OPTIMIZING HAZARDOUS MATERIALS LOGISTICS: TAKING VARIOUS PERSPECTIVES INTO ACCOUNT

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INTRODUCTION

There has been growing concerns in the past few years over hazmat related risks. One of the most important hazardous materials accidents in recent history occurred on September 21 2001 in Toulouse, France. An explosion at the AZF factory, triggered by the presence of ammonium nitrates, resulted in the death of 30 people and injured 2242 people. The factory and the surrounding commercial areas were destroyed. Adjacent homes, businesses and public facilities suffered some damage. This event raised numerous questions about current practices and hazardous materials logistics. The accident occurred in an industrial facility, a fixed installation, but could have happened during hazmat transport operations. In fact, the whole hazardous materials logistic chain could be questioned. In this context, understanding hazardous materials logistics and developing appropriate models become essential.

While authorities whish what's best for the population, firms' stance on the issue is not as clear. While some practices can increase risk levels, interviews conducted showed that in most cases, costs are simply too important to take risks into account.

In this paper, we explore authorities' and firms' conflicting views more in depth. We demonstrate how hazmat accidents can impact the public and why risk reduction measures must be taken. We illustrate why firms tend to overlook security aspect when making logistic decisions. We then present a methodology developed to optimize hazmat transportation throughout the logistic chain. This methodology contains several steps: problem formulation, identifying logistics options, identifying concerned parties, risk assessment and decision-making. Risk is assessed using two perspectives: authorities' perspective (heavily focuses on risk reduction) and firms' perspective (balancing costs and firms share of the risk). Both perspectives allow logistics options to be ranked and with such different aims, ranking results tend to differ between the two approaches. Results can be used during negotiations between the two parties.

LITERATURE REVIEW

In this section, we present literature relevant to hazardous materials logistics. Risk assessment, transportation problems and risk management are discussed. We mostly focus on studies related to hazmat transportation, which is the main focus of both methodologies developed.

Risk assessment: the case of hazardous materials transportation

Hazardous materials (flammable liquids, explosives, radioactive substances, corrosive substances, etc) are substances that could possibly harm the population, the environment and public or private property. Hazardous materials represent a risk, but how can we measure this risk? Traditionally, risk is said to be the combination of the likelihood of an event and of its expected outcome. Therefore, in the case of hazardous materials transportation, the risk related to a single hazmat shipment will be represented by product of the probability of an accident (p_i) and its expected consequences (c_i) on all road segments (i) used (Erkut et Verter, 1998):

$$R'(P) = \sum_{i=1}^{n} p_i c_i$$

This expression is often referred to as the traditional definition of risk. Keeping relatively short road segments is important since accident rates will change depending on the layout (hills, curves, tunnels, bridges, etc) and the expected consequences (more populated areas, etc) As Erkut et al. (2005) point out, in practice, we can use a road segment only if no accident occurred on the previous segment. Hence, the risk associated with a given route should be represented by:

$$R'(P) = pc + (1-p)pc + (1-p)^2 pc + ... + (1-p)^{n-1} pc$$

However, the simplified expression presented above is often preferred as the probability that an accident occurs on any road segment can be neglected. Aside from the traditional definition of risk in a way, several other definitions have been used in the literature over the years. These definitions include, but are not limited to:

Population exposure : $\sum_{i=1}^{n} c_i$

Accident probability : $\sum_{i=1}^{n} p_i$

Maximum exposure : $\operatorname*{Max}_{e_i \in P} c_i$

While models using definitions based on population exposure (or maximum exposure) try to minimize the consequences of an accident, models using definitions based on accident probability try to minimize the likelihood of accidents. Hence, depending on the definition used, risk analysis results might vary. Most definitions have received much criticism over the years, as most of them have shown deficiencies in specific situations as explained by Erkut and Ingolfsson (2005).

Hazardous materials transportation problems

Local routing problems

Local routing problems refer to the selection of the best route for a single hazmat shipment. Traditionally, this type of problem is solved with a shortest path algorithm. However, in the case of hazardous materials transportation, both risks and costs must be taken into account. Therefore, local routing problems are multiobjective in nature, and the different objectives are often contradictory.

Even if local routing problems are multiobjective in nature, some authors take only one objective (risk) into account. If the traditional definition of risk is used (see previous section), to solve this single objective problem, we will select the road segments x_j that will minimize the risk (product of the probability of an accident (p_i) and the expected consequences (C_j)). The local routing problem will be represented by (Erkut and Verter, 1998):

$$\min \sum_{j=1}^{n} (p_j C_j) x_j$$

Others have taken multiple objectives (mainly transportation costs and risk) into account. However, determining the optimal solution is not a simple task as most of the times, no single solution can simultaneously satisfy all objectives. Risk minimization and cost minimization are conflicting objectives and a tradeoff must often be made. For instance, Abkowitz et al. (1991) showed that minimum-risk routes are twice as long than the shortest path. Glickman and Sontag (1995) estimated that firms must invest between \$ 0.7 million and \$ 3.4 million in terms of additional distance travelled for every live saved.

Some have attempted to circumvent this problem by changing the problem formulation. For example, Erkut and Glickman (1997) have tried to minimize both the travel time and maximum population exposure. Traditionally, this problem would be best represented by:

$$
\begin{aligned}
&\min\ f_1 = \sum_{i,j} t_{ij} x_{ij} \\
&\min\ f_2 = \max\left\{p_{ij} x_{ij} : (i,j) \in E\right\} \\
&\text{subject to} \\
&\sum_{i \in N} x_{ij} - \sum_{k \in N} x_{jk} = \begin{cases} -1\ for j = 1 \\ 0, \text{for all } j \in N, j \neq 1, n \\ 1 \text{ for } j = n \end{cases} \\
&x_{ij} = 0 \text{ or } 1
\end{aligned}
$$

where t_{ij} is the travel time on link *i,j*, p_{ij} represents the population surrounding the link *i,j* and x_{ij} is the decision variable. However, they have transformed the second objective (f_2) into a constraint. The problem formulation then becomes:

$$
\begin{aligned}
&P(B): \min\ f_1 \\
&f_2 \leq B \\
&\text{subject to Constraints 1 and 2}
\end{aligned}
$$

The maximum population exposure allowed (parameter *B* value) must be chosen by the decision maker. This choice must be very carefully made as total distance travelled increase as the value of *B* decreases (Glickman and Erkut, 1997). Some researchers have developed other options to circumvent the conflicting objectives problem. For instance, Nembhard and White (1997) gave a weight to each objective:

$$\min(u) = w_1 u_1 + w_2 u_2$$

Here w_1 and w_2 are the weights associated to each objective u_1 and u_2. Decisions makers must determine the values of w_1 and w_2, so that the solution reflects the importance given to each objective.

The last option presented here, is the one developed by Leonelli et al. (2000). The argued that solutions obtained with the two options presented above were extremely subjective as a series of parameters had to be set by the decision maker. They suggested that risk (expected consequence of an accident) could be converted into expected costs, reducing the multiobjective problem (when only costs and risks are taken into account) into a single objective problem (costs minimization). Therefore, the total costs *TAC (i,j)* associated with an arc *(i,j)* of length *L (i,j)* can be represented by the sum of: (1) transport costs *TOC L (i,j)* on arc *(i,j)* and (2) risk-related costs on arc *(i,j)* (expected number fatalities *E (i,j)* multipled by the value of human life *HLV)*:

$$\underset{(i,j)\in A}{TAC}(i,j) = TOC\, L(i,j) + HLV\, E(i,j)$$

The problem formulation then simply becomes:

$$\min \sum_{(i,j)\in A} x_{ij} TAC(i,j)$$

However, only expected deaths costs were considered by Leonelli et al. (2000) while a hazmat accident can have many different consequences.

Global routing problems

Several hazardous materials movements can simultaneously occur on any given territory. While the local routing problem mostly interested firms (optimizing a single hazmat shipment), managing these multiple shipments to lower and distribute the risk on their jurisdiction will mostly interest authorities. This type of problem is called a global routing problem. As noted by Erkut et al. (2005), global routing problems received less attention from researchers than local routing problems. There are two main types of global optimization problems in the literature: equity considerations and hazardous materials transportation network design.

Equity refers to the fair geographical distribution of risk throughout a territory, to ensure that no geographical area and no social class suffer more than the other. Equity is rarely taken into account in local routing problems (where only one shipment is considered at a time) but is often present in global routing problems. As Zografos and Davis (1989) pointed out, equity has a price. They found out that by forcing equity on a territory, the overall risk was increased by 35%. Gopalan et al. (1990) also showed that the more authorities focus on equity, the more risk levels are high.

Designing a hazardous materials transportation networks involves closing several road segments to hazmat shipments (segments where risk is considered too high) to lower the risk on the territory. Hazardous materials transportation network design is seldom studied in the literature. It is a fairly complex problem, as closing road segments might push carriers towards alternative routes and results in higher than anticipated risk levels (Erkut et al., 2005). Also, as mentioned by Kara and Verter (2004), imposing such fees to firms and carriers might not always be realistic and other types of regulations might first be considered.

Risk management

Following a risk analysis, safety measures will generally be introduced to reduce the risk to an acceptable level, if it was too high. We cannot eliminate hazmat related risks without stopping all industrial activities. In fact, as reported by Shortreed et al. (1993), we should rather try to find the right balance between risk, cost and industrial activity benefits, to maximize the benefits for the society as a whole. In fact, according Shortreed et al. (1993), if this balance is not reached, the attention given to the hazardous materials industry could sometimes result in too much control that would not ultimately serve the public interest. We will therefore try to reduce the risk to a level said to be *ALARP* (As Low As Reasonably Practicable). By following this principle, we invest in safety measures without threatening firms' financial viability.

Authorities have the power to intervene to reduce the level of risk. In fact, Erkut and Verter (1995) stressed that governments not only have the power to intervene, but they also have the duty. According to them, as risk is primarily a social concern, we cannot rely solely on firms to take risk into account when making choice logistics. In fact, authorities' involvement is often necessary to ensure public safety and the environment. But what can authorities do exactly? In the literature and in practice, the focus is often on regulatory measures. Some current regulations include, but are not limited to:

1. setting standards for vehicles and containers used;
2. mandatory training;
3. restricting transportation on certain roads (eg, tunnels);
4. restricting transportation of certain substances;
5. mandatory emergency plans.

Firms can also take steps toward risk reduction. In fact, we argue that taking these steps might benefit them as and hazardous materials accident may impact their operations in more than one way: immediate cost, image loss, production loss, community reaction, increased insurance fees, and loss of customers, etc. There are two main ways in which a firm can achievement this: insurance and risk mitigation. In addition, risk mitigation can be aimed toward lowering accident probabilities or toward lowering potential consequences. Pate-Cornell (1996) explains that the development of a risk management policy requires choosing among several options, which requires thinking, since the sums allocated to one safety measure can sometimes be invested more efficiently in another safety measure. For example, money invested in insurance, could perhaps benefit from being invested in risk mitigation. Among the various possible risk mitigation measures, those that are the most often considered in the literature are undoubtedly the selection of a minimum-risk route and localization issues. There are obviously other risk mitigation measures (maintenance, training, choice of a supplier, choice of a carrier, etc..), but the impact of such measures is not, or little studied in the literature.

UNDERSTANDING HAZARDOUS MATERIALS LOGISTICS

The literature review presented above showed that there is a real separation between models dedicated to the industry (local routing problems) and models dedicated to authorities (global routing problems). Furthermore, we argue that local routing models may suggest logistic choices going against firms benefit: firms will pay the additional costs (longer routes to avoid sensitive areas) without obtaining anything in return. In fact, even in local routing problems, hazmat logistics is examined from society's perspective. In this section, we explore society (and authorities) perspective to better understand why steps must be taken toward risk management. Then, we explore firms' perspective to illustrate why taking these steps without further incentive might sometimes be impossible.

Society and authorities perspective

Hazardous materials accidents are generally classified into two broad categories: transportation accidents and fixed installations accidents. Furthermore, fixed installations accidents can occur either during storage or during industrial activities. While analysing MHIDAS international hazmat accidents database, Vilchez et al. (1995) found out that 39% of accidents occurred during transportation, 24.5% occurred during industrial activities and 17.4% occurred during storage. As shown by Khan and Abbasi (1999), fixed installations accidents generally result in fires or explosions (25%), a toxic release (71%) or both (4%). As shown by Oggero et al. (2006), transportation accidents generally result in spills (78%), fires (28%), explosions (14%) or toxic clouds (6%).

Hazardous materials accidents are not always as catastrophic as the explosion of the AZF factory in Toulouse in 2001. However, they all have adverse consequences for the environment, people, property or economic activity. To better illustrate this point, here are a few examples of hazardous materials accidents that occurred in the province of Quebec (Canada).

> On August 23 1988, in Saint-Basile-le-Grand, a PCBs warehouse was set on fire. The toxicity level of the cloud escaping from the blaze was unknown. 3500 people were preemptively evacuated for 18 days.
>
> On December 30 1999, a train derailed near Saint-Hyacinthe and was hit by a second train coming from the other direction. Two crew members were killed, 2.7 million litres of hydrocarbons were spilled and caught on fire and 350 families were evacuated.
>
> In April 2003, more than one million litres of paraxylene leaked from a tank located at the port of Montreal, due to the tank poor conditions. The groundwater and St Lawrence River might have been contaminated. This leak was only unveiled to the public in 2008, causing some controversy.
>
> On October 12 2005, a tanker carrying 60 000 litres of hydrosulfite toppled on its side. Some of the product was spilled, causing a fire. Highway 40 was closed for nearly a half-day.

These few cases show how many hazardous materials accidents may impact the environment (toxic cloud in Saint-Basile-le-Grand, spill in Saint-Hyacinthe, possible contamination of groundwater and the St Lawrence River at the port of Montreal), people (evacuations in Saint-Basile-le-Grand and Saint-Hyacinthe, deaths in Saint-Hyacinthe), property (destruction of the PCBs warehouse Saint-Basile-le-Grand, damaged to carriers in Saint-Hyacinthe and Montreal, product losses in all cases) and economic activity (evacuations in Saint-Basile-le-Grand and Montreal, closing Highway 40 in Montreal). Moreover, the doubts surrounding the toxicity level of the cloud escaping from the blaze of Saint-Basile-le-Grand highlight the ever-present risks to human health.

Therefore, authorities and society has a whole wish to avoid hazardous materials accidents at all costs: new laws and regulations are regularly introduced and new facilities face considerable opposition.

Firms perspective

To remain competitive, firms tend to subcontract hazmat-related activities and raw materials are bought further and further away to reduce purchase costs. While these practices can increase risk levels firms state that in most cases, costs are simply too important to take risks into account. In fact, firms are faced with complex hazmat logistics decisions: selection of the means of transportation, carrier selection, supplier selection, taking costs into accounts, taking regulations into account, taking risk into account, etc. However, current logistics models can hardly answer these questions as most are only aimed toward hazardous materials routing (tactical planning) and primarily focus on risks minimization.

Actual information on dangerous goods logistics remained relatively scarce until now, however, in a previous study (Leroux et al., 2010), we conducted a large scale survey bringing some highlights on the situation. This survey was sent to 490 hazardous materials users in the province of Quebec and we received 106 answers. We showed that while firms generally have appropriate safety management programs on-site (74.0% offer risk related information to employees, 95.1% always or often use dedicated areas to store hazardous materials, etc.), they tend to overlook transportation security aspects. As a result, transportation risks analyses are rarely conducted (52.2% never or rarely proceed to it) and carriers are rarely subject to safety audits (48.4% of respondents never proceed to it). Further interviews also showed that when making logistic decisions (transportation mode, supplier, etc.) risk is not always taken into account.

Why is this so? Why can't firms have the same level of attention to transport operations than to other industrial activities. We identified four possible causes:

1. Transportation is often subcontracted, therefore these activities are sometimes overlooked by firms: it is not their equipment, not their employees and their name (and image) is not associated with the vehicle (Leroux et al., 2009);

2. Risk management has a price and in the case of hazmat transportation, that price might simply be too high. For instance, Abkowitz et al. (1992) reported that minimum-risk roads are twice as long than minimum-length roads.

3. The economic impact of hazardous materials transportation accidents cannot be ignored, but the cost is shared with various entities (governments, public, shipper, carrier, customer) (Leroux et al., 2009b);

4. The economic impact of hazardous materials transportation accidents cannot be ignored, but accidents are so rare that the cost per kilometer traveled is relatively low. Leroux et al. (2010) showed that with a risk estimated at 0,097$/km (firms' share of the total amount in the case of road transportation) and shared among the logistic chain, financial losses following an accident are probably not high enough to influence the decision-making process.

Firms' do not necessarily want to go against authorities' wishes, but we see that in transportation, financial aspects are so important that they tend to overshadow security aspects. Yet, as the main decision-makers (suppliers' selection, customers' selection, transportation means, shipment frequency, dangerous goods carried) fixed installations should take the risks they impose upon the population during transportation into consideration. To raise their awareness some avenues could be considered. Additional legislation could be introduced, additional penalties could be imposed to the decision-maker (the fixed installation) in case of an accident and regional committees could be created to ensure correct risk management on their territory. In the following section, we will mostly focus on the last option, but no matter which option is selected, it must be carefully examined to ensure that the benefits outweigh the additional constraints to the industry.

OPTIMIZING HAZARDOUS MATERIALS LOGISTICS

The work presented in this section is part of the GLOBAL project, an initiative of INERIS in France with the participation of CIRANO and École Polytechnique de Montréal in Canada. Throughout this project, multiple hazmat related studies have been undertaken, from accident database analysis to cost analysis, allowing invaluable insight on society, authorities and industry perspective. The GLOBAL project end goal was to develop a comprehensive approach to hazardous materials risk assessment throughout the logistic chain (any transportation and storage sequence).
The risk assessment methodology presented here is the methodology developed by INERIS during the GLOBAL project (see INERIS, 2007). However, this methodology (heavily focusing on society and authorities perspective) has been altered to include firms' perspective and facilitate negotiations between parties.

Problem formulation

Depending on the context, different type of problems can be studied by the methodology developed. Here are a few examples:

> A firm wonders how to minimize the risks generated by its hazardous materials shipments. Here, the GLOBAL methodology can be used to compare the risk generated by different routing options.
>
> A government wants to develop a hazardous materials transportation network to minimize risk to the population, environment and property. Here, the GLOBAL methodology can be used to compare the different networks studied.
>
> A municipality wants to estimate the overall risk-level on its territory (hazmat-related risks, transportation and fixed installations) to see if preventive actions should be taken. Here, the GLOBAL methodology can be used for risk assessment as well as during the following negotiations between parties involved.

As we can see, even if the context varies, risk assessment and risk minimization remains the main focus of the various stakeholders described above.

Identifying logistics options

Once the problem has been defined, the different logistic options (whether they are existing or new) must be identified and information relative to these various options (cost, shipment frequency, etc.) must be gathered. For instance, in the examples presented above, the three stakeholders will respectively want to identify and characterize: the routing options (firm), the different possibilities for a hazardous materials transportation network (government) and the possible preventive actions to be undertaken (municipality). Even at this early stage of the decision-making process, particularly unsatisfactory options should be eliminated without further analysis.

Identifying concerned parties

Various parties (firms, government, municipalities, social groups, etc.) might be impacted by the different logistic options studied. Hence, these parties might be particularly interested in the decision-making process. Only the decision-maker can decide if these parties must be included in the decision making process. However, we strongly recommend establishing a collaborative approach between at least industries and authorities to take both perspectives into account. If the decision-maker wishes to establish such a collaborative approach, concerned parties should be contacted at this point to learn more about their own expectations and concerns.

For instance, in the examples presented above, the three stakeholders might respectively want to contact: territorial authorities (firm), firms whose hazmat transportation operations might be impacted by the introduction of a hazardous materials transportation network (government) and firms whose hazmat operations (transportation or at the fixed installation) might be impacted by the preventive actions (municipality)

Risk assessment following the two perspectives

As we've seen, risk is defined as the combination of the likelihood of an event and of its expected outcome, in this case hazardous materials accidents. Traditional models found in the literature typically focus on a single transportation means. However, the logistic options presented above can include various combinations of transportations means, temporary storage solutions and fixed installations (we will refer to the elements part of these combinations as *links* in this paper). Therefore, risk must be assessed for every link of every logistic option, before being summed to evaluate the risk-level of each the logistic option. Here is an example:

> A firm is considering the following logistic option for a hazmat shipment: rail transportation on 600km, temporary storage for 24hours at the rail yard, followed by road transportation on 23km. There are three links in this

logistic option. Risk will have to be assessed for rail transportation, for storage operations and for road transportation before being summed to evaluate the risk level associated with this logistic option.

However, authorities and firms perspective on the subject are extremely different. In this example, the firm will probably want to evaluate this logistic option from its own perspective: risk reduction will be necessary only if it benefits the firm (accident rates and penalty incurred outweights other financial considerations). However, society and authorities might not see things the same way and will be primarily focused on risk to surrounding populations. In this section, we propose two risk assessment methodologies, each following one of these perspectives.

Society and authorities perspective

The GLOBAL methodology primarily focuses on risks minimization. Different types of risk can be taken into account:

1. Risks to the population (deaths and injuries);
2. Risks to the environment (contamination, etc.);
3. Risks to the property (damages to infrastructures, buildings, etc.).

For every link of every logistic option (routing options, closing certain roads to hazardous materials transportation, etc.) risk to the population, risk to the environment and risk to the property will have to be evaluated using traditional risk assessment techniques seen in the literature review. Risks will then be summed up to evaluate the overall risk-level (risk to the population, to the environment and to the property) of every logistic option. However, these three types of risks cannot be directly compared and logistic options will have to be ranked using multi-criteria decision analysis techniques.

Firms perspective

As we've seen, risk minimization and cost minimization are conflicting objectives and a tradeoff must often be made. However current logistics models primarily focus on risks minimization and cannot answer firms' needs: firms will pay the additional costs (longer routes to avoid sensitive areas) without obtaining anything in return. Thus, there is a need for new models adopting the firms' point of view.
Hazardous materials accidents can financially impact firms' activities: immediate cost, image loss, production loss, community reaction, increase in insurance fees, loss of customers, etc. Hence, to adopt firms' perspective, we suggest converting risks in costs (evacuation, cleaning, traffic delays, property loss, etc.) and identifying firms' share of the total amount. Converting risks into costs transforms the multiobjective problem (costs and risks are taken into account) into a single objective problem (costs minimization) which facilitates problem solving. Therefore, the problem formulation can be represented by:

$$\min \sum_i \sum_j \sum_k x_{ijk}(R_{ijk} + c_{ijk})$$

where R_{ijk} represents the risk (translated into monetary loss) associated with logistic option x_{ijk} and c_{ijk} represents the costs (transportation and acquisition) associated with logistic option x_{ijk}. R_{ijk} and c_{ijk} of course have to be evaluated for every link before being summed to evaluate the risk-level and costs of each the logistic option x_{ijk}. This formulation directly allows logistic options to be ranked.

Decision-making

As we've seen, various parties might be impacted by hazardous materials logistics. These parties might have very different views on hazardous materials logistics and might protect very different interests. Therefore, when optimizing hazardous materials logistics, we strongly recommend establishing a collaborative approach to take all perspective into account. If not, the option selected might prove unsatisfying and might face opposition. In this paper, we mostly focused on authorities/society and firms perspectives.
For instance, if firms decided to select a logistic options without further consultations, results would directly come from the risk assessment process (firms perspective) described above and with a risk estimated at 0,097$/km (firms' share of the total amount) hazardous materials accidents can hardly influence firms decisions. If an authority decided to select a logistics option without further consultations, results would directly come from the risk assessment process (society and authorities perspective) and possible economic impact on firms' activities might be ignored.
However, when a collaborative approach is established, logistics options are ranked following both perspectives. Ranking results will of course tend to differ between the two approaches and will be up to negotiations between both parties.

CONCLUSION

In this paper, we explored authorities' and firms' conflicting views on hazardous materials logistics. We showed that hazardous materials accidents can impact the environment, people, property or economic activity, explaining why authorities and society as a whole wish to minimize hazmat related risks. We also showed that while authorities only whish what's best for the population, firms' stance on the issue is much less clear, particularly in the case of transportation. We identified four possible causes to this issue: (1) transportation is often subcontracted, (2) risk management has a price, (3) hazmat transportation accidents costs are shared among various entities and (4) hazmat transportation accidents are so rare that their cost per kilometre traveled is relative low.
We presented a methodology aimed toward hazardous materials logistic optimisation. This methodology contains several steps: problem formulation, identifying logistics options, identifying concerned parties, risk assessment and decision-making. We argued that since authorities and firms have such different perspective on the issue, a collaborative approach must be established between firms and authorities. Therefore risk is assessed following the

two perspectives (authorities and firms) and results can be used during negotiations between the two parties.

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