Risk Aggregation Methodology for Joint Fire Coordination

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Abstract: Risk management is one of the critical activities in Joint Fire Coordination. Even though it is commonly accepted that a proper risk management methodology should be applied, there are limited risk aggregation methods being used. In this paper, we propose a risk aggregation methodology for a dynamic and uncertain environment that is applied to joint mission planning.

Keywords: Risk aggregation, decomposition method, influence diagram, Dempster-Shafer.

1 INTRODUCTION

Joint Fire Coordination operations are inherently complex, dynamic, dangerous, and, by nature, involve the acceptance of risk. This however relies on the ability to properly encompass all the risks and weigh them against the operation goals and objectives. *Risk* is the expression of the likelihood and impact of an event to the achievement of an organization's objectives. Risk management is a systematic approach of identifying, assessing, understanding, acting on, and communicating risk issues [TBCS2001]. Risk information is usually collected at the lower levels of organizational structure, while situation assessment, risk analysis, and predictions, influencing decision-making are commonly performed at higher levels. Thus, the need for proper risk aggregation into an overall global risk measure(s) and systemic communication and propagation are essential for overcoming information overload of decision-makers.

Factors that make risk management in coalition military operations especially difficult include fundamental risk management differences between coalition partners, time-sensitivity, surprise, dynamism, isolation of the events, and understanding the causality chain (action-reaction-effects and consequences). During the last two decades, risk identification and assessment have been widely studied in many domains – military operations included. However, to the best of our knowledge, until recently, risk aggregation has only been addressed in financial sector.

This paper proposes a risk aggregation methodology suitable for dynamic and time-sensitive environments of joint fire coordination. Both, operational planning and plan execution are discussed. The paper is structured as follows. In Section 2, we state the problem. In Section 3, we present a review of related literature. In Section 4, we propose a risk aggregation method, and in Section 5 we describe an implementation of the method for operational planning and plan execution. The conclusion is presented in Section 6.

2 PROBLEM STATEMENT

Joint Fire Coordination are complex operations involving many organizations in uncertain settings. Triggers and consequences are very hard to separate and prioritize. Risks can be analyzed at several levels: the organization, the team, and the individual. The interdependence between risks on different levels should be considered. The Joint Fires Support process includes various tasks as illustrated in Figure 1. This process is a high-level view of the Find Fix, Track, Target, Engage, and Assess (F^2T^2EA) process used by the Army. It also incorporates the Decide, Detect, Deliver and Assess cycle used by the Air Force. There are many justifications for a rigorous and thorough risk aggregation methodology [see David2008]. Risk aggregation is more common than one can think, as at any stage of operations or at any level of organization, one should make assumptions to aggregate different measures or assessments of risk. In this paper, we focus on discussing potential new methods to address risk aggregation and disaggregation issues.

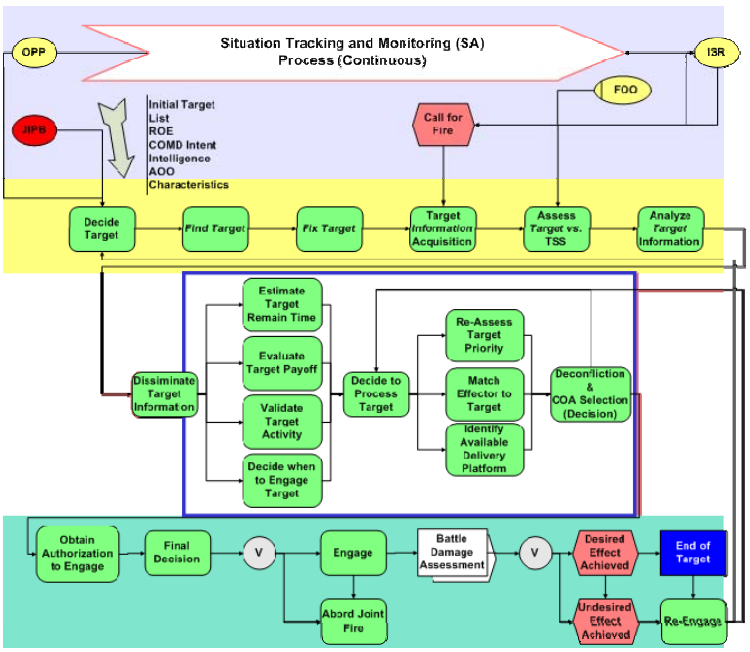

Figure 1 – Extended Joint Fire Coordination Decision-Making Process Flow

3 RELATED WORK

Risk aggregation methodologies are still at their infancy with the most advances reached in financial sector. Factors that made these advances possible are the availability of historical data as well as the possibility of expressing risks in monetary terms. Thus different risk types and risks along the organizational structure could be more easily aggregated. Widely used aggregation methodologies are simple summation of risk levels using correlation (weighting) coefficients [Pezier2003]. Nonetheless, the recent crises and collapse of important financial institutions show that risk management and risk aggregation can be further mastered even in the financial sector.

Murphy and Pate-Cornell [Murphy1996] propose decomposition of factors influencing risk to the system problems and the human behaviour related issues. The authors apply a mix of expert opinion and reliability models to arrive at risk assessment. This concept captures also the independent analysis of aerospace missions showing that problems are frequently caused by human and organizational factors, including failures of risk perception and risk communication [NASA2007].

Related to risk matrices and potential aggregation, the HSE Research report 2001/063 on Marine Risk Assessment [HSE2002] states that “A risk matrix looks at hazards ‘one at a time’ rather than in accumulation, whereas risk decisions should really be based on the total risk of an activity. Potentially many smaller risks can accumulate into an undesirably high total risk, but each smaller one on its own might not warrant risk reduction. As a consequence, risk matrix has the potential to underestimate total risk by ignoring accumulation.” Draft Standard [RM2008] suggests that risks cannot be aggregated (i.e. one cannot define that a particular number of low risks or a low risk identified a particular number of times is equivalent to a medium risk).

Alternatively, risk Aggregation might lead to loss of useful information about Risk. [David2008] suggested that risks aggregation might lead to losing the information on the detail or individual risk measures, Measures of the ‘Exposure to Possible Loss’ for Low Likelihood/High Consequence events may look the same as those for High Likelihood/Low Consequence events. When considering average and central measures of risk, the risk aggregation might lead to losing information about the distribution. Thus, the aggregation of independent risk measures should be performed with care.

Methods like weighted sum, system accident model, and influence diagrams might be used for risk aggregation. Multiple Criteria Decision Analysis methods and procedures are also good candidates for heterogeneous and hierarchical risk aggregation.

In this paper, we propose a combination of Influence diagrams, Depmster-Shafer theory, and Mission Decomposition Structure (Section 5) for risk assessment and aggregation. Dempster-Shafer theory of evidence can be used to tackle the aggregation of information received from several sources about a situation or an event. The *Dempster-Shafer theory* is based on *belief functions* and *plausible reasoning*, used to combine separate pieces of information (evidence) to calculate the probability of an event. The theory was developed by Arthur P. Dempster and Glenn Shafer and represents a generalization of the Bayesian theory. Dempster-Shafer theory is based on two ideas: i) obtaining degrees of belief for one question from subjective probabilities for a related question, and ii} Dempster's rule for combining related bodies of evidence to form a composite belief about a hypothesis. The main difference from the known probability theory is that in the Dempster-Shafer theory $P(B)+P(\overline{B})$ may be different from 1.

Dempster-Shafer theory has been effectively used in airborne sensor networks to fuse enormous amounts of uncertain and noisy information for better battlefield situation assessment [Yu2004]. It is particularly good for systems where the error rates are known and constant.

Bayesian network may be used for capturing and storing uncertainty and cause-effect relationships of a risk. A Bayesian network is a compact way of representing conditional dependencies, It is a probabilistic causal graph, *i.e.*, a directed acyclic graph whose nodes represent random variables and whose arcs represent influence or causal dependencies. Each variable has a probability distribution assigned. A node with parents has conditional probabilities – a state table with a joint probability distribution of its own states, given the states of its parents. The probability of a state of such a node depends on the previously observed states of its parents. Thus, Bayesian network captures two ‘forms’ of knowledge: i) the causal structure of the relationship between random variables, and ii) the probabilities.

Influence diagram is a generalization of Bayesian network produced by adding decision nodes. Each decision node has a number of states that represent possible alternatives.

4 PROPOSED RISK AGGREGATION METHODOLOGY

This paper addresses the following risk aggregation questions:

- How to aggregate risk related information from separate sources?
- How to aggregate homogeneous risk assessments through a hierarchical structure?
- How to aggregate heterogeneous risk assessments?

We assume that a joint operation is structured as a hierarchy with number of collaborators involved over a period of time. Also uncertainties are implied. In practice, risk aggregation is performed by a human analyst and it is based on his/her experience and expertise.

Our approach combines risk assessment and information aggregation using Influence diagrams and Dempster-Shafer theory of evidence, and risk aggregation through Mission Decomposition Structure. One can distinguish many risk types associated with joint fires coordination:

- risk of mission failure (M),
- risk to military personnel health/ life (P),
- risk of collateral damage (C), risk of important buildings damage (B), and
- risk to resources and equipment (R).

Our approach starts with a mission. We assume that the pre-planned mission can be divided in elementary actions, and we propose the following static risk aggregation approach:

1. (S1) Generate a tree-like graph representing a Mission Decomposition Structure (MDS) dividing the mission in tasks, subtasks, and actions;
2. (S2) Determine the importance weights for the edges of the MDS (representing importance of a success of a child node to a success of the parent node);
3. (S3) For each action/task, identify associated risks; and
4. (S4) For each risk, identify its core factors and generate corresponding Bayesian network, influence diagram, and a Expended Influence Diagram (EID) combining Dempster-Shaffer methodology and influence diagram.

Due to dynamic changes over time, a real-time (continuous or iterative) risk monitoring and assessment should be carried out using the following steps:

1. (D1) For each risk, assess its level, using EID;
2. (D2) For each risk type, aggregate risks over tasks, going upwards along the MDS, and
3. (D3) At each level of command and MDS, aggregate different risk types.

The MDS can be used to aggregate risks and propagate the relevant risk information to the upper levels of the mission structure or command. Only comprehensive information is presented to decision-makers and commanders. Disaggregation of the risks is also possible all the way to the action level of the mission. Also, disaggregation of aggregated risks consisting of different risk types is possible and desirable.

For the aggregation along MDS, we propose two simple ways of risk aggregation from children nodes to their parent node in the MDS:

- *Max rule*: the risk level of a parent node is equal to the maximum of risk levels of its children, and

- *Importance rule*: the risk *level* of a parent node is equal to the normalized weighted sum of the risk levels of its children. The child weight is the edge weight depending on the importance of this child to the success of the parent action/task.

Only the risks of the same type are to be combined and aggregated using these approaches. If a number of risks of the same types are associated with one node, the aggregation at this node should be done first. Note that one aggregation approach is more applicable to certain risk types. Specifically, for the mission success (M), the most appropriate would be to use Importance rule; for risks to people health/ life (P) and for risks of collateral damage, the most appropriate would be to use Max rule; and for the risk to important buildings (B) and equipment (R) any of the two may be used.

5 IMPLEMENTATION OF RISK AGGREGATION FOR MISSION PLANNING

We consider a joint fire coordination scenario as shown in Figure 2. The main activities consist of assigning resources/departments to certain tasks. Corresponding Extended Influence Diagram of the risk of collateral damage depending on the choice of Delivery Asset is given in Figure 3. The diagram contains Bayesian network showing dependencies among random variables shown in ovals, decisions (in rectangular boxes) on the choice of the delivery assets, the aggregation of information (in clouds) using Dempster-Shafer, and the risk (in diamond box). For each of the relevant risks, a corresponding EID should be created. Resulting risk levels are to be presented to commanders.

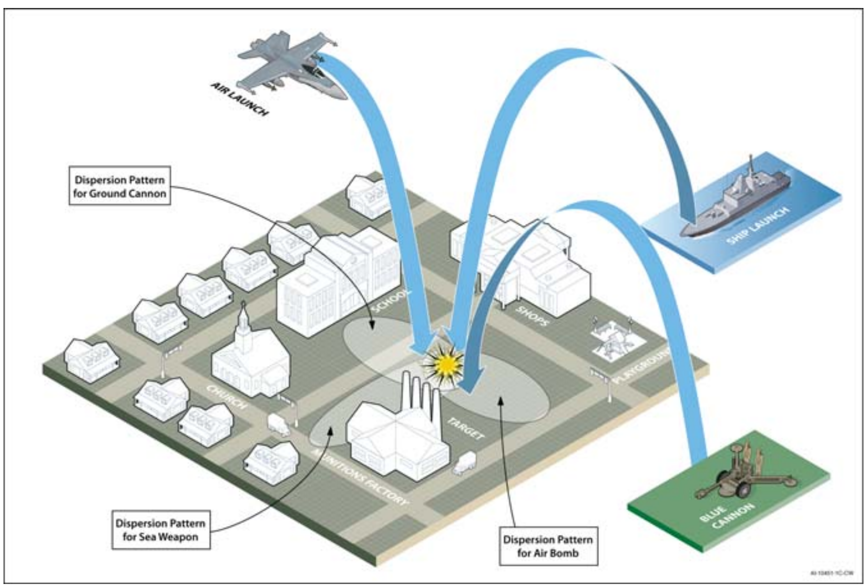

Figure 2 – An Urban Scenario of The Joint Fire Coordination

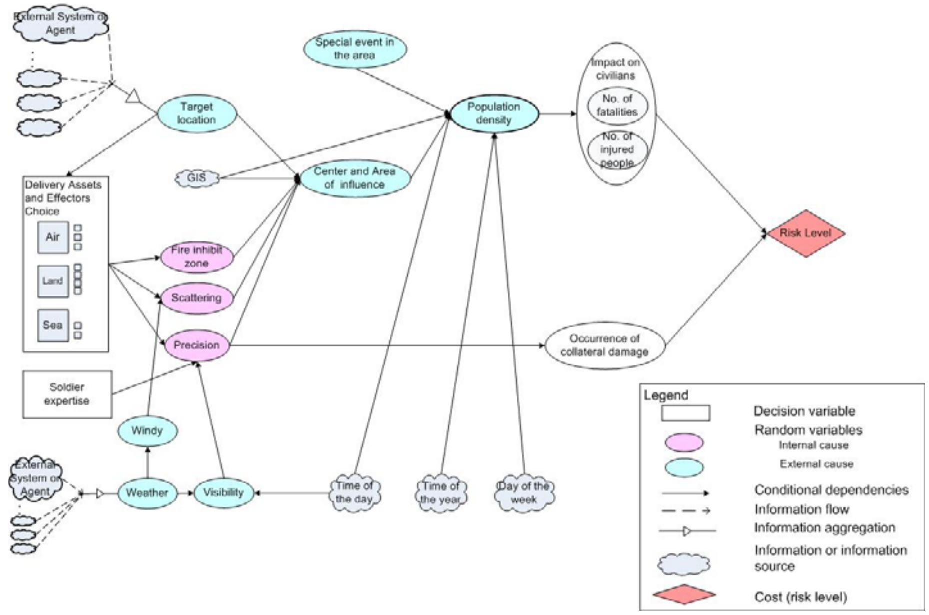

Figure 3 – Extended Influence Diagram for Risk of Collateral Damage in an Urban Scenario

An example of a Graphical User Interface (GUI) in Figure 4 provides risk levels of different actions and different types that would be beneficial to decision making and resource management (including assignment of delivery assets to targets/tasks). The risk matrix in the upper part of the figure shows the level of risk for each pair task-resource assignment pair: red cell represents the extreme risk, orange represents high risk, yellow represents medium risk, and green represents low risk. Gray cells represent invalid/incompatible assignments. The columns represent tasks, and rows represent resources (or delivery assets in joint fire coordination) to be assigned to the tasks. On the right of the Assignment table, a list of potential solutions to the (delivery asset – task) assignment problem is given. These solutions can be generated manually, by interacting with the Assignment table, or automatically if an assignment problem solver is implemented. If a solution has been accepted, the screen would update all relevant risks. Below the Assignment risk matrix, the Related Actions table shows the risk levels of related actions. In the Aggregated view, the right-mouse click on a risk within the Assignment risk matrix brings a the risk disaggregation to its elements – risk of different types: Mission risk (M), Risk to Military Personnel (P), Risk of Collateral damage (C), Risk to Equipment (R), Risk to important buildings (B). In the other views (other Tabs) representing specific risk types, the right-mouse click on a cell of the Assignment risk matrix brings a popup menu that offers the detailed information of the risk: the corresponding Influence Diagram, or the Mission Decomposition Structure with the risk position within it (see Figure 5).

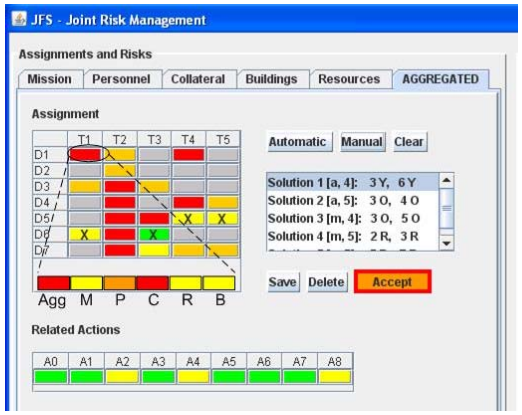

Figure 4 – Risk disaggregated by risk type

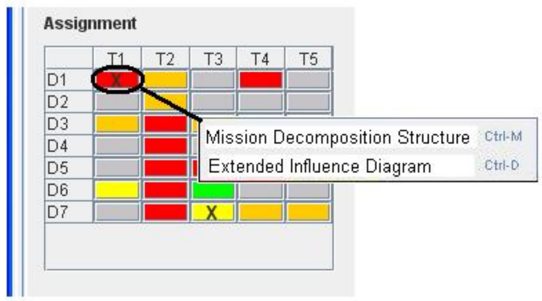

Figure 5 – Recovering corresponding MDS and EID

Aggregation of two types risks up the levels of the corresponding Mission Decomposition Structure are shown in Figure 6 and Figure 7. Figure 6 shows the risk to mission failure that has been aggregated using the Importance rule, while Figure 7 shows the risk to military personnel aggregated using the Max rule, so that higher commander will know if there is a risk at lower levels of the command/ mission structure. For the Importance Rule conversion between qualitative and quantitative representation of the risk levels is needed. The rules for conversion are presented in the lower part of Figure 6 (values relevant to conversion from quantitative to qualitative are on the left side of the graph showing qualitative risk levels, while the numbers relevant to the conversion from qualitative to quantitative is on the right side of the graph).

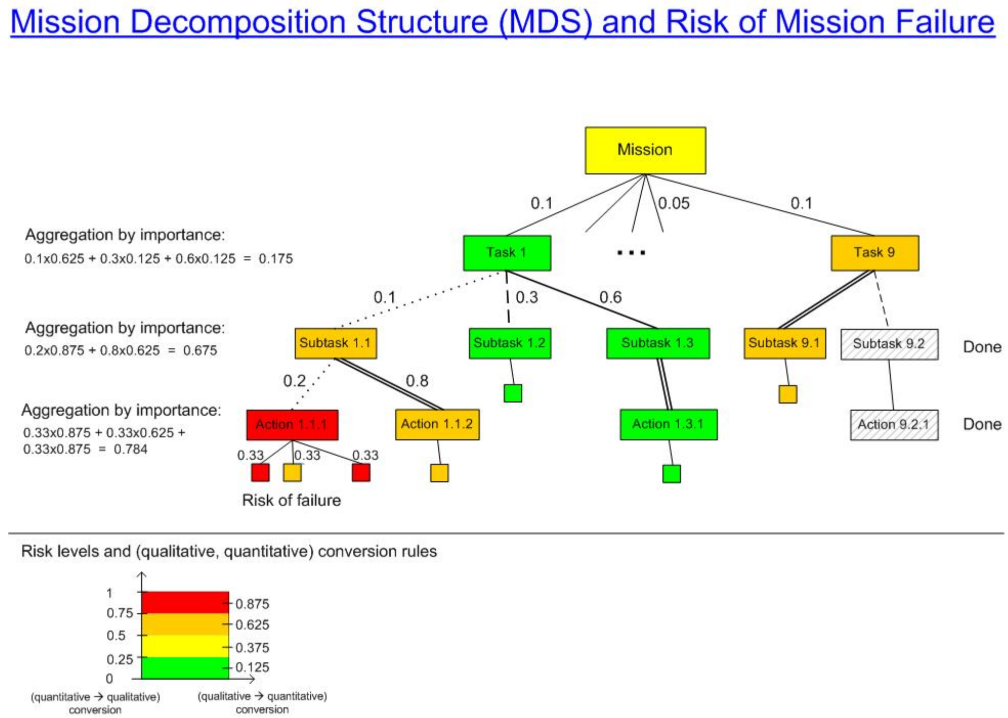

Figure 6 – Risk of Mission Failure assessed by risk aggregation through Mission Decomposition Structure

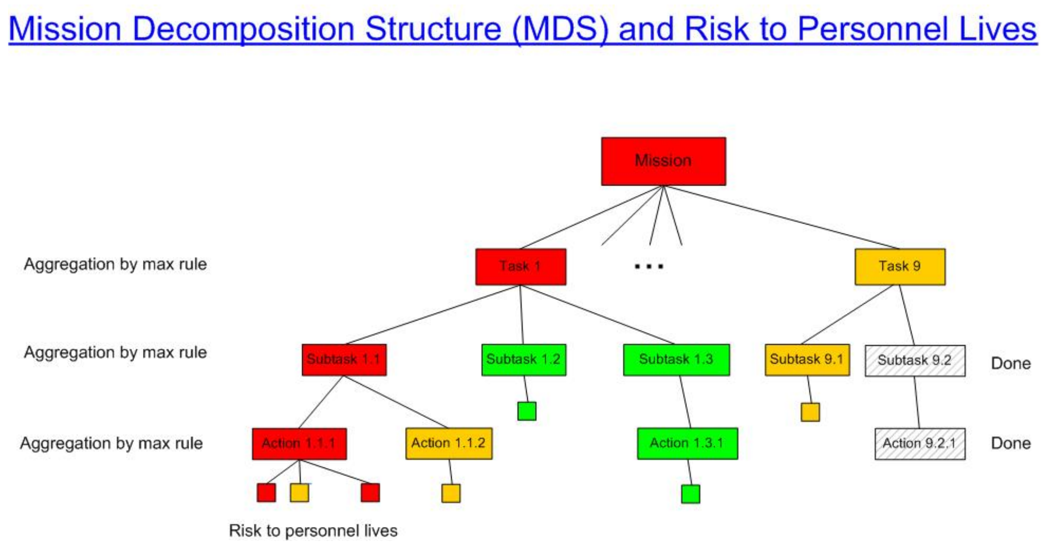

Figure 7 – Risk to Personnel Lives within a mission assessed by risk aggregation through Mission Decomposition Structure

An example of a Graphical User Interface encompassing all risk related information is shown in Figure 8. The upper left corner contains risk related information with respect to chosen delivery assets for the set of tasks. On the right of the Assignment table, there is a list of potential solutions to the decision problem of (delivery asset – task) assignments. Below are the risks of other related actions, and the lower portion of the left part of the screen shows the Gantt chart representing the actions in time. The upper right portion of the screen show summary of the risks by type, and the lower right portion of the screen shows the plan evolving over the areal map of the area of interest. As described in the previous paragraphs, the MDS and EID can be recovered for each of the risks on the left, as well as disaggregation of Aggregated Risk to risks of different types. The Screen Tabs can provide focus on only one risk type if decision maker is interested in particular related details.

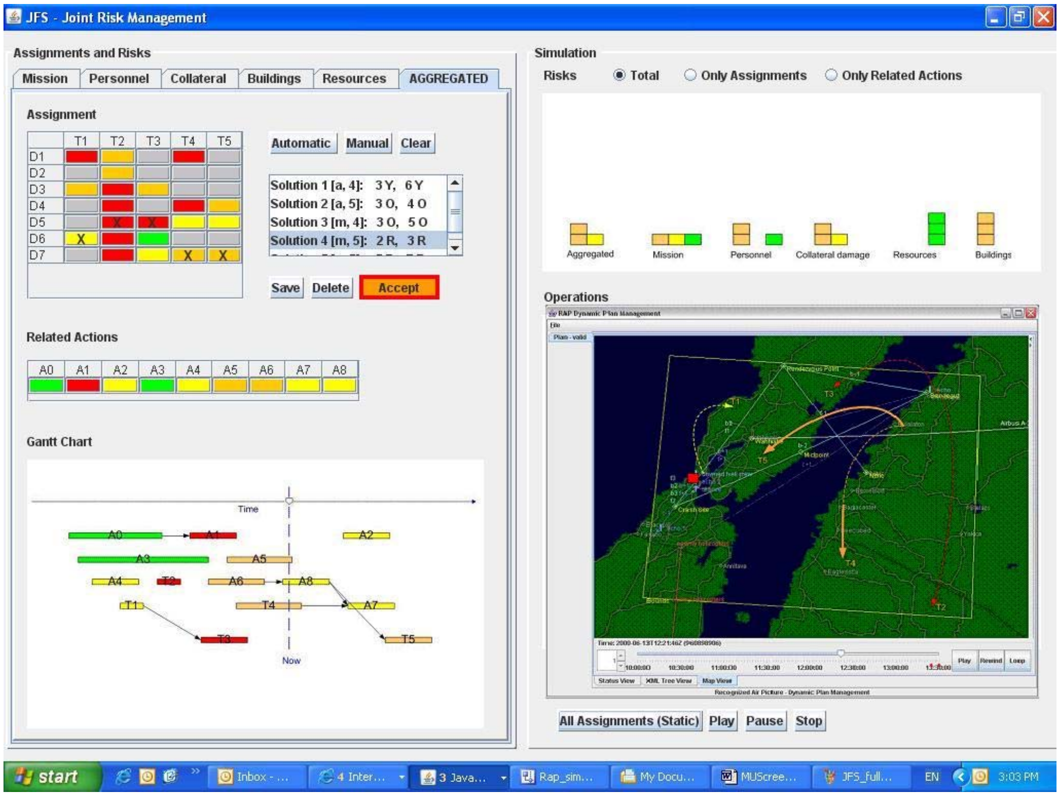

Figure 8 – A GUI screen-shot of a Resource and Risk Management System for Joint Fires Coordination

6 CONCLUSIONS

This paper proposes a risk aggregation method based on hierarchical decomposition of a mission. This aggregation methodology combines Extended Influence Diagram and Mission Decomposition Structure. This approach allows for static as well as dynamic risk monitoring and assessment. For individual assessments of risks, we used the Extended Influence Diagram which is a combination of Influence diagrams and Dempster-Shafer methodology.

This paper also presents a simplified joint fires coordination mission example involving multiple units to respond to a terrorist attack in an urban environment. This didactic example shows the importance of rigorous aggregation of risk information.

Future research directions may include developing a hierarchical framework that is a combination of the risk breakdown structure, the risk impact breakdown structure, and the mission decomposition structure. Related to the risk assessment, preliminary design of appropriate extended influence diagrams for each risk in a joint mission is needed. One could also consider multiple criteria aggregation frameworks for risk aggregation. Related to decision-support, possible is an automation of the (delivery asset, task) assignments with objective of minimizing risks.

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