THE DEVELOPMENT AND VALIDATION OF THE ENERGY

TRANSFER/CHANGE HAZARD IDENTIFICATION METHOD (ETCHIM)

A Thesis

by

SHELBY ELIZABETH HOPKINS

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Daniel A. McAdams
Committee Members,	Thomas Ferris
	Michael Moreno
Head of Department,	Andreas Polycarpou

May 2017

Major Subject: Mechanical Engineering

ABSTRACT

The world is a system that is comprised of many different types of systems that are all intertwined, creating a map of the inner workings of modern day society. The very existence of systems introduces conditions of failure, which are often referred to as hazards. Conducting a hazard analysis of a system can help designers foresee these undesired conditions of failure. The limitations of current hazard identification methods must be addressed because systems are still failing in unexpected ways. In order to create a new method for identifying hazards, an in-depth literature review is completed to understand work that has already been done, and in what areas current work can be improved. It is suggested that accidents may be viewed from an energy perspective. To explore this perspective, a case study exercise that analyzes product liability cases involving mechanical systems is completed. With the validation of seeing accidents from an energy perspective, a general structure for the method is proposed.

The new partially automated method known as the ETCHIM focuses on energy within the system and aids the designer in identifying hazards based on any unwanted changes or transfers of that energy. To assess the ETCHIM, an experiment involving human subjects is designed and conducted that compares the performance of the ETCHIM to the existing What-If/Checklist method. The results of the experiment show that the ETCHIM identifies more hazards than the What-If/Checklist. A change is made to the ETCHIM's automation that is a suggested improvement of the method. A second experiment is conducted to test the performance of the improved ETCHIM against the original. The equal performance could be attributed to an inadequate training scheme.

DEDICATION

This thesis is dedicated to those who have been injured or killed by unsafe systems and products. Your suffering is unacceptable and your story will be used to create systems that will no longer cause pain and loss.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. McAdams, and my committee members, Dr. Ferris and Dr. Moreno, for providing valuable guidance and support. I would also like to thank Courtney Dornburg, Jason Morris, Caren Wenner, Susan Stevens-Adams, and the Human Factors department at Sandia National Laboratories for the additional support, which could not be more appreciated.

Lastly, thanks to my family for setting a wonderful example of what it means to be selfless. Without such an example, the origin of this project would have never been formulated.

CONTRIBUTORS AND FUNDING SOURCES

This work was supervised by a thesis committee consisting of Daniel A. McAdams and Michael Moreno of the Department of Mechanical Engineering and Thomas Ferris of the Department of Industrial Engineering. This graduate study was supported by Sandia National Laboratories in Albuquerque, New Mexico.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

The world is a system that is comprised of many different types of systems that are all intertwined, creating a map of the inner workings of modern day society. Thinking of the world as a system requires an understanding of what actually makes up a system. In general, a system can be defined as "an interacting combination, at any level of complexity, of people, materials, tools, machines, software, facilities, and procedures designed to work together for some common purpose" [1]. In these terms, a system can be characterized in several different ways such as economical, social, or technological. For example, an automobile system is comprised of moving parts such as the transmission, engine, axle, and wheels that all operate interdependently to achieve its mission of ground transportation. System components such as cooling/heating, radio, windows, and adjustable seats work together to ensure comfort of the driver and any passengers. An automobile can be considered its own system, but further abstraction will reveal that an automobile, along with other automobiles, traffic lights, and roads, is a component within the economical ground transportation system. Different levels of abstraction detail different systems, but they all come together in a cohesive manner allowing society to effectively operate. But real-life experience reveals that systems do not always operate as expected, or intended. A system not operating as intended can lead to system failure, causing accidents or mishaps. [2]

The very existence of systems introduces conditions of failure, which are often referred to as hazards. More specifically, a hazard is "[a]ny real or potential condition that can cause injury, illness, or death to personnel; damage to or loss of a system, equipment, or property; or damage to the environment" [3]. Conducting a hazard analysis of a system can help designers foresee these undesired conditions of failure.

People actively analyze hazards all throughout the day, potentially without even realizing it. Part of living a safe life is being able to assess a situation to determine any inherent danger, and proceed accordingly. From an engineering perspective, hazard analysis is the process of identifying hazards, hazard effects, and hazard causal factors so as to “identify potential causes of accidents (…), so they can be eliminated or controlled in design or operations before damage occurs” [4]. The importance of hazard analysis is deeply rooted in the necessity to design inherently safe systems in order to uphold the first fundamental canon of engineers; to hold paramount the safety, health, and welfare of the public [5].

As aforementioned, the identification of hazards is the first step in the hazard analysis process once the system is appropriately defined. Operating under the belief that the initial identification of hazards determines the effectiveness of the proceeding analysis, this project is specifically interested in the identification phase of the hazard analysis process. This belief is rooted in the idea that without the initial identification of a hazard, it will never be considered in the later analysis phases. If a hazard is never analyzed, the system’s designers will not appropriately eliminate or mitigate the particular conditions associated with that hazard. This can lead to the occurrence of accidents that were completely unforeseen. Further, it is believed that the existence of unidentified hazards can conceivably lead to an inflated confidence in the final design. Thus, the need for a rigorous hazard identification method.

The current hazard identification processes are reliant on individuals with domain expertise, creativity in brainstorming, checklists, and “on subjective evaluation by those constructing the system” [4]. The limitations of current hazard identification methods must be addressed because systems are still failing in unexpected ways.

Accidents are still occurring due to unsafe system designs, such as the severe hand injury sustained by a construction worker in 2005 when his hand slipped into the blade of a table saw he was using to cut a piece of wood [6]. Or the tragic death of a scissor lift operator in 2008 who fell from the lift when it suddenly became unstable [7]. In an attempt to address the continued issue of hazards going unidentified during the design process of systems, the Energy Transfer/Change Hazard Identification Method, or ETCHIM, is developed.

In order to create a new method for identifying hazards, an in-depth research process is completed to understand work that has already been done, and in what areas current work can be improved. During the literature review, it is realized that accidents may be viewed from an energy perspective. To determine the validity of the theory that accidents can be interpreted as an unwanted change in energy within a system, a case study exercise that analyzes product liability cases involving mechanical systems is completed. After the entire research process, a general structure for the method is proposed.

The new method known as the ETCHIM focuses on energy within the system and aids the designer in identifying hazards based on any unwanted changes or transfers of that energy. To assess the ETCHIM, an experiment involving human subjects is designed and conducted that compares the performance of the ETCHIM to the existing What-If/Checklist method. The results of the experiment show that the ETCHIM identifies more hazards than the What-If/Checklist.

The proceeding chapters detail the steps taken to develop and create the ETCHIM. First, a discussion of existing hazard analysis and identification is provided that helps scope the relevance of the project. After proposing an underlying theory of the new method, the case study exercise that tests the validity of the underlying theory is detailed. Once an underlying theory for the method is substantiated, the development of the method's procedural steps is explained before discussing the need and creation of an algorithm that partially automates the method's process. The design and conduction of an experiment that tests the performance of the ETCHIM relative to an existing method is then described, followed by a discussion of what the results of the experiment suggest. Based on the results of the experiment, a supposed 'improvement' to the ETCHIM is explained. A discussion of a second experiment that tests the performance of the 'improved' ETCHIM relative to the 'unimproved' ETCHIM is provided. The results of the second experiment are then discussed. Lastly, the contribution of the project on hazard identification and potential opportunities for future work are discussed.

CHAPTER II

RELATED WORK

This chapter discusses some of the more notable hazard identification and analysis methods, along with an overview explaining which methods align with the work done in this project. The considerations for relevance are rooted in the process, output, and theory of the methods.

Overview of Hazard Analysis Methods

This section provides an overview of several of the most prominent hazard analysis methods.

Fault Tree Analysis (FTA)

The Fault Tree Analysis (FTA) is a technique designed to determine the root cause and probability of a top undesired event. It can be used proactively during the developmental phase of a system in order to appropriately influence the design. The FTA can also be used in a reactive manner to aid in the process of accident reconstruction. A graphical representation of the system under analysis is created and logic gates are used to connect system events and potential faults to display the appropriate causes and consequences leading to a top undesired event. An FTA can be either qualitative or quantitative. Although the quantitative FTA provides more meaningful results, it requires more experience, time, and logs that contain component failure data. The results from the FTA can be used to verify safety requirements, identify safety deficiencies and mode failures, establish preventative measures and requirements, and evaluate the adequacy of established measures. Overall, the FTA uses knowledge of the system and experienced personnel to draft a graphical representation of fault events that are connected using logic gates to determine the root cause of an undesired event, the probability of the undesired event, and identify high-risk paths within the system. [1] [8] [9] [10] [11] [12]

Failure Mode and Effects Analysis (FMEA)

The Failure Mode and Effects Analysis (FMEA) is a tool used to assess the effects that certain failure modes have on a system, similar to the FTA. The FMEA provides a quantitative analysis through the use of failure data of the system components to determine probabilities of failure. It is applicable to all types of systems and can be used at any level during the detailed design phase. There are three different approaches to conduct a FMEA, which are functional, structural, and hybrid. The functional approach focuses on the functions of the different components of the system and how they could go wrong or unsatisfied. The structural approach focuses on failure modes that are concerned with the hardware that makes up the system. The hybrid approach combines the functional and structural approaches by starting with the functional and then transitioning into the structural so that all functions and hardware components of a system are analyzed. However, the FMEA fails to identify all possible system hazards because it does not consider any multi-component failure states. Therefore, the FMEA should be used in conjunction with other system analysis techniques. [1] [13] [14] [15] [16] [17]

Preliminary Hazard Analysis (PHA)

The Preliminary Hazard Analysis (PHA) is a hazard analysis and identification technique that can be used to assess any project during the preliminary design phase. Conducting a PHA during a design phase when few detailed design specifications are available allows for changes to be easily made, and even mold the eventual specifications. Because the purpose of the PHA is to analyze hazards that have already been identified by a hazard identification method, the main areas of focus are the causal factors, effects, level of risk, and mitigation measures of the hazards. In order to perform a PHA, hazard and mishap checklists, along with other information sources such as a functional flow diagram, reliability block diagram, equipment list, and system design, are compiled and referenced. Using the information sources and initial list of identified hazards, a team of designers fill out the PHA worksheet, which includes information such as the hazard under analysis, potential causes of the hazard, the effects if the hazard is realized, and initial and final risk indexes. Once the specifications of the design become detailed enough, the PHA is terminated. [1] [18] [19] [20]

Methods Relating to Desired Process and Output

The following hazard identification methods have similar structured brainstorming processes that provide a list of hazards as the output. This particular format is the desired format for the ETCHIM.

Preliminary Hazard List (PHL)

The Preliminary Hazard List (PHL) is a hazard identification method that is used during the conceptual design phase of a product or system. The purpose of the PHL is for the team of designers to develop a list of hazards that exist within the defined scope of the analysis. There are many different scopes within a design that can include hardware, operations, or software, to name a few. In this manner, the system can be broken up into categories of the system that allow the design team to focus on certain areas at a time. Once the mission of the scope under analysis is defined and the components identified, a table is filled out that details information about the system items, the hazards associated with those items, and the effects of the hazards. The process of documenting potential hazards for each item is heavily reliant on brainstorming and referencing appropriate hazard checklists. However, the checklists utilized may not be fully adequate, which defines a disadvantage of the method. Overall, the input of the PHL is information regarding the mission of the system and its components and the output is a list of hazards associated with identified system items that can be used for further system analysis such as the Preliminary Hazard Analysis (PHA). [1] [18] [21] [22]

What-If/Checklist

The What-If/Checklist method helps the design team identify hazards within a system during any design phase. Hazards are identified through a structured brainstorming session by combining the features of the What-If Analysis method and the Checklist Analysis method. Once the system's mission and components are defined, the analysis begins with the design team asking the question, "What if…?" This question is asked in the context of what could go wrong within the system that would cause an accident. For every "What if" situation, a brief description of the potential consequences of the particular accident is provided. The designers use their knowledge of the system's design and creativity to brainstorm as many hazards as possible within the system. The structure of the process is inherent in the use of hazard checklists to help the design team brainstorm hazards. However, a checklist only contains what its author decides is important, which can be limiting when analyzing a new system. Like the PHL, the What-If/Checklist method is only designed to produce a list of hazards and does not complete any further analysis. [23] [24] [25]

Method Relating to Desired Theory

The following method assesses hazards within a system that are derived from energy sources, and is based on the theory that the unwanted transfer of energy can cause an accident. The theory that accidents occur due to the unwanted transfer of energy within a system is similar to the baseline theory of ETCHIM.

Energy Trace Barrier Analysis (ETBA)

The Energy Trace Barrier Analysis (ETBA) is a method used during the conceptual and detailed design phases that determines hazards by identifying dangerous energy sources within the system. By identifying energy sources, the design team can trace the flow of energy within the system. The purpose of tracking the energy flows is rooted in the theory that accidents can occur when there is an unwanted transfer of energy from its source to another system component. Once the energy flows are identified, the barriers protecting the other system components from these flows are assessed to determine if the imposed barriers are appropriate for hazard mitigation or elimination. In order to complete the assessment process, a table is used to document and organize details such as the specific energy source, the hazard associated with the source, targets, an initial mishap risk index, the imposed barrier, and the final mishap risk index. The targets are system components that would be adversely affected by an unwanted energy flow transfer. The initial mishap risk index is an evaluation of the hazard risk that is determined by the combination of the qualitative frequency and severity before the barrier is imposed, and the final mishap risk index is the same evaluation after the barrier is imposed. Overall, the input to the ETBA is design knowledge and identified energy sources within the system, and the output is tabulated information that assesses the energy flow barriers in terms of risk. [1] [25] [26] [27]

Takeaways

Concluding the literature review, knowledge is gained about the existing hazard identification methods along with realizations about areas of weakness that can be improved. For the scope of this project only methods that are used for hazard identification are considered for improvement. As previously stated, the PHL and What-If/Checklist methods are of particular interest based on the results they produce and the general process followed to complete them. Both the PHL and What-If/Checklist methods rely on brainstorming and hazard checklists. Brainstorming is a powerful identification technique, especially when the design team is multidisciplinary and experienced. The checklists ensure that the designers have considered as many known hazards as possible while guiding the brainstorming process. While established hazard checklists identify many hazards, they are confined to accidents that have already occurred. When engineering a completely new system, current methods can overlook new hazards due to the reliance on information stemming from existing systems. The ETBA is not included as a hazard identification process, but rather a hazard analysis methodology with an underlying theory that is of particular interest. The theory that accidents occur when there is an undesired change in energy within the system is seen as a way to dissect the cause of accidents and think of it in terms of something widely studied and exists in every system: energy. It is unknown what future systems will actually consist of, but the one thing that is certain is there will be energy involved. Creating a hazard identification method that uses the energy within the system to predict hazardous scenarios could result in an increase in the number of hazards identified, potentially leading to safer systems. In regards to the proposed process of the new method, the studied behavior of energy adds structure without taking away from the creativity of brainstorming.

CHAPTER III

THEORY VALIDATION

This chapter describes the steps taken to develop the ETCHIM such as validating the theory that accidents occur due to unwanted changes in energy and building the procedure, which includes the creation of an algorithm.

Validation Approach

The best way to learn about the causes of accidents is to study incidents that have already occurred. Studying events that have occurred gives the researcher confidence that the information is not hypothetical, but rather stems from real-world circumstances. This type of data is desirable when validating a theory that could eventually be used to predict real-world accidents.

In order to analyze an accident appropriately, finding a well-documented and accurate description of the events leading up to the incident is a necessity. A suitable place to find such descriptions is in product liability cases. Accidents found in product liability cases are serious and controversial enough for the victim to claim, in court, that the engineered product or system defected. Also, any product liability case analyzed must stem from a mechanical system that contains kinetic and gravitational potential energy to fit the scope of the project.

Validation Activities

In order to validate the proposed relationship between accidents and energy, product liability cases in the WestlawNext Database through Texas A&M are analyzed [28]. To find detailed information about a specific accident, the WestLaw database is used to find the name of a product liability case that is mechanical in nature. The name of the case is then entered into the Google search engine to find proceedings regarding the accident. A proceeding is selected and then the search for the accident information begins. Sufficient information used for documentation includes a description of the events immediately leading up to the accident along with a statement concerning the injuries sustained by the victim. The following is an excerpt from a case that provides sufficient detail:

"As the sheet moved into the machine, a sliver of metal that extended outward from the roll caught the soft part of the palm of his hand and pulled it into the stripper fingers. The force of his hand striking the stripper fingers caused them to be sucked through the rollers and into the cutters along with plaintiff's right hand and arm causing severe injuries." [29]

In some instances, the information provided about a case is not sufficient enough to understand the events leading up to the accident and any resulting consequences. The next excerpt is an example of a case that provides insufficient detail:

"This is a personal injury, product liability case regarding a shredder manufactured and marketed by Defendant Deere & Company a/k/a John Deere Company (John Deere). (...) Defendant STI and/or GTC misrepresented and/or failed to disclose or provide proper instructions for the lifting of the shredder in question for the foreseeable situation giving rise to this accident and cause which separately, independently or in combination with the above defects amounts to negligence and actual misrepresentation which was the proximate cause of the accident in question." [30]

Cases that do not provide sufficient information are removed from the assessment and not documented.

In order to appropriately scope the project, only cases mechanical in nature are analyzed, which restricts the different energy types to kinetic and gravitational potential. Overall, 82 accidents with sufficient accident information are analyzed (see Appendix for list of cases), which include ladders, elevators, saws, grinders, or conveyor belts. For this project, kinetic energy is defined as horizontal and/or vertical movement, which includes rotation. Possessing gravitational potential energy is any component whose center of gravity is ever above ground. Within the analysis of all 82 cases, the resulting injury, energy forms involved in the accident, qualitative size and weight of energized component(s), qualitative magnitude of the energy, and an interpretation of the accident in terms of energy transfers are documented. The information involving component size, weight, and magnitude are broken up into qualitative categories of large, medium, and small. For size and weight, the average human would be in the medium category. So anything reasonably smaller or larger than the average human is categorized as small or large, respectively. Concerning energy magnitude, the categorization of small, medium, and large depends on the type of energy. For kinetic energy, the magnitude is directly related to the speed in which the component is moving. A component has a large kinetic energy if it is moving, or rotating, at a speed faster than an average human can sprint. For example, a rotating saw blade has a large magnitude of kinetic energy. A medium kinetic energy is translation or rotation within the range of how fast an average human moves without technological help. Moving or rotating slower than how fast a human moves is categorized as small magnitude. For gravitational potential, a large magnitude is any height above a one-story building. A medium magnitude is the height of the average person, within reason, and a small magnitude is a height any lower than that. Table 1 displays the type of information required for the analysis that is extracted from each accident description.

Table 1: Information extracted from the description of the accident

Case	Injury	Energy type	Size	Weight	Mag. of Energy	Energy Interpretation
Dorsey vs Yoder	Nearly severed arm	Kinetic	Medium	Small	Large	The accident occurred when the large kinetic energy of the stripper's fingers was transferred to the victim's hand resulting in unwanted contact between the cutters and the victim's hand/arm.

Lifts and Ladders

Fifteen injuries are documented for the lifts and ladders category. Most injuries occurred when the human operator fell from the lift or ladder while using it to complete a task. The rest of the injuries involve the lift or ladder failing in a way that the operator fell along with the rest of the system.

From an energy perspective, the accidents occurred when a potential energy within the system inadvertently turned into kinetic energy. In general, the larger the height from which the operator fell, the more severely the victim was injured. It has been observed that the greater the potential energy within the system, the more hazardous the accidents can be.

Saws and Blades

Fifty injuries are documented for the saws and blades category. The most common accident of the fifty occurred when any body part of the operator came in contact with a sharp blade operating at high rotational or translational speeds. In some cases, a 'kickback' occurred when the blade came in contact with a denser portion of the material being cut, and other times, the user inadvertently touched the blade while in operation. There are many different causes for the user's inadvertent contact with the blade. Some cases indicated that a piece of clothing worn by the operator had been pulled into the blade's rotation. A small percentage of the accidents do not involve the operator directly coming into contact with the blade, such as some of the 'kickback' cases in which the material the operator was cutting was forced upwards striking the operator. In a few other cases, the energy of the rotating blade within the system was transferred to a smaller component by accident causing the smaller component to strike and injure a human. An example of this is one of the lawn mower cases in which the quickly rotating blades of the mower came in contact with a rock in the grass causing it to fly out from underneath the mower, striking a nearby person.

From an energy perspective, the accidents occurred when the large kinetic energy of a blade was transferred to the human operator through direct contact. Or, the accidents occurred when the large rotational kinetic energy of a blade was transferred to a stationary object resulting in either a 'kickback' of the blade or the object inadvertently gaining translational energy. The more mass the object being cut has, the more likely the saw blade itself will experience a 'kickback' rather than the object. There is clearly not a linear relationship between the mass of the object coming into contact with the blade, inadvertently or not, and the severity of the resulting injury.

Grinders

Out of the eleven cases involving grinders, ten of them involve the rotating grinder shattering, or breaking, into smaller pieces during use causing the operator to be struck by the quickly translating shards. One accident occurred when the quickly rotating grinder came loose from the spindle that attached it to the rest of its housing unit. When the grinder came loose, its rotational kinetic energy turned into translational kinetic energy and struck the operator.

From an energy perspective, every accident occurred when the large rotational kinetic energy of a system component inadvertently turned into translational kinetic energy. It is important to note that in most of the cases, the grinder broke into small shards. The shards traveling at a high velocity often posed a greater threat than an unbroken grinder because the shards had the ability to actually pierce through the operator's skin and protective equipment. For grinders, the idea that the larger the energy the more hazardous the accident does not necessarily hold true because the smaller shards may be considered less hazardous due to their smaller mass, but in many cases they are more hazardous.

Cranes

Only three cases are documented involving cranes and each accident was very different in nature. The first accident occurred when the crane was transferring a load, which hit the stationary cab of the crane causing the load to fall, severely injuring a nearby worker. Another accident occurred when the boom attached to a crane unexpectedly fell, which resulted in the death of the victim. In the third case, there were many environmental factors such as high winds and waves that led to the failure of the crane's structure leading to the human operator's injury.

From an energy perspective, in the first case, there was a sudden change in the kinetic energy of the load when it hit the cab, which led to an undesired change in the load's potential energy into kinetic energy as it fell. In the second case, much like the accidents in the lifts and ladders category, the accident occurred when there was an undesired change in the boom's potential energy to kinetic energy as it fell. The third case involved several environmental factors, but essentially the kinetic energy of the wind and the waves was transferred to the crane in a way that was unexpected and undesired. The crane's motion due to the unexpected gain in kinetic energy resulted in the failure of the crane itself causing injury to the human operator.

Elevators

Three cases are documented for the elevators category. One accident occurred when the victim was riding in the elevator and it jerked causing the rider to fall and sustain injuries. The other two accidents are similar in nature. In another case, the victim was crushed under the portable elevator when it unexpectedly fell, resulting in the death of the victim. In the last case, the victim was performing maintenance and was caught under the elevator as it unexpectedly fell, also resulting in death.

From an energy perspective, the deaths were caused by an undesired change in large potential energy to kinetic energy as the elevators fell on top of the victims. The case involving just an injury resulted in an unexpected change in the magnitude of the kinetic energy leading to a jerking motion of the elevator with the rider inside.

Belts

The accidents documented involving belts have to do with the operator's hand or clothing getting caught in a rotating belt and being pulled into an even more dangerous area of the system, such as a quickly rotating blade.

From an energy perspective, the accident occurred when there was an unwanted transfer of the belt's kinetic energy to the human operator, pulling the operator into a situation that can lead to further unwanted energy transfers such as coming in contact with the large rotational kinetic energy of a blade within the system.

Takeaways

The most important piece of information from this exercise is the interpretation of the accident in terms of energy transfers within the system because this alone can determine if the baseline theory holds true. The information contained in the Size, Weight, and Mag. of Energy columns are documented in order to determine a relationship between these factors and the severity of the injury sustained by the individual. This information is particularly important in the development of an eventual ranking system for the hazards. However, ranking the hazards is not within the scope of this project. Overall, this exercise validated the baseline theory that accidents occur when there is an unwanted change or transfer of energy within a system because all 82 accidents analyzed are successfully interpreted in terms of unwanted energy changes or transfers.

CHAPTER IV

ETCHIM DEVELOPMENT

This chapter discusses the steps taken to develop the procedure and tools needed to complete the ETCHIM, followed by an example.

Procedure Development

The purpose of the ETCHIM is to aid designers during the initial hazard identification process in realizing hazards that could potentially go unforeseen. Current methods are completely manual, so adding automation to the process can help reduce human error when completing the structured portion of the hazard identification process [31]. The ETCHIM's procedures are developed to combat the oftentimes-flawed effort of the human mind in doing 'cut and paste' tasks by allowing automation to complete such activities.

Based on the theory that accidents occur when there is an undesired change in energy, the success of the method is centered on identifying energized components within the system. In order to identify components within a system and their energies, the first step is to define the mission of the system and how each component participates. It is important to understand that a human operator is considered a system component and should be included accordingly. Defining the mission of a system can be achieved using a number of established methods. It is crucial to understand the function of each component because this feature will help the designer determine what energy forms are present. A description of the system's immediate environment must also be included. An example of what should be included in the description of the system is provided in the 'Example' portion of this section. Once the components and their functions are identified, the designer fills out the table shown in Table 2.

Table 2: Component-energy table used to document system information.

Component	Translation	Potential	Rotation

Each component identified in the system and immediate environment is listed in the first column of Table 2. In the remaining columns, an “X” is input if the corresponding component possesses that form of energy within the system and an “O” is input if it does not possess that form of energy. For instance, if Component A moves horizontally and vertically within its system, there should be an “X” in the Translation and Potential columns and an “O” in the Rotation column. Once the designer documents the required information for each component, the table is used to determine all of the possible conversions and transfers of the existing energies within the system. Using the example of Component A, the possible energy changes are:

1) Component A translation converted to potential
2) Component A translation converted to rotation
3) Component A potential converted to translation
4) Component A potential converted to rotation

If another system component, Component B, possesses potential and rotation, the possible energy transfers are:

1) Component A translation transferred to Component B
2) Component A potential transferred to Component B
3) Component B potential transferred to Component A
4) Component B rotation transferred to Component A

The given energy conversions and transfers are then used to brainstorm possible accident scenarios within the system, identifying hazards in the process. To determine the plausibility of the outputs, a system is created that mimics one of the documented product liability cases. Using the description of the system, the ETCHIM is performed and accident scenarios are identified (see Appendix for test case). At the end of the exercise, it is determined that the actual accident scenario is detected.

While brainstorming accident scenarios for the test case, it becomes evident that there are not any hazardous scenarios associated with an energy conversion to potential or a component's potential energy transferring to another component. This notion is verified in recognizing that an accident never occurred due to a change to potential or a transfer of potential from one component to another in all 82 product liability cases analyzed. Through an additional inspection of potential energy, it is recognized that a hazardous situation is not caused by a change to potential energy or a transfer of potential energy between components, but rather by an instance in which potential energy changes to translation or rotation. In conclusion, any outputs that indicate a change to potential energy or a transfer of potential energy between components are discarded from the analysis.

Due to the repetitive and straightforward nature of cross-referencing the table entries, automation is desired to perform such a task [32].

Algorithm Development

Requiring the human designer to perform a task that an algorithm can perform in a fraction of the time is senseless and wasteful. Python is used to write an algorithm that takes the entries of the component-energy table as an input, manipulate the entries to indicate the possible conversions and transfers of energy as the output, and create an editable comma separated (csv) file that displays the output for the human designer. The designer can then interact with the csv file to complete the brainstorming portion of the ETCHIM, providing desirable tools such as 'Sort' and 'Filter' along with color-coding.

The algorithm code (see Appendix) consists of one function that uses 'if-statements' and while loops to achieve its mission of creating the desired output of changes and transfers of energy. The code is designed to take a text (txt) file as the input and parse it based on spaces and lines within the file. To create such a text file, the component-energy table is created in an Excel spreadsheet with the following headers and corresponding cells:

1) ‘Component’ in cell A1
2) ‘Translation’ in cell B1
3) ‘Potential’ in cell C1
4) ‘Rotation’ in cell D1

It is important to note that when inputting the system components, only one word should be used as a descriptor. However, if multiple words are required to name a component, a space should not be included between words. For example, instead of inputting ‘Conveyor Belt’, it should be typed as ‘ConveyorBelt’ or ‘Conveyor_Belt’. This nuance stems from the way the code parses the text file. When the code detects a space, it treats the characters before and after as two different entries. A faulty output is created if the name of a component is read as two separate entries. The name of the component must be read as one entry, so it must be typed as such. A snapshot of how the Excel spreadsheet should be filled out is shown in Figure 1.

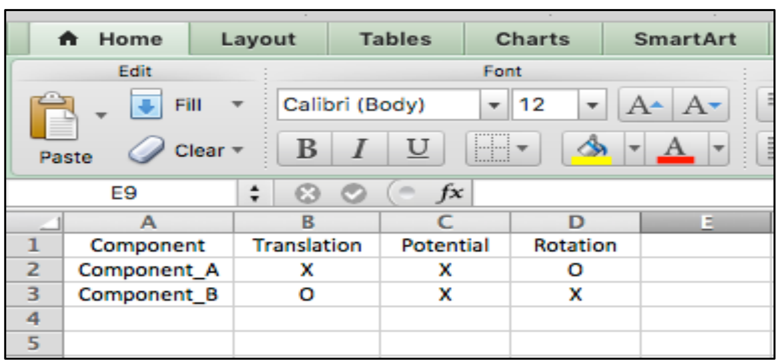


Figure 1: Snapshot of the appropriate set-up of the component-energy table in Excel.

Once the component-energy table is created in Excel, the spreadsheet is saved as a text (.txt) file with a system-appropriate name. The code is run, prompting the user to input the name of the text file. After the name of the text file is entered and the algorithm compiles, the csv file with the output appears in the same folder the text file is saved in on the computer. The designer uses the csv file to analyze the different energy changes and transfers to brainstorm possible accident scenarios. Overall, the inclusion of the algorithm provides automation in a way that can reduce human error during the repetitive task of cross-referencing the entries in the input table [31].

ETCHIM Example

An example system is provided below. The excerpt provides the system's description; Table 3 shows the corresponding component-energy table, and Figure 2 shows the algorithm output.

Jane's job is to move a log sitting at the top of a hill to the bottom of the hill where a pile of logs 5 feet high sits. In order to do this, Jane mounts and then rides atop a machine that picks up the log, moves the log to the edge of the hill, then drops the log. Once dropped, the log rolls down the hill at a high speed until it comes to a stop just before the pile without hitting it.

Table 3: Component-energy table corresponding to the system description.

	A	B	C	D
1	Component	Translation	Potential	Rotation
2	Jane	X	X	O
3	Log	X	X	X
4	Log_Machine	X	X	O
5	Pile_of_Logs	O	X	O

The Hazard Guide shown in Figure 3 helps the designer interpret the output of the algorithm and is developed using the accident energy interpretations that came out of the case study exercise.

The Hazard Guide is developed using the information gathered in the energy interpretation column of the case study exercise. It is through this information that the behavior of the different types of energies that lead to accidents is revealed. The different conversions and transfers listed as examples in the Hazard Guide stem from all 82 product liability cases analyzed in the case study exercise. So, every accident from the exercise is effectively described by the information contained in the guide. The wording within the guide is somewhat vague intentionally so it can be used for any mechanical system. Even though the guide captures every accident in the case study exercise, it is important to note that the guide is exactly that, a guide. It is meant to provide ideas of how to interpret the algorithm outputs, but is not necessarily exclusive when it comes to brainstorming.

	A
1	Jane Translation transferred to Log
2	Jane Translation transferred to Log_Machine
3	Jane Translation transferred to Pile_of_logs
4	Log Translation transferred to Jane
5	Log Rotation transferred to Jane
6	Log Translation transferred to Log_Machine
7	Log Rotation transferred to Log_Machine
8	Log Translation transferred to Pile_of_logs
9	Log Rotation transferred to Pile_of_logs
10	Log_Machine Translation transferred to Jane
11	Log_Machine Translation transferred to Log
12	Log_Machine Translation transferred to Pile_of_logs
13	Jane Translation converted to Rotation
14	Jane Potential converted to Translation
15	Jane Potential converted to Rotation
16	Log Translation converted to Rotation
17	Log Potential converted to Translation
18	Log Potential converted to Rotation
19	Log Rotation converted to Translation
20	Log_Machine Translation converted to Rotation
21	Log_Machine Potential converted to Translation
22	Log_Machine Potential converted to Rotation
23	Pile_of_logs Potential converted to Translation
24	Pile_of_logs Potential converted to Rotation

Figure 2: Algorithm output based on the component-energy table.

Hazard Guide

1) Conversion

a. A conversion from **potential** to **translational** can indicate a person or object falling/collapsing.

b. A conversion from **rotational** to **translational** can indicate a rotating object shattering, or becoming dislodged from its housing unit as it rotates.

c. A conversion from **potential** to **rotational** can indicate a person or object tipping over.

d. A conversion from **translational** to **rotational** can indicate a person or object rolling.

2) Transfer

a. A transfer of **translational** energy from one component to another can indicate a collision, or unwanted contact between the two.

b. A transfer of **rotational** energy from one component to another can indicate a collision, or unwanted contact between the two. If contact between the two components is intended within the system, this can indicate an unwanted 'kick-back'.

Figure 3: Guide used to interpret the output of the algorithm.

CHAPTER V

ETCHIM PERFORMANCE

This chapter details the steps involved to test the performance of the ETCHIM. It discusses the formal hypotheses of the experiment, setting up the experiment, the individuals involved, the data analysis approach, and the results.

Formal Hypotheses

In order to test the performance of the ETCHIM with respect to the What-If/Checklist, the collected data is used to test the following hypothesis pairs:

Null: The means of the number of hazards identified with ETCHIM and What-If/Checklist are equal.
Alternate: The mean of the number of hazards identified with ETCHIM is greater than What-If/Checklist.

Null: The frequencies of identifying the actual accident of each system with ETCHIM and What-If/Checklist are equal.
Alternate: The frequency of identifying the actual accident of each system with ETCHIM is greater than What-If/Checklist.

Null: The means of the number of hazards identified by individuals with hazard identification experience and individuals without hazard identification experience are equal.
Alternate: The mean number of hazards identified is greater for individuals with hazard identification experience.

Null: The frequencies of identifying the actual accident of each system by individuals with hazard identification experience and individuals without hazard identification experience are equal.
Alternate: The frequencies of identifying the actual accident of each system by individuals with hazard identification experience and individuals without hazard identification experience are unequal.

Experimental Setup and Methodology

To test the formal hypotheses of the project, an experiment involving human subjects is conducted. For the study, each participant analyzes two different systems that are based on two of the previously assessed product liability cases. The two systems and descriptions of their actual accident scenarios are displayed in the Appendix.

The objective of the participants is to identify the hazards that exist within each system. Because of the scope of its development, the ETCHIM only captures hazards that exist in mechanical systems. Thus, all participants are instructed to identify hazards that have to do with the mechanics of the system.

Before analyzing the systems, each participant fills out a pre-study questionnaire that asks about their level of experience in hazard identification, their highest degree received, and the nature of their occupation (i.e. engineering, business, etc.). Additionally, the individuals in the ETCHIM group complete a short worksheet training exercise that re-familiarizes them with kinetic and potential energies and how to recognize them within a system. The pre-study questionnaire and training worksheet can be seen in the Appendix.

After completing the analysis of the two systems, each participant fills out a post-study survey (see Appendix) that asks them to rate how easy the method was to use, the level of mental effort they expended during the exercise, and whether or not they would use the method again, which is followed by a free response section allowing them to provide any comments about the experience.

Pilot Study

To establish the fluidity of the experiment, a pilot test is conducted. A group of 7 individuals from Sandia National Laboratories critically evaluate the instructions of the experiment by running through it. As the participants work through the procedures, they are encouraged to ask any questions that arise concerning the required activities. The questions and subsequent answers are documented (see Appendix). After the experiment is over, the participants are given the opportunity to record any concerns about the procedures. The feedback given by the participants both during the experiment and after are used to update the instructions to establish fluidity within the procedures. The procedures of the experiment can be seen in the Appendix.

Study Comparing the ETCHIM and What-If/Checklist

To test ETCHIM, 36 individuals participate in a study that compares ETCHIM to the existing What-If/Checklist method. The participants are Sandia National Laboratories employees, have at least an undergraduate level experience in physics, are competent with Microsoft Office, and are at least 18 years old. For the control group, 19 of the participants are randomly assigned to analyze the given systems using the What-If/Checklist method. As the experimental group, the remaining 17 participants use the ETCHIM to identify hazards.

Data Analysis Approach

Two raters independently assess the data to determine the number of hazards each participant identified within each system and whether or not the actual accident scenario was identified for each system. The inter-rater agreement is determined using Cohen's Kappa [33] and is found to be 0.931. As per [34], this correlation exceeds the threshold necessary to accept the data assessment rubric, which can be seen in the Appendix.

Normality and equal variance tests are completed to determine the appropriate means comparison test for the number of hazards identified in each system. The results of each normality and equal variance test are summarized in Tables 4 and 5.

Table 4: Summary of Shapiro Wilk's normality test in JMP for each set of data.

System	Method	p-value	Significance level
1	What/If Checklist	0.23	0.05
	ETCHIM	0.13	0.05
2	What If/Checklist	0.39	0.05
	ETCHIM	0.40	0.05

Table 5: Summary of Levene's equal variance tests between the Control and Experimental data sets in each system.

System	p-value	Significance level
1	0.0005	0.05
2	0.009	0.05

Based on the results of the normality tests, all of the p-values are larger than the significance level so the null hypothesis that the data come from a normal distribution is not rejected. Levene's test for equal variances results in a rejection of the null hypothesis that the variances of the compared data are equal, which is indicated in the determination that both p-values are less than the significance level. Based on the results of these tests, Welch's test is selected to compare the means of the data because it operates under the assumptions that the data is normally distributed and have unequal variances. Also, Fisher's Exact Test [33] is selected to perform the proportions comparisons.

Results of Study

This section details the results of the experiment and provides a discussion of the implications of the results. Figures 4 and 5 display samples of the data that is gathered during the experiment.

System 1		
Crane Potential converted to Rotation	Crane tips over	Worker death, mild to severe injury, crane damage
Crane Potential converted to Translation	Crane falls over	Worker death, mild to severe injury, crane damage
Crane Translation converted to Rotation	Crane rolls over	Worker death, mild to severe injury, crane damage
Crane Translation transferred to Elevatedplatform	Crane hits elevated platform	Worker death, injury, crane loss
Crane Translation transferred to Logpile	Crane hits logpile	Equipment damage, product loss
Crane Translation transferred to Water	Crane enters water	Crane loss
Crane Translation transferred to Worker	Crane hits worker	Death, mild to severe injury
Logpile Potential converted to Rotation	logpile tips over	
Logpile Potential converted to Translation	Logpile falls	Logpile loss
Water Translation converted to Rotation	Water rolls	
Water Translation transferred to Crane	Water touches or engulfs crane	Crane loss
Water Translation transferred to Elevatedplatform	Water touches or engulfs Elevatedplatform	Non-use of Elevatedplatform
Water Translation transferred to Logpile	Water touches or engulfs logpile	Log loss
Water Translation transferred to Worker	Water touches or engulfs worker	Death, mild to severe injury
Worker Potential converted to Rotation	Worker gets dizzy, falls	Death, mild to severe injury
Worker Potential converted to Translation	Worker falls	Death, mild to severe injury
Worker Translation converted to Rotation	Worker rolls out of crane, hits elevated platform or enters water	Death, mild to severe injury
Worker Translation transferred to Crane	Worker hits crane	Injury, mild equipment damage
Worker Translation transferred to Elevatedplatform	Worker hits elevated platform	Death, mild to severe injury
Worker Translation transferred to Logpile	Worker hits logs	Injury, mild equipment damage
Worker Translation transferred to Water	Worker enters water	Death, mild to severe injury

Figure 4: A data sample from the experimental group for the first system

System 2		
saw dust and/or splinters fly into worker's face	flying dust or splinters	worker injury
table saw jams while cutting	wood projectile or worker cuts (struck by)	worker injury/death
table saw malfunctions while cutting	equipment failure	worker injury/death
uncut or cut pile of lumber is unstable	wood/lumber falls	worker injury
worker has no guides or stops at table saw	worker cuts	worker injury/death
worker is fatigued and drops or falls onto table saw	struck against equipment	worker injury/death
worker is unable to adequately lift and manage piece of uncut wood	worker strain	worker injury
worker loses control of uncut wood while cutting	worker cuts	worker injury/death
worker slips/trips while carrying uncut or cut wood	fall	worker injury

Figure 5: A data sample from the control group for the second system.

Number of Hazards Identified

In order to determine which method produced the greater number of hazards identified, the data is split into System 1 and System 2 groups and then split further into Control (What-If/Checklist) and Experimental (ETCHIM) resulting in four groups of data. Figures 6 and 7 display the means of each group analyzed.

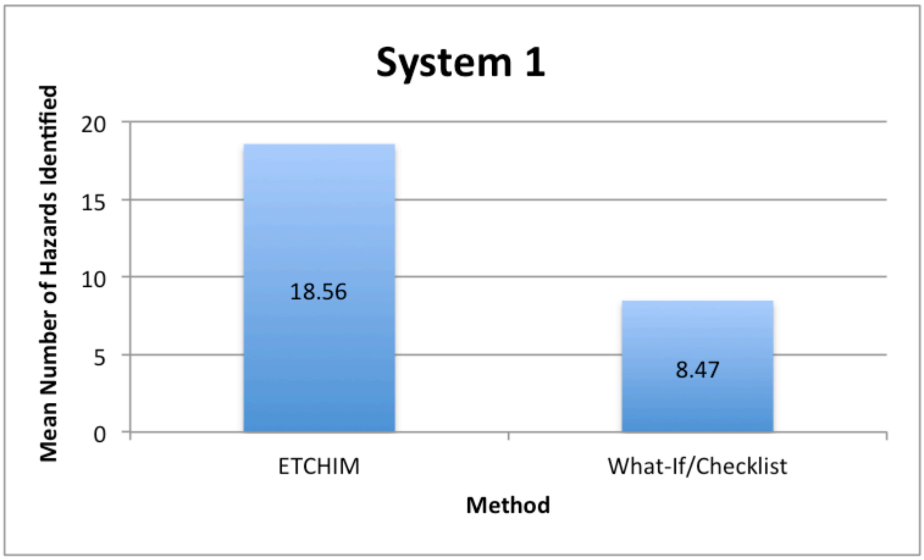


Figure 6: Bar chart showing the mean number of hazards identified for System 1 for each group.

Within the System 1 and System 2 data sets, the means of the Control and Experimental groups are compared. The null hypothesis of Welch's t-test states that the means of the two data sets are equal. The alternate hypothesis states that the mean of the Experimental group is greater than the mean of the Control group, providing a one-tailed test. The results of the means comparison for both System 1 and System 2 are summarized in Table 6.

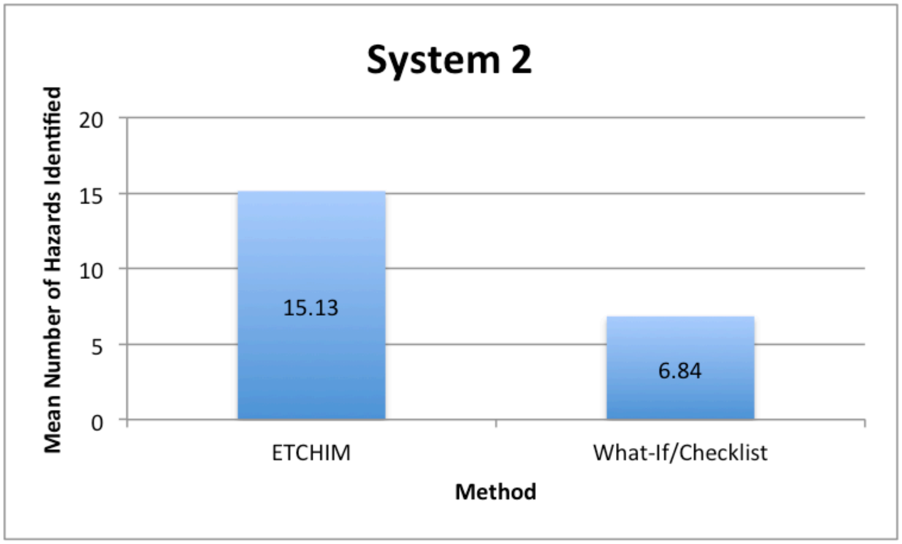


Figure 7: Bar chart showing the mean number of hazards identified for System 2 for each group.

Table 6: Summary of Welch's t-test comparing the means of the Control and Experimental data sets within each system.

System	Null Hypothesis	Alternate Hypothesis	p-value	Significance level
1	$\mu_{exp} = \mu_{ctl}$	$\mu_{exp} - \mu_{ctl} > 0$	0.0001	0.05
2	$\mu_{exp} = \mu_{ctl}$	$\mu_{exp} - \mu_{ctl} > 0$	0.0001	0.05

In both systems, the calculated p-value is less than the significance level so the null hypothesis is rejected and the alternate hypothesis is accepted. In conclusion, the number of hazards identified using the ETCHIM is significantly greater than the number of hazards identified using What-If/Checklist for both systems. More specifically, on average, the ETCHIM identified roughly 119 percent more hazards than the What-If/Checklist for System 1 and roughly 121 percent more for System 2.

Correctly Identified Accident Scenario

In order to determine which method correctly identified the accident scenarios of the systems more often, the data is split up into System 1 and System 2 groups. System 1 and System 2 are further split into Control and Experimental groups, which results in four groups. The data is presented in the form of two contingency tables, one for each system, which can be seen in Figures 8 and 9.

Count	No	Yes	Total
Control (What-If/Check)	13 36.11%	6 16.67%	19 52.78%
Experimental (ETCHIM)	7 19.44%	10 27.78%	17 47.22%
Total	20 55.56%	16 44.44%	36

Figure 8: Contingency table for identifying the actual accident in System 1.

Count Total %	No	Yes	Total
Control (What-If/Check)	8 22.86%	11 31.43%	19 54.29%
Experimental (ETCHIM)	11 31.43%	5 14.29%	16 45.71%
Total	19 54.29%	16 45.71%	35

Figure 9: Contingency table for identifying the actual accident in System 2.

The differences observed between the methods in Figures 7 and 8 are tested for significance using a proportions comparison test. The results of Fisher's Exact tests for proportions comparison for each system are summarized in Table 7.

Table 7: Summary of Fisher's Exact tests for System 1 and System 2.

System	Null Hypothesis	Alternate Hypothesis	p-value	Significance level
1	$P_{exp} = P_{ctl}$	$P_{exp} - P_{ctl} > 0$	0.986	0.05
2	$P_{exp} = P_{ctl}$	$P_{exp} - P_{ctl} > 0$	0.140	0.05

Based on the results from Fisher's Exact test, for both systems, the p-value is greater than the significance level. Thus, the null hypotheses cannot be rejected. This means there is insufficient evidence to reject the hypothesis that the proportion of correct identification of the actual accident scenario is the same for both methods. In conclusion, the ETCHIM did not perform better than the What-If/Checklist method in correctly identifying the actual accident scenarios.

Performance Assessment of Participants with Hazard Identification Experience

In order to determine the performance of participants with hazard identification experience compared to participants without experience, the data is split into System 1 and System 2 groups, and then further split up into Control and Experimental groups resulting in four groups. Within each of the four groups, a means comparison of the number of hazards identified is performed between the groups with and without hazard identification experience. The results of the four tests are summarized in Table 8.

Table 8: Summary of means comparison tests between groups with and without hazard identification experience.

System	Method	p-value	Significance level
1	What-If/Checklist	0.53	0.05
	ETCHIM	0.47	0.05
2	What-If/Checklist	0.50	0.05
	ETCHIM	0.77	0.05

Based on the results in Table 8, the null hypothesis in all four cases cannot be rejected due to the p-values being greater than the significance level. This means that there is insufficient evidence to reject the notion that the number of hazards identified by participants with hazard identification experience is not different from the number of hazards identified by participants without hazard identification experience.

Next, each of the four groups undergoes a proportions comparison to determine how well participants with hazard identification experience performed when it came to identifying the actual accident scenario in each system. These results are summarized in Table 9.

Table 9: Summary of proportions comparison between groups with and without hazard identification experience.

System	Method	p-value	Significance level (two-tail)
1	What-If/Checklist	1.000	0.025
	ETCHIM	0.302	0.025
2	What-If/Checklist	1.000	0.025
	ETCHIM	0.044	0.025

Based on the results in Table 9, the null hypothesis for all four tests cannot be rejected because all the p-values are greater than the two-tailed significance level. This means that the evidence is insufficient to reject the notion that participants correctly identify the actual accident scenario with the same frequency regardless of possession of hazard identification experience.

Discussion of Results

In terms of each method's performance, ETCHIM identified significantly more hazards in both systems than the What-If/Checklist method. However, the ETCHIM did not perform significantly better than the What-If/Checklist in identifying the actual accident in each system. This could be due to the novelty and inexperience with ETCHIM and the underlying theory that accidents occur when there is an undesired change in energy. Seeing accidents from an energy perspective may seem too technical for users not trained, or versed, in the subject area. Also, requiring the user to assess each output while referencing the hazard guide could be burdensome, especially in a time crunch. In a case such as this, it is a reasonable response for the user to stop referencing the hazard guide to lessen the burden. Even though the What-If/Checklist method requires referencing a checklist, it does not pose the same demands as ETCHIM because it doesn't require the assessment of an entire list of potential hazards. The What-If/Checklist method allows the user to end his/her analysis as soon as the brainstorming capacity has been exhausted. On the other hand, ETCHIM demands that the user assess at least the number of potential hazards listed in the output. This demand could explain the increased number of hazards identified.

In terms of the performance of participants with hazard identification experience, these individuals did not perform any better than those without hazard identification experience. The hypothesis that both groups perform equally in the number of hazards identified and identifying the actual accident of each system could not be rejected due to insufficient evidence. This is a surprising outcome considering that individuals with hazard identification experience were expected to identify more hazards and more frequently identify the actual accident scenarios. Requiring the participants to only identify hazards mechanical in nature could have played a part in leveling the performance of the two groups. Individuals with hazard identification experience may not necessarily be specifically versed in the mechanical domain. Imposing this limitation for the sake of method comparison could have affected the individuals with hazard identification experience in a way that limited their performance. A second possibility for equal performance of individuals with and without hazard identification experience is that the systems provided in the experiment are simplified to the point where experienced individuals are unable to utilize the skills that truly set them apart from inexperienced individuals.

CHAPTER VI

IMPROVEMENT

This chapter details the development, testing, and performance of the improvement made to the ETCHIM.

Improvement Development

The ETCHIM is designed in a way that the user must reference an outside source, the Hazard Guide. The suggested improvement would be to eliminate the Hazard Guide by incorporating it into the Python algorithm, which can be seen in the Appendix. The addition of the Hazard Guide to the algorithm code is substantiated by the realization that the subjectivity of the brainstorming process lies in thinking of accident scenarios, not in determining what a certain conversion or transfer of energy indicates. The behavior of energy is objective. Subjectivity arises while brainstorming the particular circumstances within the system in which a deviation will occur. The algorithm output for the same example provided in Chapter II using the improved ETCHIM can be seen in Figure 10.

	A
1	Jane runs into Log
2	Jane runs into Log_Machine
3	Jane runs into Pile_of_Logs
4	Log runs into Jane
5	Log contacts Jane *Note: If contact is intended a kick-back may occur
6	Log runs into Log_Machine
7	Log contacts Log_Machine *Note: If contact is intended a kick-back may occur
8	Log runs into Pile_of_Logs
9	Log contacts Pile_of_Logs *Note: If contact is intended a kick-back may occur
10	Log_Machine runs into Jane
11	Log_Machine runs into Log
12	Log_Machine runs into Pile_of_Logs
13	Jane rolls
14	Jane collapses or falls
15	Jane tips over
16	Log rolls
17	Log collapses or falls
18	Log tips over
19	Log shatters or dislodges
20	Log_Machine rolls
21	Log_Machine collapses or falls
22	Log_Machine tips over
23	Pile_of_Logs collapses or falls
24	Pile_of_logs tips over

Figure 10: Algorithm output for the improved ETCHIM.

With the algorithm updated, the improved ETCHIM is tested against the unimproved ETCHIM in a similar fashion as the first experiment that compared What-If/Checklist and the unimproved ETCHIM.

Testing Improvement

The following hypothesis sets are of particular interest to assess the improved ETCHIM with respect to its unimproved form:

Null: The means of the number of hazards identified for the unimproved and improved ETCHIM are equal.
Alternate: The mean of the number of hazards identified by improved ETCHIM is greater than the unimproved ETCHIM.

Null: The frequencies of identifying the actual accident of each system for the improved and unimproved ETCHIM are equal.
Alternate: The frequency of identifying the actual accident of each system using the improved ETCHIM is greater than the unimproved ETCHIM.

For this experiment, there are 40 participants who are graduate students at Texas A&M University. Half of the participants carry out the experiment's exercises using the unimproved ETCHIM (control) while the other half use the improved ETCHIM (experimental). The procedures for the experiment are identical to those of the first experiment, except instead of completing the training worksheet, the participants receive a lecture on ETCHIM. The information included in the PowerPoint lecture can be seen in Appendix.

Data Analysis

For the number of hazards identified, the normality tests of the data indicated that the data come from a normal distribution. Levene's test for equal variance indicated that the data come from distributions with equal variances, unlike the first experiment. Tables 10 and 11 show the results of the normality and equal variance tests.

Table 10: Results of Shapiro Wilk's normality test in JMP statistical software for each data set.

System	Method	p-value	Significance level
1	Unimproved	0.33	0.05
	Improved	0.94	0.05
2	Unimproved	0.41	0.05
	Improved	0.08	0.05

Table 11: Results of Levene's test for equal variance in JMP for the data sets within each system.

System	p-value	Significance level
1	0.45	0.05
2	0.38	0.05

The data shows that all of the p-values are larger than the significance level, so the null hypotheses cannot be rejected, which indicates the distributions are treated as normal and have equal variances. Thus, the Student's t-test [33] is used to compare the means of the improved and unimproved data sets.

Results of Testing

This section presents the results of the experiment in tabular and graphical form, followed by an explanation of the results.

Number of Hazards Identified

Figures 11 and 12 display the means of the number of hazards identified for each group analyzed.

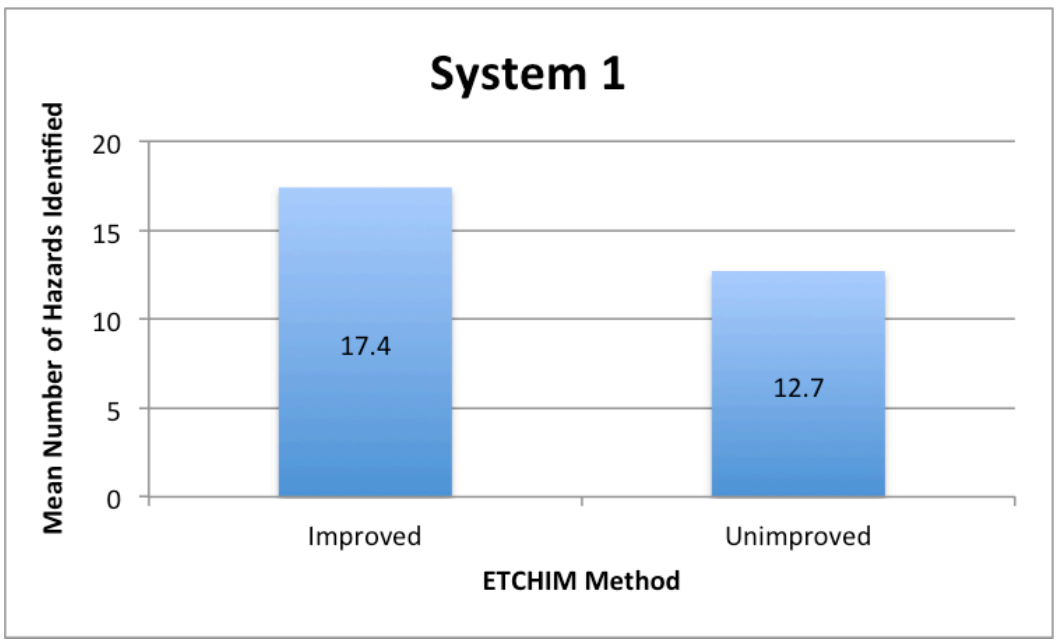


Figure 11: Bar chart showing the mean number of hazards identified for System 1 for each group.

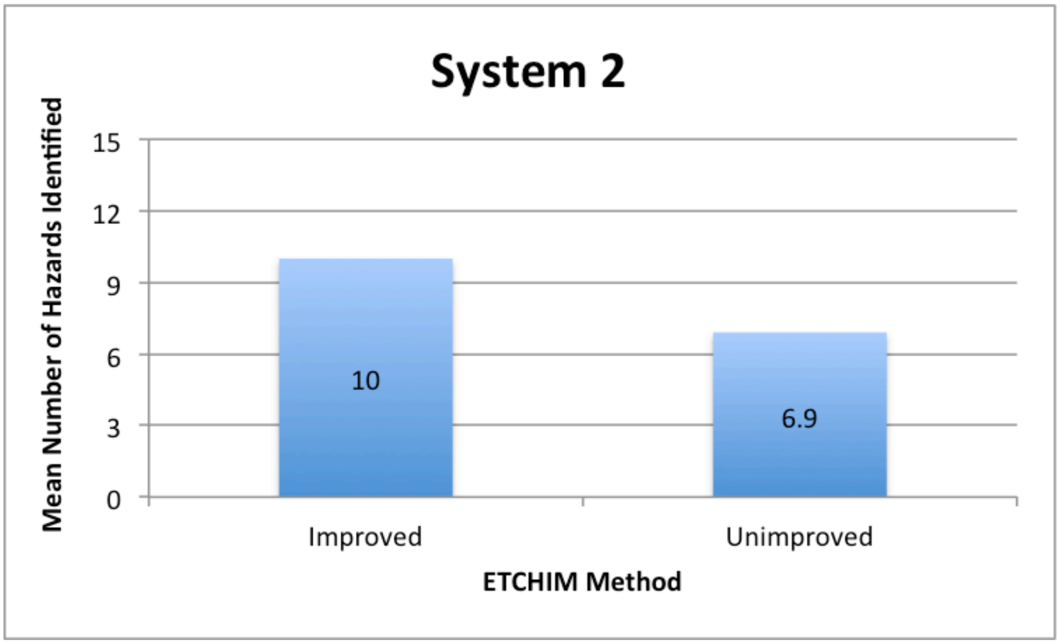


Figure 12: Bar chart showing the mean number of hazards identified for System 2 for each group.

Table 12 details the statistical results of the Student's t-test for the means comparison.

Table 12: Comparison of the means of the number of hazards identified using Student's t-test.

System	Null Hypothesis	Alternate Hypothesis	p-value	Significance level
1	$\mu_{exp} = \mu_{ctl}$	$\mu_{exp} - \mu_{ctl} > 0$	0.03	0.05
2	$\mu_{exp} = \mu_{ctl}$	$\mu_{exp} - \mu_{ctl} > 0$	0.03	0.05

Correct Identification of Actual Accident

Figures 13 and 14 show the contingency tables produced for the frequencies of identifying the actual accident.

Count	No	Yes	Total
Improved	14 35.00%	6 15.00%	20 50.00%
Unimproved	18 45.00%	2 5.00%	20 50.00%
Total	32 80.00%	8 20.00%	40

Figure 13: Contingency table for identifying the actual accident in System 1.

Count	No	Yes	Total
Improved	9 22.50%	11 27.50%	20 50.00%
Unimproved	11 27.50%	9 22.50%	20 50.00%
Total	20 50.00%	20 50.00%	40

Figure 14: Contingency table for identifying the actual accident in System 2.

Table 13 details the statistical results of Fisher's Exact tests for the proportions comparisons.

Table 13: Results of Fisher's Exact tests to determine if the improved ETCHIM identified the actual accident more frequently for each system.

System	p-value	Significance level
1	0.12	0.05
2	0.38	0.05

Based on the results in Table 12, the improved ETCHIM (experimental) identified a greater number of hazards for both systems than the unimproved ETCHIM (control) for both systems because the p-values are smaller than the significance level, which indicates a rejection of the null hypothesis. Even though the improved ETCHIM identified more hazards, the results in Table 13 indicate that there is insufficient evidence to reject the hypothesis that the improved ETCHIM identifies the actual accident equally as frequently as the unimproved ETCHIM for both systems.

Discussion of Results

The improvement of the ETCHIM is designed to help participants identify the actual accident of each system more than the participants using the unimproved ETCHIM, but not necessarily identify more accidents. Thus, the results of the experiment are not expected, which could be due to a combination of reasons. The first reason being that even though participants using the unimproved method had to reference the separate hazard guide, they were still able to effectively use the guide, leveling the performance of the improved ETCHIM. For the first system, identifying the actual accident was heavily reliant on the participants' recognition that the ocean's waves should be considered a major environmental component of the system's immediate environment. Many participants, in both groups, were unable to recognize the waves as a system component, which is believed to be due to a lack of training, or experience, in the method. For the second system, participants oftentimes recognized that the piece of wood coming in contact with the saw blade was intended within the system. However, despite the guidance provided directly in the output of the improved ETCHIM, many participants were unable to recognize that the hazard in that particular contact was rooted in the potential for the wood to kickback toward the operator. It is believed that the lack of recognition in this situation could be due to a lack of training, or experience, in the method.

CHAPTER VII

SUMMARY AND CONTRIBUTION

This chapter provides a summary of the project, along with a discussion of the contribution of the work and what can be done moving forward.

Summary

The inspiration of this project was the realization that engineered systems are still failing in ways that injure the human user or critically damage equipment. As an engineer, the need to keep the public safe initiated a deep look into current hazard identification methods to discover any weaknesses or limitations that could be combated through redevelopment. The methods that were found to be of particular interest were the Preliminary Hazard List (PHL), What-If/Checklist, and Energy Trace Barrier Analysis (ETBA). The structure of the PHL and What-If/Checklist methods were very similar to the envisioned structure for ETCHIM, which is designed to solely identify hazards within a system while providing a brief, preliminary assessment of the hazard consequences. The output list of hazards can then be used as an input to techniques and methods that are designed for hazard analysis such as the Preliminary Hazard Analysis (PHA), Fault Tree Analysis (FTA), and Failure Modes and Effects Analysis (FMEA). Rather than structure, it was the ETBA's underlying theory that accidents occur when there is an undesired transfer of energy within a system that aligned with the interest of the project. The development of the ETCHIM was centered on the pursuit of meshing the structure of the PHL and What-If/Checklist methods and the theory of the ETBA in a way that automation could be introduced and more hazards identified.

To develop the ETCHIM using the theory that accidents occur when there is an unwanted transfer of energy within a system, the underlying causes of accidents had to be explored. This was achieved by analyzing product liability cases found in the WestlawNext database through Texas A&M [28]. The product liability cases selected were limited to those of a mechanical nature so that the analysis included only kinetic and gravitational potential energy forms. The decision to scale all energy forms to kinetic and gravitational potential was made to ensure understanding and confidence in the proceeding development. Analyzing the product liability cases resulted in the confirmation that accidents can be interpreted in terms of undesired energy transfers or changes within a system, which provided verification of the ETCHIM's underlying theory. The exercise also provided insight into how kinetic and potential energies operate within a system and the possible consequences if an energy flow is disrupted in an undesired way. Using the knowledge gained from the case study exercise, development of the ETCHIM's method began.

To determine changes or transfers of energy in a system, it is crucial to first identify the energized components. Therefore, the first step of the method requires the designer to use a decomposition of the system based on the functions of each component to tabulate the components and corresponding energies assuming the system functions as intended. Once the information is tabulated, an automatic manipulation of the information is performed in a Python script to provide the designer with an output that considers all the unwanted transfers of, and changes in, energy within the defined system. The output is essentially a list of potential hazards within the system and the designer is then tasked with the exercise of brainstorming accident scenarios associated with each potential hazard. In order to help the designer interpret the provided output, a separate hazard guide was created using the information gathered during the case study exercise. The effectiveness of the newly developed ETCHIM had to be measured.

In order to assess the ETCHIM, an experiment was designed to compare it to an existing method. Due to the particular interest expressed by Sandia National Laboratories, the What-If/Checklist method was chosen to be the control method. Once the experiment was fully designed, a pilot study was conducted to refine the procedures and required activities. After refinement, the actual experiment included 36 Sandia National Laboratories employees, 19 of which acted as the What-If/Checklist (Control) group and 17 as the ETCHIM (Experimental) group. The results of the experiment concluded that the ETCHIM identified more hazards than the What-If/Checklist method, the evidence was insufficient to reject equal frequencies of actual accident identification for the ETCHIM and What-If/Checklist in each system, and individuals with existing hazard identification experience did not perform better than those without. In an attempt to create an ETCHIM that performs better than the What-If/Checklist in identifying the actual accident scenario, a suggested improvement was made.

The ETCHIM's requirement to reference a separate hazard guide to interpret the Python code output was believed to be a source of error when identifying the actual accident in each system. Thus, the hazard guide was incorporated into the Python script so the information presented in the guide is reflected within the output. This action eliminated the requirement to reference a separate information source. Another experiment was designed to test the improved ETCHIM with the unimproved. For the experiment, 40 mechanical engineering graduate students at Texas A&M University participated with 20 of them acting as the control (unimproved) group and the other 20 as the experimental (improved). The results of the experiment indicated that the improved ETCHIM identified more hazards for both systems than the unimproved. However, the improved did not necessarily correctly identify the actual accident scenario more than the unimproved. Thus, the incorporation of the hazard guide in the Python script did not affect the performance of the ETCHIM in the identification of the actual accident. With this result, it is believed that the success of identifying the actual accident in each system could be rooted in the level of training and experience using the ETCHIM.

Contribution

Throughout this project, a hazard identification method (ETCHIM) was developed and tested. Compared to the What-If/Checklist, the ETCHIM identified more hazards in each analyzed system, but did not identify the actual accident more frequently. The inability of the ETCHIM to identify the actual accident more frequently than the What-If/Checklist is believed to be rooted in the inherent inexperience in using a novel method, along with the requirement of referencing a separate guide. In attempting to improve the method, the hazard guide is incorporated into the algorithm output so the user does not have to reference an outside source. Without understanding the costs and benefits of different training methods, the Texas A&M individuals testing the improvement of the ETCHIM receive a different training than the Sandia individuals in the first experiment. It is highly believed that the lecture-style training for the second experiment is inadequate compared to the worksheet-style training of the first experiment. With proper training, it is believed that the improved ETCHIM will perform better than the What-If/Checklist at identifying more hazards and the actual accident scenario. Thus, the exploration and creation of a training scheme for the ETCHIM is necessary. Future work could also include precision and recall experiments to compare the ETCHIM and existing methods where precision is concerned with how many of the hazards identified are actually hazards and recall is concerned with whether or not all of the hazards in the system are identified.

It is important to recognize that the ETCHIM was developed using mechanical products and only considers kinetic and gravitational potential energy forms within systems. Future work would include studying and adding other forms of energy such as electrical, chemical, and thermal to broaden the application of the ETCHIM to more systems.

In its essence, the ETCHIM provides both a structured and creative approach to identify hazards within a system from the perspective that unwanted changes in energy cause accidents. The process of first identifying system components and associated energies is a logical endeavor that creates a framework for developing an algorithm output that is tailored to the system. The creative process of brainstorming accident scenarios is where the designer can really shine.

REFERENCES

[1] - Chapanis, A., Human Factors in Systems Engineering. John Wiley & Sons. 1996.

[2] - Ericson II, Clifton A. Hazard Analysis Techniques for System Safety 1st Edition. John Wiley & Sons, Inc. Hoboken, New Jersey. 2005.

[3]- Department of Defense: Standard Practice for System Safety. MIL-STD-882D. February 2000.

[4] - Leveson, Nancy G. Engineering a Safer World: Systems Thinking Applied to Safety. Chapter 8: STPA- A New Hazard Analysis Technique. MIT Press. 2011.

[5] - Code of Ethics for Engineers. National Society of Professional Engineers. July 2007.

[6] - Osorio v. Home Depot U.S.A., Inc. FindLaw, Thomson Reuters. 2017 http://caselaw.findlaw.com/us-1st-circuit/1581695.html

[7] - Sappington v. Skyjack Inc. FindLaw, Thomson Reuters. 2017 http://caselaw.findlaw.com/us-8th-circuit/1320031.html

[8] - Andrews, J.D. and T.R. Moss, Reliability and Risk Assessment, 2nd ed., Longman Scientific & Technical, 2002.

[9] - Henley, E.J. and H. Kumamoto, Probabilistic Risk Assessment and Management for Engineers and Scientists, 2nd ed., IEEE Press, 1996.

[10] - NASA, Fault Tree Handbook with Aerospace Applications, version 1.1, NASA, August 2002.

[11] - Roberts, N.H., W.E. Vesely, D.F. Haasl, and F.F. Goldberg, Fault Tree Handbook, NUREG-0492, U.S. Government Printing Office, Washington, DC, 1981.

[12] - Schneeweiss, W.G., The Fault Tree Method, LiLoLe, 1999.

[13] - MIL-STD-1629A, Procedures for Performing a Failure Mode, Effects and Criticality Analysis, 1980.

[14] - AIAG, FMEA-3 Potential Failure Mode and Effects Analysis, 3rd ed., Automotive Industry Action Group (AIAG), July 2002.

[15] - IEC 60812, Analysis Techniques for System Reliability--Procedure for Failure Mode and Effects Analysis (FMEA), 2nd ed., 2001.

[16] - McDermott, R., R. Mikulak, and M. Beauregard, The Basics of FMEA, Productivity, Inc., 1996.

[17] - Stamatis, D.H., Failure Mode and Effect Analysis: FMEA from Theory to Execution, Quality Press, American Society for Quality, 1995.

[18] - Roland, H.E. and B. Moriarty, System Safety Engineering and Management, 2nd ed., Wiley, New York, 1990.

[19] - Stephans, R.A., System Safety for the 21st Century, Wiley, Hoboken, NJ, 2004.

[20] - Vincoli, J.W., A Basic Guide to System Safety, Van Nostrand Reinhold, New York, 1993.

[21] - Stephenson, J., System Safety 2000, Wiley, New York, 1991.

[22] - System Safety Society, System Safety Analysis Handbook 2nd Edition, System Safety Society. 1999.

[23] - Stephenson, J., System Safety 200: A Practical Guide for Planning, Managing, and Conducting System Safety Programs, Wiley, New York, 1991.

[24] - Guidelines for Hazard Evaluation Procedures Third Edition. John Wiley & Sons, Inc. Hoboken, New Jersey. 2008.

[25] - Hammer, W., Handbook of System and Product Safety, Prentice Hall, Inc., New York, 1972.

[26] - Barrier Analysis, DOE-76-451, SSDC-29, Safety Systems Development Center, EG&G Idaho, Inc., July 1985.

[27] - Hocevar, C.J. and C.M. Orr, Hazard Analysis by the Energy Trace Method, Proceedings of the 9th International System Safety Conference, 1989, pp. H-59--H-70.

[28] - Products Liability Cases, Thomson Reuters WestLaw, 2017. https://1-next-westlaw-com.lib-ezproxy.tamu.edu

[29] – Dorsey v. Yoder Company, 331 F. Supp. 753 (E.D. Pa. 1971). Justia US Law. http://law.justia.com/cases/federal/district-courts/FSupp/331/753/1401265/

[30] – Escalante v. Deere & Co. Casetext, Inc. 2016. https://casetext.com/case/escalante-v-deere-co

[31]- Haight, Joel M. Automated Control Systems: Do they reduce human error and incidents?. Professional Safety: Safety Engineering. May 2007. www.asse.org

[32] - Haight, J.M. and Kecojevic, V. Automation vs. human intervention: What is the best fit for the optimal system performance? Process Safety Progress Journal, 24(1), 45-51. 2005.

[33] - Montgomery, Douglas C. Applied Statistics and Probability for Engineers 6th Edition. John Wiley & Sons. 2014.

[34] - Fleiss, J.L. Statistical Methods for Rates and Proportions (2nd ed.). John Wiley & Sons. New York. 1981

APPENDIX

A1: List of documented product liability cases

Sansom v Crown Equipment	Plante v Hobart Company	Pate v Columbia Mach. Inc	Robertson v Superior PMI, Inc
Jackson v Louisville Ladder Inc	Horstmyer v Black and Decker	Mullins v MGD Graphics Systems	Karns v Emerson Electric Co
Peart v Dorel Juvenile Group	Kessler v Bowie Machine Works	Burke v Spartanics Ltd	Smith v Dainichi Kinzoku Kogyo Co
Masello v The Stanley Works	Dorsey v Yoder	Burt v Makita USA	Deviner v Electrolux Motor
Sappington v Skyjack Inc	Siemer v Midwest Mower	Gillispie v Sears Roebuck	Childress v Gresen Mfg. Co
Burke v Quick Lift	Purkey v Sears Roebuck	Johnson v Black and Decker	Moore v Powermatic
Santos v Sunrise Medical	DePree v Nutone Inc	Gross v Black and Decker	Robertson v Norton Co.
Oettinger v Norton Co.	Ward v Hobart Mfg. Co.	Ross v Black and Decker	Schenfeld v Norton
Taylor v Paul O. Abbe	Herman v C.O. Porter Machinery	Van Scoy v Powermatic	Trowbridge v Abrasive Co
Bjerk v Universal Engineering Corp	Henrich v Cutler Hammer Co	Stolarik v Hendrick Mfg.	Tomao v A.P. de Sanno
Hagan v EZ Mfg. Co.	McPhee v Oliver Tyrone	Cates v Sears Roebuck	Bustamante v Carborundum
Tipton v Bergohr GMBH-Siegen	Sowles v Urschel Laboratories	Hood v Ryobi American Corp	Daleiden v Carborundum
London v MAC Corp of America	Perkins v Emerson Elec Co.	Hutchison v Urschel Laboratories	McGrath v Wallace Murray Corp
Belec v Hayssen Mfg. Co.	Poland v Beaird-Poulan	Connelly v Sears Roebuck	Twigg v Norton Co
Clarke v LR Systems	Hopkins v Chip-In-Saw, Inc	Browne v Bark River Culvert	Stokes v L. Geismar
Osorio v One World Technologies	Post v Textron	Harrison v Otis Elevator	Williams v Monarch Mach. Tool Co., Inc
Briney v Sears, Roebuck	Lenior v C.O. Porter Machinery Co.	Mesman v Crane Pro Services	Campbell v Robert Bosch Power Tool
Walk v Starkey Machinery	Webb v Rodgers Machinery Mfg. Co.	Hamilton v Emerson Elec. Co.	Young v Aeroil Products
Rogers v Ingersoll-Rand	Geboy v TRL	Hagans v Oliver Machinery	Brown v Link Belt Division

Porchia v Design Equipment Co.	Schlier v Milwaukee Elec Tool Corp	Jackson v Baldwin Lima Hamilton
Charpie v Lowes Home Ctrs.	Dorman v Emerson Elec	Wade v Diamant Boart

A2: Example of the 'test case' for ETCHIM

Product Liability Case: Sansom v Crown Equipment

System Description:

System involves the human operator using a forklift to retrieve a pallet being stored on a shelving unit and move it to a new target destination. There are two forklifts being used by different operators at the same time, but independently of one another.

Component-energy table:

Component	Translation	Potential	Rotation
Operator	X	X	O
Pallet	X	X	O
Lift 1	X	X	O
Lift 2	X	X	O
Shelving unit	O	X	O

Output (First Column) and brainstorming (Second Column): Actual accident in red

Operator Translation transferred to Pallet	Operator runs into Pallet causing injury
Operator Translation transferred to Lift 1	Operator runs into Lift 1 causing injury
Operator Translation transferred to Lift 2	Operator runs into Lift 2 causing injury
Operator Translation transferred to Shelving unit	Operator runs into Shelving unit causing injury
Pallet Translation transferred to Operator	Pallet hits operator as it moves causing injury
Pallet Translation transferred to Lift 1	Not applicable
Pallet Translation transferred to Lift 2	Pallet hits Lift 2 while being transferred by Lift 1 causing product damage
Pallet Translation transferred to Shelving unit	Pallet hits Shelving unit while being transferred by Lift 1 causing product damage
Lift 1 Translation transferred to Operator	Lift 1 malfunctions and runs over Operator causing serious injury or death
Lift 1 Translation transferred to Pallet	Lift 1 hits the Pallet off the Shelving unit causing injury or damage to equipment
Lift 1 Translation transferred to Lift 2	Lift 1 runs into Lift 2 during operation causing injury or damage to equipment
Lift 1 Translation transferred to Shelving unit	Lift 1 runs into Shelving unit causing damage to the equipment
Lift 2 Translation transferred to Operator	Lift 2 hits the operator causing serious injury or death
Lift 2 Translation transferred to Pallet	Lift 2 hits Pallet unitentionally causing damage to equipment
Lift 2 Translation transferred to Lift 1	Lift 2 runs into Lift 1 causing injury or equipment damage
Lift 2 Translation transferred to Shelving unit	Lift 2 runs into Shelving unit causing damge to equipment
Operator Translation converted to Rotation	Operator trips in a way that they roll causing injury
Operator Potential converted to Translation	Operator falls off Lift 1 causing serious injury
Operator Potential converted to Rotation	Operator trips causing injury
Pallet Translation converted to Rotation	Pallet rolls off Lift 1 while being trasferred causing product damage
Pallet Potential converted to Translation	Pallet falls from Lift 1 or Shelving unit causing injury or product damage
Pallet Potential converted to Rotation	Pallet tips off of Lift 1 or Shelving unit causig injury or product damage
Lift 1 Translation converted to Rotation	Lift 1 rolls while moving causing serious injury or damage to equipment
Lift 1 Potential converted to Translation	Lift 1 collapses causing serious injury
Lift 1 Potential converted to Rotation	Lift 1 tips ove causing serious injury or damage to equipment
Lift 2 Translation converted to Rotation	Lift 2 rolls while moving causing damage to equipment
Lift 2 Potential converted to Translation	Lift 2 collapses causing damage to equipment
Lift 2 Potential converted to Rotation	Lift 2 tips over causing damage to equipment
Shelving unit Potential converted to Translation	Shelving unit collapses causing injury or product damage
Shelving unit Potential converted to Rotation	Shelving unit tips over causing injury or product damage

A3: ETCHIM Algorithm code in Python

```
num = input("Input the filename of your text file without the .txt at the end and hit enter: ")
num1 = str(num)+'.txt'
data = open(num1)
readData = data.read()
r = [x.split() for x in readData.split('\n')]
r.pop(0)

t = 0
while(t < len(r)):
    if(r[-1] == []):
        r.pop(len(r)-1)
    else:
        print()
    t = t + 1


def energies(a):
    num1 = str(num)+'_hazards.csv'
    list1 = []
    g = 0
    while (g < len(a)):
        c = 0
        while(c < len(a)):
            if(a[g][0] != a[c][0]):
                if("X" in a[g][1].upper()):
                    list1.append(a[g][0]+" Translation transferred to "+a[c][0])
                else:
                    print()
                if("X" in a[g][3].upper()):
                    list1.append(a[g][0]+" Rotation transferred to "+a[c][0])
                else:
                    print()
            else:
                print()
            c = c + 1
        g = g + 1


    f = open(num1,'w')
    for ele in list1:
        f.write(ele+'\n')
    f.close


    list2 = []
    while(len(a) != 0):
        if ("X" in a[0][1].upper()):
            list2.append(a[0][0]+" Translation converted to Rotation")
        else:
            print()
        if ("X" in a[0][2].upper()):
            list2.append(a[0][0]+" Potential converted to Translation")
            list2.append(a[0][0]+" Potential converted to Rotation")
        else:
            print()
        if ("X" in a[0][3].upper()):
            list2.append(a[0][0]+" Rotation converted to Translation")
        else:
            print()
        a.pop(0)

    f1 = open(num1,'a')
    for ele in list2:
        f1.write(ele+'\n')
    f1.close

energies(r)
```

A4: Two systems analyzed during the experiment

System 1

Product Liability Case: Brown v Link Belt Division

The mission of this system is to move a pile of logs sitting on a dock over the ocean's waves to an elevated platform using a crane. The flow diagram displayed in Figure 1 shows the significant functions involved in the process. Figure 2 provides a visual depiction of the system.

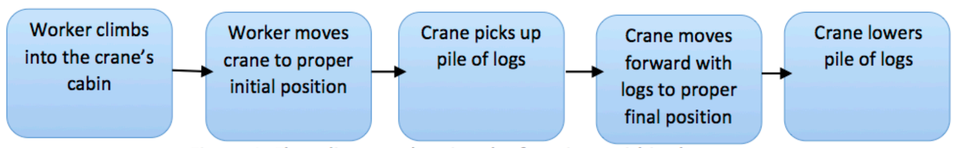


Figure 1: Flow diagram showing the functions within the system.

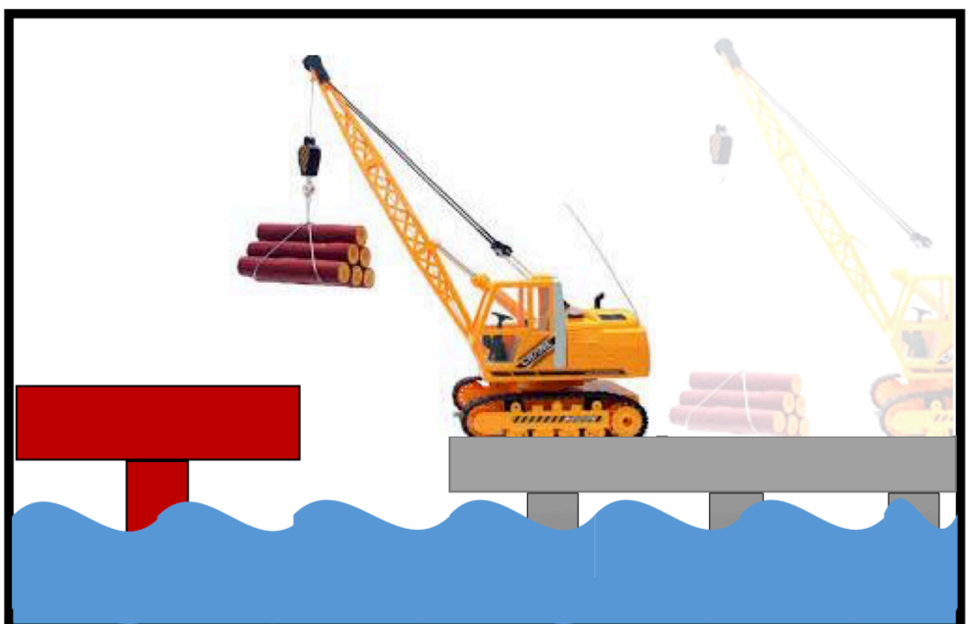


Figure 2: Visual depiction of the system.

Actual Accident Scenario: The ocean's waves crash against the crane as it transfers the load to the platform resulting in the loss of the crane.

<u>System 2</u>

Product Liability Case: Webb v Rodgers Machinery Mfg. Co.

The mission of this system is to take a piece of wood (2" x 4"x 15") from the 'uncut' pile, cut it in half using the table saw, and put the newly cut piece in the 'cut' pile. The flow diagram in Figure 3 shows the significant functions involved in the process. An aerial visual depiction of the system is displayed below in Figure 4.

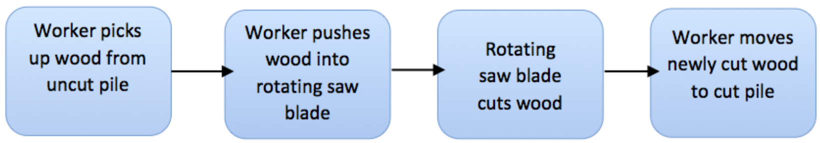


Figure 3: Flow diagram showing the functions within the system.

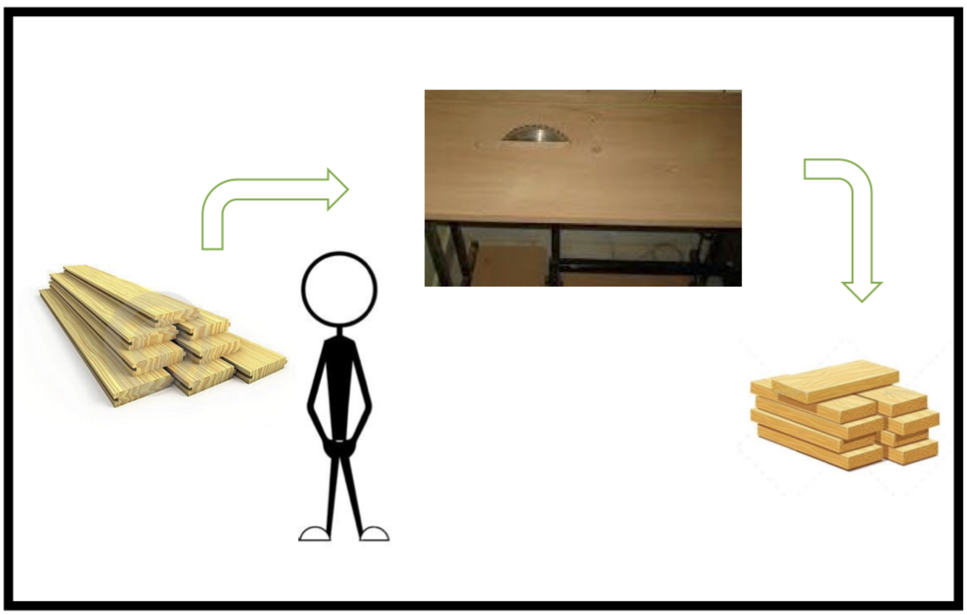


Figure 4: Visual depiction of the system.

Actual Accident Scenario: As the operator cuts the piece of wood with the rotating saw blade, a 'kickback' of the wood occurs resulting in harm to the operator.

A5: Pre-experiment activities

Pre-study Questionnaire

1) Do you have any experience in hazard identification? Yes____ No____

1.a) If yes, check your level of expertise.

Novice ____ Competent____ Proficient____ Expert____ Master____

2) Check the description that best describes your occupation.

Engineering, Sciences____ Business, Arts____

3) Check the highest degree you have received.

High School/GED____ Bachelor's____ Master's____ Doctorate____

ETCHIM Training Worksheet (the answers are given in blue)

Introduction

The effectiveness of this hazard identification method is heavily reliant on the identification and understanding of kinetic and potential energies within a given system. This short briefing will give you an overview of both kinetic (translational and rotational) and potential (gravitational) energies and how to identify them in a system. Once the training is complete, you will apply these concepts to the actual experiment.

Kinetic (Translational)

Definition: Refers to lateral and vertical movement of a person or object's center of gravity.

Example: Person walking, climbing, or riding on a machine, a machine that transports something, an object being transported

Change Implications: A change to translational energy can imply a person falling or tripping and an object falling or inadvertently pushed.

Kinetic (Rotational)

Definition: Refers to rotational movement of a person's center of gravity or an object's center of gravity.

Example: Person rolling, spinning gear, spinning blade

Change Implications: A change to rotational energy can imply a person tipping over or an object tipping over.

Potential (Gravitational)

Definition: Refers to any component that has its center of gravity above ground level.

Example: Upright worker or machine, any object not laying horizontally on the ground

Exercise 1: An ice skater is competing in the Olympics and possesses potential and kinetic energy during the routine. Determine which description of the ice skater's actions best describes each energy form. Type the number associated with the energy form in the space next to the action. Use each energy form once.

1. Translational	3 Ice skater jumps into the air
2. Rotational	1 Ice skater slides across ice in a straight line
3. Potential	2 Ice skater spins around

Exercise 2: A box is stored and moved around a warehouse. Determine which description of the box's actions best describes each energy form. Type the number associated with the energy form in the space next to the action. Use each energy form once.

1. Translational
2. Rotational
3. Potential

2	Box is tipped over to empty its contents
3	Box is stored on a shelf 4 ft. above ground
1	Box is pushed across floor

Exercise 3: For the system described below, determine what forms of energy the components listed in the Component-Energy table possess throughout the system's operation. For instance, if a component possesses translational and potential, but not rotational in the system, put an 'X' in the 'Translational' and 'Potential' columns and an 'O' in the 'Rotational' column associated with that component.

System Description: Jane's job is to move a log sitting at the top of a hill to the bottom of the hill where a pile of logs 5 feet high sits. In order to do this, Jane rides atop a machine that picks up the log, moves the log to the edge of the hill, then drops the log. Once dropped, the log rolls down the hill until it comes to a stop just before the pile. The log machine is designed in a way that it does not have to turn during operation.

Component-Energy table:

Component	Translational	Potential	Rotational
Jane	X	X	O
Log	X	X	X
Log Machine	X	X	O
Pile of logs	O	X	O

Exercise 4: For the system described below, identify the primary components that are directly involved in the process and surrounding components that might interact with the primary components. List them in the 'Components' table below. Note: There are more rows in the table than needed.

System Description: At the airport, Henry's job is to transport an oversized piece of luggage from the straight, interior conveyor belt to the designated plane. In order to do this, Henry picks up the luggage from the conveyor belt, carries the luggage to the cart, and then drives the cart to the loading area for the plane. As Henry is driving the cart to the loading area, there is another cart in operation that has the same purpose as Henry's cart, but works independently.

Components
Henry
Luggage
Conveyor_Belt
Primary_Cart
Surrounding_Cart

A6: Post-experiment Activity

Post-study Questionnaire

1) Rate the method's ease of use.

   Very Easy___ Somewhat Easy___ Neutral___ Somewhat Difficult___ Difficult___

2) Rate the level of mental effort you expended.

   Light___ Some___ Moderate___ Substantial___ Extreme___

3) Would you use this method again? Yes____ No____

4) Please add any additional comments about your experience/the method you used:

A7: Questions and Answers from Pilot Study

Question: In regards to Exercise 3 on the training worksheet, I said that the log pile has translational energy in the case that the log rolling down the hill hits the pile. Why isn't this correct?

Answer: When filling out the component-energy table, you must only account for the energies that are present during the successful completion of the system's mission. It explicitly says in the system description that the log rolling down the hill stops before hitting the pile. Assuming it hits the pile is actually the identification of a hazard, not defining the intended system.

Question: If a component within one of the systems has to turn around in order to achieve the mission, is that considered rotation?

Answer: The rotation column is reserved for system components that are rotating at a high angular velocity, such as a rotating circular saw blade. A component turning in a controlled manner can be classified as translational. In the end, it is up to the designer to decide.

Question: The first system mentions the ocean's waves. Are the waves considered a part of the system?

Answer: Moving fluids, such as water, can be considered system, or environmental, components because they have mass, can translate, rotate, or have potential. Remember that immediate environmental components should be included as system components.

Question: If I forgot to name the system components using only one word, do I need to go back and make the names only one word in the Excel table?

Answer: Yes. If the system component names have two words with a space, the output is not correct. Condense the names with two words into a name without a space, save the file into a text file, and run the algorithm again with the corrected file.

A8: Procedures of the Experiment

Experimental (ETCHIM)

Hazard Identification Study

Scenario:

Imagine that you are a part of a team that is in the process of designing two different systems and your job is to identify hazards within the systems that compromise the user's safety. For this study, a hazard is defined as any source within the system that can potentially harm or have adverse health effects on the human user. To scope the problem, focus on hazards that have to do with the **mechanics** of the system, so do not consider possible thermal or electrical hazards. You will be given descriptions of two different systems and asked to identify hazards within each one. Follow the directions below to complete your task. If you have any questions about the instructions, please feel free to ask.

Directions:

1) In the 'Study' folder, open the file called 'Systems'.
2) Read the description of the first system.
3) In the 'Study' folder, open the Excel file called 'Data Table'.
4) List the system's components in the first column of the table.
5) For each component, put an 'X' in the energy columns that the specific component possesses within the system. Put an 'O' in the energy columns that the component does not possess.
6) Save As → Select Current Folder →
   *File name: <participant ID#>_<system#>
   Save as type: Text (MS-DOS) (*.txt) → Save → Yes → Minimize Excel window
   *For example, if your participant ID# is 12345 and you are working on the first system, the file name will be: 12345_1
7) In the 'Study' folder on the desktop, double click the file 'Algorithm.py'.
8) Follow the prompts in the Python window that pops up.
9) Open the csv file in the 'Study' folder that appears with the following filename: <participant ID#>_hazards.csv
10) Column A lists all possible changes in and transfers of energy within the system. Use this list to help you identify hazards, or accident scenarios, for the system. Document any accident scenarios you've identified in Column B. See the Hazard Guide provided to help interpret the outputs.
11) In Column C, provide a short description of the potential consequences of the accidents in Column B.
12) Save the file using Ctrl+S or File→Save.
13) Repeat steps 2-11 for the second system.

Control (What-If/Checklist)

Hazard Identification Study

Scenario:

Imagine that you are a part of a team that is in the process of designing two different systems and your job is to identify hazards within the systems that compromise the user's safety. For this study, a hazard is defined as any source within a system that can potentially harm or have adverse health effects on the human user. To scope the problem, focus on hazards that have to do with the **mechanics** of the system, so do not consider possible thermal or electrical hazards. You will be given descriptions of the two different systems and asked to identify hazards within each one. Follow the directions below to complete your task. If you have any questions about the instructions, please feel free to ask.

Directions:

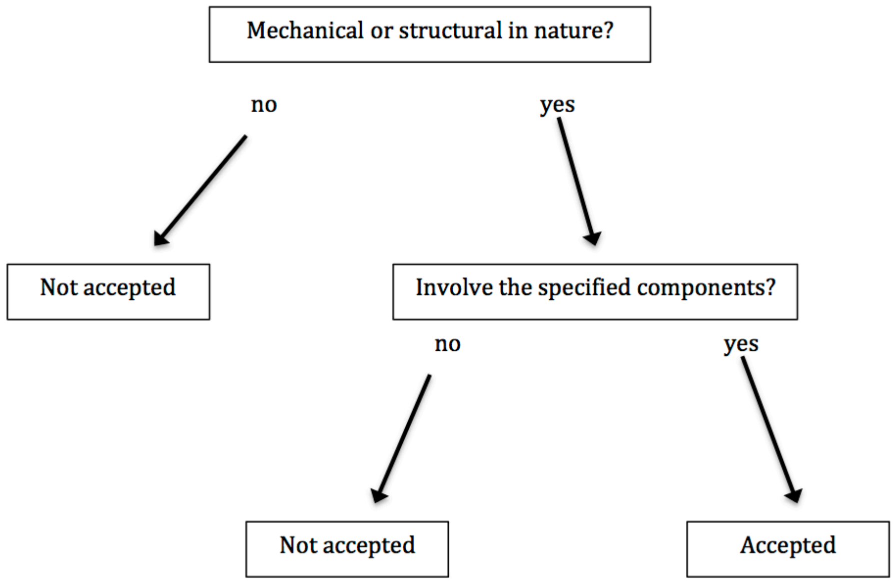
1) Read the description of the first system.
2) Brainstorm accident scenarios by asking the question "What if…?"and document them in the provided table. Use the hazard checklist provided to help with the brainstorming process (see example below).
3) In the 'Hazard Type' column of the table, give a short description of the hazard type (see example below).
4) In the 'Consequence' column of the table, give a brief description of the potential consequence of the accident (see example below).
5) Repeat steps 1-4 for the second system.

What if...	Hazard Type	Consequence
The worker falls off the ladder	Fall	Serious injury or death

Hazards	Hazard Descriptions
Electrical (Fire)	Use of electrical power that results in electrical overheating or arcing to the point of combustion or ignition of flammables, or electrical component damage
Electrical (Static/ESD)	Moving or rubbing of wool, nylon, other synthetic fibers, and flowing liquids can generate static electricity; can result in ignition of flammables or damage to electronics
Electrical (Loss of Power)	Safety-critical equipment failure as a result of loss of power
Ergonomics (Strain)	Damage of tissue due to overexertion or repetitive motion
Ergonomics (Human Error)	A system design, procedure, or equipment that is error-provocative
Excavation (Collapse)	Soil collapse in a trench or excavation as a result of improper of inadequate shoring
Fall (Slip, Trip)	Conditions that result in falls from height or traditional walking surfaces
Fire/Heat	Temperatures that can cause burns to the skin or damage to other organs; require a heat source, fuel, and oxygen
Mechanical (Vibration)	Vibration that can cause damage to nerve endings, or material fatigue that results in a safety-critical failure
Mechanical Failure	Typically occurs when devices exceed designed capacity or are inadequately maintained
Mechanical	Skin, muscle, or body part exposed to crushing, caught-between, cutting, tearing, shearing items or equipment
Noise	Noise levels that result in hearing damage or inability to communicate safety-critical information
Radiation (Ionizing)	Alpha, Beta, Gamma, neutral particles, and X-rays that cause injury by ionization of cellular components
Radiation (Non-ionizing)	Ultraviolet, visible light, infrared, and microwaves that cause injury to tissue by thermal or photochemical means
Struck by	Accelerated mass that strikes the body causing injury or death
Struck Against	Injury to a body part as a result of coming into contact with a surface in which action was initiated by the person
Temperature Extreme	Temperatures that result in heat stress, exhaustion, or metabolic slow down such as hypothermia
Visibility	Lack of lighting or obstructed vision that results in an error or other hazard
Weather Phenomena	Self explanatory

https://www.osha.gov/Publications/osha3071.pdf

A9: Assessment Rubric Flowchart



Specified Components
*Some people might use a variation of these names (i.e. Person for Worker).
This is acceptable.

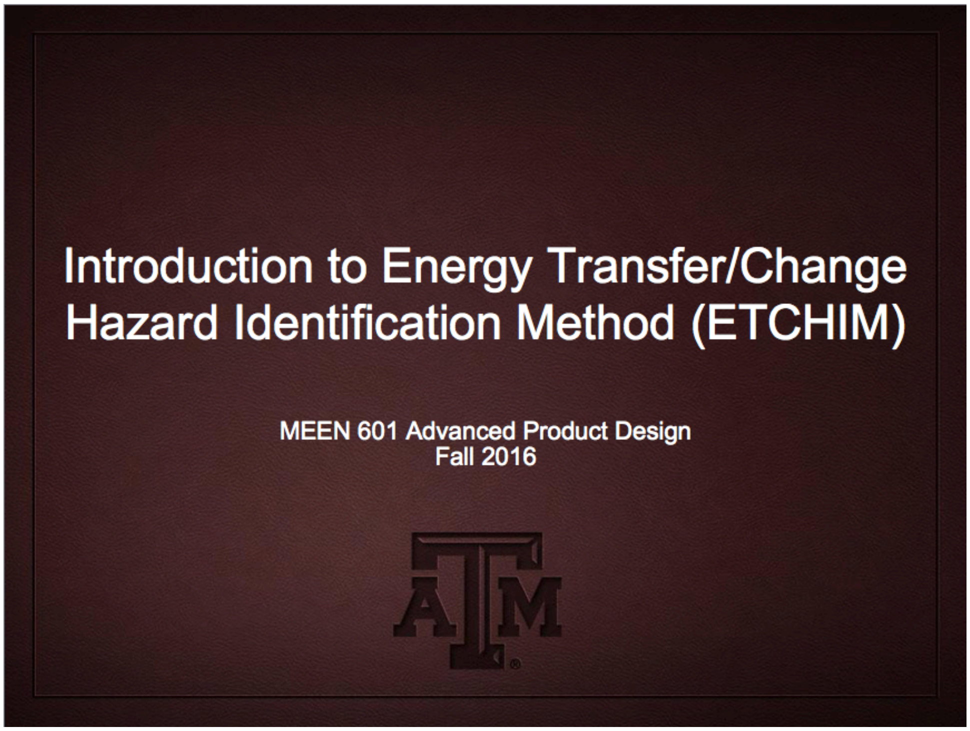
System 1
Worker
Crane
Log pile
Dock
Platform
Waves

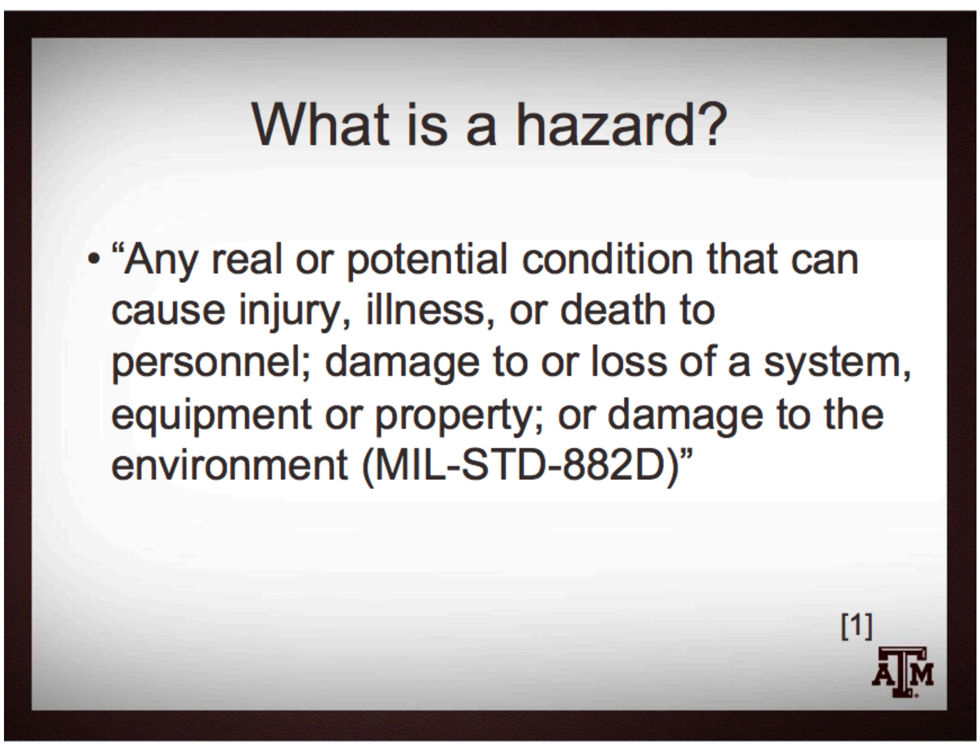
System 2
Worker
Uncut pile
Cut pile
Carried wood
Saw/Table

A10: ETCHIM Algorithm code with Hazard Guide incorporated

```
num = input("Input the filename of your text file without the .txt at the end and hit enter: ")
num1 = str(num)+'.txt'
data = open(num1)
readData = data.read()
r = [x.split() for x in readData.split('\n')]
r.pop(0)

t = 0
while(t < len(r)):
    if(r[-1] == []):
        r.pop(len(r)-1)
    else:
        print()
    t = t + 1


def energies(a):
    num1 = str(num)+'_hazards.csv'
    list1 = []
    g = 0
    while (g < len(a)):
        c = 0
        while(c < len(a)):
            if(a[g][0] != a[c][0]):
                if("X" in a[g][1].upper()):
                    list1.append(a[g][0]+" run(s) into "+a[c][0])
                else:
                    print()
                if("X" in a[g][3].upper()):
                    list1.append(a[g][0]+" contact(s) "+a[c][0]+" *Note: If contact is intended a kick-back may occur")
                else:
                    print()
            else:
                print()
            c = c + 1
        g = g + 1


    f = open(num1,'w')
    for ele in list1:
        f.write(ele+'\n')
    f.close


    list2 = []
    while(len(a) != 0):
        if ("X" in a[0][1].upper()):
            list2.append(a[0][0]+" rolls")
        else:
            print()
        if ("X" in a[0][2].upper()):
            list2.append(a[0][0]+" collapses or falls")
            list2.append(a[0][0]+" tips over")
        else:
            print()
        if ("X" in a[0][3].upper()):
            list2.append(a[0][0]+" shatters or dislodges")
        else:
            print()
        a.pop(0)
    f1 = open(num1,'a')
    for ele in list2:
        f1.write(ele+'\n')
    f1.close

energies(r)
```

A11: ETCHIM PowerPoint Lecture





Why Hazard Identification?

- Hazard identification is a crucial part of developing system safety
- Most aspects of life are compromised of systems (i.e. house, automobile, power grids) and are a necessity of modern living
- Systems provide exposure to mishaps leading to injury or damage in the event of a failure [1]

Example

- Columbia disaster (2003) [3]
  - The space shuttle broke up as it entered the Earth's atmosphere on its return
  - Left wing was damaged by a piece of foam that fell from the shuttle's external tank
  - Atmospheric gases bled into the shuttle through the breached wing causing it to disintegrate
- Other examples?

Work Related to ETCHIM

- Methodology
  - What-If/Checklist
  - Preliminary Hazard List (PHL)
- Theory
  - Barrier Analysis (BA)
  - Change Analysis

What-If/Checklist

- Produces a table describing potential accident scenarios within a system and a brief description of the effects
- Combination of What-If Analysis and Checklist Analysis
  - What-If: freeform brainstorming session in which designers think of "What if" scenarios where an accident can occur
  - Checklist: structured use of established checklists to determine the existence of hazards within the system that are contained in the list
- Applied during the conceptual design phase

[2]

Preliminary Hazard List

- Identifies and lists potential hazards and mishaps that may exist within a system
- Similar to a brainstorming session
  - Can be made more structured with a checklist
- Can be applied to any type of system during its conceptual, or preliminary, design phase
  - This allows the engineer to allocate resources appropriately

[1]

Barrier Analysis

- Identifies hazards associated with hazardous energy sources
- Implemented by identifying energy flow that may be hazardous so that appropriate barriers can be developed to protect equipment and personnel
- Can analyze systems of all types during the detailed and preliminary design phases
- Relies on disciplined, consistent, and efficient procedures to discover energy hazards in a system

[1]

ETCHIM Theory

- Based on the theory that accidents occur when there is an undesired change in energy within a system
- The ability to identify energetic components within a system is necessary.
- Developed using mechanical systems, so method can only be used to track kinetic and gravitational potential energy.
  - Translation (kinetic) – horizontal or vertical movement
  - Rotation (kinetic) – angular movement
  - Gravitational Potential – any component whose center of mass is above the ground

ETCHIM Process

- Describe the activities of the system including major components and immediate environmental components.
- Determine the energy each component possesses throughout the mission of the system.
- Tabulate components and corresponding energies, and input into code.
- Use code output to help identify hazards, or accident scenarios, within the system.

ETCHIM Code

- Takes the table of system components and corresponding energies as the input.

Component	Translation	Potential	Rotation

- Provides an output that describes the possible changes and transfers of energy within the defined system.

Example

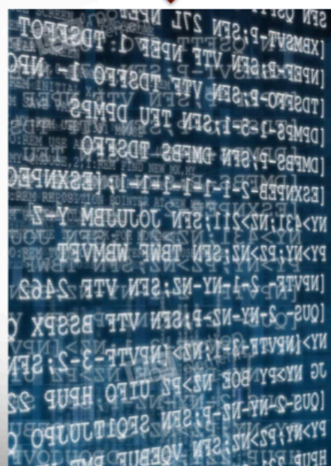
- System Description
  - System involves the human operator using a forklift to retrieve a pallet being stored on a shelving unit and move it to a new target destination. There is a second forklift being operated in the vicinity as the primary forklift.

- Component-energy table

Note: Use an underscore instead of a space when naming system components!

Component	Translation	Potential	Rotation
Operator	X	X	O
Pallet	X	X	O
Lift_1	X	X	O
Lift_2	X	X	O
Shelving_unit	O	X	O

Component	Translation	Potential	Rotation
Operator	X	X	O
Pallet	X	X	O
Lift_1	X	X	O
Lift_2	X	X	O
Shelving_unit	O	X	O



	A
1	Operator Translation transferred to Pallet
2	Operator Translation transferred to Lift_1
3	Operator Translation transferred to Lift_2
4	Pallet Translation transferred to Operator
5	Pallet Translation transferred to Lift_1
6	Pallet Translation transferred to Lift_2
7	Lift_1 Translation transferred to Operator
8	Lift_1 Translation transferred to Pallet
9	Lift_1 Translation transferred to Lift_2
10	Lift_2 Translation transferred to Operator
11	Lift_2 Translation transferred to Pallet
12	Lift_2 Translation transferred to Lift_1
13	Operator Translation converted to Rotation
14	Operator Potential converted to Translation
15	Operator Potential converted to Rotation
16	Pallet Translation converted to Rotation
17	Pallet Potential converted to Translation
18	Pallet Potential converted to Rotation
19	Lift_1 Translation converted to Rotation
20	Lift_1 Potential converted to Translation
21	Lift_1 Potential converted to Rotation
22	Lift_2 Translation converted to Rotation
23	Lift_2 Potential converted to Translation
24	Lift_2 Potential converted to Rotation

Things to Consider

- Filling out the component-energy table is a somewhat subjective task due to the variant determination of 'major' components and their corresponding energies.

- The 'rotation' energy box is reserved for components that possess a particularly large angular velocity such as the blade of a power saw.

- Fluids can be considered major system components because they can have energy (i.e. rivers, wind, etc.).

References

[1] - Ericson II, Clifton A. *Hazard Analysis Techniques for System Safety 1st Edition.* John Wiley & Sons, Inc. Hoboken, New Jersey. 2005.

[2] - *Guidelines for Hazard Evaluation Procedures Third Edition.* John Wiley & Sons, Inc. Hoboken, New Jersey. 2008

[3] - Howell, Elizabeth. *Columbia Disaster: What Happened, What NAZA Learned.* Space.com. Feb 1, 2010. http://www.space.com/19436-columbia-disaster.html

Texas A&M University
&
Sandia National Laboratories

TEXAS A&M UNIVERSITY