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A simulation-based risk analysis technique to determine critical assets in a logistics plan

Rajesh Thiagarajan [a], **Hing-Wah Kwok** [a], **Greg Calbert** [a], **Don Gossink** [a], **Slava Shekh** [a] **and Tony Allard** [a]

[a] *Command, Control, Communications and Intelligence Division,*
Defence Science and Technology Organization, Edinburgh SA 5111.
Email: Rajesh.Thiagarajan@dsto.defence.gov.au

Abstract: Identifying risks in military logistics planning is essential. Particularly, identifying risks that emanate due to unforeseen unavailability of key transport assets during a defence mission is vital to evaluate the robustness of contingencies built in to support the mission's logistics plan. An unforeseen unavailability of a transport may be caused by unscheduled maintenance or its assignment to another concurrent mission. Replacing unavailable specialized transport assets such as strategic lift ships and aircraft during an on-going mission generally mandates significant re-planning effort and time. Therefore, it is essential to examine and revise contingency arrangements before a logistics plan is put into action. One method to achieve this is by simulating the logistics plan with asset unavailabilities and observing the corresponding consequences. The *consequence* of an asset's unavailability as determined using simulation together with the *likelihood* of the unavailability occurring are then used to derive the risk the asset poses to a logistics plan.

This paper describes initial research conducted to develop a *risk analysis technique* that determines the risks posed by transport assets in a logistics plan. We present a metric called *failure threshold* that serves as a measure of the consequence an asset's unavailability has on a plan. The failure threshold of an asset is a point in time within a plan such that unavailability of the asset before the threshold will cause the plan to fail. We also present a binary-search based algorithm that determines the failure threshold of an asset by simulating the effects for such unavailability at different points of time within the plan. The consequence, as determined by the failure threshold of an asset's unavailability is combined with a user-specified likelihood to derive the risk posed by the asset. The risk analysis technique presented in the paper is built as an extension to the multi-agent logistics distribution and movements planning system presented in (Marsh, et al. 2010).

The risk analysis technique presented in the paper determines critical assets in a plan, where unavailability of critical transports may cause the plan to fail. The identification of critical assets allows planners to effectively incorporate suitable contingencies such as improving maintenance of critical assets or sourcing additional assets before the plan is put into action. In order to effectively plan contingencies, it is essential to have the ability to measure the effect the contingency arrangement has on a plan. To this end, we show that the failure threshold of an asset can be used to determine whether sourcing an additional asset with similar capability reduces the risks in the plan.

Keywords: *Simulation, risk, logistics, transports, planning, transport unavailability*

1. INTRODUCTION

Logistics planning is a vital part of any military operation planning process. A logistics plan covers troop movement, equipment movements, and supplies movement. Identifying *risks* in a military logistics plan is vital to evaluate the robustness of the plan. While there are multiple factors that could be a source of risk in a plan, in this paper we focus on the risks that emanate due to the unavailability of transports. Previous studies such as (Peck 2005) and (Rodrigues, et al. 2008) have also identified *transport unavailability* as a key source of risk in a supply chain environment and have argued that contingencies that compensate potential transport losses in a plan are essential to effectively address such risks.

In the military planning context, loss of key transport assets may have a detrimental impact on the plan. For example, if a plan involves numerous sea routes then loss of sea transports during the mission may even lead to mission failure. Logistics planners, who provide logistics support for military operations, generally include contingency strategies, like the formation of a sufficiently large and diverse pool of logistics assets enabling replacement of a failed asset with a similar one, to compensate potential transport losses during the execution of a plan. However, the effectiveness of such arrangements are not known until the plan is put into action. Moreover, replacing unavailable specialized transport assets such as strategic lift ships and aircraft during an on-going mission generally mandates significant re-planning effort and time. Therefore, it is essential to examine and revise contingency arrangements before a logistics plan is put into action.

In order to objectively evaluate contingency arrangements in a plan, it is essential to determine the risk that emanates due to unforeseen unavailability of each individual transport in the plan. An unforeseen unavailability of a transport may be caused by unscheduled maintenance or its assignment to another concurrent mission. If a transport's unavailability poses a high risk to a plan, in spite of the pre-specified contingency arrangements, then the arrangements have to be revised appropriately to mitigate the risk. On the other hand, if a transport's unavailability poses a low risk to the plan then some of the pre-specified contingency requirements may be relaxed appropriately. Some previous studies such as (Wilson 2007) and (Hendricks, et al. 2005) have studied the impact of transport disruptions on different supply chain models. However, to the best of our knowledge, there are no studies directed towards objectively measuring the risk posed by transports in a military plan.

To address this gap, we propose a *risk analysis technique* that determines the risks posed by transport assets in a logistics plan by simulating the logistics plan with asset unavailabilities and observing the corresponding consequences. The use of simulation allows for risks to be detected before a plan is put into action thereby providing a platform to evaluate and revise contingency strategies. The risk analysis technique proposed in this paper employs a new metric called *failure threshold* that serves as a measure of the consequence an asset's unavailability has on a plan. The failure threshold of an asset is a point in time within a plan such that unavailability of the asset before the threshold will cause the plan to fail. In this paper, we show how the *failure threshold* of a transport is used to determine the *consequence* the transport's unavailability has on a logistics plan. We present a technique to efficiently compute the *failure threshold* of a transport by simulating a logistics plan with unavailabilities introduced at different points of time within the plan chosen using the binary search principle. We also show how the risk analysis technique presented in this paper combines the *consequence* of a transport's unavailability and the *likelihood* of the unavailability occurring using a risk matrix to derive the risk the transport poses to a logistics plan. To evaluate the feasibility of the risk analysis technique, we have implemented it as an extension to the multi-agent logistics distribution and movements planning system presented in (Marsh, et al. 2010).

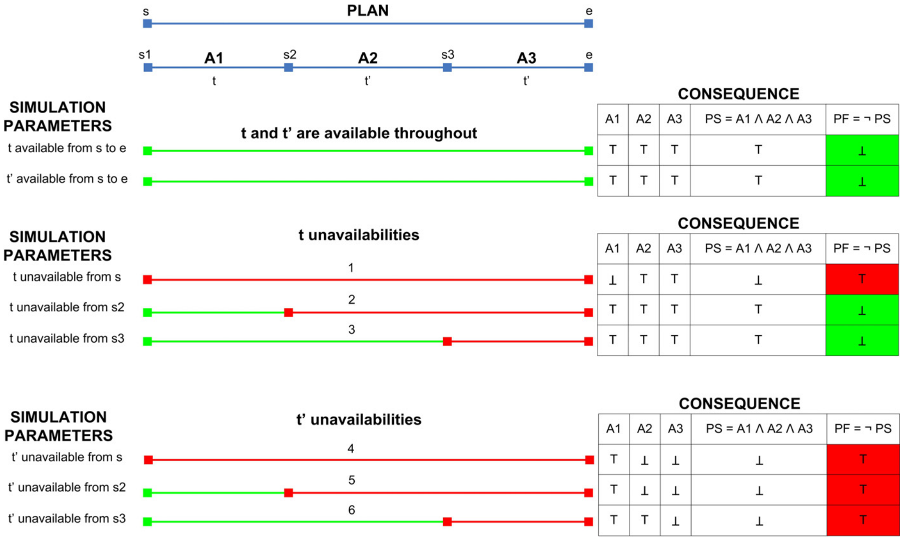
Additionally, we also show that the *failure threshold* of a transport can be used to determine whether sourcing an additional asset with similar capability reduces the risks in the plan. We show how the difference between the threshold after and before the new addition can be used as an indicator of the effect the new addition has on a plan.

2. SIMULATION-BASED RISK ANALYSIS TECHNIQUE

For a given logistics plan, the *risk analysis technique* presented in this paper determines the risk posed by a transport in the plan. We present a metric called the *failure threshold* of a transport that aggregates the consequences observed across multiple simulations, where the transport is made unavailable at different points of time in the plan. The *consequence* of a transport's unavailability as denoted by its *failure threshold* together with the *likelihood* of the unavailability occurring are then used to derive the *risk* the transport poses to a logistics plan.

2.1. The *failure threshold* metric

Firstly, we present the idea behind the *failure threshold* metric using a simple example. Consider the fictitious plan with two transports *t* and *t'* presented in Figure 1, which begins on day *s* and ends on *e* and is comprised of sequential activities *A1* [performed by *t*], *A2* [performed by *t'*] and *A3* [performed by *t'*]. The idea is to simulate unavailabilities of each transport individually and aggregate the corresponding consequence observations. In Figure 1, the blue horizontal lines denote the plan that consists of three activities. The horizontal lines in simulations 1-6 show the availability profile of *t* and *t'*. For example, in simulation 2 the transport *t* is available between *s* and *s2* (shown in green) but it becomes unavailable after *s2* (shown in red). The figure also shows the consequence observed for each simulation in the form of a truth table entry. The truth table records a *true* or *false* value against each of the activities indicating whether the corresponding availability profile causes an activity to fail. The truth table also shows two aggregate checks: plan success [*PS*] and plan failure [*PF*]. A plan succeeds if all its activities are successful otherwise the plan fails. Since [*PF* = *true*] is a negative impact, they are shown in red. As [*PF* = *false*] implies [*PS* = *true*], these entries are in green.



A1	A2	A3	PS = A1 ∧ A2 ∧ A3	PF = ¬ PS
T	T	T	T	⊥
T	T	T	T	⊥

A1	A2	A3	PS = A1 ∧ A2 ∧ A3	PF = ¬ PS
⊥	T	T	⊥	T
T	T	T	T	⊥
T	T	T	T	⊥

A1	A2	A3	PS = A1 ∧ A2 ∧ A3	PF = ¬ PS
T	⊥	⊥	⊥	T
T	⊥	⊥	⊥	T
T	T	⊥	⊥	T

Figure 1. Computing failure thresholds of transport using simulation

If both *t* and *t'* are available throughout the plan then activities *A1*, *A2* and *A3* proceed as planned and the plan succeeds [*PS* = *T*]. However, if either *t* or *t'* become unavailable, depending on when the unavailability occurs, the plan may fail [*PF* = *T*]. Note that in the failure threshold computation context, unavailability of a transport is assumed to be permanent. That is, if a transport becomes unavailable on particular day within the plan then it is not available for remainder of the plan. The characteristics of this assumption are discussed in Section 2.3.

Consider simulations 1, 2 and 3 from Figure 1, where *t* becomes unavailable from days *s, s1, and s2* and corresponding consequences are observed. It is evident from the corresponding truth table that if *t* becomes unavailable before *s2* then the plan fails [*PF* = *T*] because *t* is essential to perform *A1*. Unavailability of *t* after *s2* does not have any impact on the plan and the plan succeeds [*PS* = *T*] because *t* is not required after *s2*. The failure threshold of *t* is the point before which unavailability of *t* causes [*PF* = *T*], in this case it is *s2*. Similarly, consider simulations 4, 5, and 6 from Figure 1, where *t'* becomes unavailable from days *s, s1,* and *s2*. As the corresponding truth table shows, if *t'* becomes unavailable anytime during the mission then plan fails [*PF* = *T*]. The failure threshold of *t'* is the point before which unavailability of *t'* causes [*PF* = *T*], in this case it is *e* because unavailability of *t'* at any point before *e* will cause the plan to fail.

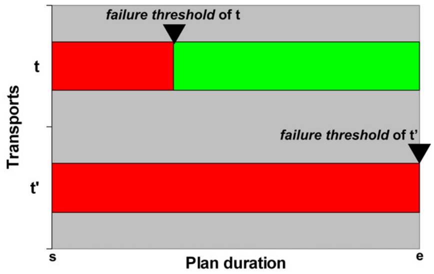


Figure 2. The failure threshold of transports t and t'

From the consequences of simulations 1 till 6, it is evident that while the unavailability of *t* during certain times may be tolerated, the unavailability of t' will always cause the plan to fail. Therefore, *t'* is relatively more critical to the plan than *t*.

We adopt the *failure threshold* of a transport as a metric to quantify this relative criticality observed through simulations. The *failure threshold* of a transport is defined as the point in time within the plan such that

- unavailability of the transport from a point before the threshold will result in plan failure, and
- unavailability of the transport from a point after the threshold will not have any impact on the plan.

Once the *failure threshold* of a transport *t* is determined, the consequence C_t the unavailability of *t* has on a plan that starts on day *s* and ends on day *e* is defined as the ratio of the *failure threshold* of *t* to the total plan length.

$$C_t = \frac{\textit{failure threshold} \text{ of transport} \, t - s + 1}{e - s + 1} \tag{1}$$

The scenario presented in Figure 1 demonstrates the idea behind the failure threshold approach using a simple plan involving two transports and three sequential activities. Since the failure threshold approach evaluates every transport in a plan individually, it scales well to evaluate large and complex military logistics plans, which often involve large number of different transports including strategic lift ships and aircrafts performing concurrent activities.

2.2. The *failure threshold* Approach vs. Monte Carlo simulation of concurrent failures

As described in Section 2.1, the *failure threshold* is individually computed for every transport in the plan. That is, apart from the transport being evaluated the remaining transports are assumed to be available throughout the plan. It may be argued that this assumption is too restrictive to handle situations where multiple transports may become unavailable within the plan. In an earlier experiment, we addressed this assumption by adopting a Monte Carlo simulation method that allows multiple transports in a plan to become unavailable at stochastic points of time based on some pre-determined probabilities of the transports becoming unavailable. Our analysis showed that a significant number of simulation runs were required to assess the criticality of transports with high probabilities of becoming unavailable. Furthermore, an enormous number of simulation runs were required to infer the criticality of those transports with low unavailability probabilities, making this method impractical to evaluate large logistics plans. The *failure threshold* approach presented in this paper aims to provide a holistic risk assessment of a plan by measuring the consequence of transport unavailabilities individually and allowing the logistics planner to infer the overall assessment by looking at the “sum of parts” rather than just the individual thresholds.

2.3. Permanent Unavailability Assumption

As mentioned earlier, in the failure threshold computation context, if a transport becomes unavailable on a particular day within the plan then it is assumed not to be available for remainder of the plan. This assumption may seem too restrictive at first glance because temporary unavailability of a transport on a particular day for a few days is more likely to occur than it going permanently unavailable for the reminder of the mission. Nevertheless, this assumption was adopted for the reasons discussed below.

In military logistics planning, specifying exact unavailability profiles prior to a mission is difficult because the unavailability may stem from various different sources. For example, a transport may be withdrawn from an ongoing mission for a few days to engage in an emergency natural disaster response. A Monte Carlo simulation model that simulates transport unavailabilities based of the probability of the transport becoming unavailable for *n* days seems like an alternative. However, this models also suffers from the scalability issues discussed in Section 2.2. The permanent failure approach, on the other hand, is a good first test to quickly assess the risk a transport poses because evaluating a plan under permanent unavailability determines the worst case risk arising from the transport. In the future, we plan to extend our risk analysis technique to accommodate temporary transport unavailabilities.

2.4. Scope of the *failure threshold* Metric

In our model, a transport unavailability may cause one or more of the following issues: *delay*, *shortage of supplies*, and *mission failure*. The concept of plan failure [*PF*] used within the *failure threshold* approach abstracts from these individual issues and treats them all uniformly. That is, a plan failure [*PF*] is assumed if at-least one of the issues occur as a result of a transport becoming unavailable. The *failure threshold*, therefore, acts as a single encapsulating measure of the consequences a transport's unavailability has on a plan instead of three different measures for each issue.

2.5. Computing the *failure threshold* of a transport

Let us consider the case of computing the *failure threshold* of transport *t* in the plan in Figure 1. One technique to compute the threshold is to iteratively make *t* unavailable on everyday starting from *s* until *e* and observe the corresponding consequence in the accompanying truth table. The table will contain $n = e - s + 1$ entries. The *failure threshold* of *t* is the last day on which plan failure is observed [$PF = true$] in the corresponding truth table. The worst case complexity of this technique is linear $O(n)$, where *n* is the plan duration. Therefore, this approach is unsuitable for large plans.

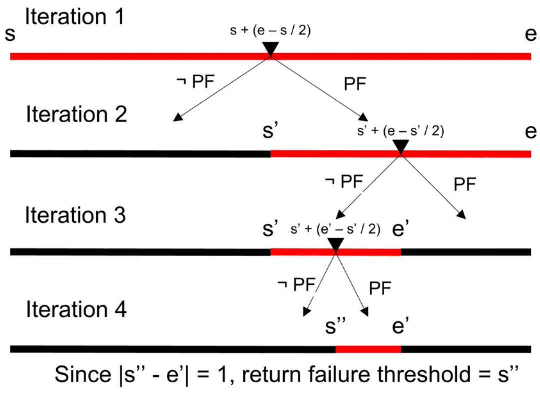


Figure 3. Computing *failure threshold* of a transport using binary search.

To address the complexity issue, we determine the *failure threshold* of a transport by simulating the effects caused by its unavailability at different points of time chosen using the binary search principle. The idea behind this technique is as follows. Let us assume *x* to be a day at the half way point between days *s* and *e* and assume that a transport *t* becomes unavailable from x onwards. If this unavailability causes the plan to fail *PF*, then any unavailability during days before *x* will also cause *PF* because the asset is permanently unavailable. Hence, the day when the last *PF* occurs or the *failure threshold* will only be after *x*. Therefore, the search for the threshold can be directed towards days $x + 1$ until e. Similarly, if unavailability from *x* onwards does not cause PF, then the focus can be shifted to days *s* until $x - 1$. Figure 3 shows the threshold computation iterations between *s* and *e*. The red regions denote the search space in each iteration, while the black regions denote intervals pruned from search. In each iteration, transport unavailability is introduced at the mid-pint of the red interval and the effect of the plan is observed. If *PF* occurs due to the unavailability, the search slides rightwards otherwise it proceeds leftwards. Since this technique is based on binary search, the worst case complexity is logarithmic $O(\log n)$ making it efficient even while analysing large plans. The *failure thresholds* of transports *t* and t' from the scenario in Figure 1 computed using binary search method are presented in Figure 2, which shows that with a greater threshold *t'* is relatively more critical to the plan than *t*.

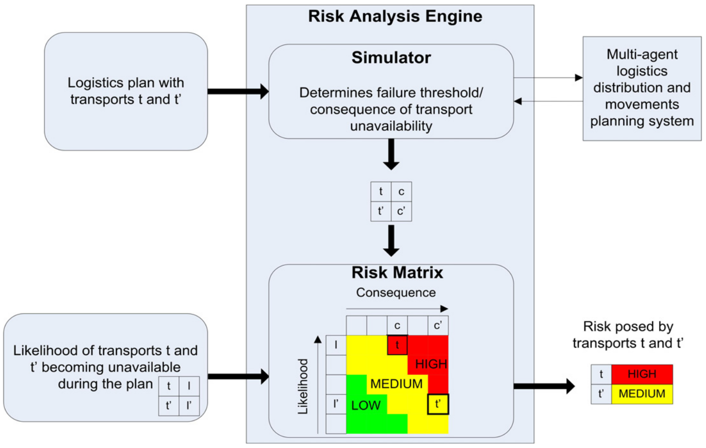


Figure 4. Computing risk posed by the transports in a plan

2.6. Computing and conveying risks

The *consequence* C_t, as determined using Equation (1), of a transport's unavailability is only a measure of the impact the transport's unavailability has on the plan. To compute the actual *risk* R_t posed by the transport, it is essential to also factor in the *likelihood* L_t of the transport's unavailability occurring. In military logistics planning, the likelihood of a transport's unavailability depends on various factors such as mission's location and weather etc,. Therefore, we refrain from automatically predicting likelihoods and allow the logistics planner to specify them based on current circumstances.

The risk posed by a transport R_t is defined below.

$$R_t = C_t \times L_t \tag{2}$$

The assessments computed by our approach are conveyed as colored risk categories using a likelihood-impact matrix, such as the one prescribed in (Standards Australia 2009), that scales a transport's risk based on its unavailability consequence and corresponding likelihood. Graphical depiction of risk was chosen over numerical or textual methods as previous studies, such as (Smerecnik, et al. 2010), have shown that visual models improve risk comprehension.

The risk computation and conveying process is shown in Figure 4, where the Risk Analysis Engine expects a logistics plan along with the unavailability likelihoods. The engine computes the *consequence* of every transport unavailability by repeatedly invoking the Multi-agent logistics distribution and movements planning system presented in (Marsh, et al. 2010) to compute the *failure threshold* of the transport. The *risk* posed by a transport is then conveyed by mapping the *consequence* and *likelihood* of the transport's unavailability onto a risk matrix. Figure 4 shows the risk computation and conveying process for transport *t* and *t'*. Although the consequence *c'* of *t'* becoming unavailable is greater than *c*, the risk posed by *t* is greater because *c* is more likely to occur.

3. ADDRESSING RISKS BY ADDING AN ADDITIONAL TRANSPORT

The risk analysis technique presented in the paper determines critical transports in a plan, where unavailability of critical transports may cause the plan to fail. The identification of critical transports allows logistics planners to effectively incorporate suitable contingencies to address the risks that arise from transport unavailabilities. To an extent transport failures can be avoided by periodical maintenance of the assets in the plan. While periodical maintenance of a transport reduces the likelihood of structural and mechanical failures, this strategy does not cover other sources of unavailabilities in the military planning context such as unscheduled maintenance or its assignment to a concurrent mission.

Another method to address the risk is by adding extra transports in the event of an unavailability (Tang 2006). The problem with this approach is that replacing unavailable specialized transport assets such as strategic lift ships and aircraft during an on-going mission generally mandates significant re-planning effort and time. Therefore, it is essential to examine and revise contingency arrangements before a logistics plan is put into action. In order to effectively plan contingencies, it is essential to have the ability to measure the effect the contingency arrangement has on a plan. That is, for example, if the contingency arrangement to mitigate transport risks in a plan is to source additional transports then means to evaluate the effect of adding extra transports is essential for effective planning. To this end, we show that the *failure threshold* of a transport, in addition to measuring the consequence of the transport's unavailability, can also be used to determine whether sourcing an additional transport with similar capability reduces the risks in the plan.

3.1. Using *failure threshold* to measure the effect of adding a new transport

In Section 2, we showed how the *failure threshold* of a transport is used to derive the risk it poses to a plan and demonstrated our approach using the scenario presented in Figure 1. Using the process shown in Figure 4, transport *t* was deemed to be of HIGH risk to the plan. In order to reduce the risk, assume that the logistics planner has decided to source in an extra transport t_1 with capability similar to *t*.

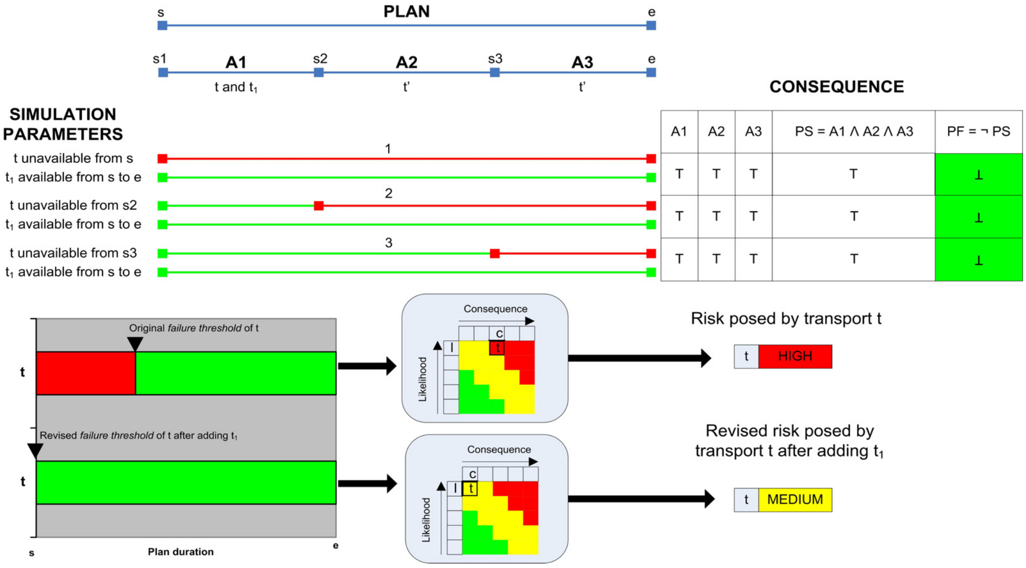


Figure 5. Reducing risk by adding a new transport

In this section, we show how the *failure threshold* metric is used to measure the effect of adding t_1 to the plan. Consider simulations 1, 2 and 3 from Figure 5, where *t* becomes unavailable from days *s, s1,* and *s2* and corresponding consequences are observed. It is evident from the corresponding truth table that if *t* becomes unavailable then the newly sourced in transport t_1 compensates for it. Therefore, unavailability of *t* does not have any impact on the plan and the plan succeeds [$PS = T$]. As a result, the accompanying truth table does not have any plan failures. Therefore, the *failure threshold* of *t* is reduced to the plan start day *s* thereby reducing the *consequence* C_t to the lower end of the scale. As shown in Figure 5, this consequence combined with the likelihood reduces the risk from HIGH to MEDIUM. Therefore, addition of t_1 to the plan has the positive effect of reducing the risk posed by *t*.

In general, the reduction of the *failure threshold* of a transport after sourcing in an additional one with similar capability from its original *failure threshold* is a measure of the effect the new addition has on a plan. Substantial reduction in the threshold implies that the newly added transport significantly improves the plan's prospects. Minimal or no reduction in the threshold can be used as a trigger to focus on alternative contingency measures.

4. SUMMARY AND FUTURE WORK

In this paper, we presented a *risk analysis technique* that determines transports that are critical to a plan by deducing the risks they pose using simulation. We presented the *failure threshold* metric to measure the consequence a transport's unavailability has on a plan. We demonstrated how the *failure threshold* of a transport is an objective measure of the impact the transport's unavailability has on a plan. We presented a binary search based *failure threshold* computation technique that scales well to evaluate large logistics plans in comparison to a brute force approach.

We demonstrated how our risk analysis process that computes the risk posed by a transport by mapping the *consequence*, as determined by the transport's *failure threshold*, and the user-specified *likelihood* onto a risk matrix. Moreover, we also showed that the *failure threshold* metric can also be used to determine whether sourcing an additional asset with similar capability reduces the risks in the plan.

We plan to continue this research by investigating the following extensions. Currently the *failure threshold* metric only concerns a single transport at a time, we plan to investigate techniques to extend the metric's scope by allowing concurrent transport unavailabilities. As mentioned in Section 2.2, this amounts to addressing the issue of dealing with transports with low unavailability probabilities. Techniques such as importance sampling are relevant in this context. Subsequently, we plan to generalize this idea to be able to measure the impact of adding multiple new transports to a plan. In addition, we also plan to extend the risk analysis technique to evaluate temporary transport unavailabilities.

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