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Utilizing the Human, Machine, and Environment Matrix in investigations

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Abstract

"How did we get into this situation?" How many times has this question been asked at the outset of an investigation, or more importantly, at the completion of an investigation? If the answer is not readily and thoroughly apparent, the investigation is not complete. Subsequently, those who will have the responsibility for correction of the conditions leading to the incident will not have all the information necessary to properly complete their task.

For many years, in many writings, the Human/Machine interaction and its impact on process design has been discussed. The same impact should be examined when performing incident investigations. Consideration of the interaction of human and machine along with the environment in which they are used has long been recommended by the National Safety Council, in both design and investigation.

Keywords: Accident; Investigation; Incident; Human factors; Change; Management; Interviews; Litigation; Third party injuries; Data collection

1. Background

On February 3, 1959, the wreckage of a four passenger Beech-Bonanza airplane carrying Richard Valenzuela (Ritchie Valens), Charles Holley (Buddy Holly), Roger Peterson, and Jiles P. Richardson (J.P. "Big Bopper" Richardson) was found. Their airplane had gone down in the middle of the night enroute from Mason City Airport in Iowa to Fargo, North Dakota. All three passengers and the pilot died on impact.[1]

Incidents like these can be explained, but due to the subject and intensity of most situations a specialist is needed to perform an accurate analysis. In some incidents, these accidents result in litigation. In these cases, the companies call upon experts, engineers, and/or investigators to the investigation site to perform an analysis. The investigators collect data and evidence, document the scene, and interview all witnesses and persons involved.

Through the collection of this data a complete scientific analysis is done. The data, observations, and logic need to be organized to facilitate clearer thoughts and conclusions. The analysis is also done in accordance to a code of ethics for an engineer to ensure the work is done with all honesty, integrity, equity, and impartiality. Their work is dedicated to the protection, safety, and well being of all persons. Once an analysis is completed, the findings are presented to the companies, and then all necessary information is given to the proper parties involved with the investigation. The presentation of the concluding analysis should contain no bias and uphold their neutrality in the case and follow all professional standards. At the conclusion of the investigation, the findings can result in recommendations for updated standards, improved safety regulations, and improved practices for both the worker and the employer.

An example of such an event is the toughened tire testing for tires placed on sport-utility vehicles and lightweight trucks. After 700 people were injured and over 200 people died, an investigation was made of the Firestone tires and Ford Explorer combination. The tires on sport-utility vehicles and lightweight trucks will now have to pass the higher standards of tests for passenger-vehicle tires starting in 2007.[2,3] Another example is the development of the Second Generation air bags. The air bag was developed to improve the safety of the driver and passenger in head on collisions. Investigations resulted when people were being seriously injured or killed when the air bag deployed. From

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[1] On this day: 1959—Buddy Holly killed in air crash. BBC News, 6/17/04 (http://news.bbc.co.uk/onthisday/hi/dates/stories/february/3/newsid_2802000/2802541.stm).

[2] Federal Standards for Tires tightened. *The Detroit News Auto Insider*, 6/22/04 (http://www.detnews.com/2003/autoinsider/0306/24/c01-201315.html).

[3] Feds Issue New Tire Safety Standards. *Consumer Affairs.com*, 6/22/04 (http://www.consumeraffairs.com/news03/tire_safety.html).

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the conclusions of these investigations, air bags are now being made to inflate/deploy with 20–35% less energy.[4]

2. Introduction

An incident can be defined as an unplanned occurrence that result in injuries, fatalities, loss of production, or damage to property and assets. Without a firm understanding of the cause of an incident, prevention of future occurrences becomes extremely difficult. Preventing incidents is extremely difficult in the absence of an understanding of their causes. Over the past 80 years, a variety of incident causation theories have been proposed. Some of them include the following.

Single Event Theory is basically a "common sense" approach that regards an incident as being the result of a single, one-time easily identifiable, unusual, unexpected occurrence. All responsibility for the incident is placed on a single event or cause. This approach is simplistic in the extreme, and in general, an investigation that adopts such an approach does not produce a quality report or result in effective corrective or preventative actions.

The Domino Theory evaluates the incident as a series of related occurrences, which culminate in a final event that results in injury or illness. Like dominos, stacked in a row, the first domino falling sets off a chain reaction of related events. It is assumed that eliminating any one of these events would result in the chain being broken and the incident prevented. According to W.H. Heinrich (1939, 1931?), who developed the theory, 88% of all incidents are caused by unsafe acts of people, 10% by unsafe actions and 2% by "acts of God." He proposed a "five-factor incident sequence" in which each factor would actuate the next step in the manner of toppling dominoes lined up in a row. The sequence of incident factors is as follows:

1. ancestry and social environment;
2. worker fault;
3. unsafe act together with mechanical and physical hazard;
4. accident;
5. damage or injury.

In the same way that the removal of a single domino in the row would interrupt the sequence of toppling, Heinrich suggested that removal of one of the factors would prevent the incident and resultant injury; with the key domino to be removed from the sequence being number 3.

Multiple causation theory is related to domino theory, but it recognizes that for a single incident there may be many contributory factors and that only a particular combination of these factors will lead to an incident. According to this theory, the contributory factors can be grouped into the following two categories: behavioral and environmental. The former category includes factors pertaining to the worker, such as improper attitude, lack of knowledge, lack of skills or inadequate physical, and mental condition. The latter category includes improper guarding of other hazardous work elements and degradation of equipment through use and unsafe procedures. The major contribution of this theory is the highlighting of the fact that rarely, if ever, is an incident the result of a single cause or act.

A variety of other incident causation models have been developed in recent years, but almost all share one common thread: the need to look at the incident from a wide perspective taking into account contributing factors from three primary sources—the human participant, the apparatus involved, and the environment in which the incident occurs. In a typical incident, all three sources interact and contribute to both the likelihood of an incident and its severity.

One of the critical elements in any incident investigation is compiling the necessary information in such a fashion that the causal chain can be determined. Often, data is available, but is haphazardly organized so that no recognizable patterns within it are apparent. This paper will discuss techniques for organizing incident-related information via a nine-element matrix, which addresses the Human, the Machine, and the Environment elements during three critical time phases—before, during and after the incident. Methods for defining and selecting criteria for each of the nine elements will be explored. Examples of type and depth of data and information for each of the nine elements (cells) will be presented, as well as answers to such questions as:

- How is the appropriate time frame for the "Before" incident period selected?
- Why do we look at the after incident time period?
- How do we collect and store data using these methods?
- How do we analyze data using these methods?
- How does this correlate with the scientific method?

3. History

The "Human–Machine–Environment Matrix" as described in this paper was developed by Alphonse Chapanis and Paul Fitts of the Army's Aero Medical Laboratory during World War II. Both were tasked with investigating airplane accidents that had been determined to be the result of "pilot error."[5] Due to the rapidly increasing complexity of aviation technology and the resulting human error, their investigations became progressively more challenging as time went on. Fitting the incident data into the "Human–Machine–Environment Matrix" allowed them to better organize their work product and data, as well as facilitating the development of clearer thought and conclusions.

The Federal Aviation Administration was one of the first governmental agencies to routinely use the "Human–Machine–Environment Matrix" in their investigations, with many civilian firms rapidly following suit. The organizational structure of the

[4] Air bags. *Ford Motor Company*, 6/17/04 (http://www.ford.com/en/innovation/safety/airbags.htm).

[5] New Book Release: *The Chapanis Chronicles: 50 years of Human Factor Research, Educations, and Design*. Human Factors and Ergonomics Society, 7/12/04 (http://cstg.hfes.org/bookchapanis.html).

	Before	During	After
Human			
Machine			
Environment			

Fig. 1.

matrix applies equally well to aircraft or automobile crashes, fires and explosions, structural mishaps, and other types of incidents. The categorization process helps to clarify whether the incident was the result of human error, mechanical fault, environmental conditions, or some combination of the three factors.

4. What is the Human–Machine–Environment Matrix?

The "Human–Machine–Environment Matrix" has also been called the "Nine-Box Matrix." For purposes of brevity, the two terms will be used interchangeably.

The matrix is basically a tool used to organize the sequence of events before, during, and after an incident occurs into readily understandable basic categories. The matrix is organized into three vertical columns based on the time frame during which the contents are applicable, with three rows breaking out the contributions within the time frames of the potential contributing elements (the Human, the Machine, and the Environment) (see Fig. 1).

The start and end of each time interval will vary by incident. Interview questions, data collection, and investigation strategies could differ also. Additional investigation into the sequence of events will determine if certain events played a significant or crucial role in the incident. It is not always clear in what order the events occurred. For example, did the man have a heart attack that caused the automobile accident or did the heart attack result from the automobile accident? Did the item's damage cause the fire/explosion or did the fire/explosion cause the item to be damaged?

All too often an inexperienced investigator will focus only on the physical facts immediately around the location and time frame of the incident. Establishing Human, Machine, and Environment factors leading up to the incident are crucial in determining all the elements connected with the incident.

5. Defining the matrix

5.1. Time dimensions

A number of critical issues must be resolved prior to attempting to enter data into the matrix for examination. One of the most common is "How is the "Before" time limit established? All of us have probably heard the tale of the king's horse losing a nail from its shoe, resulting in the loss of the kingdom. This provides a perspective for establishing the "Before" limit. Generally speaking, the investigation should go back in time until "all was well" or the entire system was operating and performing in the designed manner.

One of the fundamental tenets of process safety management is management of change. Tracing incident-related process changes from the inception of the process to the time of the incident is the correct procedure. The investigator must examine the original process design intent to insure that the design was based on correct assumptions. An investigation performed by one of the authors found that after the process description changed one essential preposition, the result was an eventual explosion. Another investigation found that the original design intent for a piece of equipment assumed a continuous flow through a drain. During the ensuing 50 years of use, it became clear that such an assumption was unfounded. Such an examination highlights the value of maintaining process and equipment data and information. Considering the sometimes rapid changes in ownership and staff that can occur in today's world, this can be even more important. Additionally, as with PHA studies previous incident history can be very revealing. Were there any previous incidents? Were those incidents investigated? What were the results of the investigations? What corrective steps were taken? Were those steps effective?

In some cases, the "Before" timeframe is determined by the "Human" element in the matrix. The following set of questions can aid in determining the "Human" start point:

- When was the individual employed?
- What training did the individual have (both before and during employment)?
- Were there any other individuals involved (frequently there are) and how?
- In the case of third parties or contractors, what were the contract scope and terms? In some cases with subcontractors, this may be complex.
- What other positions did the individual hold at the facility and before?
- Had training kept pace with process changes (including increasing production rates)?

In some cases the "Environment" as it effects either the machine, the working conditions, or the person may determine the "Before" time period. In one investigation, it was found that an operations group had been substituting for trained operators for two years prior to an incident in order to continue facility operations through a strike.

How is the "During" time frame established? This time frame may vary during the course of the investigation as information clarifies the sequence of events. Normally, the "During" time frame starts with such critical events as when a process upset detected, when starting up of process from a down period, or the entry of the "person" into the process.

The boundary between "During" and "After" is normally set at the point where the process or equipment is automatically or manually shutdown following an incident.

In some cases, the aftermath of decisions made because of an incident are incidents in themselves or else exacerbate the extent of the original incident. Such was the case in the Sandoz fire, where the environmental impact after the fire was significant, or the radioactive aftermath of the Chernobyl incident. The end of the incident investigation time frame, therefore, occurs when all elements involved (the Human, the Machine, and the Environment) are stabilized. This may mean further monitoring during the investigation. This may also mean investigation of the events and proceedings following the incident. It should be kept in mind that the time frames for each incident may be different, and that no "hard and fast" rules are possible.

Once the time frames of the matrix have been defined, it is important to work from the beginning to end when populating it with data. In interviews and other information and data collected, it is important to identify time. At some point in the analysis, observations noted in interviews or actions taken and their time relationship may be crucial to determining the true sequence of events. The TapRoot System teaches using self-adhesive notepaper so that items can be easily moved or inserted.

After collecting data from all sources, there will be several versions of the sequence of events that must be merged into a single common time-line. It is often critical that anomalies or inconsistencies between time-lines be resolved. Once the sequence of events is established, the actions or conditions of the Human, Machine, and Environment at particular points in time can be examined.

5.2. The elements

The Human factor may include several individuals that may have been involved in varying degrees with the incident. These may include:

- the injured,
- witnesses,
- equipment installers,
- operators,
- maintenance personnel,
- management, and
- engineers.

Considerable thought should be put into determining all the individuals that might have relevant input. This may include those knowledgeable from previous incidents. Each individual involved should be interviewed with time lines and event sequences established. Typical "Human" elements would include such information as gender, age, health, training level, experience, past safety and accident records, distractions, medications, etc.

The "Machine" element may range from a single machine to a group of machines to an entire process. Once again, historical data for the machine and the operating data for the process are important, as is examination of the design intent for the equipment from both from the process design and the equipment manufacturer's perspective. In one incident, the manufacturer's rating for sight glass was important in determining the pressure exerted on a vessel. Were the instrument readings accurate? Where were the sensing points? Were interlocks and/or alarms installed and operational?

The "Environment" should be viewed from two perspectives. First, the environment under which the equipment or process (this could include internal effects such as corrosion) proceeded, and second, the environment in which the human operators performed.

For the process and equipment, the Environment will include such information as the historical exposure to process conditions, physical conditions and weather conditions. There are a myriad of gradual process conditions that can degrade the equipment. In one incident, the effects of static electricity from cleaning mops was the root cause for computer failures. Close physical and scientific examination of equipment (or pieces) can often provide a history of the conditions that have been present in the past. Has the process and equipment been operated as per the design intent? It is important to be thorough in such examinations, since process subtleties may be key issues. In one incident, a change in the raw material supplier was the cause of an accident. Was the equipment or process intended to operate in the internal and external environment present?

The human environment may also be highly variable. There are the workplace guidelines that address heat, light, weather, noise, and other variables, but such conditions may combine to increase stress on workers. When interviewing individuals involved in an incident, some key questions to ask include:

- Where were you?
- What did you see, hear, smell, feel, etc.?
- When was that?
- What were you doing?
- What did you do (and how)?
- What was the weather?
- What were you wearing (safety gear often limits sight and hearing)?
- What were the conditions at the time? (process noise, steam, lighting often obscure view).

6. Interactions within the matrix

While the nine-element matrix provides an excellent framework for identification and categorization of important issues in each of the three areas on which an incident analysis must focus, it suffers from one major drawback. Many often critical issues do not fall neatly within the broad categories of "Human," "Machine," or "Environment," but rather are interactions within these areas. A second complementary method of categorizing data that highlights these interactions is often necessary.

Use of a Venn diagram such as that illustrated in Fig. 2 is a good method for accomplishing this. The diagram highlights the fact that interactions between two or even three of the major elements of the incident analysis matrix are categorically different from the elements themselves. As can be readily seen, the primary interactions are Human–Machine, Human–Environment, Machine–Environment, and the triple interaction between all three elements.

Human/Machine interactions are those that relate to the design of machines or processes with regard to the capabili-

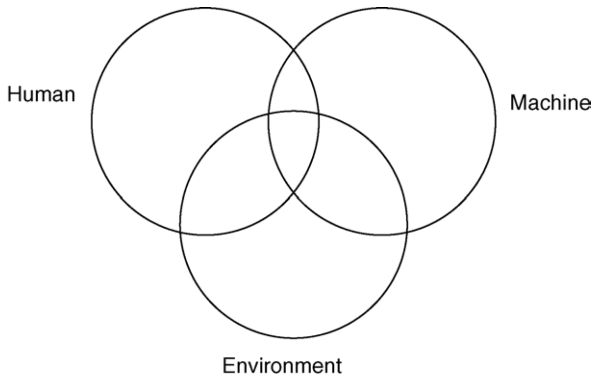

Fig. 2.

ties and limitations of their human operators. These can include such issues as:

- Guarding design (size, location, type).
- Information processing/flow/machine design (involving such issues as information presentation style, rate, type, format, etc.).
- Industrial ergonomics (the effects of work on the human body, human strength, body sizes, reach envelopes).
- Operator behavior and performance (reaction time, rate stress, safety consciousness, fatigue, vigilance).
- Warnings and Instructions (comprehensiveness, understandability, formatting, detectability).
- Machine Design and Affordances (Does the design of the machine suggest a particular method of interaction? Is this method compliant with the actual intended operation of the machine?).

Workplace and task design (Is the workplace optimally designed for the task to be performed by the operator, or is it likely that the operator will have to "work around" the design rather than "working with" it?)

Human/Environment interactions may involve such issues as perception, performance, and behavioral issues with regard to the workplace. The "environment" in this case may not only include such issues as noise, lighting, vibration, temperature and other "physical" environmental considerations, but also such "social environment" issues as work rate and pacing, the safety climate of the workplace, etc. Many investigators make the mistake of assuming that human performance parameters that are often obtained in a more-or-less ideal situation remain constant even when the environment in which the task is performed is radically different. Simple consideration of the comparative ability of a truck driver to detect and identify an obstacle in the roadway during daylight versus night timeframes readily illustrates that such assumptions may be questionable at best, and actively misleading under many conditions.

Machine/Environment interactions may involve such issues as corrosion when machinery is used under damp environmental conditions, machine overheating whether from excessive use or adverse environmental conditions, changes due to extreme cold weather, and a variety of other issues where the environment in which the equipment is put to use is other than the one for which it was designed. The triple interaction (Human/Machine/Environment) covers a wide range of potential issues as well, ranging from the likelihood of repetitive stress injuries due to combined excessive required levels of operator force and high repletion rates to degradations in human performance stemming from continually changing shift work schedules to the effect on human performance from such effects as vibration, noise level, and other factors related to machine operation.

Whatever interaction effect is of interest, it is important to recognize that both equipment and operators only perform at optimal levels within a relatively narrow environmental (both social and physical) range. Large deviations from this idea may potentially result in equally large deviations in performance and incident likelihood. Such interactions must be carefully considered in the analysis of any incident scenario.

7. Scientific method

How does the scientific method interact with this approach? The scientific method teaches us to establish potential causes and hypotheses and then to test each for validity. If the results of the investigation have been properly entered into the Nine-Box Matrix, all of the necessary information should be readily available to either propose or eliminate hypotheses. Frequently, the final examination of surviving hypotheses will lead to testing, modeling or a requirement for further information collection or refinement. However, if the information has been collected and categorized properly, such additional information collection should not lead to even further hypotheses.

Many unskilled investigators take the approach of hypothesizing a single cause for an incident and then assiduously collecting information in an attempt to prove their hypothesis. This approach for investigating a machinery failure is visually represented in Fig. 3.

Unfortunately, such an approach is contrary to the dictates of good science. There remains a vast area of potential causation that remains completely unexplored. The proper approach

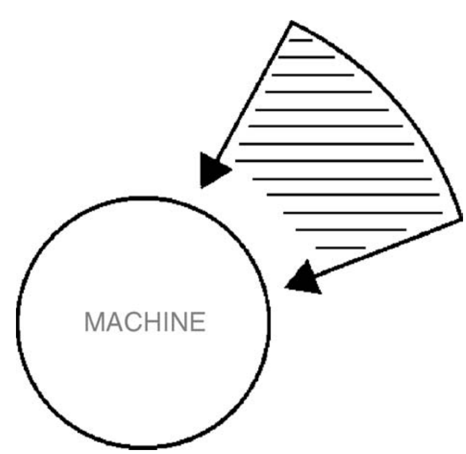

Fig. 3.

is to collect information first, which then forms the basis for an explanatory hypothesis. The hypotheses generated then drives further data collection or experimentation. Approaching the an incident investigation with the intention of proving a hypothesis propounded prior the collection of any data, may result in a supportable cause for an incident; what it cannot do is to eliminate other potential causes or put the likelihood of the investigated possible cause into perspective with regard to other potential causes. Just because a potential causal chain is consistent with the facts of an incident, it does not imply that this is the only potential cause that is consistent. One is reminded of the old joke:

Sherlock Holmes: "Watson, I deduce that you had eggs for breakfast."
Dr. Watson: "That's astounding, Holmes. How did you guess that."
Sherlock Holmes: "Based on the fact that you have egg yolk on your waistcoat."
Dr. Watson: "Astounding, Holmes. Only one problem. I had waffles for breakfast this morning. I had eggs for breakfast yesterday. I simply have not changed my clothes since then."

Employing the matrix to collect and organize all available information helps to prevent the investigator from becoming channeled onto only a single approach or possible cause. The organization of all of the available data and it's ease of assimilation allows him or her to examine the incident from a variety of perspectives, easily eliminating potential causes based on contrary evidence or lack of supporting evidence. The potential for arriving at the correct cause for an incident and being able to direct preventative actions appropriately is thus greatly enhanced.

8. Summary

The Human–Machine–Environment Matrix along with the recommended Venn interaction diagram is an ideal methodology for organizing information developed during incident investigations. Proper employment of both leads to rapid identification of areas where more information is required, ease in causative hypothesis generation, and straightforward rejection of unsupportable hypotheses. It also has the added benefit of preventing the investigator from becoming focused on a single potential cause too early in the analysis.