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OPTIMIZATION APPROACHES FOR DANGEROUS GOODS LOGISTICS: PROBLEMS AND TRADE-OFFS

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Abstract: *Logistics systems processing dangerous goods face stricter regulatory and technical constraints as well as higher safety requirements compared to classical logistics applications. This paper gives an overview of typical optimization problems arising in dangerous goods logistics, focusing on transportation, storage and inventory, facility location, and fleet or resource allocation problems. Special consideration is given to risk exposure and safety aspects, which are directly considered in optimization problems of dangerous goods logistics rather than being treated as external constraints. Selected numerical examples demonstrate how classical optimization problems are altered when accounting for risk, thereby allowing to illustrate safety–cost trade-offs common in dangerous goods logistics such as efficient routing vs. societal risk, inventory buffering vs. concentration of hazards, or efficient resource allocation vs. resilience.*

Keywords: *dangerous goods logistics, logistics optimization, risk-aware decision making, regulatory constraints, multi-objective optimization, safety–cost trade-offs, hazardous materials transportation.*

1. INTRODUCTION

Transporting, storing, and handling dangerous goods is essential for modern supply chains. Dangerous goods are goodsgoods transported by every industry, from chemicals over pharmaceuticals to foodstuff and consumer goods. However, hazardous materials logistics is also one of the most challenging logistics subdomains since accidents can have severe consequences for humans, the environment, or material assets. Accidents range from relatively harmless material spills over dangerous goods fires to transportation accidents with mass-casualties. As a result, logistics decisions involving dangerous goods typically face stricter regulatory constraints and safety requirements than comparable classical logistics problems.

In the past decades, growing amounts of dangerous goods being transported, urbanization, and overall tighter safety requirements have added additional complexity to logistics decisions of hazardous materials. In classical logistics optimization, trade-offs normally need to be made between efficiency, cost, and service performance. However, when transporting and storing dangerous goods, additional, often conflicting objectives such as safety, risk exposure, or regulatory compliance need to be considered.

Typically, these problems formally become multi-objective optimization problems that need to be solved by exploring trade-offs between conflicting objectives. Furthermore, constraints specific to dangerous goods logistics such as road-route restrictions, time-window constraints, incompatibility, or segregation constraints in storage often fragment the feasible solution space. As a result, routing and logistics planning problems become risk-aware optimization tasks where safety is directly considered in optimization models.

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While practical importance and scarcity of data are known issues of hazardous materials transportation literature in general, current literature on optimization of dangerous goods logistics is even more scattered across individual problem types. Research literature often focuses on narrow sub-problems such as hazardous materials routing or warehouse safety, while literature overviews on main optimization tasks in dangerous goods logistics are scarce. Furthermore, there is often a gap between practition-oriented models requiring extensive data availability and academic research that lacks interpretability for practitioniors.

Motivated by these gaps in state-of-the-art literature, this paper provides a structured overview of the main optimization problems in dangerous goods logistics and highlights their main characteristics, objectives, and trade-offs. Sections three and four provide an overview of transportation and routing, storage and warehouse, inventory management, and fleet/resource allocation optimization problems while special consideration is given to safety aspects and risk. Furthermore, selected numerical examples are provided to illustrate how classical optimization models can be extended to account for risk as well as regulatory requirements. Overall, this paper bridges the gap between academic optimization modeling of dangerous goods logistics and practitionior decision-making by providing a conceptual discussion along with quantitative examples.

Building on identified challenges and decision trade-offs from the introduction section, there exists a growing body of literature that discusses various aspects of dangerous goods logistics from safety, operational, and optimization perspectives. However, due to high heterogeneity in scope, methods, and optimization focus, current literature gives little insight into how common optimization problems are structured and addressed across the whole dangerous goods logistics system. Therefore, the following literature review section focuses on reviewing major streams of literature regarding optimization of dangerous goods logistics with special consideration to how risk, regulatory constraints, and trade-offs are accounted for.

2. LITERATURE REVIEW

In this chapter, the research results in the field of logistics optimization of dangerous goods are summarized. This section includes a descriptive and a content analysis. Within the frame of the literature review, Scopus was used to identify the most important scientific results regarding optimization in the field of logistics operations with dangerous goods. The review focuses on the highlight and main research directions of transportation, packaging, loading, unloading and warehousing.

Firstly, the relevant terms must be defined. In this first phase I have chosen a simply keyword: “dangerous goods AND logistics” to find a wide range of articles to perform a descriptive analysis of articles. Initially, 293 articles were identified.

As Fig. 1 shows, “dangerous goods logistics” has been researched in the past 40 years. The first article in this field was published in 1985. The number of published papers focusing on different aspects of dangerous goods logistics has significantly increased in the last 20 years; it shows the importance of this research field.

We can analyze the distribution of published articles per year and per source, as shown in Fig. 2.

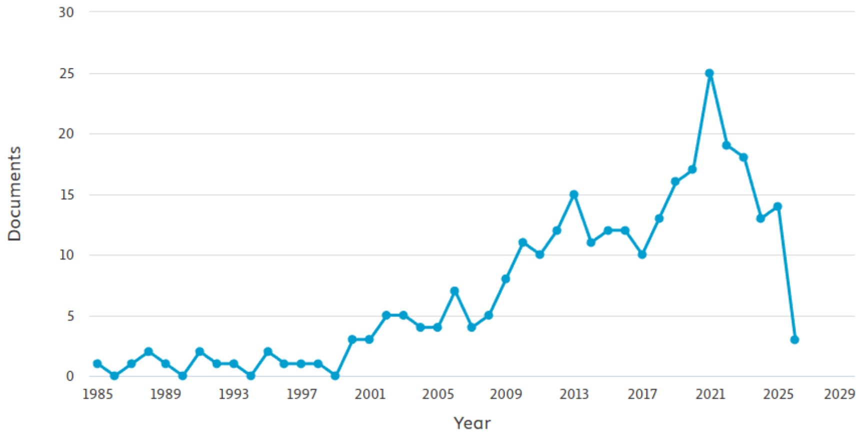

Figure 1. Published articles per year in the field of dangerous goods logistics resulted by a Scopus search (Source: www.scopus.com)

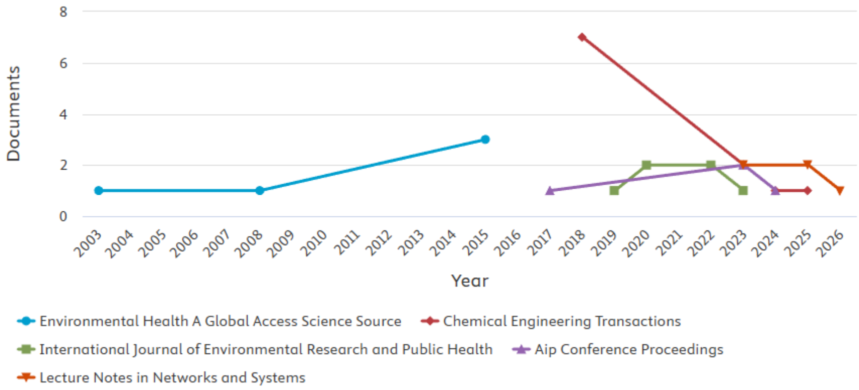

Figure 2. Published articles per year per source in the field of dangerous goods logistics resulted by a Scopus search (Source: www.scopus.com)

It can be seen, that a wide range of articles in the field of logistics of dangerous goods has been published in five scientific journals: Environmental Haealth A Global Access Science Source, Chemical Engineering Transactions, International Journal of Environmental Research and Public Health, Aip Conference Proceedings, and Lecture Notes in Networks and Systems. The title and the main topic of these scientific journals shows, that dangerous goods logistics covers multidisciplinary sciences. The CiteScore is shown in Fig. 3.

The analysis of the subject area of research works shows (see Fig. 4), that the most important subject areas in the Scopus are the followings: engineering, medicine, computer science, environmental science and social science.

Articles resulting from the initial search are reviewed by subject matter of the title and abstract through content analysis performed by the authors. After content analysis, additional keywords are used to search for articles in Scopus to obtain articles relevant for the literature review section.

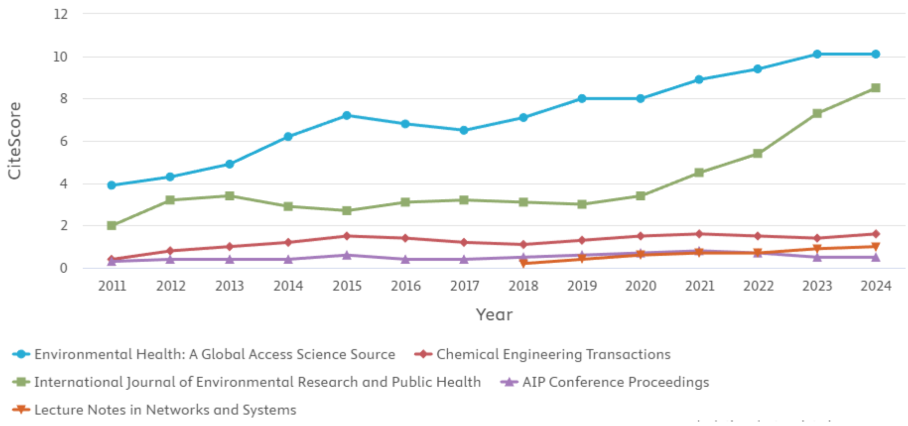

Figure 3. CiteScore publication per year in the field of dangerous goods logistics resulted by a Scopus search (Source: www.scopus.com)

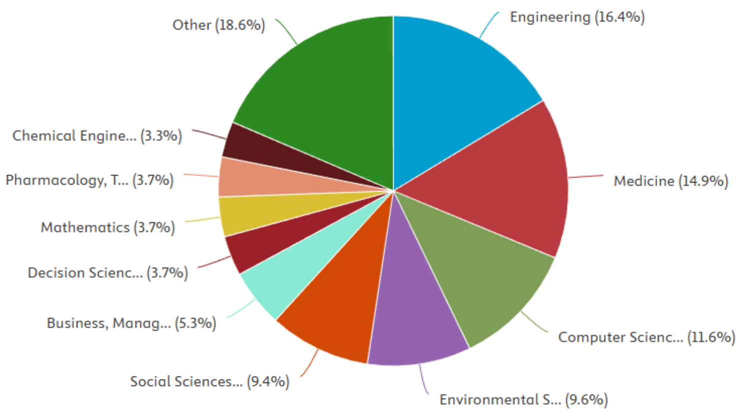

Figure 4. Published articles by subject area related to dangerous goods logistics resulted by a Scopus search (Source: www.scopus.com)

Research on dangerous goods logistics has significantly grown over the last 20 years. The continuously increasing volume of dangerous goods being transported, steadily rising safety and environmental requirements, as well as a growing societal awareness towards safety have led to various publications on different topics ranging from risk assessment to routing, warehouse safety, digitalization, or decision-support techniques.

A major topic in research on dangerous goods transportation is centered around risk analysis and modeling. Quantitative and probabilistic approaches for accident probability and accident severity prediction have been applied to road, rail, and maritime dangerous goods transportation [1-3]. Other studies emphasized the systemic nature of risk and analyzed relations between infrastructure and operations on the occurrence of accidents [4-5]. Agent-based and data-driven techniques were used to understand behavioral aspects and complex interactions in hazardous materials transportation [6-7].

Routing and transport-network related problems also account for a major portion of current literature. Modified shortest-path approaches were used to account for safety and exposure aspects in routing hazardous goods, especially in urban environments where the societal risk is typically high [8-9]. Graph-theoretical approaches were leveraged to identify vulnerable parts of a logistics or transport network that process dangerous goods [10]. Common findings in these studies are that efficiency-related objectives are inherently conflicting with risk exposure minimization.

Research on storage and warehouse safety and optimization mainly focuses on handling segregation and compatibility constraints while allocating inventory to storage locations. Early research focused on storage technologies that prioritize safety when storing dangerous goods [11]. More recent studies propose warehouse optimization models while accounting for compatible storage and capacity constraints [12-13]. Opportunity cost assessments were conducted to measure the inefficiency introduced by safety-driven constraints on warehouse optimization [13].

Several studies proposed multi-objective decision-making or evaluation frameworks for various applications in dangerous goods logistics. Decision-making frameworks considered risk distribution along different logistics subsystems and performed risk-weighted optimizations [14]. Others applied group decision-making techniques to evaluate the safety of transport enterprises that handle dangerous goods [1] or assess hazardous goods suppliers and service providers [15]. Sensor placements were optimized to increase safety and monitoring capabilities when transporting dangerous goods.

Research on digitalization and smart systems have also gained considerable attention in recent years. Methods like RFID, wireless sensor networks, IoT, or blockchain were proposed to track dangerous goods shipments, ensure compliance with safety and regulatory requirements, and enable realtime monitoring of goods and vehicles [16-18]. Digital twin–based methods and advanced-analytics were applied to accident investigation root-cause analysis and prevention decision-support, especially in rail transportation and port environments [4-5]. Computer vision methods were leveraged for automatic dangerous goods detection and classification during cargo handling and inspection processes [19].

Finally, recent publications have discussed emerging transport modes as well as considerations for hazardous goods logistics. For example, uncrewed aerial vehicles (UAVs) are discussed for medical as well as dangerous goods transport. These studies discuss whether existing regulatory frameworks are applicable, analyze UAVs' safety performance, and compare risk reduction capabilities to conventional transport modes [20-22]. Stakeholder-oriented analyses address coordination between public authorities, logistics service providers, and infrastructure owners when shipping dangerous goods [23-24].

In summary, research literature shows that dangerous goods logistics is marked by various optimization problems that account for multiple objectives, high uncertainty, and strict constraints. Although literature focuses on specific aspects such as routing, storage safety, risk-analysis, or digitalization, only few publications provide a general overview of applied optimization models or show how classical optimization techniques can be altered to fit the particular context of dangerous goods logistics. Therefore, this paper seeks to close this gap by discussing key optimization problems and supporting discussion with numerical examples.

3. CHARACTERISTICS OF DANGEROUS GOODS LOGISTICS

When comparing conventional logistics with logistics systems involving dangerous goods, the latter is inherently characterized by a higher level of associated risk. These risks result from the goods' physical and chemical properties as well as the potential negative consequences that accidents might have on humans, material assets, and the environment. Accidents can lead to casualties, contamination of goods or the environment, damaged infrastructure, and long-term social and ecological impacts. As a result, logistics systems that handle dangerous goods are typically subject to more regulatory, technical, and organizational constraints than logistics systems for general freight.

Important characteristics of dangerous goods logistics include regulatory intensity and safety/risk awareness. Regulations relevant for logistics activities involving dangerous goods range from international treaties over federal laws to organization-specific standards and typically cover areas such as goods classification and labeling, packaging and handling procedures, vehicle and facility requirements, routing restrictions, transportation protocols, personnel training, and emergency response planning. Regulatory requirements must be adhered to under any circumstance, which implies that not all logistics decisions are feasible beforehand but instead depend on fulfillment of regulation-specific criteria. For this reason, optimization models concerned with dangerous goods logistics must incorporate regulations as core components of the problem instead of applying them as external constraints to the decision-making process.

The centrality of risk and safety considerations is another major difference to classical logistics optimization. Performance of logistics activities is often evaluated by cost efficiency, travel time, and service level. Dangerous goods logistics not only requires consideration of risk-related performance measures, they must actually be incorporated into the decision-making process. For example, a cost-efficient and time optimal transportation route could go through heavily populated areas and cause high societal risk in case of an accident. Similarly, high inventory levels could buffer fluctuating demand but cause high potential impact in case of a storage accident. Common to these examples is that they require moving from single-objective optimization to risk-aware and multi-objective optimization.

Heterogeneity of goods is another trait of dangerous goods logistics. Dangerous goods include all kinds of goods that are considered flammable, toxic, corrosive, environmentally hazardous, explosive, etc. Furthermore, there are often incompatibility relationships between different goods, meaning that certain goods cannot be stored or transported in proximity (or at all) to one another. As a result, handling and storing dangerous goods is not only about optimizing flows of goods, it is also about optimizing the interactions between goods.

Logistics activities of dangerous goods typically require dedicated infrastructure and equipment. Vehicles need to comply with specifications that are often more stringent than for general freight (protective equipment, safety installations, monitoring equipment), and warehouses must follow stricter building codes (specialized warehouse layouts with safety zones, ventilation systems that can handle hazardous gases or fires, fire protection systems). Hence, resources such as transport vehicles and warehouses are more constrained in their allocation and deployment than generic logistics resources. For example, due to dedicated equipment and desired redundancy in vehicles and facilities, resource utilization is often lower than in conventional logistics to provide extra capacity in case of disruptions or poor vehicle availability.

Uncertainty and the system's sensitivity to disruptions is yet another aspect that is amplified in dangerous goods logistics. Vehicle breakdowns, road accidents, weather conditions, blocked routes, or regulatory inspections can result in disruptions that significantly alter optimized plans. However, as opposed to classical logistics contexts, disruptions may immediately elevate risk exposure (e.g., by forcing transportation through small villages or residential areas), cause delays that violate regulatory phosoiring requirements, or have other safety-improving actions that inherently feel inefficient from a cost- or time-optimization perspective. Dangerous goods logistics therefore requires robust and seemingly less-efficient planning to account for these disruptions.

Multiple stakeholders with partly-conflicting priorities are usually involved in decisions on dangerous goods logistics. These include shippers, logistics providers, carriers, local communities, regulators, and emergency response units. Emergency units and local communities will typically prioritize safety and environmental aspects, while operators will seek to keep operations as efficient as possible. As a result, the decision-making process around dangerous goods logistics has to transparently weigh stakeholder requirements against each other. Fig. 5 visualizes trade-offs between logistics-related cost efficiency and achieved safety level in dangerous goods logistics.

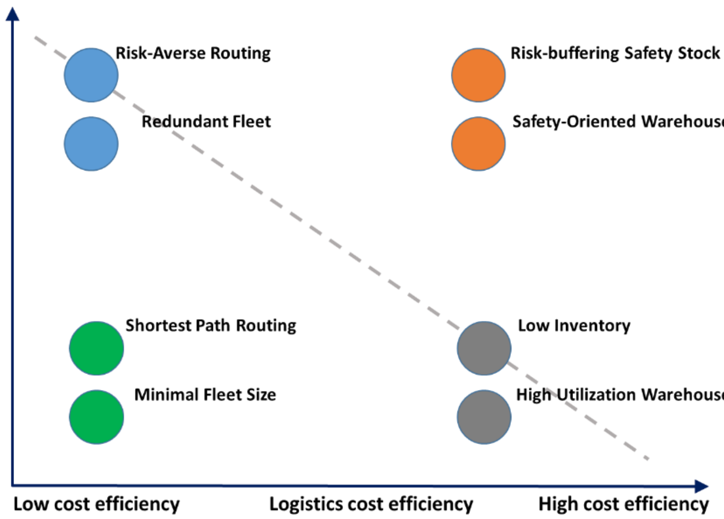

Figure 5. Trade-offs between logistics cost efficiency and safety level in dangerous goods logistics

Cost efficiency can be increased by various means in inventory management, routing, warehouse, and fleet-related decisions. While these decisions often allow for improved safety performance (e.g., storing goods closer to each other increases safety stock functionality and reduces transport risk), they are likely to increase the negative impact in case of accidents or disturb other safety-related best practices.

To summarize, inherent differences between classical logistics and logistics of dangerous goods imply that traditional logistics optimization models are ill-suited if applied directly. First, the problem must be assessed on how it is affected by regulations, safety aspects, system heterogeneity, and built-in redundancy. Then, classical optimization problems can and have to be reformulated to account for these properties of dangerous goods logistics. An understanding of these core characteristics is essential to identify and structure the main optimization problems in dangerous goods logistics presented in section four.

4. CORE OPTIMIZATION PROBLEMS IN DANGEROUS GOODS LOGISTICS

As previsously stated in section one, classical optimization problems must be altered when applied in dangerous goods logistics contexts. This section gives an overview of what the author sees as the four main optimization problem areas in dangerous goods logistics and provides remarks on how they differ from classical counterparts.

4.1. Transportation and routing optimization

Routing and transportation of dangerous goods is often considered the most critical part of the logistics chain. Several studies propose to assess infrastructure and fleet vulnerabilities of transportation networks processing dangerous goods from routing-optimized perspectives. Optimization models usually expand classical vehicle routing problems or shortest path problems by integrating safety- or risk-related criteria into the optimization model. Commonly, transportation problems are no longer focused on minimizing distance or transport time. Instead, trade-offs between cost, risk exposure, regulations, and service requirements must be balanced.

Route restrictions are likely the defining property of dangerous goods routing problems. Roads, tunnels, bridges, and urban areas might be restricted or subject to time-dependent access regulations for vehicles carrying hazardous materials. These restrictions effectively split up the feasible transport network into smaller subnetworks, reducing the number of feasible routes between an origin and destination. Graphically, this implies that the feasible solution space is no longer concontiguous, making mathematical solution more complex.

Safety-aware routing approaches further complicate the routing problem by adding additional criteria such as population exposure along a route, accident probability, or potential accident severity to the optimization objective. While an efficient route may pass through or near densely populated areas, safer routes may have to detour, increasing distance and operational cost. This creates an explicit trade-off between efficiency and safety which is especially present in urban environments. Often, routing decisions become multi-objective problems where cost and risk are minimized simultaneously or combined into a weighted objective function.

Time-windows, capacity constraints, and fleet-heterogeneity add additional complexity to routing problems, especially when classes of dangerous goods are prevented from co-transportation. Combined, the mentioned properties transform dangerous goods routing problems into complex combinatorial optimization problems that most likely cannot be solved to optimality but require heuristic solution approaches.

Let us now define a risk-weighted routing in dangerous goods transportation problem. Assume we have a simplified network between an origin O and destination D that allows for three different routes (A, B, and C). Each route is associated with a cost of transportation and a risk-exposure score based on distance passing through areas with high population density and accident probability (Table I).

The routing problem is formulated as a weighted single-objective optimization:

$$C_i = c_i \cdot x_i + \mu \cdot r_i \cdot x_i \rightarrow min, \tag{1}$$

where c_i is the cost of route i, r_i is the risk score of route i, $x_i \in \{0,1\}$ indices the selected route, and μ represents the relative importance of safety.

For $\mu = 0$, Route A is selected as the cost-minimizing solution. For $\mu = 5$, the objective values are as follows:

$$C_A = 800 + 5 \cdot 90 = 1{,}250\ EUR,$$
$$C_B = 950 + 5 \cdot 40 = 1{,}150\ EUR, \qquad (2)$$
$$C_C = 1{,}100 + 5 \cdot 20 = 1{,}200\ EUR.$$

The optimal solution shifts from Route A to Route B. This example illustrates how incorporating risk into routing decisions leads to safer but more expensive routes.

Table I.
Input parameters of a risk-weighted routing in dangerous goods transportation problem

Route	Cost [EUR]	Risk score
A	800	90
B	950	40
C	1,100	20

4.2. Storage and warehouse optimization

Storage and inventory decisions also play an important role in dangerous goods logistics. While storage accidents are typically less likely than during transportation, stored goods still represent a high concentration of hazards. Storage and warehouse optimization problems of dangerous goods typically focus on warehouse layout design, allocation of inventory to storage locations, or shelf assignment of goods. Whereas classical warehouse optimization seeks to maximize warehouse space utilization and efficiency of material flows, dangerous goods warehouse optimization also has to ensure regulatory compliance and limit potential consequences of accidents that might occur.

A key difference to classical warehouse optimization is the strict set of segregation and compatibility rules that have to be considered during warehouse layout planning and material flow design. Certain goods cannot be stored next to certain other goods and have to meet minimum separation distances. These constraints directly influence storage layout, capacity utilization, and assignment of inventory to storage locations.

Warehouse location problems also come into play when deciding where to locate central or regional warehouses for dangerous goods. Locating warehouses closer to customers might reduce transport distance and, subsequently, risk exposure during transportation. However, this might lead to higher local risk concentrations which might be undesirable from a regulatory or public opinion perspective. Remote warehouse locations might reduce risk exposure but increase transport distances.

Regulatory stock limits and requirements like maximum quantities of dangerous goods per storage zone restrict the solution space and are treated as hard constraints in optimization models. As a consequence, many optimization models concerned with dangerous goods warehouse seek to maximize risk containment and compliance instead of pure efficiency.

Assume we have a dangerous goods warehouse consisting of four storage zones (Z1-Z4) of capacity 2 pallet positions each. We want to store six different palletized dangerous goods items in our warehouse. Further, there are two incompatible classes of dangerous goods, Class A and B. Class A consists of three flammable goods (A1-A3) and Class B of three oxidizing goods (B1-B3) (Table II).

Table II.
Input parameters of a warehouse storage allocation under compatibility constraints problem

Zone	Distance from dock [m]	Capacity [pallets]
Zone 1	5	2
Zone 2	8	2
Zone 3	12	2
Zone 4	15	2

The decision variable y_{kz} equals 1 if pallet k is assigned to zone z, and 0 otherwise. The objective is to minimize total internal handling distance:

$$C = \sum_{k=1}^{k_{max}} \sum_{z=1}^{z_{max}} d_z \cdot y_{kz} \to min. \tag{3}$$

If no compatibility restrictions are considered, the six pallets are assigned to the closest available zones (Z1, Z2, and Z3). The total handling distance is

$$C_{no\ compat} = 2 \cdot 5 + 2 \cdot 8 + 2 \cdot 12 = 50\ m. \tag{4}$$

Due to incompatibility, pallets of Class A and Class B cannot be stored in the same zone. Therefore, each zone may contain pallets from only one hazard class:

$$C = \sum_{k \in A} y_{kz} + \sum_{k \in B} y_{kz} \leq 2. \tag{5}$$

As a result, one hazard class must be assigned to the more distant zone Z4. A feasible assignment is: Class A pallets stored in Z1 and Z2, Class B pallets stored in Z3 and Z4. The resulting total handling distance becomes:

$$C_{compat} = 2 \cdot 5 + 2 \cdot 8 + 2 \cdot 15 = 56\ m. \tag{6}$$

The introduction of compatibility constraints increases the total handling distance by

$$\vartheta = \frac{56 - 50}{50} = 12\%. \tag{7}$$

This increase represents the operational cost of regulatory compliance and safety requirements. The example demonstrates that warehouse optimization in dangerous goods logistics is not driven solely by efficiency considerations; instead, segregation and compatibility rules can force suboptimal spatial assignments that trade cost efficiency for safety.

4.3. Inventory management and safety stock optimization

Inventory-related optimization of dangerous goods must also consider trade-offs between operational buffering and risk. Classical inventory models are concerned with finding the ideal reorder points and order quantities to minimize ordering- and holding costs while providing a certain level of service. Inventory management of dangerous goods also has to consider trade-offs between transportation risk (frequency of shipments), storage risk (inventory levels), and regulatory limits on inventory quantities.

Safety stock in dangerous goods logistics often has a different function than in classical logistics because demand uncertainty is typically not the main driver for safety stock optimization. Instead, safety stock levels are mainly determined by an operational need to buffer transportation. However, higher inventory levels might again increase the potential impact of storage accidents.

Degradation, shelf-life, or inspection requirements further constrain long-term storage of certain dangerous goods. These constraints must be accounted for during inventory optimization of chemicals or pharmaceutic goods.

Due to strong interrelations with routing and storage problems, inventory optimization of dangerous goods cannot be isolated. Decisions about safety stock levels will directly affect transport frequency, warehouse capacity utilization, and overall risk exposure of the logistics system.

Let's define a risk-adjusted safety stock decision problem. Consider a dangerous goods product with annual demand $D = 1{,}200$ units. The ordering cost is $K = 400$ EUR per shipment and the holding cost is $h = 12$ EUR per year. Additionally, a transport risk cost of $R_T = 600$ EUR per shipment and a storage risk cost of $R_S = 8$ EUR per average inventory unit are defined. The total cost function becomes

$$TC(Q) = (K + R_T) \cdot \frac{D}{Q} + (h + R_S) \cdot \frac{Q}{2}. \tag{8}$$

Substituting values:

$$TC(Q) = 1{,}000 \cdot \frac{1{,}200}{Q} + 20 \cdot \frac{Q}{2} \tag{9}$$

The optimal order quantity is:

$$Q_{opt} = \sqrt{\frac{2 \cdot D \cdot (K + R_T)}{(h + R_S)}} = \sqrt{\frac{2 \cdot 1{,}200 \cdot 1{,}000}{20}} \approx 346\ units. \tag{10}$$

Compared to the classical EOQ (245 units), the risk-adjusted policy favors larger batches, reducing shipment frequency and transport exposure.

4.4. Fleet and resource allocation optimization

Fleet-related optimization refers to optimization problems that allocate vehicles, equipment, and organizational resources to process and transport dangerous goods. Vehicles transporting dangerous goods typically also require regular technical inspections and drivers have to undergo specialized training. Both constraints limit the available fleet that can be allocated to customer orders.

A trade-off that must be considered during optimization of vehicle and resource allocation is the aspect of efficiency vs. redundancy. High resource utilization increases transport cost and time because there is less buffer in case of disruptions, maintenance, or emergency response. On the other hand, higher redundancy increases resilience and safety of operations but might come with increased fixed costs.

Similar trade-offs come into play when allocating emergency response resources, monitoring equipment, or safety equipment. These resources do not directly increase efficiency of logistics operations but allow for reduced response times in case of accidents and, therefore, effectively reduce risk exposure and expected disruption cost.

To illustrate the trade-off between fleet utilization and system reliability in dangerous goods logistics, consider a transport operator that must serve 10 dangerous goods shipments per day. Each specialized vehicle can safely perform up to 3 shipments per day, taking into account regulatory and operational constraints. The minimum feasible fleet size is therefore

$$m_{min} = \left\lceil \frac{10}{3} \right\rceil = 4. \tag{11}$$

Each vehicle incurs a fixed daily operating cost of $F = 500$ EUR. Due to inspections, maintenance, or technical failures, a vehicle is assumed to be unavailable with probability $p = 0.1$. If the available fleet capacity is insufficient to serve all shipments, an emergency handling cost of $C_{emerg} = 3{,}000$ EUR is incurred, representing rerouting, subcontracting, and regulatory compliance risks.

With the minimum fleet size of four vehicles, the unavailability of any single vehicle reduces daily capacity to 9 shipments, which is below demand. The probability that at least one vehicle is unavailable is

$$P_{fail}^{(4)} = 1 - (1-p)^4 = 1 - 0.9^4 \approx 0.34. \tag{12}$$

The expected daily cost with one redundant vehicle becomes

$$E(C_4) = 4 \cdot F + P_{fail}^{(4)} \cdot C_{emerg} = 2{,}000 + 0.34 \cdot 3{,}000 = 3{,}020\ EUR. \tag{13}$$

Next, consider adding one redundant vehicle, resulting in a fleet size of five vehicles. In this case, capacity remains sufficient even if one vehicle is unavailable, as $4\times3=12\geq10$. Capacity shortages occur only if two or more vehicles are unavailable. The corresponding probability is

$$P_{fail}^{(5)} = 1 - \left[\binom{5}{0} \cdot 0.9^5 + \binom{5}{1} \cdot 0.1 \cdot 0.9^4\right] \approx 0.081. \tag{14}$$

The expected daily cost with one redundant vehicle becomes

$$E(C_5) = 5 \cdot F + P_{fail}^{(5)} \cdot C_{emerg} = 2{,}500 + 0.081 \cdot 3{,}000 = 2{,}743\ EUR. \tag{15}$$

Although adding a redundant vehicle increases fixed operating costs, the expected total cost is lower due to the substantial reduction in disruption-related expenses. This result illustrates that, in dangerous goods logistics, fleet redundancy is not inefficiency but a rational safety-oriented optimization decision, justified by the high consequences of service disruptions and regulatory non-compliance.

4.5. Integrated and multi-objective optimization perspective

While the optimization problems discussed above can be analyzed individually, dangerous goods logistics systems are characterized by strong interdependencies between transportation, storage, inventory, and resource allocation decisions. Decisions in one domain inevitably affect others, often shifting risk rather than eliminating it. For example, increasing safety stock reduces transport exposure but raises storage risk, while rerouting vehicles may reduce societal risk at the expense of higher inventory requirements.

As a result, dangerous goods logistics optimization is inherently multi-objective, requiring decision-makers to balance cost efficiency, safety, regulatory compliance, and service performance simultaneously. Integrated optimization approaches that explicitly model these interactions are essential for capturing system-level trade-offs and supporting informed decision-making.

5. Discussion and Conclusions

Safety and risk management considerations are inherent parts of any logistics system that handles dangerous goods. In comparison to classical logistics systems, however, they play a more prominent role in both practice and optimization. Instead of being treated as external constraints to a logistical problem, the logistics of dangerous goods requires safety and risk to be accounted for directly in decision-making processes and optimization models.

The system-wide and multi-dimensional nature of risk is one of its main characteristics. Since accidents can occur during transportation as well as storage, handling of dangerous goods is subject to risk exposure at multiple points in the supply chain. This requires accounting not only for the probability of accidents to occur but also for potential accident severity. Practically, this is often done by developing composite risk indicators that combine accident probability, exposure (e.g., population near infrastructure), and consequence severity into a single value. Composite risk indicators allow for including safety as part of the objective function of an optimization problem instead of handling it only through hard constraints.

Safety and risk can be accounted for in various ways from an optimization point-of-view. A simple method is so-called risk-weighted optimization where safety aspects are included into cost-based objective functions. This allows exploring trade-offs between efficiency and risk by adjusting weighting parameters of safety-related terms. A different approach is based on true multi-objective optimization where cost, risk, and e.g., service are considered separate objectives and Pareto-efficient solutions are analyzed. While both methods have been applied in logistics and dangerous goods logistics specifically, multi-objective optimization might be more suitable to frame and solve dangerous goods logistics problems. This is true since most decisions need to balance trade-offs between efficiency and safety.

Another thing to note about risk is its duality with regulatory compliance. Regulations can be thought of as non-negotiable constraints of the logistics problem. For example, there are restrictions on where trucks transporting dangerous goods are allowed to drive, how much of certain goods can be stored in one warehouse, or with which other goods certain dangerous goods are incompatible. However, especially safety-related regulations can also be interpreted as minimum safety standards that optimization seeks to improve from a safety perspective. Proper models treat constraints and efficiency improvement separately.

Optimization models must deal with the inherent uncertainty of logistics. Demand for products is hard to forecast. Vehicle and resource availability is affected by unforeseen maintenance, logistical disruptions, weather, and many other stochastic events. Since accidents are, by definition, also uncertain, deterministic optimization models might yield solutions that do not adequately reflect the risk exposure of certain decisions. Robust and scenario-based optimization have shown promising results when solving logistics optimization problems. Since robustness is often desirable over being nominal-optimal in dangerous goods logistics, they are particularly suitable for accounting for uncertainty.

Last but not least, safety and risk must be considered from both an organizational and stakeholder perspective. Decision-making around dangerous goods logistics will seldom be made by a single entity. Regulations put forth by public authorities need to be adhered to, communities might need to be included in decision-making, and of course there are emergency units who will have to respond if prevention fails. For optimization models to be accepted by regulative bodies and the public, they have to be interpretable. Practically, this means that modeling assumptions have to be clear and that trade-offs between conflicting objectives such as efficiency and safety are made explicit. Optimization models can then not only be used to aid decision-making but also to communicate and justify those decisions.

Risk and safety are not afterthoughts to dangerous goods logistics. On the contrary, they shape how problems are perceived, modeled, and solved. Optimization models that incorporate risk and safety aspects allow for making informed decisions that consider efficiency, but also abide by safety regulations and meet societal expectations.

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