-scan	★★★	Every container (and -part) under water on specified depth level aside the sonar boat	Continuous	- Manual observations - Scanning only part of water column - Not effective for containers hidden under sand layer	Search area	★★	N.A.
Magnetometers	★★	Every container under water	Continuous	- Manual observations	Search area	★★	N.A.

5 Inventory of container content identification methods

Basically, there are two methods that help to identify the container contents. The first follows the data and document trail and should represent what is inside a container. The second composes of intrusive and non-intrusive technologies to determine its contents. We will start with the first.

5.1 Data trail in maritime container transport chains

This section provides an overview of the various data sets and their availability, where these data sets specify the contents of containers. The context of this section are containers that are found at sea, either drifting or at the bottom of the sea. There are different steps to be taken to retrieve data of container content, namely (1) to identify a vessel and thus shipping line and (2) retrieve data of container content. Both steps will be described.

5.1.1 Vessel and shipping line identification

It is assumed that a container number is known. There are basically two use cases for a container either found drifting or at the bottom of the sea, namely:

1. Vessel known – the vessel and thus the shipping line that carried a container is known. Several container tracking solutions are on the market to track containers during ocean carriage, such as INTTRA or Track-trace. However, these systems do not cover all container carriers. Vessel and shipping line data can be identified for requesting data.
2. Vessel unknown – in this case a container is found drifting somewhere in the sea or at the bottom of the sea. There are two ways to detect a potential vessel and thus shipping line that had carried such a container, based on drifting patterns at sea:
    a. A lane can be identified and a probable time window in which a drifting container would be at the location of that lane. All vessels can be identified passing that lane in the time window, based on available data of coast guards. The shipping lines of these vessels are requested to provide whether they carried the drifting container.
    b. Another option is to draft a geofence, including time windows, where a drifting container could have been and compare this map with AIS or LRIT data of vessels. Potential vessels can be identified, and thus shipping lines.

5.1.2 Container data identification

To identify container data, the different stakeholders involved in maritime container transport will be analysed on their capability to provide certain data. It involves shipping lines, forwarders, and shippers/consignees. This thorough analysis of logistics roles, procedure and data exchange is needed to understand the limitations and challengens in achieving supply chain visibility. An overall view of data availability is given by the figure, that can be used as a reading guide. This text describes all potential cases where relevant data can be stored; it does not provide a flow chart of steps to be taken to retrieve the data.

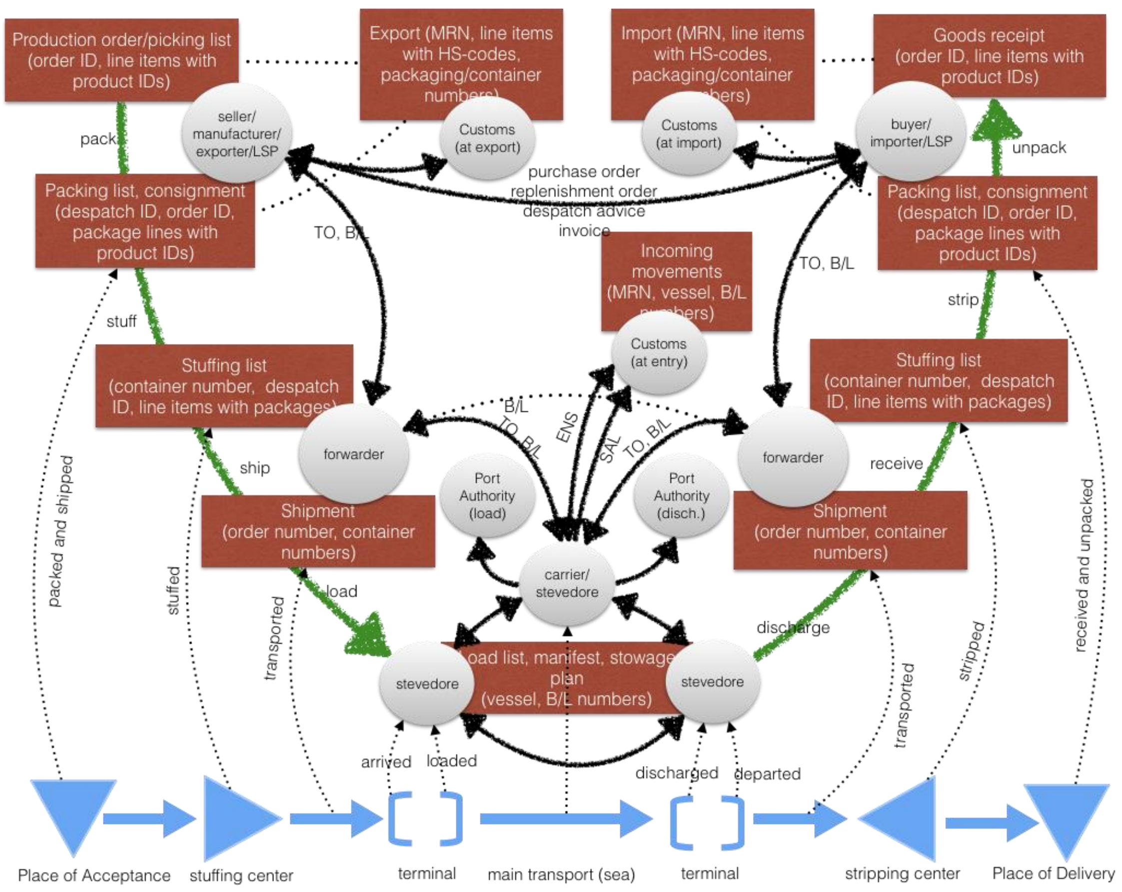

Figure 7: Overview of data availability.

5.1.3 *Terminology shipment and consignment*

Terminology is of importance for data retrieval. There are two terms to identify cargo that is transported, generally used as follows:

- *Consignment* – a consignment is all cargo (packages) that is transported as one set from a place of acceptance to a place of delivery at the same time. It is the set of goods offered by a shipper at a place of acceptance for transport to a place of delivery controlled by the consignee. Pallets, boxes, and containers are examples of packages used for transport.
- *Shipment* – a shipment is all cargo that is offered to a carrier for transport between two locations at the same time.

Whereas a consignment represents the end-to-end view, a shipment is about a single transport leg with one carrier. Several consignments can be combined to one shipment and one consignment can be broken into different shipments. For instance, a consignment of many containers can result in a shipment per container. Cargo of a consignment can be stuffed in a container. A container can contain cargo of one (FCL – Full Container Load) or more (LCL – Less Than Container Load) consignments. In case of an FCL container, the shipping line may be responsible for picking up the container at the origin and delivering it to its destination. This is called ‘carrier haulage’. The other option is transport between a port of loading and a port of discharge, called ‘merchant haulage’, where a shipper/consignee or its representative (forwarder) delivers a container to a port of loading or picks up a container at a port of discharge.

5.1.4 *The different roles in maritime container transport*

To understand possibilities and difficulties in following the data trail of the container contents, we need to understand the different roles involved in maritime container transport.

5.1.4.1 *Shipping line*

Identification of a vessel does not automatically give the identification of the shipping line responsible for transport of that container. A vessel can operate in a so-called alliance meaning that a vessel carries containers of different shipping lines or Non-Vessel Operating Common Carriers (NVOCC). There is always one responsible shipping line, which has the stowage plan, listing the containers and their stowage location. Based on a container number, the responsible shipping line can refer to the shipping line or NVOCC that is responsible for the container.
A shipping line in its turn only has a description of what a container could contain, which is called ‘Said To Contain’ of STC. A shipping line (or more generally, a carrier) and a stevedore (or more generally, a hub or terminal operator) are not allowed to have knowledge of the actual content of a container according legal restrictions (Rotterdam Rules and the Hague-Visby rules). In case a container carries dangerous cargo, the shipping line has this data, stored according to international agreed codes.

The responsible shipping line shares the following data sets:

- Declarations of containers to be loaded to a customs authority in the country of discharge (or first country of call in the EU) via an Entry Summary Declaration (ENS) and actual declaration of discharge via a Summary Declaration for Temporary Storage (TSD). These declarations are based on STC. The ENS and TSD are derived from the manifest of a vessel. The ENS and TSD declarations contain a so-called Harmonised Systems (HS) code for goods classification from a customs perspective. The current ENS procedure requires a 4-digit HS code, in the Union /Customs Code, the ENS should include a 6-digit HS code. The value of the HS-code for a container in an ENS or TSD declaration is based on STC and may thus not classify the actual goods. The HS system is being effectively used for tariff determination, but has its limitations in use for identifying controlled goods, such as hazardous wastes, ozone-depleting chemicals, endangered species, and nuclear materials and precursors. Revision of the existing HS system is being considered, often referred to as HS2.0.
- Dangerous goods declarations (and declaration of other data sets) to a port authority at arrival and departure of a vessel in a port area. This is by the dangerous goods manifest mentioning only those containers that carry dangerous goods.
- Stowage plans and voyage schemes are shared with stevedores. Stevedores also share these stowage plans amongst each other, especially if these stevedores are part of the same organization. Stowage plans contain all relevant data for optimal stowage vessels, like dangerous goods details, weights, dimensions, oversized values, etc. of each container.

The dangerous goods declaration will be shared with the coastguard, only for vessels in the area of responsibility of a coastal guard.
A shipping line produces a Bill of Lading (B/L) or waybill to its customer.
A B/L contains data required for formalities and handling of containers (STC and potential HS-code for ENS/TSD, stowage data, dangerous cargo, etc.), and relevant data of the chain like shipper, consignee, forwarder, and notify(-ies). In case of an LCL container, the shipper may not be mentioned; instead the forwarder acts as shipper of the shipment of a container.
In case of carrier haulage, a shipping line may perform forwarding services on behalf of its customer. These are described under the role ‘forwarder’.

5.1.4.2 Forwarder

A forwarder may act on behalf of one or more shippers to arrange transport and formalities like customs declarations. These customs declarations may involve export and import, or transit at destination. Whenever a forwarder performs customs declarations - and transport services, the service deliveries of both are strictly separated (‘separation of concerns’). The department providing the transport services is not allowed to access declaration data, since this declaration contains information about the actual cargo to be transported. This is to prevent any unauthorised operations like theft of valuable cargo.
Export – and import declarations can be performed by different forwarders.
A forwarder at import can differ from the one at export, but could also be part of the same organization. Furthermore, an export declaration is not necessarily identical to an import declaration.

At export, an HS-code of the goods will be given that eases the outgoing of these goods. At import, an HS-code will be given that gives the lowest import VAT. Export – and import declarations are fed by purchase orders, invoices, and packing lists produced by a customer of a forwarder (see further).
Export - and import declarations can only be used to retrieve cargo details in case they share a container number. Transport data sets relevant to transport services of a forwarder do not contain the actual cargo details. Whereas the export and import declaration are at consignment level (or multiple consignments when necessary), the stuffing list (if available; details of stuffing are not always given) and the data produced to a shipping line is at container level. In case of LCL containers, the container numbers are not provided in an export declaration; they will appear to customs in an ENS produced by a shipping line. In case of an FCL container, the container number will be part of the export (and import) declaration.

5.1.4.3 Shipper/consignee

A shipper is the organization or entity that produces a consignment for shipment to a consignee.

There are several reasons to initiate a consignment, for instance:

- Buy-sell: a consignee acts as buyer of products of a seller, where the seller takes the role of shipper. A purchase order, invoice, and packing list are shared between buyer and seller. One purchase or may result in one or more consignments and several purchase orders can be packed into one consignment. One invoice may contain details of one or more purchase orders. In eCommerce, one purchase order will give one invoice and one consignment.
- Buy-sell: a consignee acts as buyer of products of a seller, where the seller takes the role of shipper. A purchase order, invoice, and packing list are shared between buyer and seller. One purchase or may result in one or more consignments and several purchase orders can be packed into one consignment. One invoice may contain details of one or more purchase orders. In eCommerce, one purchase order will give one invoice and one consignment.
- Stock replenishment: a shipper initiates a consignment to be shipped to a warehouse to have sufficient stock for delivery to customers. A logistics service provider can perform this function on behalf of the producer (VMI – Vendor Management Inventory) and thus acts as shipper. There is no purchase order or invoice involved, since the products don’t change ownership. Furthermore, they can be stored under customs regime in the warehouse at destination, so there might not necessarily be an import declaration (the import declaration will be produced when products are actually sold from the warehouse to a buyer).
- Repair and maintenance: triggered by an end-user of a product or a maintenance service provider, an enterprise ships a part to that customer. Whether or not a purchase order or invoice are part of data sharing depends on the organizational relation between a (local) maintenance service provider and a manufacturer (OEM- Original Equipment Manufacturer).

A purchase order and invoice (or replenishment order) are the basis for export and import declaration. These orders contain the actual products that are shipped. An invoice has the actual value of the products, but an invoice is not always available (e.g. in the case of stock replenishment).

A shipper and consignee may also do the export and import declarations.
A package list contains the relation between the actual packages and the goods as mentioned in a purchase – or replenishment order. In case of repair and maintenance, the packing list contains all products that are shipped to solve a particular problem. A package list results in the so-called line items of a consignment that has to be shipped via a transport service of a forwarder.

5.1.5 Lack of visibility

There are two ways to identify the container number of containers that were fallen from aboard during the sea voyage. One way is after having localised the fallen containers, to visually confirm the unique ISO 6346 International Shipping Container Standard Information reporting mark. Obviously, this can be done for washed up containers, floating containers and salvaged containers, but not for containers broken in pieces, or lost sunken containers. Another approach is to use the stowage plan and confirm which containers are still on board or unloaded. In case of substantial damage in/to the bays, an accurate validation can only be made afterwards when the vessel arrived in the port of discharge. Localisation methods, like the LoRa Gateway approach can help in this identification stage.

When knowing the container number, we can identify the vessel and shipping line carrying this container during the incident. The methods for this were described in the previous section.

When knowing the vessel and shipping line, the corresponding manifest and B/L can provide among others the reported shipper, consignee, the HS-codes of the reported cargo, and the port of loading and port of discharge. The dangerous goods manifest can identify if the lost containers were reported containing dangerous goods and include a 4-digit UN number and an EmS number, referring to the Emergency Response Procedure to be followed in case of incidents.

If the description of the HS-codes is too general, additional information can be retrieved by shipment identification. With the shipment identification, the transport order number can be retrieved and exporter, seller, importer, buyer, purchase order, packing list, and stuffing list details can be identified. This information includes product identification details and number of boxes, collies, items.

In theory, this information can be linked, and corresponding data elements can be retrieved, supported by (real-time) visibility platforms. In practice, such linkages between vessels, container, shipment, transport order, purchase/production order are often not stored. Retrieving this information afterwards is a time consuming process and depends on collaboration of all actors involved in the processes to follow this data trail.

An alternative track is to follow the declaration data. If the container was exported from the EU, an export declaration has been submitted and a movement reference number was allocated. If the port of destination was an EU port, an ENS has been submitted to the customs authority in first European port of call in the vessel schedule. As described in the previous section, the HS-codes allocated to import and export declarations for the same consignment may differ.

5.2 Smart devices for cargo identification

Low cost passive RFID tags may be an alternative container identification method, complementary to the ISO 6346 International Shipping Container Standard Information reporting mark. As described before under the communication technologies, its application however is limited to readers above water and within a small distance from the tag. And these tags cannot store much data.

An alternative is to apply tags that can exchange more data than just a few bits, up to more than 1 megabit. In theory, the stuffing data or B/L data could be written onto the tags, though the reluctance in the market to make this type of data transparent is even bigger than exchanging the corresponding data elements governed by data governance principles.

Combine this with cryptography to encrypt the data is technically possible, though cost increasing. And the data governance to facilitate decryption can also enable authorized actors to get access to the linked data from end-to-end visibility platforms.

5.3 Intrusive and non-intrusive inspection of the container contents

Inspection methods can be applied to containers being salvaged, washed ashore, or floating on the water level. Most obvious way is to open the container for physical inspection. If there is suspicion of narcotics smuggle, the target container is being guarded by both customs and police and either subject to physical inspection of the container or guarded and monitored in order to catch drugs traffickers in the act.
An alternative intrusive way is to drill a hole in the container and take a sample of the gas and/or liquid for further analysis.

Non-intrusive inspection methods like high energy x-ray container scanning and radiation detection are normally applied to support inspection authorities in their supervision role without or limited disturbing or disrupting the logistics supply chains. Mobile scanning equipment could be transported to the shore, but this is rather unlikely. In case of suspicion of dangerous gases or liquids inside a container, Raman spectroscopy has been used in several research projects as a means to detect explosives from a safe distance using laser beams.
Use of sniffer police dogs seems to be a more flexible and cheaper method for this type of incidental use.

5.4 Effectiveness of policies

There is an ongoing debate on policies to support customs risk management in increasing customs visibility of the container contents and other contextual information (e.g. ultimate consignor and consignee). The revision of the ENS procedure including the obligation to submit a 6-digit HS code is an intermediate result of that debate.

Policies to endorse the visibility of goods descriptions from purchase orders is currently not in question.

5.5 Summary

If we want to know the contents of a container that was fallen overboard (drifting, sunk or washed ashore), we can follow the data trail. Knowing the container number, we can identify the vessel and shipping line carrying the container during the incident and request the corresponding carrier to provide cargo details. These will include the high level 4-digit HS-code descriptions based on ‘said to contain’, or in case of dangerous goods the 4 digit UN dangerous goods code description. When following the customs declarations corresponding to the consignments in the container, we find similar 4-digit HS codes. Full visibility solutions would bring us to the detailed goods descriptions on purchase orders and invoices. But as we see, this end-to-end visibility is often lacking.

Encrypted tags attached to the container could technically contain cargo details, but it would have huge impact on the way global supply chains are being organised. This sensitive commercial data should be (over)written on the tags during container stuffing and stripping. A secure interface with container visibility platforms could offer similar functionality against lower costs.

Non-intrusive inspection is not a standard procedure for stranded containers, and physical inspection is only be done ashore if there is a serious suspicion of narcotics smuggle. Its relevance for incidents with fallen containers is limited.

Table 3: Overview of the identification methods. The effectiveness of the each technique is described in four columns: (1) reliability in terms of a star-rating (1-5 stars, in which more stars represent a more reliable method), (2) the coverage describes the scope of the method, (3) the rationale, and (4) the limitations provide a list of disadvantages to the method. The last three columns describe the feasibility of the technique, in terms of: (1) scalability defining the domain of the method, (2) costs in terms of a star-rating (1-5 stars, in which more stars represent a cheaper method) and (3) logistics value to describe the added benefit to the end-to-end logistics.

	Effectiveness				Feasibility (Commercial)		
Technology	**Reliability**	**Coverage / Applicability**	**Rationale**	**Limitations**	**Scalability**	**Costs**	**Logistics value**
Carrier data visibility	★	All B/Ls All carriers	Risk assessment	- Quality and level of detail B/L goods description (STC, HS 4 digit) and dangerous goods manifest (UN 4 digit)	All container carriers	★★★★	N.A.
Customs data visibility	★	Incoming containers (ENS HS codes), export containers (HS code from expert declaration	Risk assessment	- Visibility limitations (declared HS codes) - Data privacy regulation	European (ENS-exchange)	★★★	N.A.
End-to-end supply chain visibility	★★★	Only if link with PO and/or PL is captured in visibility system	Risk assessment	- Lack of end-to-end visibility - Supply chain collaboration	Global	★	- Visibility benefits for downstream actors
Encrypted tags with cargo details	★★★★	Dangerous goods containers or all containers	Instant results with reader	- Requires legislation and enforcement - Resistance from trade	Global	★	N.A.
Manual container inspection	★★★★★	All shores, after salvage	In case of smuggle suspicion	- Container must be salvaged on land - Inspection Authority risk management	Low	★	N.A.
Sample of gas or liquid (hole drilling)	★★	Floating or stranded containers	Confirm dangerous gases of liquids	- Only when container is floating or salvaged an intact	Low	★	N.A.
Sniffer dogs	★	Stranded containers	In case of smuggle suspicion	- Only for salvaged containers - Only for inspection purposes	Low but flexible	★★★	N.A.
Raman spectroscopy	★	Stranded containers	In case of suspicion of dangerous explosive gases or liquids	- To detect dangerous explosive gases or liquids	Low	★	N.A.

6 A step change in container tracking applications

The problem with deployment of container tracking technology was that it was very costly, both in terms of the cost of the devices as well as the challenge in returning to their owners' devices that aren't permanently affixed to containers or other assets. This has been reconfirmed in research projects like Smart-CM, CASSANDRA and CORE, see section 1.3.

But now, LPWAN communication technology applied in a mesh network allows for low cost end-to-end container tracking applications, that offer functionality in the harsh environment of containers being shipped across the world and allowing for ultra-low battery use making reverse logistics of the smart devices redundant.

We see substantial investment from ocean carriers in commercial LPWAN-applications, even joint ownership of such solution providers by ocean container carriers. These solutions offer full integration with the reefer units, include already a number of sensors in the device (monitoring temperature, humidity, shocks and door opening), integrate GPS for situations where the low energy mesh network is not offering connectivity, and allow for easy integration of additional sensors. Think of ethylene sensors monitoring ripening status of perishable goods underway their destination.

The current investments in smart container tracking – already substantial and beyond the pilot stage - may be the first step in wider deployment programme by ocean carriers and boost the introduction of smart tracking applications in container terminals, empty depots, inland terminals or distribution centres. Such applications may speed up the deployment pace. Other recent initiatives also aim to accelerate the digital transformation in containerised shipping and logistics, think of multi-carrier collaboration in the launch of the Digital Container Shipping Association (DCSA) and in recent blockchain initiatives. Such initiatives further support these smart container tracking deployment programmes.

As such, the whole sector can benefit from this deployment in monitoring and localising incidents with fallen containers. It may be considered to accelerated the take up of such smart container tracking devices by developing policies and/or legislative measures for monitoring stowage integrity and tracking functionality above water levels for dangerous goods containers.

7 Signature

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