A CONSTRAINT-BASED APPROACH FOR EARTHQUAKE CASUALTY MODELING IN MANUFACTURING SYSTEMS

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ABSTRACT

This research project uses a macro-systems approach to earthquake injury estimation and the integration of scenario consequences into an event tree analysis. This approach is based on the constraint satisfaction theory and its associated algorithms. We using this approach to model the effects of earthquakes on safety of manufacturing systems. More specifically, we provide the structure of a decision tree whereby the effects of a number of simultaneous variables can be traced in producing negative safety and health consequences, given the relevant system constraints. The shell uses symbolic reasoning or constraint propagation to show the results of each manipulation of constraints or trade-offs for five sets of variables: Primary Hazards, Secondary Hazards, Shaking Hazards, Behavioral Hazards, and Production Hazards.

INTRODUCTION

The recent earthquakes in Northridge, U.S.A and Kobe, Japan proved that even the most advanced communities in earthquake preparedness are still vulnerable to these large earthquakes. Recent estimates have been only useful in raising the awareness of the communities as to the devastating effects of these events. For instance, it was estimated that a day-time earthquake of magnitude 7.5 would result in up to $32 billion in shaking losses and an estimated 4,000 fatalities along the Newport fault (Litan, Krimgold, Clarkand and khadilkar, 1992). Another more alarming estimate was given by Shah (Science News, 1994) that a magnitude 7 tremor in the Los Angeles basin could result in $125-145 billion in damage and kill 2000 to 5000 people. However , like other earlier estimations, these casualty consequences of earthquakes have been based on assumptions and formulas that may not consider the full context of this large multi-variable problem domain. Moreover, these estimates do not give us a full picture of the interactive nature of the casualty-causing factors in a particular set of structures. For example, the guidelines offered under ATC-13 assumes deaths and injuries are primarily caused by structural failures. But, recent research suggests that some deaths and a significant percentage of injuries are caused by non-structural elements such as building contents.

Additionally, these non-structural elements and building contents appear to take on a more hazardous form in our today's industrial and manufacturing environments. In a strong earthquake in Japan (January 15, 1993, Kushiro-oki, R 7.8) only two persons were killed; one by a falling ceiling light in an office and the second by gas poisoning (EERI, 1993).

This research project uses a macro-systems approach to earthquake injury estimation and the integration of scenario consequences into an event tree analysis. This approach is based on the constraint satisfaction theory and its associated algorithms (see Mackworth, 1987 for survey of these algorithms; Dechter, 1987 for an application to truth-maintenance; Rit,1986 for a temporal event scheduling). The constraint satisfaction framework is a more natural way of interrelating a fairly large number of interactive system variables within a deductive tree structure or model. An earlier development from this model has been validated for an adaptive management information system in a high-technology manufacturing environment. We are now attempting to use this model (and its associated information system) to study the effects of earthquakes on safety of manufacturing systems. More specifically, we provide the structure of a decision tree whereby the effects of a number of simultaneous variables can be traced in producing negative health and safety consequences, given the relevant system constraints.

RESEARCH IMPORTANCE AND OBJECTIVE

Manufacturing systems are highly integrated work operations. For most organizations, the competition to achieve certain market share or even to stay in business depends on small incremental (continuous) improvements in work and organizational systems. Therefore, any interruption in the production operations may negatively impact the long-term profitability of the production system. After a serious catastrophe, BASF Corporation Director of Insurance stated, "Business interruption losses can be a major threat to a company and in the worst cases could lead to bankruptcy for even the biggest of companies." (Bean, 1994)

A major concern in today's manufacturing organizations is the integration of customer demand and supply into the strategic business objectives. Even if the damaged business can maintain a continued supply by virtue of partial operations, the customers may find it necessary to look for secondary sources of supply in case their now-damaged primary supplier fail. If supply is interrupted, these customers must go elsewhere immediately, and their orders may be difficult to regain. Generally speaking, the business losses due to the human infrastructure may have roots in the following categories:

- Loss of employees (injury, death) and their skills.
- Increase in unemployment compensation premiums and potentially expensive legal actions against the company.
- Increase in cost of training new and retraining the old employees who have been out of job for a period of time.
- Increase in production errors which result in overall production inefficiency.

Also, there may be up to three times more costs labeled as "hidden" or "indirect" costs which the current accounting systems are not able to track (Capettini, 1994).

In Southern California, operations managers are mostly concerned about the devastating effects of earthquakes on their business operations. Earthquake recovery planning has become an important component in many company policies for identifying essential needs, authority delegation and damage case scenario analysis (Lichterman, 1985). Our research is designed to provide a pre-earthquake qualitative damage and injury analysis tool for emergency and disaster managers. The initial development of this tool will be limited to providing qualitative estimates of employee injury and death in a manufacturing system.

THEORETICAL FRAMEWORK

Today's manufacturing organizations are faced with a challenge in their efforts to prepare for natural or man-made disasters. The cross-functionality of a large number of the variables affected by a disaster is complex and poses theoretical as well as computational challenges for manufacturing managers decision-making process.

Artificial Intelligence has found numerous applications in supporting decision-making in organizations, but few in managing the complex issues related to disaster impact assessment and emergency management. The problem of capturing and managing this complexity requires computational structures similar to process design in multi-layer dynamic system behavior. In this effort we are proposing to build upon a computational design framework which encompasses the design of human-related as well as other system components variables in a highly-integrated human-technology organizations (HITOP, see Gasser, et al, 1993). This framework is based upon a decision support system which helps managers to analyze changes in their current operations for adequacy of integration among technology, organization, and people issues, as well as to identify new design choices. A newer development of this shell called ACTION is designed for users to become change agents in manufacturing design decisions (Hulthage, 1994).

CONSTRAINT-BASED MODELING PROCESS

The earthquake injury evaluation problem is specified as a set of constraints to be satisfied (e.g. high-pressure steam generators must satisfy pressure relief mechanisms) and a set of objectives to be optimized (e.g. possibility of steam line ruptures after an earthquake). In this model, evaluation uses constraint propagation to generate values for important evaluation properties of a manufacturing operation captured by the ACTION shell. In this model, ACTION helps an evaluator to relax constraints for an overconstrained problem set and to add constraints to an underconstrained problem set. In such an evaluation procedure, the evaluator can add constraints, make choices based on preferences or to make arbitrary choices until all but one choice remains. The shell uses symbolic reasoning or constraint propagation to show the results of each manipulation of constraints or trade-offs between objectives. To simplify the process, each domain concept (e.g. variable) is associated with a set of constraints that have a subset of qualitative range of values (e.g. low, medium, high) that are deemed appropriate for that concept's definition. Therefore, any change in the constraints on one concept could constrain values on other concepts. This approach employs an algorithm that follows chains of dependencies in order to make all necessary updates introduced as a consequence of new constraints. This approach is different from ordinary constraint satisfaction algorithms in that constraints are changed monotonically toward narrower and narrower constraints, producing a linear complexity for tree our tree-shaped constraint network. If the tree contains any cycles, a supplementary algorithm will be used to manage the time and space limitations.

MODEL ARCHITECTURE FOR CASUALTY ESTIMATION

The current architecture represents a set of objectives (goals) to be optimized and a set of detailed, hierarchical constraints based on the theory mini-models, that describe how to optimize for these objectives. At this point in time, we are developing a detailed constraint model of the possibility of achieving one objective: minimizing employee injury and death. We have a large number of constraints, trade-offs, and value assignments for five sets of variables (concept domains) that form the theory mini-models. These five sets of variables are: Primary Hazards, Secondary Hazards, Shaking Hazards, Behavioral Hazards, and Production Hazards (Figure 1).

Mini-models define a constraint network in terms of domain concepts and their relations. The top (root) of each of these mini-models is an organizational objective (e.g. minimize production hazards or minimize primary structural collapse) and the bottom of each is determined by input data from theory or user constraints. As can be seen from Figure 1, our mini-models are approximately tree-shaped.

The earthquake casualty model in a manufacturing environment can be large and complex. To limit the size and complexity, the constraints within the mini-models are viewed as (a) constraint among variable values or arguments ("e.g." if earthquake resistance design is <inadequate>, then the severity of injuries is more than <minor>, (b) desired level of correlation between variable values ("e.g." if MMI is <large> and shaking duration is <larger>, then the shaking effect is <significant>), or (c) desired level of congruence (qualitative match) among variable values ("e.g." we place a check mark or a color code in a relational table containing variables and their associated values representing all the feasible combinations: red, green, and blue signify negative, positive, and neutral influences). Then this approach becomes one of searching through the possible value assignments to variables for acceptable, highly-evaluated process.

Each of the five domain specific problem space is further related to a number of variable sets, and so on (only the Production Hazard branch is explored in this paper). To show the preceding variable set relationships for the Production Hazards, four sets are presented on Figure 2. Factors which influence the work environment itself may include hazardous material dispersions, distribution of airborne particulates (e.g. dusts), release of substances with high temperatures, etc. Two factors are assigned to the ability of equipment to resist earthquakes: resistivity of large integrated machining centers (e.g. CNC) and smaller manufacturing equipment. Energy distribution systems are another source of occupational hazards which may involve maintenance quality of the system, appropriate design of natural gas systems, and design of electrical systems with respect to earthquake shaking disturbances. The fourth factor in this node is the shaking resistance of the material handling systems which may include programmed robots and associated tools, instability of conveying mechanisms, maintenance quality, and size and weight of objects being handled. Now, as expected, each one of these variables are further influenced by a number of other variables which comprise the entire tree-shaped model (not shown here).

A first version of the model has been developed using variables identified from earthquake casualty literature. A test version of the software is being simultaneously written to obtain preliminary computational requirements. The next step will be to collect data through an on-site examination of an industrial facility damaged by a recent earthquake. A generic questionnaire set has been developed to obtain detailed information on each model variable. The questionnaire is designed to produce response sets that match the variable set qualitative range of values (e.g. low, medium, high) which can be easily used as inputs to the shell. Also, the design of the questionnaire allows for responses by any employee who has knowledge about the operational facility before and after the earthquake. Further developments are subject to additional research funding.

CONCLUSION

The proposed model is designed to identify potential hazard areas and procedures during an earthquake as well as predicting casualties and potential capital losses due to equipment or structural damage to manufacturing systems.The system can also be used to aid the emergency managers, concerned with earthquake casualties, in pre-accident analysis and post accident investigation.

The impetus behind this development effort is the lack of casualty estimation software in work-related settings. Also, traditional earthquake loss estimation methodologies have mostly taken into account the physical damages from shaking forces. There is a need for methods that estimate the human casualties with reference to specific structural settings. A major advantage of this approach is that the system does not require quantitative data (e.g. variables, arguments, algorithms), exclusively. The other advantage of this system is its flexible mini-models which can be added or deleted throughout its validation process.

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BIOGRAPHY

Dr. Rahimi has a B.S. and an M.S. in Industrial Engineering from West Virginia University and a Ph.D. in Industrial Engineering and Operations Research (with specialization in Human Factors Engineering) from Virginia Polytechnic Institute and State University. He has had 10 years of teaching experience in system safety and ergonomics subjects. His research interests involve the safety aspects of production systems. He is on the Editorial Board of the *Journal of Safety Science* (formerly *Journal of Occupational Accidents*).

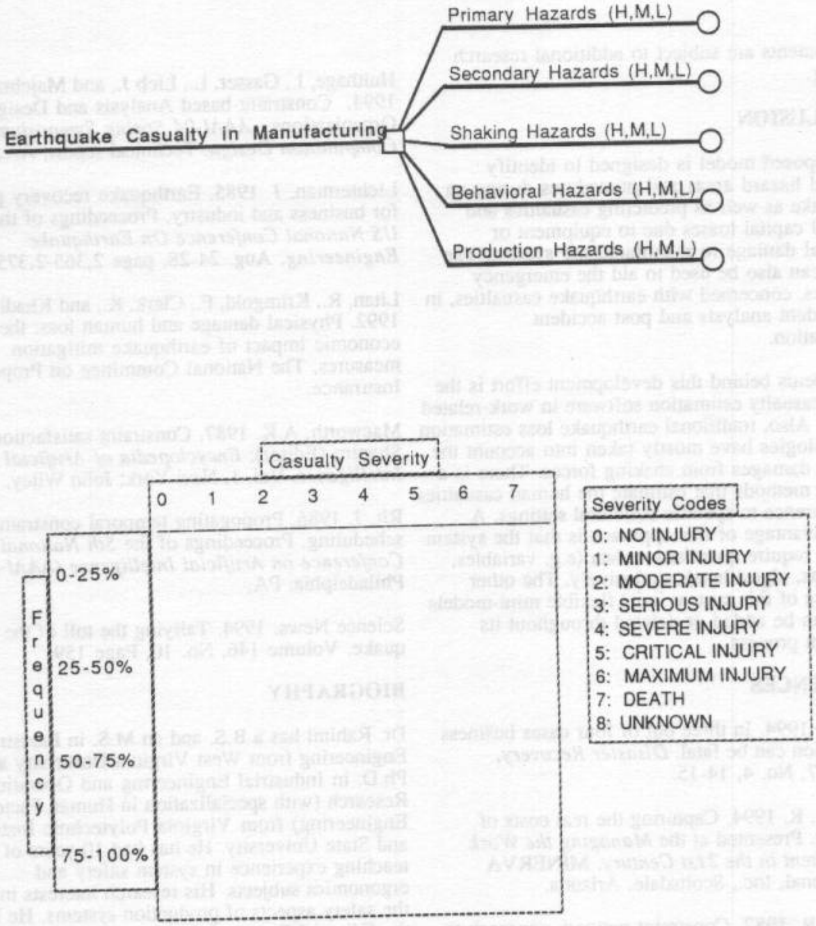

FIGURE 1. The first node for the constraint-based tree model incorporates five major hazards in a manufacturing system due to an earthquake. Each hazard is constrained (to the casualty consequence) by a two dimensional severity versus frequency table.

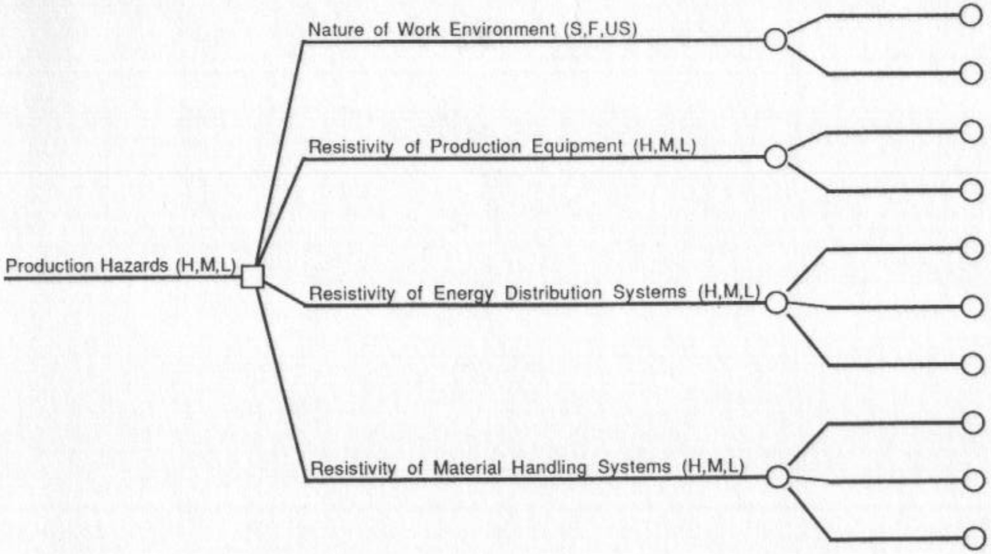

FIGURE 2. The Production Hazards node is expanded to include a number of variables in its domain. Each node expands to a number of other branches to contain all system variables identified as important in the model validation phase.