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Transport Damage Analysis of Dangerous Goods: State-of-the-art Report for Baltic Ports

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Abstract

The transport of dangerous goods incorporates hazards, which may seriously affect people, property and the environment in various adverse ways. One preventive measure is to require sturdy, certified packaging and tanks, which can withstand occurring transport stresses and thus reduce the likelihood of leakage and damage.

For non-dangerous goods, there is also a risk of damage by excess transport stresses, and the same challenge of designing an adequate protection, now primarily for the goods themselves, is obvious. Most dangerous goods accidents result in insignificant consequences, as fatalities or major releases of substances are relatively rare.

The transport of dangerous goods has since many years been harmonized internationally between different modes of transport, based on the UN Model Regulations (2017). A weakness of the UN performance tests is the small number of test objects. There is a significant likelihood that an approved packaging will fail if tested a second time, or conversely, if a failed packaging is retested it will likely pass, if reasonably well constructed. Several attempts have been made to characterize and quantify the stresses, which occur during transport of both dangerous and non-dangerous, but sensitive goods. It includes both mechanical loads, from vibrations, impact, stacking or lateral forces, and climatic factors, such as high or low temperature, temperature variations or moisture by condensation or precipitation.

When comparing damage rates for different modes of transport, one should have in mind that there is a relationship between the utilization of a specific mode of transport and the value and weight of any particular type of goods. Energy and agriculture products, which are lower-value and higher-weight goods, are more likely to be moved by ship and pipelines, while electronics and precision instruments, which are higher-value and lower-weight goods, are moved by air. As a consequence, the dangerous goods of the lower-value/higher-weight type would typically be handled at a seaport, while goods of higher-value/lower-weight would pass through an airport.

In a cargo handling perspective, those goods are different and require different actions, and the damage patterns are also different. Most investigations on transport damage were carried out near the turn of the century and were partly very thorough but can now appear aged. A first step for future research in this area should be a simple risk assessment for the traditionally most common causes of cargo damage (shock and impact, vibration, stacking overload, torn packaging, moisture, mould, wet packaging, overheating, freezing, overpressure, leakage and fire) but also in relation with lost goods reasons (theft, jettison). It is essential to achieve a good understanding of whether the trends regarding cargo damage and loss are changing or stable over time, in order to assess the relevance of available data and the need for new investigations.

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1 OBSERVED PROBLEM AND REPORT OBJECTIVES

As indicated by their designation, the transport of dangerous goods incorporates hazards, which may seriously affect people, property and the environment in various adverse ways. One preventive measure is to require sturdy, certified packaging and tanks, which can withstand occurring transport stresses and thus reduce the likelihood of leakage and damage. For non-dangerous goods, there is also a risk of damage by excess transport stresses, and the same challenge of designing an adequate protection, now primarily for the goods themselves, is obvious.

Nevertheless, transport damage occurs with different causes, such as accidents, unsatisfactory packaging, rough transport conditions, unprofessional stowage, stacking and segregation, displaced lashings, and many varieties of negligence and ignorance. With the focus on packagings for dangerous goods, and also packagings for other sensitive products, this report aims to describe the environmental and technological prerequisites for a safe transport. The report can thus be used as a guidance for designing and testing packagings and packages for the transport, in particular when rates of damage has been observed that are believed greater than normal.

1.1 Background

The HAZARD project aims at mitigating the effects of major accidents and emergencies in major multimodal seaports in the Baltic Sea Region, all handling large volumes of cargo and/or passengers. Ports, terminals and storage facilities are often located close to residential areas, thus potentially exposing a large number of people to the consequences of accidents.

Topics include harmonization and implementation of safety and security standards and regulations, communication between key actors, the use of risk analysis methods and adoption of new technologies. Leakage of hazardous materials, fire on a passenger ship at a port, oil spill in port areas as well as explosion of gases or chemicals are types of disastrous events that are addressed in the HAZARD project.

This report will highlight the problem of cargo damage with a particular focus on the risk for leakage of transported hazardous materials in packages, tanks or containers. Such accidental events may occur anywhere in the transport chain, when cargo is carried on board ships, in trains or in lorries.

The greatest risk is however in the nodes of such a transport chain, i.e. harbours, terminals or intermediate storage facilities, where the goods are handled, loaded, unloaded and transferred, thus seaports are a focal point in this respect. In the ports damaged packages and containers must be identified and relevant mitigating and preventive safety measures taken.

1.2 Impact of the problem

Within the industry, the term inventory shrinkage is used to describe the loss of products between the point of manufacture or purchase from the supplier and the point of sale. According to the report, “National Retail Security Survey” (NRSS, 2002), the average shrinkage rate is 1.8 percent of total annual sales.

This shrinkage rate corresponds to a total loss of 33.21 billion USD annually in the U.S. From a security point of view there are normally four different main sources of shrinkage: employee theft, shoplifting, administrative error, and vendor fraud, thus in principle ‘shrinkage’ addresses only the issue when goods are physically lost, but a large source of losses is also the damaging of goods; this means that the goods is still around but unable to continue to be a part of the intended supply chain.

In order to capture the impact for losses during transportation, a reasonable way is to utilise the insurance claims for freight forwarders’ liability. In the freight industry, liability insurance is designed to offer specific protection against third party claims. The key element in liability insurance is the contract between the parties involved. Contracts which specify liability between a Freight Forwarder (FF) or a Logistics Service Provider (LSP) and a cargo owner are referred to as Freight Forwarder Liability (FFL).

One of the world’s leading LSPs has, in order to control and simplify handling customer claims for the FFL, developed a claims database. All claims on the LSP are registered in the database, even invalid claims. Nevertheless, the FFL database provides a good indication about what causes problems for the LSP to fulfil the cargo liability toward the goods owners. The claims database contains more than 26,000 claims annually. Breakage or cargo damage is the biggest source of shrinkage (Ekwall, 2009). It stands for around 90% of the LSP net cost linked to FFL and 83% of claimed value. This alone would lead to the conclusion that cargo damage in general is a big concern for involved actors.

2 DANGEROUS GOODS RISKS AND SAFETY MEASURES

Most dangerous goods accidents result in insignificant consequences, as fatalities or major releases of substances are relatively rare. In order to prevent such events and severe consequences, it is important to investigate and learn also from the incidents or so-called near-misses, as is routinely done in aviation. Findings will underpin risk analyses, which are essential in all proactive safety work.

Few such incidents are reported, however. As an example, the Swedish competent authority for dangerous goods transport, MSB (The Swedish Civil Contingencies Agency), reports in total 24 such incidents for 2015, of which eight refer to traffic accidents, three to loading and unloading of packaged dangerous goods, six to loading and unloading of tanks, and seven to events during transport (four road, two rail, one air and none sea).

The obvious conclusion is that most incidents are never reported, which likely applies in all the Baltic Sea countries. As observed also in the EU project BaltPrevResilience (2016): "Some general input on the use of statistical data on accidents was that more knowledge is needed about statistics in our different countries. Existing statistic data must be presented so that the data can be used and it must be made known, the data may otherwise be brilliant but not useful".

Several publications and handbooks address risk and safety, covering the philosophy of risk management and safety work, methods and tools for risk analysis, risk control, cost vs. benefit assessment and decision-making, and best practices in many applications. One review of methods is provided within the HAZARD project by Moreno Parra et al. (2018). Also, the established practice of risk and safety assessment was defined and structured by the IMO as Formal Safety Assessment (FSA, 2002).

FSA is an instrument for pro-active measures to prevent and mitigate accidents and meant also as a tool for rule-making, as described there: "FSA is a structured and systematic methodology, aimed at enhancing maritime safety, including protection of life, health, the marine environment and property, by using risk analysis and cost benefit assessment.

FSA can be used as a tool to help in the evaluation of new regulations for maritime safety and protection of the marine environment or in making a comparison between existing and possibly improved regulations, with a view to achieving a balance between the various technical and operational issues, including the human element, and between maritime safety or protection of the marine environment and costs". Thus it is intended to be used by risk analysts, safety managers, researchers, competent authorities and other stakeholders with the aim to manage risk and safety, primarily within, but not restricted to, the maritime sector.
Formal Safety Assessment (FSA) consists of five steps:

1. Identification of hazards (a list of all relevant accident scenarios with potential causes and outcomes);
2. Assessment of risks (evaluation of risk factors);
3. Risk control options (devising regulatory measures to control and reduce the identified risks);
4. Cost benefit assessment (determining cost effectiveness of each risk control option); and
5. Recommendations for decision-making (information about the hazards, their associated risks and the cost effectiveness of alternative risk control options is provided).

In simple terms, these steps can be reduced to:

1. What might go wrong? = identification of hazards (a list of all relevant accident scenarios with potential causes and outcomes)
2. How bad and how likely? = assessment of risks (evaluation of risk factors);
3. Can matters be improved? = risk control options (devising regulatory measures to control and reduce the identified risks)
4. What would it cost and how much better would it be? = cost benefit assessment (determining cost effectiveness of each risk control option);
5. What actions should be taken? = recommendations for decision-making (information about the hazards, their associated risks and the cost effectiveness of alternative risk control options is provided).

The joint European project SEALOC (Pålsson et al., 1998) used FSA to assess three cases, including container transport of dangerous goods. Of immediate interest for maritime safety in the Baltic Sea is the application of FSA to the regional level in the MIMIC project (P. Haapasaari et al., 2015).

2.1 International and national regulations

The transport of dangerous goods has since many years been harmonised internationally between different modes of transport, based on the UN Model Regulations (2017).They are continuously updated and revised. The following are core parts of the Model Regulations:

- Classification, with a detailed Dangerous Goods List,
- Packing and Tank Provisions,
- Consignment Procedures, including marking and labelling, and
- Requirements for the Construction and Testing of Packagings, Intermediate Bulk Containers (IBCs), Large Packagings, Portable Tanks, Multiple Element Gas Containers (MEGCs) and Bulk Containers.

The UN Model Regulations are, as stated, model regulations for the international dangerous goods regulations of the different modes of transport, ADR, RID, IMDG Code and ICAO

Regulations, for road, rail, sea and air transport, respectively. Also nationally, these regulations have been adopted with minor changes, in the interest of facilitating free movement and trade. The regulations take into account the different damaging properties of substances by specifying the classification in nine different classes, some of which are further subdivided, so Class 1—Explosives, Class 2—Gases, etc. Then, to specify the degree of hazard, each substance is characterised by a packing group, I, II or III, where I represents the greatest hazard, thus requiring the most rigorous packing method and strongest packaging.

As dangerous goods do not represent a danger when confined to its packaging or tank, the requirements for the construction and testing of these are essential in the safety philosophy of the regulations. Packagings are subjected to a type-testing scheme, representative of the stresses that may be encountered in transport and handling. Successful testing and fulfilment of construction specifications lead to a type approval and the specific UN marking of the packaging.

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2.2 Risks according to classification

Dangerous goods are classified into different classes, depending on the type of hazard they represent. The main nine classes represent the following properties,

1. Explosives
2. Gases
3. Flammable liquids
4. Flammable solids
5. Oxidising substances
6. Toxic and infectious substances
7. Radioactive material
8. Corrosives
9. Miscellaneous dangerous goods

There are technological criteria for inclusion of substances and articles in the respective class.

Thus, **explosives** are materials or items which have the ability to rapidly conflagrate or detonate as a consequence of chemical reaction (meaning that explosives are capable by chemical reaction of producing gases at temperatures, pressures and speeds as to cause catastrophic damage through force and/or of producing otherwise hazardous amounts of heat, light, sound, gas or smoke). There are six divisions of explosives, ranging from division 1.1, substances and articles which have a mass explosion hazard, to division 1.6, extremely insensitive articles which do not have a mass explosion hazard.

Gases are defined by dangerous goods regulations as substances which have a vapour pressure of 300 kPa or greater at 50° C or which are completely gaseous at 20° C at standard atmospheric pressure, and items containing these substances. The class encompasses compressed gases, liquefied gases, dissolved gases, refrigerated liquefied gases, mixtures of one or more gases with one or more vapours of substances of other classes, articles charged with a gas and aerosols. There are three divisions of gases, division 2.1, flammable gases, division 2.2, non-flammable, non-toxic gases, and division 2.3, toxic gases.

Flammable liquids are defined by dangerous goods regulations as liquids, mixtures of liquids or liquids containing solids in solution or suspension, which give off a flammable vapour (have a flash point) at temperatures of not more than 60–65°C, liquids offered for transport at temperatures at or above their flash point or substances transported at elevated temperatures in a liquid state and which give off a flammable vapour at a temperature at or below the maximum transport temperature (meaning that flammable liquids are capable of posing serious hazards due to their volatility, combustibility and potential in causing or propagating severe conflagrations).

Flammable solids are materials which, under conditions encountered in transport, are readily combustible or may cause or contribute to fire through friction, self-reactive substances which are liable to undergo a strongly exothermic reaction or solid desensitised explosives. Also included are substances which are liable to spontaneous heating under normal transport conditions, or to heating up in contact with air, and are consequently liable to catch fire and substances which emit flammable gases or become spontaneously flammable when in contact with water. There are three divisions of flammable solids, division 4.1, flammable solids, division 4.2, substances liable to spontaneous combustion, and division 4.3, substances which, in contact with water, emit flammable gases.

Oxidisers are defined by dangerous goods regulations as substances which may cause or contribute to combustion, generally by yielding oxygen as a result of a redox chemical reaction.

Organic peroxides are substances which may be considered derivatives of hydrogen peroxide where one or both hydrogen atoms of the chemical structure have been replaced by organic radicals. (Specifically, oxidisers, although not necessarily combustible in themselves, can yield oxygen and in so doing cause or contribute to the combustion of other materials. Organic peroxides are thermally unstable and may exude heat whilst undergoing exothermic autocatalytic decomposition. Additionally, organic peroxides may be liable to explosive decomposition, burn rapidly, be sensitive to impact or friction, react dangerously with other substances or cause damage to eyes.) There is a division for each category, i.e. division 5.1, oxidising substances, and division 5.2, organic peroxides.

Toxic substances are those which are liable either to cause death or serious injury or to harm human health if swallowed, inhaled or by skin contact. **Infectious substances** are those which are known or can be reasonably expected to contain pathogens. Dangerous goods regulations define pathogens as microorganisms, such as bacteria, viruses, rickettsiae, parasites and fungi, or other agents which can cause disease in humans or animals. There is a division for each category, i.e. division 6.1, toxic substances, and division 6.2, infectious substances.

Dangerous goods regulations define **radioactive material** as any material containing radionuclides, where both the activity concentration and the total activity exceeds certain pre-defined values. A radionuclide is an atom with an unstable nucleus and which consequently is subject to radioactive decay.

Corrosives are substances which by chemical action degrade or disintegrate other materials upon contact (meaning that corrosives cause severe damage when in contact with living tissue or, in the case of leakage, damage or destroy surrounding materials).

Miscellaneous dangerous goods are substances and articles which during transport present a danger or hazard not covered by other classes. This class encompasses, but is not limited to, environmentally hazardous substances, substances that are transported at elevated temperatures, miscellaneous articles and substances, genetically modified organisms and micro-organisms and (depending on the method of transport) magnetised materials and aviation regulated substances.

2.3 Risks according to packing groups

Packing groups represent the degree of danger within the types of danger shown by the classification. The packing groups accordingly determine the level of protective packaging required for dangerous goods during transportation.

- Group I: substances presenting high danger, where the most protective packaging is required,
- Group II: substances presenting medium danger,
- Group III: substances presenting low danger, where less protective packaging is required.

Packing groups are assigned in accordance with criteria that differ between the different classes. For example, in class 3, flammable liquids, the flashpoint and to some extent the boiling point are decisive for the packing group.

The packing group thus determines the performance of the packaging. In the UN performance test scheme, packagings have different requirements regarding drop height, test pressure etc. for packing group I, II and III, respectively.

3 PACKAGING AND TANK REQUIREMENTS

In conformity with the model regulations (UN Model Regulations, 2017) the international regulations for dangerous goods (ADR, RID, IMDG) prescribe performance requirements for packagings, intermediate bulk containers (IBC) and so-called large packagings (an outer packaging for inner packagings). These are type-testing procedures, which in a relatively simple and inexpensive way simulate transport stresses, or as it is often referred to, ‘normal transport conditions’. It is now a well-established performance testing programme, but nevertheless the test methods and the criteria for passing are sometimes questioned, with regard to their ability to ensure sufficient safety and protective functionality for the goods transport.

The performance testing scheme for dangerous goods packagings comprises a drop test, basically with drop height 0.8 m, 1.2 m and 1.8 m for packing group III, II and I, respectively and a stacking test, which simulates a 3.0 m stack with similar packagings, in case of plastics during 28 days in +40° C. For packagings for liquids, also a leakproofness test and a hydraulic pressure test are performed. For plastics packagings, there is also a requirement to verify the chemical compatibility with the intended contents.

For IBCs the testing scheme is similar, but with the addition of lift tests, and, for flexible IBCs (such as big bags), a tear test, a topple test and a righting test. In particular for metal IBCs, there are also more rigorous material, construction, and quality assurance and inspection requirements. This is also the case for portable tanks for dangerous goods, where detailed construction and inspection requirements are given, but fewer performance tests.

A weakness of the UN performance tests is the small number of test objects. There is a significant likelihood that an approved packaging will fail if tested a second time, or conversely, if a failed packaging is retested it will likely pass, if reasonably well constructed. As an example, assume that a plastics jerrican has a probability of 0.8 (80%) of passing when dropped 1.2 m in a diagonal orientation. Three samples are tested, so the probability of passing is $0.8^3 = 0.51$ (51%), so it may or may not pass. If two such test series are performed, the probability of both passing is 0.26, so in one case out of four the pass results will be confirmed. Of course the situation improves with higher quality of the packagings.

4 MEASUREMENTS AND EVALUATION OF THE TRANSPORT ENVIRONMENT

Several attempts have been made to characterise and quantify the stresses, which occur during transport of both dangerous and non-dangerous, but sensitive goods. It includes both mechanical loads, from vibrations, impact, stacking or lateral forces, and climatic factors, such as high or low temperature, temperature variations or moisture by condensation or precipitation. In some cases biological and other factors in the transport environment must also be taken into account.

There are a myriad of reports on the topic, covering shock, vibration or temperature measurements in specific transport situations and the consequential influence on different kinds of goods. However, most generally applicable results in this field were published up to, say, 2003, when focus shifted from cargo safety toward security in transport, due to concerns following the terror attacks and perceived increasing cargo theft at the time.

Pioneering work then, concerning the measurement and evaluation of transportation stresses, were two German investigations, GGVPM (1987), specifically targeted at the transport of packaged dangerous goods, and Theseus (1995), addressing portable tank transport of dangerous substances. These research projects have provided important knowledge about material properties and statistical safety analysis and about the relationship between normal or abnormal transport conditions and cargo damage. They influenced the dangerous goods regulations regarding construction and testing requirements for packaging and tanks, although less than expected, due to cost-benefit considerations.

Based on data from GGVPM and other sources a typical transport chain with two nodes and three links can be imagined, with the respective transport conditions that are not unlikely to apply, as in **Table 1**.

Table 1: *Typical transport chain with occurring stresses (authors, from several sources)*

	Storage and loading, inland	**Storage and loading, port**	**Road transport**	**Rail transport**	**Sea transport**
Stacking height	4 m	5–6 m	2 m	2 m	4–8 m
Duration	20 days	45 days	3 days	3 days	30 days
Fall	6 times, thrown or dropped from fork lift	6 times, thrown, 2 times fork lift, 2 times crane lift	Fall from stack, due to vibrations, uneven road	Fall from stack, due to switching	No defined falls
Lateral compression	Drums on fork lift	Setting down, or lifting slings	Braking or curves	Switching	Rolling, load displacement
Vertical impact	Fork lift, edges, cart across tracks	Setting down of pallets and containers	Uneven road	Switching	Slamming

Reported data on mechanical conditions are further shown in **Table 2** and **Table *3***, regarding impact and stacking.

Table 2: *Impact types and their distribution between small and large packages (GGVPM 1987)*

Type of impact	Mass ≤ 20 kg	Mass > 20 kg	Total
Free drop	90%	10%	63%
Throw	100%	0%	18%
Overturning	22%	78%	18%
All impact types	80%	20%	100%

Table 3: *Stacking height of dangerous goods packages and type of stack (GGVPM 1987)*

Height (m)	Percentage	Uniform stack	Irregular stack
≤ 1.2	45%	67%	33%
1.2–3.0	42%	61%	39%
3.0–8.0	13%	80%	20%
> 8.0	0%	-	-

The UN testing scheme referred to above is developed in order to cover above-average transport conditions. For all kinds of goods, for distribution testing of packagings, packages and transport units there are several sets of standards available, for example ASTM (such as ASTM D4169, 2016), ISTA (as described in the ISTA Guidelines, 2018) or ISO (as summarised in ISO 4180:2009). General environmental testing is also elaborately described in the IEC 60068 series of standards, starting with IEC 60068-1:2013. Tests are usually designed to emulate various transport conditions, such as those in **Table 4**.

Table 4: *Types of transport stresses and their causes (compiled by authors)*

Mechanical	
Impact, vertical	Packages fall to the floor during loading and unloading, from nets, pallets, conveyors, vehicles etc. Toppling. Throwing.
Impact, horisontal	Vehicles braking or accelerating. Swinging cranes. Rapid deceleration of conveyed or rolling packages. Throwing
Vibration	From handling equipment. Engine and transmission in road vehicles. Wheels, suspension and rail condition in railway vehicles. Machine vibrations in ships. Engine and aerodynamic vibrations in airplanes.
Compression	Stacking. Transient loads during transport. Compression from lashings, crane lifting, slings, grappler arms etc.
Shearing	Uneven storage conditions. Uneven lifting by inadequate methods or equipment.
Penetration, puncture and tearing	Hooks, protruding objects. Inadequate handling or handling equipment.
Climatic	
High temperature	Sunlight. Nearby boilers, heating systems, etc. Solar heat in warehouses or uninsulated vehicles. High ambient temperature.
Low temperature	Unheated storage space. Air transport in unheated cargo space. Refrigerated storage.
Low pressure	Increasing altitude, in some airplanes with non-pressurised cargo holds.
Light	Sunlight, ultraviolet radiation. Artificial light.
Water, fresh	Rain, during movements, loading, unloading, warehousing and storage. Puddles and flooding. Condensation.
Water, contaminated	Salt water spray on deck. Salt water accumulated in docks, cargo holds etc. Bilge water. Industrially contaminated water.
Dust	Wind-borne particles of sand etc.
Water vapour	Atmospheric moisture, natural or artificial.
Biological	
Micro-organisms, fungi, mildew, bacteria	Ubiquitous, adapting to various conditions. Require moisture, will usually not grow or proliferate below 70% R.H. Grow in a broad temperature interval.
Beetles, moths, flies, ants, termites	Development unlikely below 15° C. Relative humidity of 70% favours most insects, but some develop in drier conditions. Source is usually eggs in packaging material or influence from other packages or the environment.
Mites	Like insects, but more sensitive to dry conditions (below 60% R.H. critical).
Rodents	Present in warehouses, sheds, storage areas, cargo holds etc. Attack most materials.
Contamination from other cargo	
Packaging materials	Deleting marking, printing etc. by rusty metal straps or wires. Moist packaging material influencing water-sensitive materials, glue, or metal components.
Leaking contents	Damaged container for liquids or solids. Adjacent packages may be partly or totally destroyed.

It is generally agreed that commonly occurring transport stresses and their causes can be described as in **Table 4**, applicable to dangerous and non-dangerous goods alike. The ensuing consequences are briefly described in **Table *6***.

5 ACCIDENTS AND INCIDENTS

5.1 Stakeholder experience

A limited survey was performed for indicative purposes, with respect to a few (20) stakeholders' view of cargo damage specifics, not particularly restricted to dangerous goods. **Table 5** displays a summary of such views.

Table 5: *Shared experience by stakeholders (compiled by authors)*

Insurance companies	▪ Cargo damage very frequent ▪ Not possible to state any mode of transport or any transport chain more damage-prone than others. ▪ Most common categories are theft and mechanical stress influence ▪ Road and rail: mechanical factors dominate ▪ Air transport: moisture commonest cause of damage ▪ Handling causes much damage
Transport companies	▪ Losses and theft in terminals are the most serious problems
Manufacturing and sales companies	▪ Better packing and stowage have reduced the transport damage problem. Handling in terminals is critical; much careless processing has been observed.
Accumulated findings	▪ 21% of reclaimed goods are damaged ▪ 69% assess the transport environment, by own experience, field studies, dialogue with transporter, dialogue with packing consultant. For the others, there is allegedly no need, or they have no resources to do it. ▪ Damage causes and numbers: Mechanical (shock 8, compression 6, vibration 4), climatic (moisture 5, temperature 2), theft 4, water 3, corrosion 1. ▪ 62% test the product in conditions ready for transport. Test methods used: drop 4, pressure 2, compression 1, leakproofness 2, crash 1, vibration 4, field trial 3. ▪ 75% state that transport properties are considered already at the product development and design stages ▪ The packaging is designed at product development (6), start of series production (6), product design (4), or is constantly improved (1)

The table is a snapshot of views and opinions from a very limited number of stakeholders. It is not difficult to find contradictory statements both by selecting other interviewees and by consulting literature on the subject. For example, several sources claim that sea transport is far more damage-prone than, say, air transport. It is still to be analysed, however, whether the relatively low-value goods by sea and high-value ones by air validate one statement or the other.

5.2 Types of cargo damage

A systematic view of several types of cargo damage can be compiled from a classical handbook, edited by Grundke (1997), as in **Table 6**.

Table 6: *Types of cargo damage related to environmental factors (Grundke (1997), edited by authors)*

Factors	Physical changes	Chemical changes	Biological changes
Mechanical stresses	Fracture, deformation, scratches, rips, leakage; separation, changes in bulk density	Reactions in unstable products	Damage which opens up for attacks by micro-organisms
Rising temperature	Heat expansion, overpressure, bursting of containers. Phase changes, separation, permeation, ageing of material	Chemical disintegration, accelerating reaction processes, ageing of material	Growth of micro-organisms. Increased activity of vermin
Sinking temperature	Condensation, separation, ice wedging, deteriorated material properties	Frost damage	Frost damage
Increasing air humidity	Changes in hygroscopic material of consistency, properties and appearance	Corrosion, accelerated reaction processes	Growth of micro-organisms
Decreasing air humidity	Changes of consistency, properties and appearance, dehydration	Chemical changes (dry oxidation)	
Radiation, light	Heating, ageing of material	Triggered reactions, ageing of material	Various changes
Air pollution	Absorption, smell and taste changes	Reaction with products	Allelopathy
Air movements	Accelerated evaporation, contamination, mechanical damage	Transport of aggressive substances	Infection of micro-organisms
Dust, sand	Contamination, scratches, surface damage performance disturbances	Chemical reactions, e.g. corrosion	Supports attacks by vermin and micro-organisms
Decreasing air pressure	Internal overpressure, performance disturbances		

Table 6 provides a basic insight into the consequences of the different damage mechanisms. Usually a chain of adverse events precede the observed damage, as demonstrated below (**Figure 2** and **Figure *3***).

5.3 Methods of analysis

To characterise the impact strength of an object, sometimes a damage limit is tested and calculated by plotting the average force, F_a, of a shock impulse that the object can just withstand, against the duration of that impulse. The limit curve will approach asymptotically the static load F_0, which will just cause damage (see **Figure 1**).

Figure 1: *Limit of damage for shock tolerability (authors' illustration)*

Schematically the diagram shows that a certain average force is more damaging, when the shock impulse has a longer duration. This is of course expected, as the impulse ($\int_0^t F dt = F_a t$) then is greater.

Condensation may become a severe problem under, in particular, the following circumstances.

1. Air humidity condensates on cold objects, such as when ships move between climate zones.
2. Hygroscopic goods that are exposed to cold air will have a migration of moisture from within, which condensates in the colder surface layer. From there condensation moves successively inward, as the goods cool off.
3. At an external temperature drop, the walls of cargo holds, railway cars or containers become cooler, and large amounts of water can form on them by condensation and even flow onto the floor.

Usually the development of cargo damage is complex, with several factors contributing. It can be represented by a fault tree, showing how root causes and deviations combine to form a 'top event' (the immediately observed damage). A couple of examples are shown in **Figure 2** and **Figure *3***.

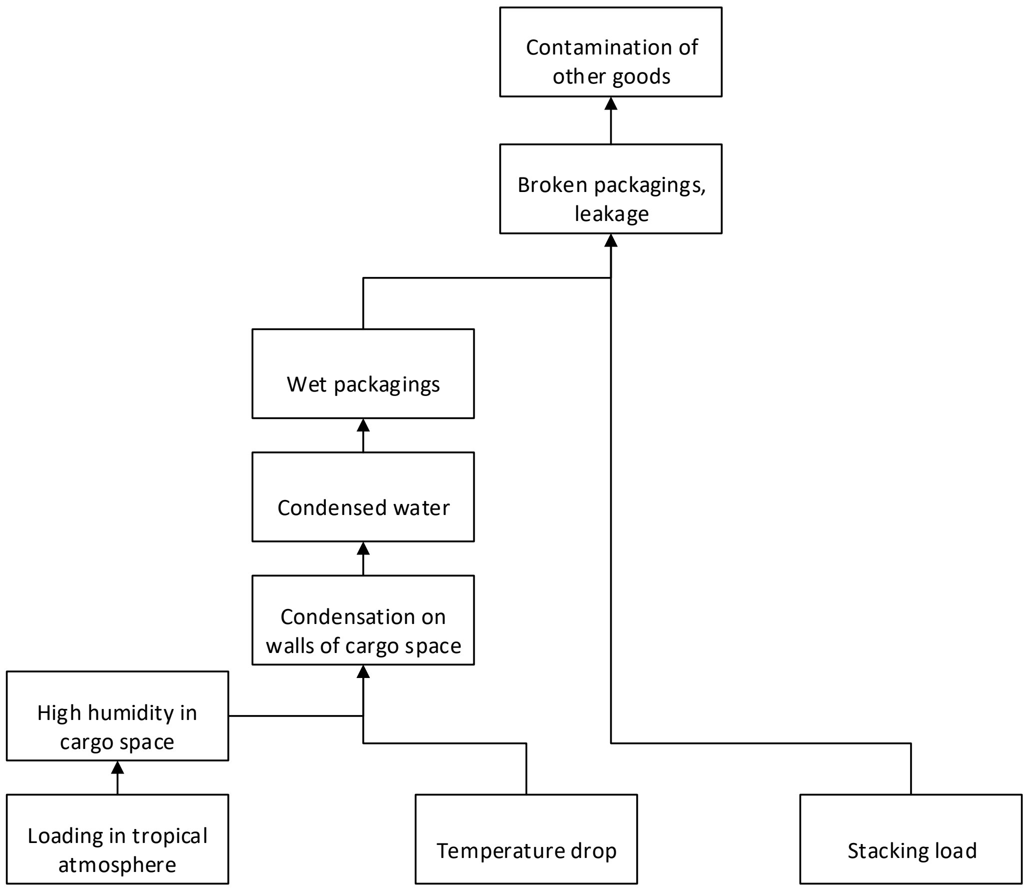

Figure 2: *Chain of events leading to contaminated goods (authors' observations)*

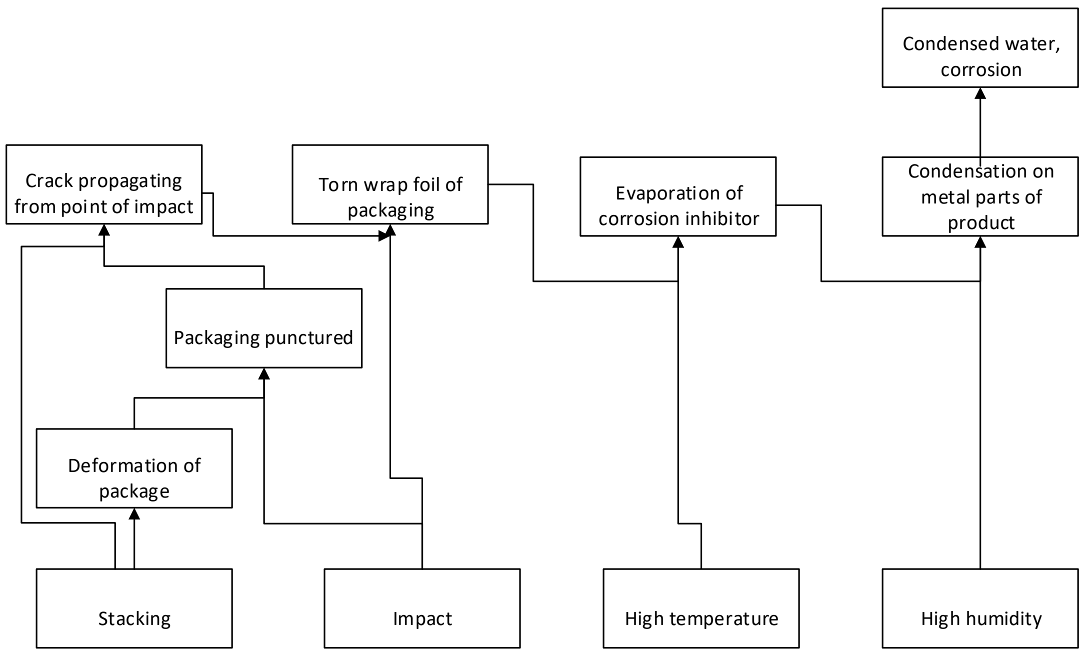

Figure 3: *Chain of events leading to corrosion damage (authors' observations)*

The diagrams in **Figure 2** and **Figure 3** form, as noted above, a sort of fault tree, depicting how deviations at successive steps combine to create damage to the cargo. Elaborated fault trees use also logical gates, AND and OR, to specify how factors combine. It can be assumed that the present diagrams contain only AND gates, viz. both contributing events are combined to get the next one at each step. So, for example in Fig. 3, both the stacking load and the puncture from the impact are necessary to create the propagating crack.

6 REPORTED DANGEROUS GOODS FLOWS AND ACCIDENTS

6.1 Maritime flows and other transport

There is a significant amount of dangerous goods being transported at sea. MSB has collected statistics of such goods passing through Swedish ports and for other Baltic Sea ports, the amount received from or sent to Swedish ports. However, the latest report is from 2006 but may still give an indication (MSB, 2006). The findings are summarised in **Figure 4** for the month of September. It should be noted that tanker ships are not included, meaning that primarily Class 3, flammable liquids, is underestimated, and that there is a disclaimer that some transport companies have not participated in the investigation.

Data also for other countries for the years 2002–2006 was collected and presented in connection with the European Interreg project DAGOB, Safe and Reliable Transport Chains of Dangerous Goods in the Baltic Sea (DAGOB 2007). The report presents statistics of dangerous goods transport by sea, road and rail for six countries in the Baltic Region, viz. Finland, Estonia, Latvia, Lithuania, Germany and Sweden, and discusses briefly the shortcomings of available data, noting that the collection of data is inconsistent and varies between countries.

There is no evidence found that the situation has changed significantly since 2007. By country, the total amounts of transported dangerous goods have in some cases changed over the years 2008–2017. (Eurostat, 2019a). So, for Estonia, there is a reported decrease over those ten years of 77%, Poland shows an increase of 53%, while the other Baltic Sea countries stay at the same order of magnitude, with some small fluctuations from year to year.

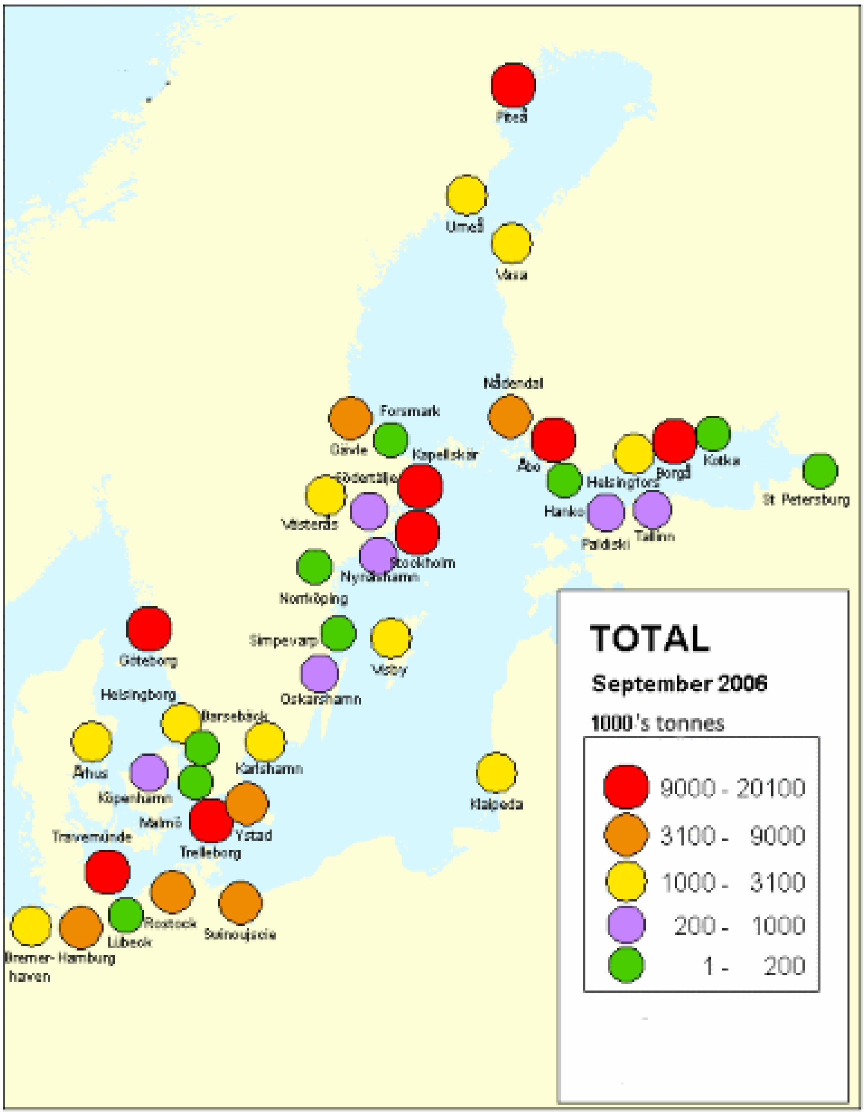

Figure 4: *Indicative dangerous goods volumes (except tankers) in ports, Sept. 2006 (Oscarsson, 2006, App. IV)*

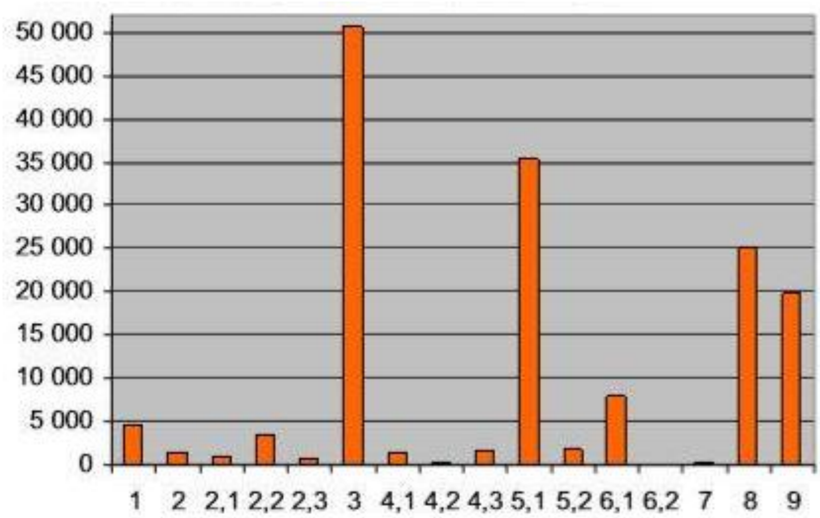

Figure 5: *Amount (tonnes) of dangerous goods of different classes, transferred in Swedish ports, Sept. 2006 (Oscarsson, 2006, p. 26)*

For commodities of all kinds sent abroad, 31% by cargo weight and 15% by cargo value are transported by ship. For commodities imported to Sweden, 69% by cargo weight and 26% by cargo value are transported by ship (Transport Analysis, 2017; Sjöfartsverket 2018).

An example of risk assessment for handling of explosives in ports was made for the Port of Felixstowe (Moreton et al., 1994). It is an unusual effort by applying quantitative risk assessment, which, as was stated, identified a number of safety issues not normally considered. One result was that, although the risk of an accident involving a passenger vessel was assessed to be extremely low, the operators of the port had instituted an appropriate traffic management system to eliminate this risk.

6.2 Reporting of accidents

The Swedish system for reporting dangerous goods accidents has been examined, where an analysis of reported accidents (MSB, 2014) served as a basis. The report is in Swedish, but some highlights are mentioned here.

When accidents or incidents have occurred, where there has been an imminent danger of injury, the operator carrying, loading or unloading dangerous goods has an obligation to report the incident to MSB, for all modes of transport, and to the Transport Agency as regards sea transport and aviation. MSB is also responsible for a national collection of reports on municipal rescue efforts, including those involving dangerous goods. Such reports form the basis for **Figure 6**, showing the number of reported discharges, **Table *8***, categorising the events by accident type, **Table *9***, direct causes, and **Table *10***, underlying causes of dangerous goods accidents. There are several sources of error in this material, due to the subjectivity of those reporting and the design of the report forms, thus, much has not been reported, and much falls into the category of 'other'.

The total of transported cargo in Sweden was 584 million tonnes in 2010, of which domestic transport was 64%, thereof 86% by road, 11% by rail and 3% by sea. International transport was predominantly carried out by sea. A rough estimate is that 10, 3 and 5 million tonnes are dangerous goods on road, rail and sea, respectively.

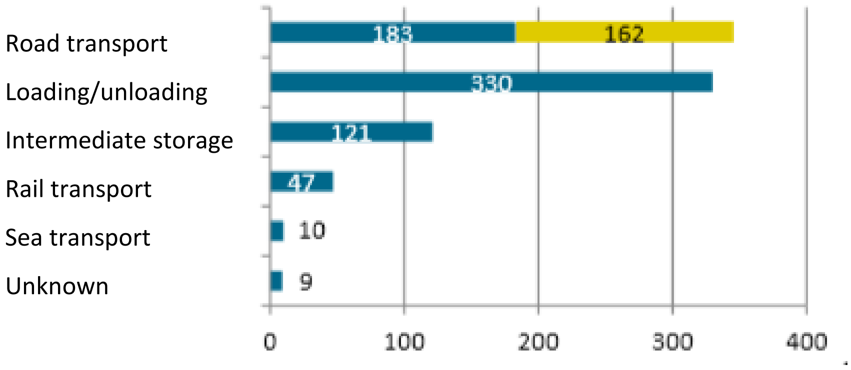

Figure 6: *Number of reported discharges of dangerous substances, including traffic accidents (yellow), by the Swedish rescue services, 2007–2012 (MSB, 2014)*

During the period 2007–2012, the number of vehicle units that did not meet the requirements of ADR varied between 13 to 22 percent for Swedish-registered vehicles, 16 to 22 percent for foreign-registered vehicles from another EU country and 7 to 22 percent for other foreign-registered vehicles.

Table 7 shows the criteria to be applied for reporting by operators in case of a dangerous goods accident.

Table 7: *Criteria for reporting by operators (MSB, 2014)*

- Personal injuries directly related to the transported dangerous goods leading to intensive care, hospitalisation of at least one day, inability to work for at least three consecutive days or deaths.
- Dangerous goods emissions of at least 50 kg or litres in transport category 0 or 1, 333 kg or litres in transport category 2 or 1000 kg or litres in transport category 3 or 4.
- Direct hazard of release of hazardous goods in the same amounts as above, for example due to damage to tanks or containers, the vehicle rolled or fire in the immediate vicinity.
- All events with contagious substances (Class 6.2) and emissions of radioactive substances (Class 7), or if packages are damaged.
- Damage to property or environment exceeding 50 000 Euro.
- Events when the authority initiated the evacuation of persons or blockages by public transport managers for at least three hours, caused by hazards from the dangerous goods.

Due to the general measurements made on occupational traffic, no negative impact has been demonstrated for foreign-registered vehicles compared to Swedish-registered vehicles, from neither an environmental nor a traffic safety point of view.

Table 8: *Dangerous goods event types 2007–2012 (MSB, 2014)*

Type of event	During transport	Loading, unloading	Total
Fire	7	6	13
Explosion	1	1	2
Leakage or discharge	43	87	130
Other	72	29	101
Of the six fires at loading, unloading, two could be attributed to faulty packing of the dangerous goods			
Of the two explosions, one was by erroneous unloading of DTPA into a hydrogen peroxide tank. The other was a very severe accident, where a road tanker with petrol collided with a lorry. One driver died, the other vas severely injured.			
For leakage and discharge, oil and petrol are the most typical substances to be released during transport, usually caused by traffic accidents.			
More than half of ’other’ events are traffic accidents. A large amount of the rest relates to discovery of improper marking and packing of dangerous goods.			

Table 9: *Direct causes of dangerous goods accidents, 2007–2012 (MSB, 2014)*

Direct cause	Number	Direct cause	Number
Run-off-road	50	Cargo securing	4
Rollover	41	Fire in cargo	3
Overfilling	22	Faulty track/operation problem	3
Leakage of packaging	21	Unknown	3
Collision with vehicle	16	Hose failure	3
Package punctured by sharp object	14	Tyre fire	2
Leakage in valve	12	Incorrect degree of filling	2
Evasive action	10	Reaction between substances	2
Leakage in gasket	10	Engine fire	1
Package fell to ground	10	Other	101
Incorrect packaging	4	**Total**	**334**
Note: Some events have more than one cause			

Table *10* is of particular interest in a human-technology-organisation context, where a salient feature is the analysis of events, where causes and causes of causes are identified to the organisational level, in order to find systematic inadequacies in the work environment.

Table 10: *Underlying causes of dangerous goods accidents, 2007–2012 (MSB, 2014)*

Background causes	**Number**	**Background causes**	**Number**
Equipment issues	***135***	Bad working conditions	1
Component of equipment faulty	16	Lack of commitment or knowledge in management	0
Inadequate maintenance	13	Other organisational issue	35
Faulty design	8	***Human error***	***172***
Technology-related problems	8	Mistakes or negligence	46
Incompatible material vs. Substance	5	Rules or instructions not observed	21
Foreign object or substance	3	Misunderstanding	21
Other technological or equipment fault	1	Intentional action	3
Organisational issues	***80***	Missed signal, indication or symbol	2
Inadequate self-inspection	20	Illness	2
Lack of training, information or instructions	16	Stress	2
Inadequacies in work supervision or management system	6	Alcohol or drugs	0
Inadequate legislation or regulation	2	Other human error	75
		Total	**387**

Also later examples of typical accidents and incidents can be found in the MSB statistics material, referred to above (MSB 2015), which essentially confirms the picture.

At a European level, Eurostat has compiled information on dangerous goods accidents 2006–2015 (Eurostat 2019b), which indicates that few such accidents occurred during the ten-year period (7 in Finland, 0 in Estonia, 6 in Sweden, 14 in Latvia, 45 in Lithuania, 31 in Germany). There are large differences between countries, some of which should be attributable to the size, transport conditions and transport density of the country, but likely also to reporting routines, uncertainty about definitions and reporting obligations, etc. Rather substantial numbers of unreported cases can also be suspected. The figures are totally incompatible with e.g. those reported in **Figure 6**.

6.3 Port handling

Ocean vessels and airplanes are transporting over 70 percent of all goods entering and exiting the USA (Tomer & Kane, 2015). The rest is moved using trucks, railroad and pipelines. The utilisation of a specific mode of transport is stated to be linked to the value/weight of any particular type of goods. Energy and agriculture products, which are lower-value/higher-weight goods, are more likely to be moved by ship and pipelines, while electronics and precision instruments, which are higher-value/lower-weight goods, are moved by airplanes.

These links between type of modes of transport and type of goods would be about the same for the rest of the world as well. This would lead to that the dangerous goods of the lower-value/higher-weight type would pass through a seaport, while goods of higher-value/lower-weight would pass through an airport. Furthermore, this will lead to different dangerous goods related issues, linked to either an airport or a seaport. In an airport different types of dangerous goods are linked to electronics, dominatingly, while in a seaport they are linked to either volume goods like bulk shipment of oil or other chemical products or smaller quantities of the same type. From a handling perspective, they are different and require different actions.

For pipeline handling of dangerous goods, the issue of preventing leakage and upholding an overall good quality of the equipment is of great importance. The intersections between different systems (ship/port and port/truck) are of importance, just like in other types of process-oriented industry. This stresses the use of standardised connexions like valves, reservoirs and other types of equipment infrastructure. The majority of preventive dangerous goods related actions are taken already at the design stage of the port.

For handling dangerous goods within the flow of containers and other types of cargo-carrying equipment, there are less of pre-planned activities and more of flexibility and adaptation by the port operators, as the dangerous goods regulations in this case demand better knowledge from all involved actors, as the solutions are not pre-planned in the same way as in the bulk situation. The different terminals need to handle containers both from a dangerous goods perspective and also from a normal container handling situation. This means loading, unloading and reloading as well as storage of both loaded and empty containers.

From a dangerous goods perspective, it is important to understand that some combinations of dangerous goods multiply the possible impact from an accident, while other combinations add nothing to the danger. This means that port handling must consider combinations of dangerous goods types when handling, storing and moving comprise these types.

The port handling must consider both the goods themselves and their packagings and packing methods, due to issues like shock and impact. The sensitiveness of the goods to shocks, including the absorbing effect from the packaging, is of great importance. The same reasoning goes for vibration, moisture, freezing, heating, and pressure. Different contributing factors can be various damage to the packaging (due to stacking overload, careless handling or insufficient protection) or simply improper handling from the port operator’s point-of-view.

7 DISCUSSION

Transport damage has different causes, such as accidents, unsatisfactory packaging, rough transport conditions, unprofessional stowage, stacking and segregation, displaced lashings, and many varieties of negligence and ignorance. The shrinkage during distribution and transport is approximately 0.14 percent of annual sales for all types of products, and the cost for cargo damage could be up to 90 percent of that number (Ekwall 2009). This report addresses the occurrence of cargo damage for general cargo and in particular for cargo classified as dangerous goods. For both types of goods the packaging is of great importance in order to reduce transport damage that may or may not constitute a risk for society and the environment. With the focus on packaging for dangerous goods and other sensitive products, this report aims to describe the environmental and technological prerequisites for a safe transport.

The report can thus be used as a guidance for designing and testing packaging and packages for the transport, in particular when rates of damage has been observed that are believed greater than normal. One preventive measure, which is mandatory for dangerous goods, is to require sturdy, certified packaging and tanks, which can withstand occurring transport stresses and thus reduce the likelihood of leakage and damage. For non-dangerous goods, the same challenge of designing an adequate protection, now primarily for the goods themselves, is obvious.

Most dangerous goods accidents result in insignificant consequences, as fatalities or major releases of substances are relatively rare. This is many due to all the work, historically, invested into preventing dangerous goods accidents, mainly under the UN umbrella. In order to prevent such events and severe consequences, it is important to investigate and learn also from the incidents or so-called near-misses, as is routinely done in aviation. Findings will underpin risk analyses, which are essential in all proactive safety work.

The transport of dangerous goods has since many years been harmonised internationally between different modes of transport, based on the UN Model Regulations (2017). The core parts of the model regulations, as well as all international mode-specific regulations, are classification, including a detailed dangerous goods list, packing and tank provisions, consignment procedures, where marking and labelling are prescribed, and requirements for the construction and testing of packagings.

The dangerous goods regulations take into account the different damaging properties of substances by specifying the classification in nine different classes. As dangerous goods do not represent a danger when confined to their packaging or tank, the requirements for the construction and testing of these are essential in the safety philosophy of the regulations.

With few exceptions, the consequences of dangerous goods accidents have been low, especially considering what can happen if something goes wrong. The intricate system of regulations controlling dangerous goods transport has in different ways reduced both the probability for a dangerous goods incident and adverse consequences. In common for all of these regulations is that they are based on a risk management process thinking, which entails processes resulting in new packaging designs, tests and other risk mitigation features. As a whole it would minimise the risk for dangerous goods accidents.

The other side of transport damaging of goods is found in the transport environment and different practical handling stages during shipment. Several attempts have been made to characterise and quantify the stresses, which occur during transport of both dangerous and non-dangerous, but sensitive, goods. It includes both mechanical loads, from vibrations, impact, stacking or lateral forces, and climatic factors, such as high or low temperature, temperature variations or moisture by condensation or precipitation. In some cases, biological and other factors in the transport environment must also be taken into account.

When comparing damage rates for different modes of transport, one should have in mind that there is a relationship between the utilisation of a specific mode of transport and the value and weight of any particular type of goods. Energy and agriculture products, which are lower-value and higher-weight goods, are more likely to be moved by ship and pipelines, while electronics and precision instruments, which are higher-value and lower-weight goods, are moved by air. As a consequence, the dangerous goods of the lower-value/higher-weight type would typically be handled at a seaport, while goods of higher-value/lower-weight would pass through an airport. In a cargo handling perspective, those goods are different and require different actions, and the damage patterns are also different.

The practical application of these different regulations for dangerous goods, as well as regulations and other programmes for non-dangerous goods to reduce transport damage of cargo, needs to be established, as the main focus for goods and transport-related adverse issues has shifted to antagonistic threats, which includes theft and terrorism, following the attacks in New York and Washington in 2001. However, earlier research has pointed out that cargo damage is up to nine times as costly as criminal attacks against the transport network (Ekwall, 2009). Most investigations on transport damage were carried out around the turn of the century and were partly very thoroughly made but can now appear aged.

A first step for future research in this area should be a simple risk assessment for the traditionally most common causes of cargo damage (shock and impact, vibration, stacking overload, torn packaging, moisture, mould, wet packaging, overheating, freezing, overpressure, leakage and fire) but also in relation with lost goods reasons (theft, jettison). It is essential to achieve a good understanding of whether the trends regarding cargo damage and loss are changing or stable over time, in order to assess the relevance of available data and the need for new investigations.

Thus, there is also a need to verify to which extent results from previous research in this area can be validated and taken into account, and, importantly, which ones of all involved actors who need to take a greater responsibility to further reduce costs, linked to transport damage globally.

8 CONCLUSION

The transport of dangerous goods incorporates hazards, which may seriously affect people, property and the environment in various adverse ways. One preventive measure is to require sturdy, certified packagings and tanks, which can withstand occurring transport stresses and thus reduce the likelihood of leakage and damage. This specific risk linked to transport can be avoided by adapting to international standards for packaging construction and handling, which all depends on the different specific attributes in the shipped products or substance.

For non-dangerous goods, there is also a risk of damage by excess transport stresses, and the same challenge of designing an adequate protection, now primarily for the goods themselves, is obvious. The report can be used as a guidance for designing and testing packagings and packages for the transport, in particular when rates of damage has been observed that are believed greater than normal. These standardised tests are designed to resembles reality as much as possible but still fully repeatable. These test results into packaging design, shipping instructions and other types of guidelines.

The risk for transport damage is present everywhere in the transport chain, but the greatest risk is in the nodes of such a transport chain, i.e. harbours, terminals or intermediate storage facilities, where the goods are handled, loaded, unloaded and transferred. Thus seaports are a focal point in this respect. In the ports damaged packages and containers must be identified and relevant mitigating and preventive safety measures taken. In order to better understand why cargo still gets damaged during shipment more research is needed.

A first step for future research in this area should be a simple risk assessment for the traditionally most common causes of cargo damage (shock and impact, vibration, stacking overload, torn packaging, moisture, mould, wet packaging, overheating, freezing, overpressure, leakage and fire) but also in relation with lost goods reasons (theft, jettison).

Together with this, it would be of interest to have a good understanding of whether the trends regarding cargo damage and loss are changing or stable over time. The thorough work with dangerous goods packaging standards, as well as other standards for protecting the goods during shipment, may have solved large parts of the main problem but as transport systems change, so does the handling of goods in them. This would result in changed causes and factors for goods becoming damaged.

All the standards aside, there will always be relatively weak points in any system, and it would be of interest to better understand what needs to be done and which actor to be responsible. It could be linked to packaging issues or to more of a quality system approach (e.g. ISO etc.) or even better training of staff and other personnel, working both directly and indirectly with the goods.

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HAZARD project has 15 full Partners and a total budget of 4.3 million euros. It is executed from spring 2016 till spring 2019, and is part-funded by EU's Baltic Sea Region Interreg programme.

HAZARD aims at mitigating the effects of major accidents and emergencies in major multimodal seaports in the Baltic Sea Region, all handling large volumes of cargo and/or passengers.

Port facilities are often located close to residential areas, thus potentially exposing a large number of people to the consequences of accidents. The HAZARD project deals with these concerns by bringing together Rescue Services, other authorities, logistics operators and established knowledge partners.

HAZARD enables better preparedness, coordination and communication, more efficient actions to reduce damages and loss of life in emergencies, and handling of post-emergency situations by making a number of improvements.

These include harmonization and implementation of safety and security standards and regulations, communication between key actors, the use of risk analysis methods and adoption of new technologies.

See more at: http://blogit.utu.fi/hazard/