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EVIDENCE-BASED MODELS TO SUPPORT HUMANITARIAN OPERATIONS AND CRISIS MANAGEMENT

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Abstract: *The term humanitarian operation (HO) is a concept extracted from the need to perform supply chain operations in special, risky, and critical events. Understanding and implementing operations under such conditions is a strategic responsibility. Due to its importance, we design a framework for organizational learning from major incidents through root cause analysis The case studies contain a purely industrial disaster; Bhopal and a mixed industrial-natural disaster; Fukushima. An approach is proposed for organizational safety by incorporating techniques related to root cause analysis, by incorporating a hybrid of analytical tools in an innovative dynamic framework and applied to one case study. We also describe the benefits of using such hybrid of techniques. Moreover, we employ the analytic hierarchy process, which is applied to the second case study. We incorporate models to analyse data related to the two major disasters. The case studies in two organizations are then compared with respect to their causes and effects along with the models adopted to support HO& crisis management (CM). The main outcome of this work is demonstration of the use of hybrid modelling techniques to analyse disasters in terms of humanitarian operations and crisis management.*

Key words*: Operations management, analytic hierarchy process, humanitarian operations management, organizational learning, fault tree analysis.*

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1. Introduction

The main theme of the paper is to propose a set of innovative models in a hybrid modelling methodology. In doing so, we propose an integration of tools in a dynamic framework and demonstrate the benefits of such analysis through applying these techniques to case studies. Although different models are applied to the two case studies, a comparison is then performed between the two cases in terms of their features and type of analysis performed.

Studies related to humanitarian operations (HO) and crisis management (CM) have identified the lack of adequate empirical data as a common challenge found in the majority of the research work (Starr & Van Wassenhove, 2014). The final link in the humanitarian supply chain, that is, contact with beneficiaries of HO, was addressed by Balcik and Ak (2014) and again the data challenge was highlighted in this work. Procurement issues in HO were also addressed (Eftekhar et al., 2014). There were also other lines of investigation, including one related to the incorporation of IT-enabled multi-agency HO to enhance mutual benefits in refugee camps (Ergun et al., 2014). Differentiation of goals and objectives in HO (Gralla et al., 2014), and the concept of trading off between two conflicting objectives of equity towards beneficiaries versus cost-efficiency in HO, were also investigated (McCoy & Lee, 2014).

HO and CM may vary from one disaster to another depending on the type and scale of the disasters. A disaster may be classified with respect to its cause and level of controllability from a purely natural disaster, almost out of causal control, up to a purely man-made disaster with high controllability. The scale could also reflect the effects, ranging from a small local disaster with minor impacts and losses to a large national/international scale with major impacts and casualties. HO&CM could aid both categories with respect to various causes and effects. It has been noted that experience gained from disaster management assists the stakeholders involved to take decisions and promotes the effective establishment of response (Gupta et al., 2016).

In the structuring process of a decision problem a vague situation is transformed into a structured problem with a set of well-defined elements, relations and operations to represent the informing factors, including the views, opinions and values of multiple decision-makers (Ishizaka & Labib, 2009). HO&CM problem structuring does not necessarily lead to an optimal solution, but it helps in finding critical elements. For example, structuring HO&CM responses to nuclear incidents and social impacts needs a systematic approach that considers various challenges and issues attached to nuclear incidents. A system index (Heng & Tao, 2014) was introduced to help policymakers predict the impacts of nuclear accidents in order to reduce risks to public safety. They used the multiple-attribute decision-making method linked to the Analytic Hierarchy Process (AHP) to indicate indices such as public opinion and emergency resources and their weights along with a set of plans against nuclear accidents (alternatives), such as: taking iodine, shelter and evacuation, were set. The factors contributing to disasters and their impacts with the challenges and constraints for HO&CM have also been studied based on experts' perceptions. For example, challenges such as communication in chemical, biological, radiological and nuclear (CBRN) disasters and finding the best practices for structuring tasks and principles with citizens were studied through a questionnaire survey from the perspective of experts (Ruggiero & Vos, 2015). Communication across HO&CM actors and beneficiaries, including the public, is a key challenge in the pre-disaster stage of operational preparation/prevention while considering ethical issues. The lack of basic knowledge about hazardous materials such as radiation and viruses will increase the impacts and potential risks of disasters. One of the best communicating practices in the pre-/post-disaster stage would be using online communication and social media monitoring (assuming electricity is available) with sufficient trained staff and support tools and solutions taking into consideration ethical issues (Ruggiero & Vos, 2014). For instance, Erlandsson et al. (2017) analysed the reasons why donors make charitable decisions towards victims in different conditions. Chávez et al. (2017) used Bayesian methods in time preference research in intertemporal decision-making in risky choices to estimate parameters in delay discounting to avoid potential abuse. Yazdani et al. (2019) proposed selective OR methods incorporating a fuzzy ANP model and failure mode and effect analysis (FMEA) for risk evaluation of several construction projects related to water reservoirs/dams. Various internal, external and technical factors were evaluated to acquire the riskiest projects, which would necessitate exceptional attention being given to the dams from pre-construction to post-construction and during their usage.

A literature survey undertaken by Altay and Green (2006) of the papers published to address HO&CM aspects using operational research (OR) methods indicates differentiation of the OR tools applied for modelling various HO&CM problems at pre-/post-disaster stages over a decade. Although numerous OR methods, such as mathematical programming, decision theory, queuing theory, heuristic methods, probability theory and statistics, and simulations have been used in the area of HO&CM and supply chain management, there is still a lack of adequate applications of OR models to highlight critical success/failure factors influencing the performance of HO&CM efforts. According to Galindo and Batta (2013) no major changes or developments in the field of OR application in HO&CM have appeared since the work of Altay and Green (2006). Solid research is still required to re-establish the well-intended perception with a system view reflecting all the influencing factors (Starr & Van Wassenhove, 2014).

The post-disaster analysis must include retrospective analysis via root cause analysis (to learn from failures/successes) followed by a disaster and prospective analysis to find safety measures and plan HO for preparation for/presentation of a new disaster (Cacciabue & Vella, 2010). This paper focuses on post-disaster analysis, i.e. retrospective and prospective analysis, while considering in-disaster real-time incidents and immediate rescue operations.

This paper provides a selection of (hybrid) OR models that have been applied to analyse two disaster case studies. The rationale behind the choice of case studies and hybrid tools is provided later on where the two cases are compared using several theoretical lenses. Hence, the core research question related to why a comparison of the two case studies is needed is answered in Table 1 in the paper, where the analysis in terms of cause and effect, recovery response, and retrospective and prospective analysis are compared.

The main research motivation is to investigate selected two major disasters; one man-made and the other combined natural and made-made, and then a set of propose innovative hybrid analytical methods are applied as way of demonstration of their utility.

The structure of the paper is as follows. After this introduction and review of the study background, Section 2 outlines the research methodology with the rationale behind the choice of case studies. In Section 3, we have two subsections. Section 3.1 examines the data related to the case study of the Bhopal disaster and the developed models for analysis. Section 3.2 proposes the data related to the case study of the

Fukushima disaster and the developed models for analysis, which incorporate a multiple-criteria decision analysis (MCDA) approach using the analytic hierarchy process (AHP) technique. Section 4 provides a framework for learning from disasters through comparative analysis of the disasters within the HO&CM context. We outline the main conclusions of the paper in Section 5.

2. Research methodology

The aim of the research is to explore HO&CM influencing elements and structure them through suitable OR models for further insight. The paper intends to build knowledge from learning from failures concerning HO&CM that occurred in two major disasters, which have been selected due to the suitability of the available data for using the analytical models. The research consists of three stages: 1) study of major disasters; 2) selecting suitable disasters for the study based on the availability of the data (volume and type); and 3) selecting suitable analytical methods with respect to HO&CM. Accordingly, FTA, RBD, MCS and AHP are used to structure the disasters' HO&CM aspects due to exploring elements concerning causes and effects, the relationship/impact of each element with/on the others and the multicriteria nature of HO&CM critical factors while considering alternative strategies for tackling a disaster.

The paper promotes the concept of 'hybrid modelling' focused on 'HO&CM cases'. This is in line with Shanthikumar and Sargent (1983) who classified hybrid approaches into: either a 'hybrid model' in the form of procedures, or 'hybrid modelling' ie independent types of models. In this paper, we will focus on the hybrid modelling, where different modelling approaches (FTA, RBD and MCS from the reliability analysis domain) and AHP (from multiple-criteria decision analysis) are utilized independently in two cases to study the single theme of HO&CM. This is in contrast to Stephen and Labib (2018), who developed a 'hybrid model' approach to one case study where an output of one model acted as an input to the subsequent model. Hence, in this paper we demonstrate that the use of independent models, 'hybrid modelling', can help us to better understand a certain phenomenon.

The paper is an attempt to match the proposed models with possible integration that can connect tangible and intangible aspects of HO&CM for a disaster. The authors initially studied a number of disasters for evaluation and analysis prior to selecting the proposed models and decided to study the two disasters due to data availability, the homogeneity of the HO&CM aspects with the proposed models and the limit on the length of the paper.

The paper contributes to finding suitable analytical models according to ease of use of the data in terms of type, scope and volume. The proposed models are shown in an integrated structure, which can enhance the addressing of specific challenges, feasibilities and barriers from different perspectives.

3. The case studies

3.1. The case of the bhopal disaster

The case of Bhopal was previously studied by Labib and Champaneri (2012) in terms of the provision of root cause analysis; by Ishizaka and Labib (2014) through the proposal of a new logical gate for the analysis; by Labib (2014) where generic lessons were extracted; and by Labib (2015) where it was compared to the Fukushima disaster and the unlearning phenomenon was investigated. In this section, we extend the analysis to address the humanitarian operations and crisis management aspects of the disaster. We also provide evidence of the involvement of stakeholders in the investigation and the use of OR techniques. In our investigation, it was noticed that cut set analysis provides more insight than just using fault tree analysis. This is further enhanced by the systems approach to technical and organizational analysis.

3.1.1. Background

The following text in this section is a summary adapted from the literature, and more details can be found in Labib (2015). The incident occurred at midnight on December 2, 1984 when the tank number 610 (which is one of existing three tanks) containing a lethal toxic gas called methyl isocyanate (MIC), was contaminated with water causing exothermal chemical reaction phenomena, which leaked into the atmosphere. The investigation found out that there was two types of failures; first, that the VGS was not sufficiently well designed due to its inability to handle a leak of that magnitude, and second, and to make matters even worse, it was under maintenance during the incident and hence not available at the time of the incident. In other words there were elements of both bad design and bad operation and maintenance (Labib, 2015; Chouhan, 2005).

3.1.2. Modelling the HO&CM Aspects of Bhopal using FTA, RBD and MCS

In his account of the disaster, Chouhan (2005), who had first-hand experience of the disaster as he was one of the employees of Union Carbide at Bhopal and produced a comprehensive analysis of Bhopal, stated that there was no evacuation plan for the neighboring area/communities (Chouhan, 2005)

The first author conducted a series of workshops. This was attended by experts in the chemical process industry. Among the participants, there was an Indian engineer who was originally from Bhopal and was quite young when it happened. It was interesting to see his account of the accident and especially the fact that several of his young relatives were born suffering from disabilities, which demonstrates the extent of the disaster and the effects not just on the direct casualties but also on the next generation. The FTA model in Figure 1 shows a revised and extended model provided by the investigation of one of the groups (Labib, 2015). However, in this paper we extend the analysis of this case study by developing a systems dynamics approach to analyse failures.

3.1.3. Fault Tree Analysis (FTA)

A fault tree is a structured method for identification of causal factors and the logical relationships among them. The undesirable event is located at TOP of the hierarchical model and the different causes failures constitute the basic events further down in the tree. The causes of the TOP event are 'connected' through logic gates such as AND gates (all inputs/causes needed for the above failure to occur) and OR gates (one of the inputs/causes are needed for the above failure to occur). The authors built a fault tree analysis (FTA) model as shown in Figure 1, which was then mapped into a reliability block diagram (RBD) as shown in Figure 2, and then a cut set analysis was performed on the derived RBD model in order to assess vulnerability of the system, by analyzing combinations of scenarios that can cause a complete failure of eh while system. The rationale behind the logic expression for the top event of Bhopal and how his derived can be explained as follows. A major accident in any process industry can be attributed to either due to lack of design integrity or lack of good operation and maintenance. In other words, problems originate from either bad design or bad use. One can also include a third factor which relates towards the attitude towards safety. Hence in our proposed FTA model of Bhopal, we selected the major causal factors to be attributed to poor design, lack of safety and poor maintenance. The rationale behind the incorporation of a top AND gate is that all three factors contributed simultaneously to the realization of the top event of Bhopal disaster (BD).

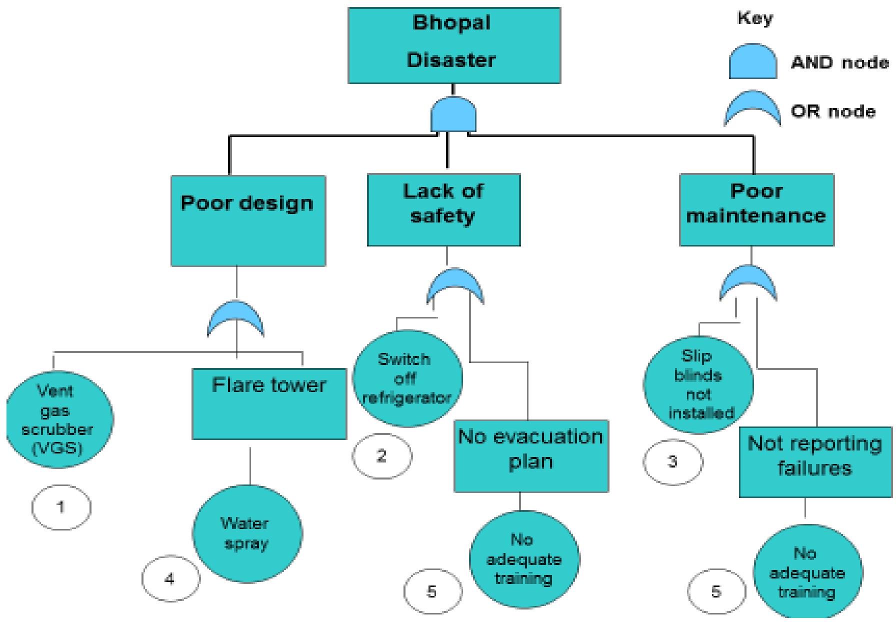


Figure 1. The developed FTA model for the Bhopal disaster

Note that with respect to the idempotent laws (x.x = x and x + x = x), they remove repeated events within cut sets, and repeated cut sets (Sinnamon & Andrews, 1997). Within the law of absorption (x + x.y = x) removes non-minimal cut sets since x.y is redundant. Thus, the logic expression for the top event Bhopal Disaster (BD) derived by Labib (2015):

BD = (1 + 4).(2 + 5).(3 + 5)

BD = (1 + 4).{2.3 + 5.3 + 2.5 + 5.5}

BD = (1 + 4).{2.3 + 5.3 + 2.5 + 5} [Applying idempotent law: x.x = x]

BD = (1 + 4).{2.3 + 5.3 + 5} [Applying absorption law: x + x.y = x]

BD = (1 + 4).{2.3 + 5} [Applying absorption law: x + x.y = x]

This is the simplest possible and can be used to redraw an equivalent fault tree.

BD = (1 + 4).{2.3 + 5}

BD = {1.2.3 + 2.3.4 + 1.5 + 4.5}

Therefore, minimal cut sets are: 1.2.3; 2.3.4; 1.5; 4.5. Note that the minimum number of boxes are 1.5 and 5.5, where 5 is common in both. Also note that 5 is equivalent to 'No adequate training'.

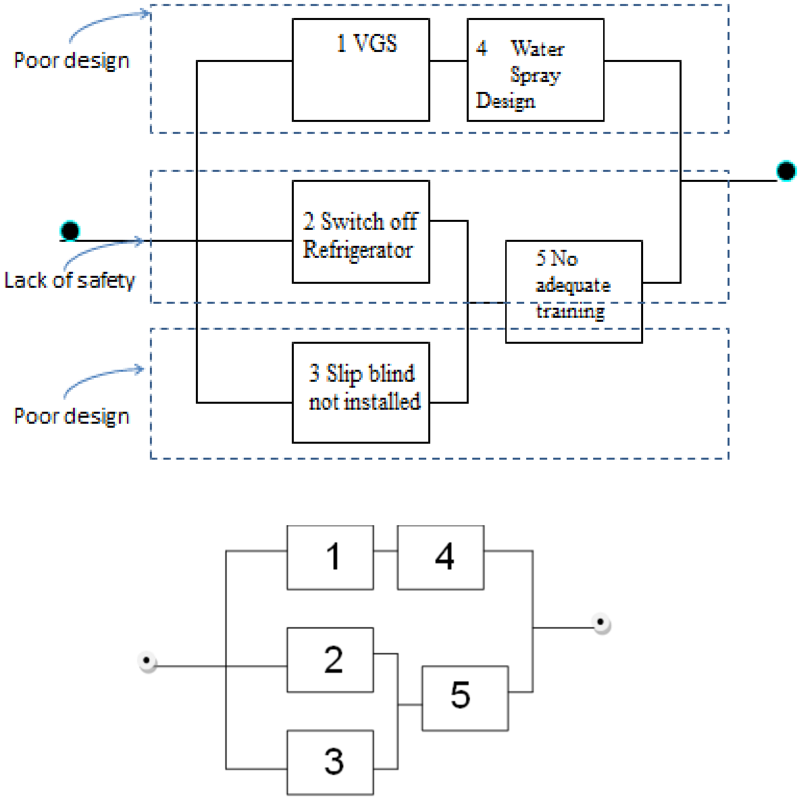


Figure 2. The equivalent RBD of Bhopal with/without description of boxes

To appreciate the benefit of using an RBD, the following scenario was provided by Labib (2014): Given a limited amount of budget for improvement, the scenario of 'No adequate training' is crucial (a root cause) of the RBD system using minimum cut set analysis. Available literature also verifies this argument. See the work of Chouhan (2005), who was a technical eyewitness of the incident and in his account, there was major cut back in spending on training across the plant prior to the disaster. This shows the ability of such analysis to capture and extract implicit knowledge. Also, in terms of HO, there is evidence, as reported by Leveson (2004), that the emergency squad staff at Bhopal were not sufficiently qualified and skilled to control such a disaster. This observation coincides with the root cause analysis we carried out that shows the significance of the effect of a lack of training on this disaster.

3.1.4. A systems approach to technical and organizational safety

In this section, we extend the analysis of Bhopal to a variation of a systems dynamics rather than a reliability approach. Such an approach has its advocates, including Leveson (2004), Hollnagel (2004) and Woods and Cook (2002). A systems approach can be characterized by three features, according to Leveson et al. (2009): “(1) top-down systems thinking that recognizes safety as an emergent system property rather than a bottom-up summation of reliable components and actions; (2) focus on the integrated sociotechnical system as a whole and the relationships between the technical, organizational and social aspects; and (3) focus on providing ways to model, analyze and design specific organizational safety structures rather than trying to specify general principles that apply to all organizations. The FTA and RBD of the Bhopal disaster are shown in Figures 1 and 2, respectively, and can be represented as a control system as shown in Figure 3 in the form of controlling the water level in a storage tank, which is a similar model to that provided by Aven and Aven (1992). The dynamic modelling here is based on a hydraulic system of a tank that stores an amount of fluid with valves and sensors (limit switches) controlling the flow.

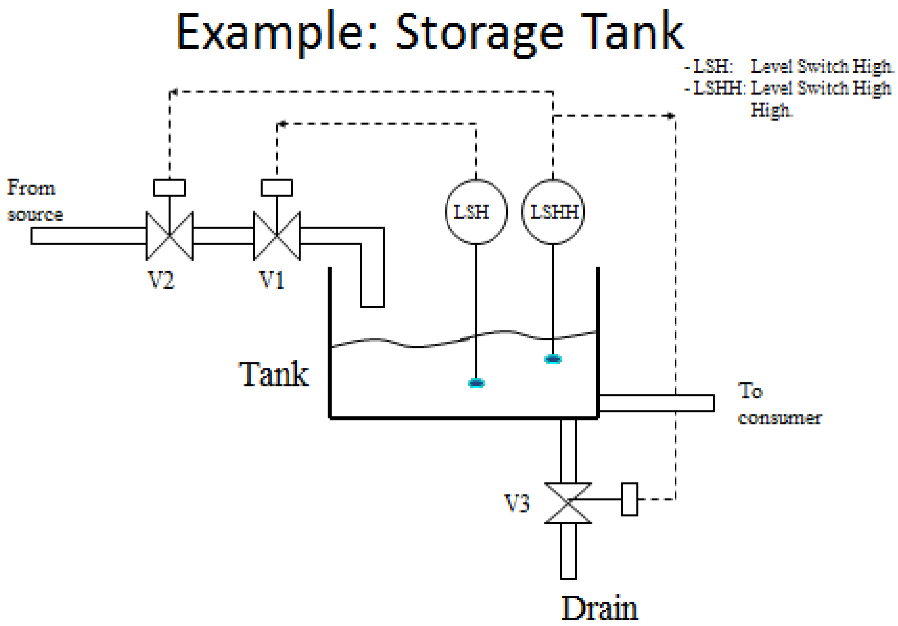


Figure 3. Representing the FTA of the Bhopal disaster as a storage tank system

Note that both the FTA and the RBD models of the storage tank example are shown below in Figure 4. Note that from the RBD, one can extract some useful lessons for prevention. For example, if one is given resources to spend on prevention, the most vulnerable box according to the RBD would be box number 5 as its failure affects two boxes (2 and 3), compared to any other box whose failure will only affect less than two boxes. Now, box 5 turns out to be the LSHH signal, according to the FTA model. As an outcome of going back to the tank illustration in Figure 3, one can accordingly come up with recommendations such as initiating more preventative maintenance checks on the LSHH, or even redesigning the tank to separate the signal into two different signals. Another line of thinking concerns minimum cut sets (MCS), which can be done either algebraically as shown above or simply by imagining having a pair of scissors that can cut through the circuit of the RBD model. Accordingly, cutting through just two boxes, say 4 and 5, will cause the complete failure of overfilling the tank to occur. Boxes 4 and 5 turn out to be related to the two signals of the LSH and the LSHH, according to the FTA model. Consequently, if one needs to prevent such a failure at all costs then perhaps, we need to rely on two different electrical power stations to supply the tank with electricity instead of just relying on one source of electrical power. All these analyses demonstrate the power of modelling FTA followed by an RBD followed by MCS. Therefore, the tank storage example can be considered a simulation, or a mental model, of a control system that represents Bhopal as shown in Figure 5.

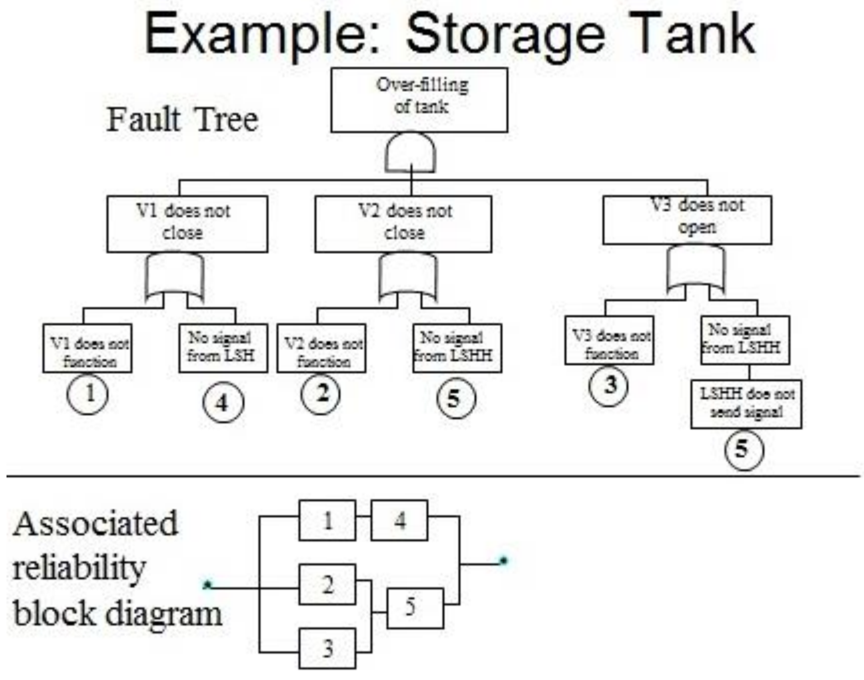


Figure 4. The equivalent FTA and RBD models for the storage tank problem

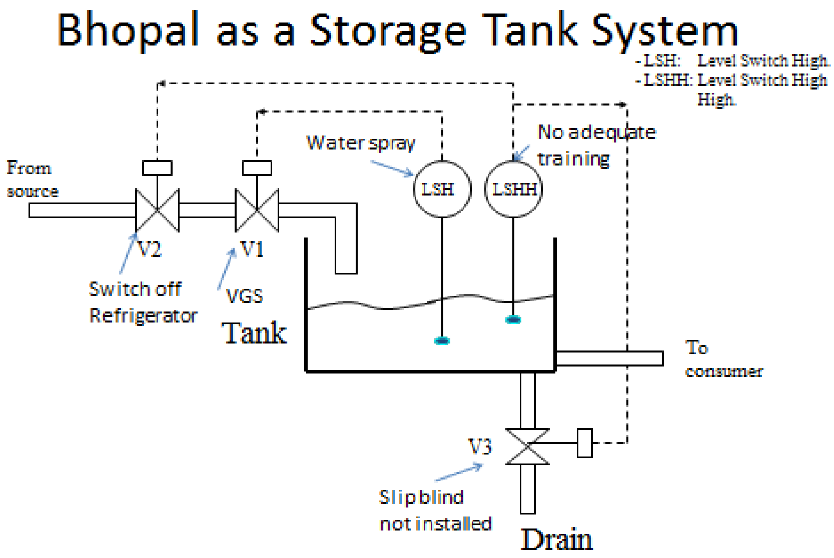


Figure 5. Bhopal as a control system

Please note that in the reliability block diagram (RBD), actions to be taken to increase reliability are not only related to the logical structure of the RBD (i.e. the connections among blocks) but also to the value of the reliability of each block. However, since reliability figures, especially if they relate to qualitative assessments as in the case of a failure such as Bhopal, are difficult to measure unless this is done in experimental conditions or if historical data are available, we assume that all blocks are equally weighted. Hence, the important factor becomes related to the nature of the configuration of how the blocks are linked to each other, where a series structure implies a weak link as compared to a parallel structure that implies a strong connection, such as in the case of redundancy.

In order to understand this mechanism as a mental map, we have three main subsystems, or control systems, as illustrated in Figure 6, which are attributed to design control and safety. The first control loop of poor design contains the VGS and water spray, whereas the second control loop of a lack of safety contains switching off the refrigerator and no adequate training. Finally, the third control loop of poor maintenance contains the issue of slip blind not installed and no adequate training. The three control loops are highlighted as dotted circles in Figure 6.

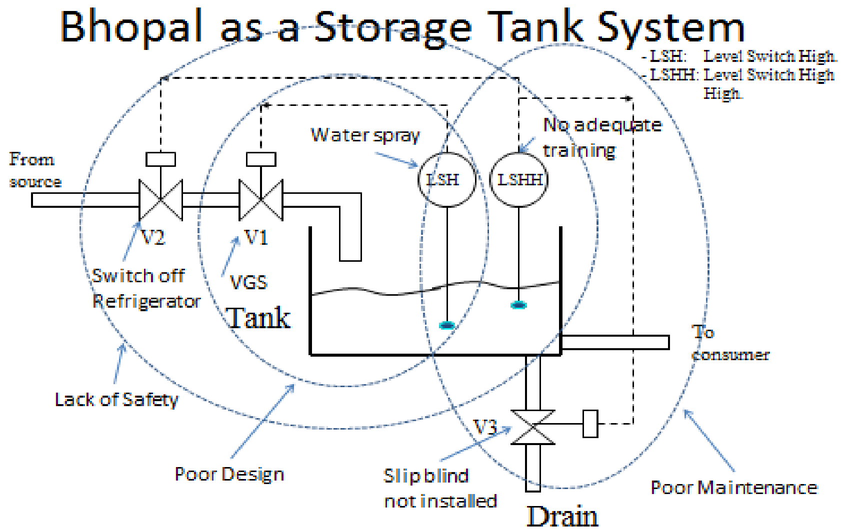


Figure 6. Bhopal as a control mechanism

Notice that in Figure 2, the RBD of the tank is replaced by Bhopal's equivalent system derived from FTA. Such a system approach enriches our understanding of the fundamental problems that caused the disaster as well as acting as a mental model, so that when deterioration in any of the three control systems is realized, an action can be triggered to respond. Such an approach can be considered a variation of systems dynamics, but not exactly the same. It also shows that by using such a dynamic system one is able to capture sociotechnical aspects of a disaster. The reasons and benefits for the selection of these hybrid techniques are illustrated in Figure 7 below. The use of FTA facilitates problem structuring in terms of modelling the causal factors and their relationships via the use of the logic gates (AND and OR gates). These relationships are then fed into the RBD, which translates the logic gates into series configurations (for OR gates) and parallel configurations (for AND gates). Such configuration provides the decision maker with an initial overall view about vulnerabilities in the whole system. Such vulnerability analysis is then further analyzed using the MCS analysis, where a sensitivity (what if) analysis is carried out to examine various possible combinations of failures (scenarios). Such sensitivity analysis can inform the decision maker about safety barriers in terms of either their effectiveness or need for new ones. Finally, the use of SDA provides a higher-level understanding of how each of the factors affect the performance of the whole system. In such dynamic analysis one is able to simulate factors which tend to be qualitative in nature and hence ideal for understanding socio technical aspects of the disaster.

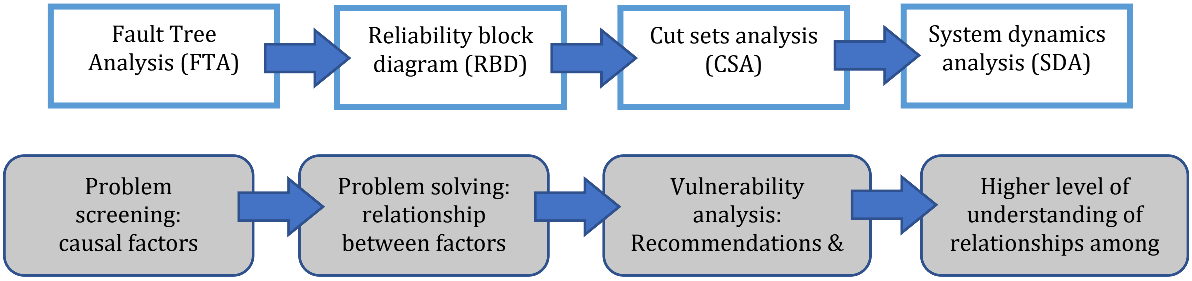


Figure 7. Benefits of the hybrid framework

3.2. The case of the FUKUSHIMA nuclear power plant disaster

Fukushima is considered, together with Chernobyl, the worst disaster to have occurred in the nuclear power industry. The case of Fukushima has previously been studied (Labib, 2014) and extended (Labib & Harris, 2015; Labib, 2015). In this section, we extend the analysis to address the humanitarian operations and crisis management aspects of the disaster. We also provide evidence in the form of investigation reports recounting observed incidents with real and reliable information. We also describe the use of OR techniques carried out for such an investigation.

The first author organized a workshop to investigate the Fukushima disaster. The participants were from several industries including oil and gas, electric power and nuclear power generation. The workshop was part of a masters-class related to learning from failures.

3.2.1. Background of the Disaster

The disaster is fully described in Labib (2014). It is expected that the reactor will take about 50–60 years to be decommissioned, i.e. for the plant to be accessed and cleared of any radioactive material.

3.2.2. HO&CM Aspects of Fukushima

Due to the earthquake and the tsunami, the power was lost around Fukushima. The rescue squad and the operators were working in very harsh conditions, trying to cope with three simultaneous disasters: the earthquake, the tsunami and the nuclear meltdown. Many of them were trying to resolve the situation at the nuclear plant while they had just lost many of their family members as a consequence of the earthquake linked to the tsunami. In addition, with the lack of electrical power, the operators could not access the gauges in the control room to assess the condition of the reactors. They sometimes had to dismantle car batteries to give them just enough power to glance at the indicators in the control room to discover the reactor’s condition.

The disaster is considered a classic example of double jeopardy, and reflects the effects of a multi-hazard combination of an earthquake and a tsunami on the infrastructure system. It is also considered to be a ‘beyond design’ phenomenon, in which safety factors were not taken into account during the initial design stages, which in turn affected the response to the disaster. They are suffering from psychological agony due to the fear of radiation exposure, separation from their family, separation from their community, disruption of communities, loss of work, uncertainty about the future, and so on'. The accident has not only deprived people of their homes and lives but also destroyed their communities and caused them to feel the loss of personal pride and dignity. Activities such as decontamination of houses, rain gutters, gardens and borders of woods are expected to take place after agreeing with the residents on the methods of decontamination of their houses and gardens and the place for temporary storage of decontamination waste to be generated as a result. It is expected that the storage volume will range between 15 and 28 million square metres. Moreover, the economic impact of the disaster at Fukushima is enormous as agricultural and fishery businesses are still banned in the neighbourhood of Fukushima Daiichi. The sales of tourism within the region have been reduced by 90%. The shutdown of nuclear power plants has caused a rise in electricity prices, and a 26% increase in $CO2$ emissions in the electricity generation sector (National Academies of Sciences, Engineering, and Medicine, 2016).

Fukushima had a less severe impact than Chernobyl in terms of health-related radiological consequences (National Academies of Sciences, Engineering and Medicine, 2016). The Fukushima disaster poses an interesting challenge with respect to evacuation efforts (National Academies of Sciences, Engineering and Medicine, 2016). As mentioned before, a 20 km radius evacuation zone determined by the Japanese authorities is considered by many to be quite adequate. Questions were rightly posed by the Japanese community: Does the American government know something that we don't? This incident prompts the question "What is the appropriate role of foreign authorities in providing recommendations to its travelling or relocated citizens in a nuclear emergency?"

3.2.3. Sources of Empirical Evidence

Various accident investigation teams published their judgment on the causes of the accident and lessons learned, including Aoki and Rothwell (2013), who analysed the key related reports. Two apparent schools of thought exist. One school of thought held by TEPCO (the company in charge of Fukushima) argues that the Fukushima catastrophe was an unavoidable outcome of a natural disaster as it was "beyond the conceivable hypothetical possibilities" (soteigai in Japanese), which is a view previously held by those who believe in normal accident theory (NAT), a term coined by Perrow (1984) that refers to accidents that are so complex by nature that they cannot be foreseen or stopped.

A second school of thought argues that there was regulatory oversight and inadequate management and emergency response that allowed the accident to unfold as it did. A particularly strong message came from Dr Kurokawa, the Chairman of the NAIIC, in his report: "[O]ur report catalogues a multitude of errors and wilful negligence that left the Fukushima plant unprepared for the events of March 11, 2011. What this report cannot fully convey is the mindset that supported the negligence behind this disaster. What must be admitted – very painfully – is that this was a disaster 'Made in Japan'. Its fundamental causes are to be found in the ingrained conventions of Japanese culture: our reflexive obedience, our reluctance to question authority, our devotion to 'sticking with the programme', our groupism and our insularity" (Kurokawa, 2012). The nuclear regulators lacked the knowledge and the responsibility to secure nuclear power safety. The independence of the nuclear watchdog from the ministries and the operators caused the regulatory state, where the industry had a great influence over the regulator.

The investigation of a nuclear accident's impact generally concentrates on the technical tangible elements limited to the disaster region. However, the social intangible impacts of such disasters are rarely studied (Heng & Tao, 2014; Lindell & Perry, 1990). In order to avoid social fear and disorder, macro-analysis of social impacts is crucial and needs to be appropriately studied (Slovic, 2012).

A holistic analytical method using a system index can be employed to analyse influencing factors concerned with nuclear disaster scenarios and help policymakers to foresee the possible outcomes in order to avoid (or reduce) threats to public safety (Heng & Tao, 2014). Since the Fukushima disaster, the debate about the safety of the nuclear industry has been highlighted, particularly in Japan, the U.S. and several European countries. In Japan, the initiative for embracing nuclear energy as the main source is called the 'nuclear village' (genpatsu mura). There are many debates in the press about the viability of this initiative.

3.2.4. OR Models of the Fukushima Disaster Based on the AHP

The AHP was used to support decision-making in terms of selecting the best strategy for of energy based on multiple criteria, in order for a country such as Japan to decide in the aftermath of the nuclear disaster. The AHP was chosen due to its ability to deal with both qualitative and quantitative measures, its ability to model a hierarchical structure as a mental model, its ability to provide feedback on the consistency of judgments to the decision-maker and its ability to provide sensitivity (what if) analysis. For information about the AHP, the reader is advised to consult with Saaty (1980), Ishizaka and Labib (2011), Abdi and Labib (2011), Muhammad et al. (2021) and Alosta et al. (2021).

3.3. The nuclear safety debate and the humanitarian view

Inspection of the serious accident at Fukushima directs us back to the basic question: 'What went wrong?'

The humanitarian views of the nuclear authorities usually vary as they might consider the serious accident as offering an opportunity to restrengthen nuclear power, instead of a justification for signaling the lesson that nuclear power is seen as a threat to the public and should be scrapped. The consensus at the World Nuclear Fuel Cycle 2011 Conference was in favor of this idea because nuclear energy has been providing utility power globally for a long time, despite the accident at Fukushima. This statement was derived from experts' knowledge with minimum application of the decision support tools available at the time. There are two conflicting views regarding Japan's nuclear power and accordingly two alternative decisions can be derived as follows:

Option 1 – Use alternative sources such as Green Energy instead of Nuclear: This is mainly supported by the environmental agencies and the humanitarian organizations.

Option 2 – Keep the Status Quo but improve current design of Nuclear Power Stations: This comes from a common opinion derived from nuclear industry professionals.

Option 3 – No Change: In other words, keep the status quo.

3.4. Application of MCDA

The economy criteria refer to economic and financial measures such as cost and value for money. The image criterion is related to the authorities' opinions. The feasibility criterion refers to technical feasibility. The AHP hierarchy is developed and illustrated in Figure 8.

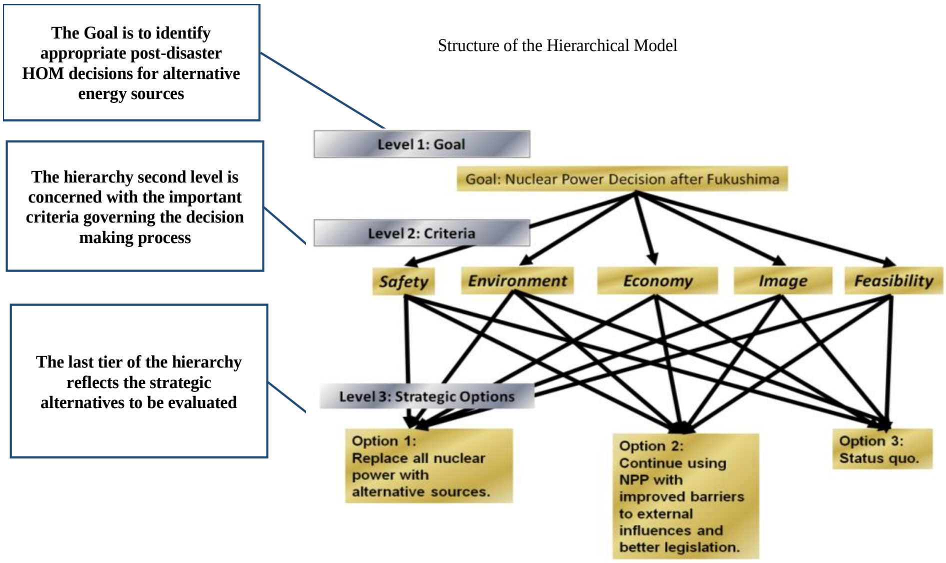
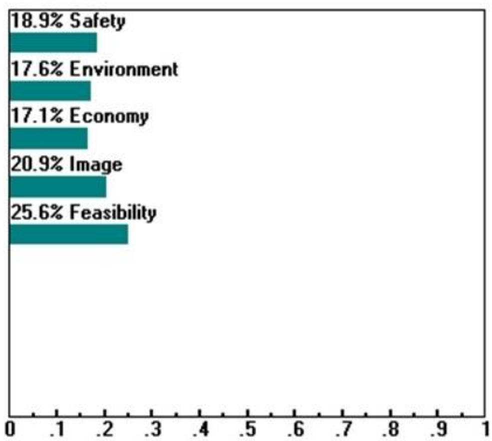


Figure 8. The AHP hierarchy for the Fukushima disaster

3.4.1. AHP results

Figure 9 represents the model output in terms of the priorities given to the criteria and alternative decisions. It highlights that the option 'enhance nuclear safety' is the most preferred alternative.



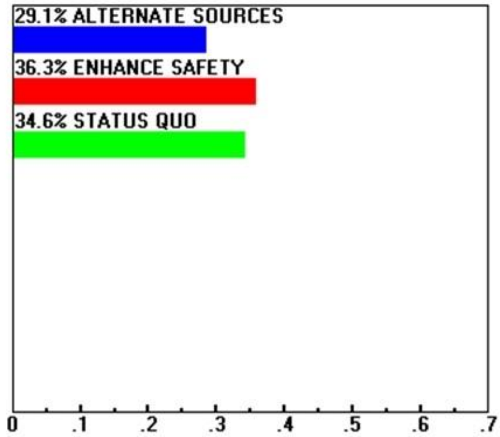


Figure 9. The AHP model outputs showing priorities of criteria (on the left) and alternatives (on the right)

3.4.2. Conclusion of the group of participants:

This group employed the AHP to evaluate the future options for nuclear power usage in Japan following the Fukushima accident. Their study demonstrates the applicability of the AHP and MCDA for HO&CM. The proposed model provides a framework that encourages a number of key stakeholders to evaluate and resolve the nuclear power debate. The AHP model, coupled with the usage of expert knowledge, could improve the reliability of the model findings and alternative solutions.

Although there are other MCDM methods compared to AHP such as FUCOM (Pamučar et al., 2018), and BWM (Rezaei, 2015), we tend to agree with (Pamučar et al, 2018) in that there is no agreement upon the best method of determining criteria weights. However, judging by the current number of papers in using AHP, it is still ranked as one of the most used methods for MCDM. Due to its simplicity and offer of feedback on consistency of judgements as well as a facility to carry out a what if (sensitivity analysis) (Pamučar & Savin, 2020; Pamučar & Dimitrijevic, 2021).

4. Comparative analysis of the two case studies

This section overviews the OR methods used for analysis of the two large-scale disasters. The decision support tools were selected mainly according to the way in which the decision problem was defined for each disaster along with the type and range of available data, which played a crucial role in finding a matching practicable technique.

• A typical detached AHP model for disasters with mixed causes

Due to diverse views obtained from a number of data sources available for the second case study, i.e. for a mixed (industrial-natural) disaster the data sets were compiled and MCDA, through the use of the AHP, was used for selecting an alternative energy source as a post-disaster recovery/reconstruction stage. Since there were no reliable and consistent data required for performing unified root cause analysis, no FTA model was proposed as being suitable for reflecting both causes and exploring industrial-natural failures. The mixed-cause disaster seemed to be too complex to derive a unified root because the analysis included both industrial and natural causes and effects as in the case of the second case study.

• Root cause analysis of past incidents through FTA for disasters with a uniform cause

Root cause analysis of past incidents was used through FTA for analysis of the technical causes and for exploring pre-disaster failures of the first (industrial) case study.

• FTA integrated into another analytical tool for disasters with a uniform cause

FTA was used for the first case study with a uniform cause respectively linked to: 1) an RBD for finding critical failure(s) and a systems approach, as a mental model, for exploring a control mechanism and potential control loops based on the underlying disaster factors that affected the first (industrial) disaster; and 2) the AHP for synthesized ranking of the direct disaster causes and the factors that contributed to the disaster impacts appeared in the second case study. Table 1 summarizes comparative analysis of the disasters with respect to various aspects, including the disaster type/degree of cause and effect, controllability, HO&CM and the OR models and analysis so that HO&CM communities can benefit.

Table 1. Comparative analysis of the case studies

Criteria	Bhopal	Fukushima
Models	FTA+RBD	AHP
Neutrality/ objectivity of disaster	Low	Medium
Cause	Manmade	Mix (Manmade + Natural)
Effect	Major	Major
Pre disaster preparation	Very Low	Low
Controllable cause	High	Medium
Controllable effect	High	Medium
Dependence on Pre- disaster HOM	High	High
Dependence on Post- disaster HOM	High	High
Recovery response	Very Low	Low
Retrospective Analysis	High	High
Prospective Analysis	High	Medium

5. Discussion and conclusion

The main contribution of this work is the use of hybrid modelling techniques to analyse disasters in terms of humanitarian operations and crisis management (HO&CM). Such tools are often used as 'mental models' for both problem solving and problem structuring. Problem solving is an efficiency measure (doing things right), for example setting priorities of actions for allocation of resources. Problem structuring is about effectiveness (doing the right thing), for example brainstorming of possible scenarios of causal factors that lead to a disaster. Unfortunately, most researchers tend to use OR models for the former rather than the latter. This is partly due to our original definition of risk and risk assessment. Risk is broadly defined, and assessed, based on a combination of severity and occurrence. Whilst it is relatively easy to quantify severity, occurrence, as a performance measure, is often difficult to assess and it can be claimed as misleading as a measure in the first place.

In this paper it has been demonstrated that the use of OR techniques independently can contribute to a better understanding and therefore potentially better management of the HO&CM cases. For example, the hierarchal structures of FTA and the AHP can help in brainstorming causal factors. Moreover, a systems approach can facilitate mental modelling, which can lead to better problem structuring and decision analysis. In addition, the use of the AHP for setting priorities should be based on ranking for resource allocation to all factors according to their weight rather than utilizing it as a selection exercise and just allocating resources to the top-of-the-list factors and ignoring the rest. In other words, all possibilities need to be considered and resources need to be allocated to all possibilities with varying weights to realize the shift in emphasis from probability to possibility. In doing so, a more robust position is reached, thereby reducing the possibility of error or failure.

Since data availability and accuracy, along with uncertainty, is the most crucial part of modelling HO using OR models, as future research, the authors can develop the proposed models incorporating fuzzy sets for considering vague data, which can be used as the models' inputs in a fuzzy range in order to facilitate learning HO&CM more realistically through analysis of a range of solutions/outcomes. Although the concept of hybrid modelling has been demonstrated for HO&CM, it can also be applied to cases related to safety science and security studies, where the main difference between safety and security lies in the intention.

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