Mobile Virtual Reality — An Approach for Safety Management

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1. Introduction

Workplace safety is paramount for all production sectors throughout the world. However, every year the number of occupational injuries attracts concerns on the safety management for every industry. Existing studies have endeavored great efforts on injury causations and found that more than half of workplace accidents are due to human errors.

For most human errors, professional training is believed to be an effective safety enhancement and management approach. Active and interactive training is often of higher level of comprehension while the passive methods of learning are not as effective, especially for adult learners. Most current electrical safety training programs in terms of video tape, paper-based handouts or slide shows can hardly present the electrical hazards vividly to trainees and, on the other hand, the trainees are not provided enough opportunity to participate in these activities. In fact, it is believed that an active and interactive training program can lead to a better comprehension of training material [1]. Such participatory training brings a real life aspect into the training in an "it can happen to you" scenario and allows the trainees to relate to conditions and regulations in real life situations and with a life or death importance. The best scenario is when people do not have to consciously think about following safety procedures because it is second nature to them.

Safety training as safety management means has been existing for years, however what type of training can be the effective approach remains a question. Rooney, et al. [2] suggested that effective training should comprise of both the initial skill training and further refreshing training to reduce human mistakes. The initial skill training is generally conducted in the classroom and supplemented with on-the-job experience. It prepares workers for experiences they will routinely encounter and those they will infrequently encounter. If training does not include the infrequent events or situations, the likelihood of successfully handling such situations will depend solely on the problem solving and decision making skills of the worker. In addition to initial training, refresher training on non-routine or modified tasks will minimize worker mistakes and reduce the potential for a worker's skills to deteriorate. A refresher training program is needed to assist workers in developing and maintaining a high skill level. Such a program will address a worker's loss of skills and enhance skills beyond the initial training level.

Following the same logic, virtual reality (VR) technology becomes an innovative method to promote the training effectiveness. VR-based training has been used with varied successes in many industries such as fire-fighter training, mine safety training, safe procedure in surgical training, security in refineries, safe equipment operation, and civil engineering education. Specifically within the construction industry, VR technology has been used for constructability analysis of precast concrete structural analysis application development [3], electrical design and installation [4], construction prototyping.

Mobile virtual reality (MVR) is an adoption of VR simulation on mobile/portable devices connected to cloud technology for end users. Besides the inclusion of features from VR, another important characteristic of the MVR-supported training programs is the flexibility (in terms of time and location) that they offer to the user. In traditional classroom-based training/ instruction, availability of the training provider and trainees need to be coordinated to schedule the training session. MVR, especially when designed for use with a mobile device, allows for convenience of location and time. The user can participate in the training in a job trailer, office, or conceivably the back of a truck with a smart phone. There is no limitation to classroom or training schedules. Tracking the user performance can be built into the applications, which reduces the need for direct trainee observation. Taking mining as a MVR example, users are able to explore sights and sounds of a virtual mine shaft where the screen of the iPad or iPhone is a window into the mine and interact with the environment via the touchscreen. Based on their activities, the trainee is sent messages and questions, and the mine shaft environment changes to match the response criteria.

Current training modes do not count for all learning style and result in information transfer losses (see gaps in Figure 1a). In terms of safety training, information transfer losses include the loss between the information to be expressed and the expressed information (gap 1) and the loss between the expressed information and delivered information (gap 2). Current static two-dimensioned training modes limit the types of safety information and the pool of information receivers, leading to gap 1. Some dangerous tasks and safety issues cannot be allowed for trainees to rehearsal and practice in real life, leading to gap 2. On the contrary, MVR increases a third dimension and mobility, expands the portions of both expressed and delivered information, and eventually helps to deduce the gaps of information losses (see Figure 1b).

The effectiveness of information perceiving is also confined to traditional training modes. As stated before, for adult trainees, interactive and active training methods instead of passive methods can lead to a better comprehension of training material. Such participatory training brings a real life aspect into the training in an "it can happen to you" scenario and allows the trainees to relate conditions and regulations with real life situations and a life or death

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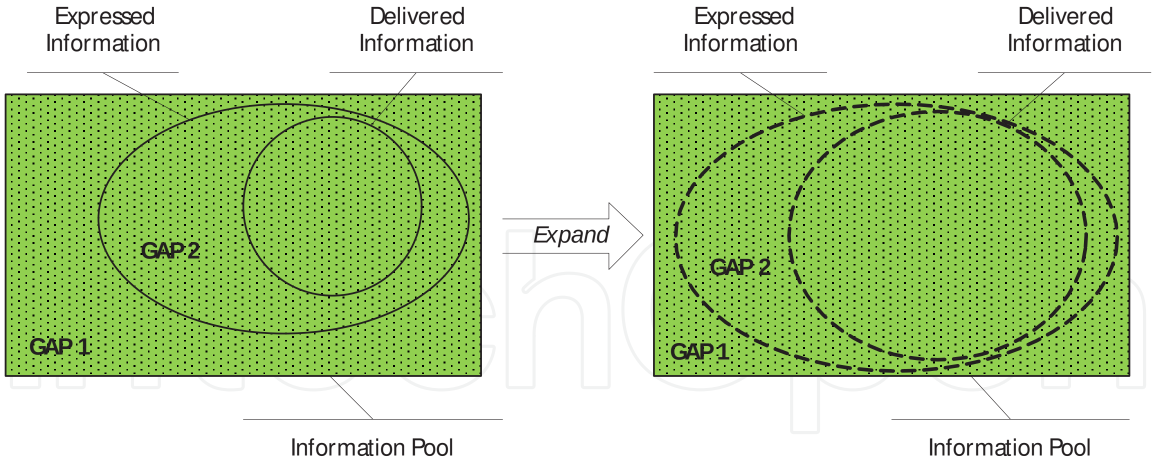

Figure 1. Information transfer in traditional training (L) and MVR-supported training (R)

importance. The best scenario is when people do not have to consciously think about following safety procedures because it is second nature to them. However, current electrical safety training programs in terms of video tape, paper-based handouts or slide shows can hardly present the electrical hazards vividly to trainees and, on the other side, the trainees are not provided enough opportunity to participate in.

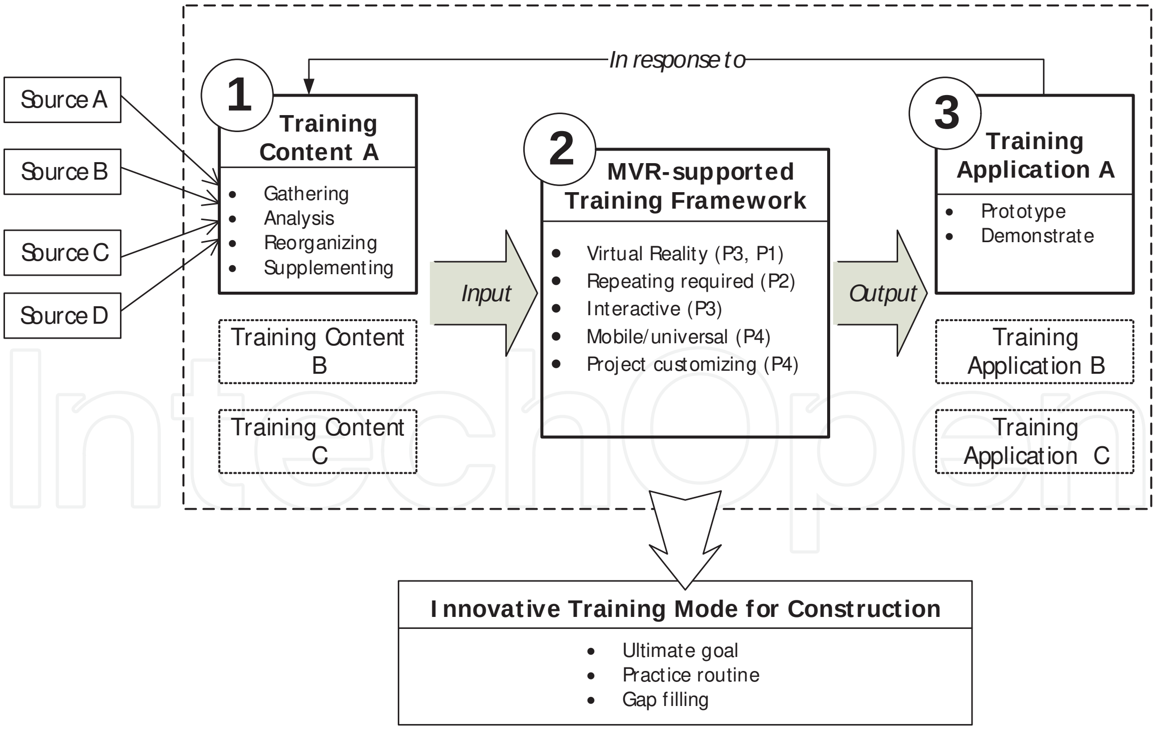

Figure 2. Program development framework

This chapter introduces such comprehensive approach that incorporates real-world safety concerns into virtual-world simulations. The approach includes three steps: (1) real-world data collection and coding using a text analysis method; (2) scenarios determination using latent class clustering; and (3) simulation in a virtual environment. The whole process enables to transfer existing safety failures reflected in injuries into training points in a 3D virtual environment for users to practices. This chapter will also provide an example to demonstrate the approach using electrical fatality data from the U.S. construction industry. Mostly, the data and programs demonstrated in this chapter are selected from the author's previous works (Zhao and Lucas, 2014; Zhao et al., 2014b; Zhao et al., 2014c). Fig. 2 gives the framework of the demonstration case of electrical safety in the construction industry.

2. Real-world data collection

This section introduces a systems method to collect real-world accident cases and extract information for building the virtual program. Here, the author takes an example from the electrical safety in the construction industry to demonstrate the data collection process.

2.1. Factor background

As Figure 3 shows, the ideal solution for integrating construction safety innovation in electrical contracting (EC) needs to fit: 1) the technical and cultural nature of the industry in terms of innovation, 2) the needs of small construction firms and 3) the nature of hazards for ECs. This solution needs to be safer, affordable, accessible, participatory and context/task-specific while integrating technology innovations into practical routines to achieve higher effectiveness and better human habitus in construction. Also, this solution needs to respect human learning behavior and human cognitive rules. As a result, an innovative training approach such as the MVR appears to be a viable solution.

Relevant factors need to be distilled to represent the cases. A fishbone (or Ishikawa) diagram is a helpful tool to complete this step. Based on events and causal factors thinking, the fishbone diagram provides a systematic way of breaking down a complicated problem and identifying areas for data collection. Figure 4 illustrates fishbone diagram to generate factors which are used in the electrical safety example in the next section.

2.2. Data collection example

The example choose the data from U.S. electrocution investigation reports. These reports provide an historical perspective from 1989 to 2012. This period of time was also deemed appropriate, as it contains data during many of the years previously reported with alarming statistics on electrical incidents in US construction.

The fishbone mapping tool also provides an accessible process for distilling complex reporting structures into salient categories of data for study. As a result, (previously shown in Figure 4), 13 factors were categorized using five categories which included: when, who, where, what and how. Under each category, 13 related factors were created based on the information gathered from FACE reports as well as from extended literature reviews. Therefore, using

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these factors, information from narrative text can be coded into an information table (shown in Figure 5).

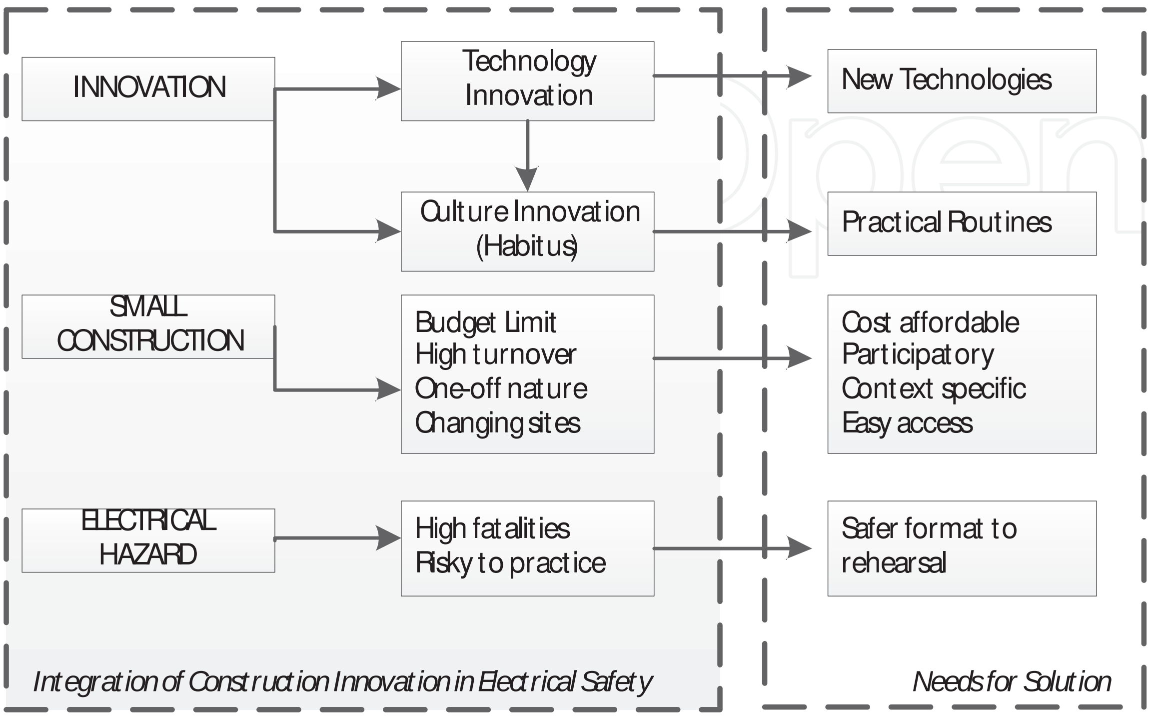

Figure 3. Needs for construction innovation in electrical safety

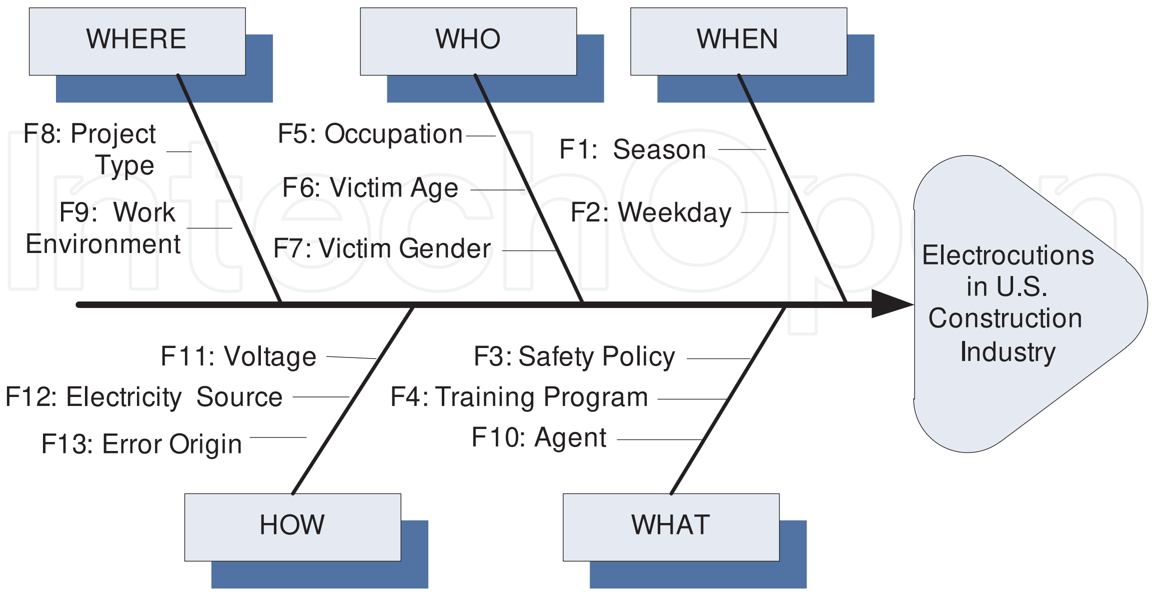

Figure 4. An example of fishbone diagram

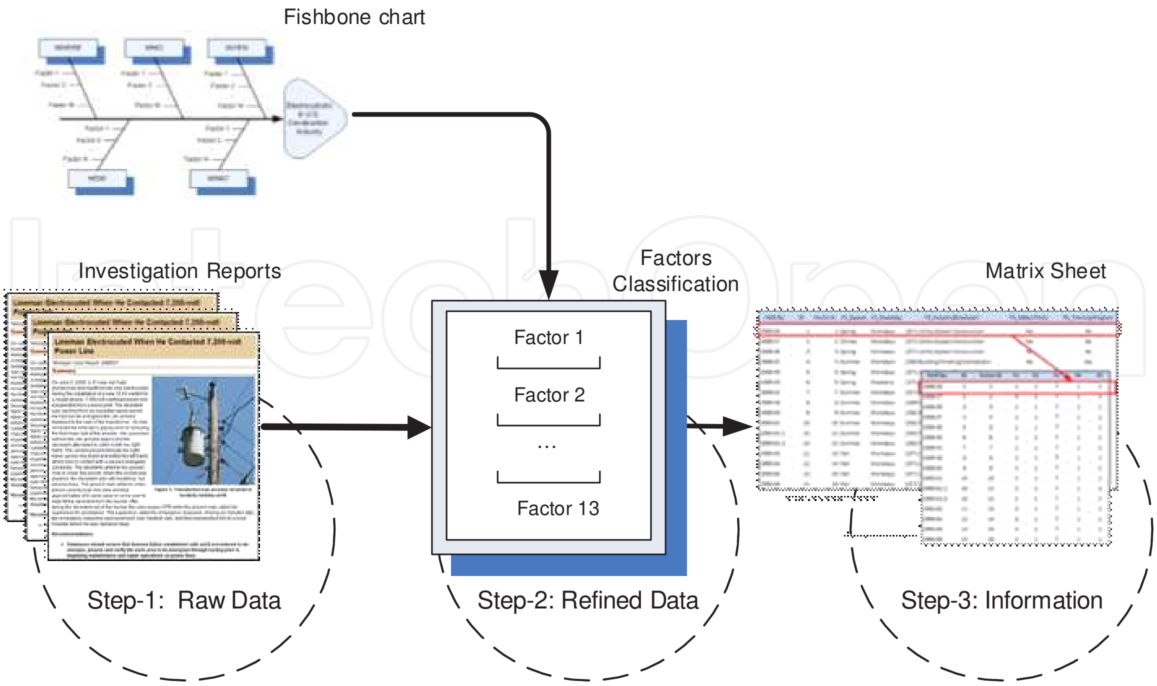

Figure 5. Coding process diagram

3. Scenarios identification

This section elaborates a statistical method to build the connection between real-world data and virtual elements. Typical elements in a scenario comprise characters, scenes and events. The characters, including the trainee, represent all roles who participate in the simulation. Here, characters can be created based upon the training target's demographic features. The scenes depict necessary circumstances such as time, place and properties, which are created in accordance with the factor values of a hazardous pattern. The events refer to all the training tasks, hazards associated with the tasks and the respective safety procedures.

3.1. Statistical analysis

The statistical method is the Latent class analysis (LCA). LCA has some merits over other similar techniques (de Oña et al., 2013): (1) being able to use different type of variables; (2) being able to choose different type of statistical criteria; and (3) being able to using subsequent membership probabilities with maximum likelihood method. Latent classes are unobservable subgroups or segments. Cases are homogeneous within the same latent class while distinctive from each other in different latent classes, depending on certain criteria (Vermunt, 2008). The latent class analysis is a technique to identify the smallest number of latent subgroups or clusters that are sufficient to explain all the associations among manifest variables in a sample group. As shown in Figure 6, a latent class is represented by *N* distinct categories/values of a nominal latent variable.

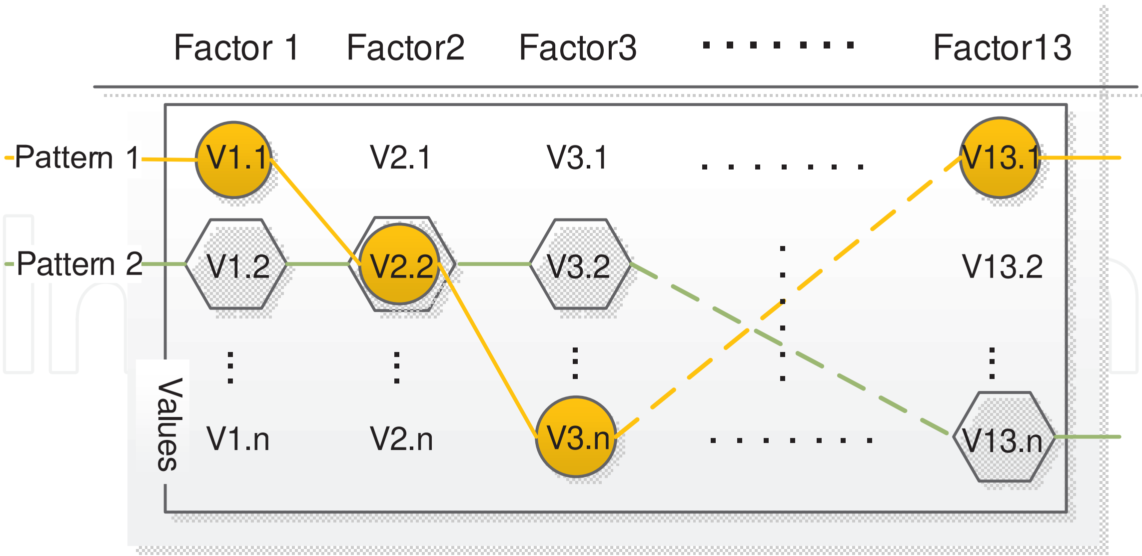

Figure 6. Coding process diagram

Recently, LCA is able to include mixed-scale-type variables and covariates, and thus has been adopted in a wide-range of research areas including accident analysis (Collins and Lanza, 2010; Depaire et al., 2008). Given *X* representing the latent variable with value *Y*, and suppose *M* be the LC number and *N* be the variable number. A particular LC is enumerated by the index *x*, *x*=1, 2, …, *M*, with value set *Y* ($y_1, y_2, \ldots, y_n$). The aim of LCA is to determine the vector notation *Y*, referring to a complete injury system pattern, by computing the conditional multivariate probabilities *P* (*Y*=*y*), as:

$$P(Y=y)=\sum_{x=1}^{M}\left[P(X=x)\prod_{n=1}^{N}P(Y_n=y_n \mid X=x)\right] \quad (1)$$

where *P*(*X*=*x*) denotes the proportion of injury cases belonging to LC *x*.

The most widely used LC fitting criterion is the likelihood ratio chi-squared statistic L^2. L^2 builds on the likelihood of the data under the null hypothesis relative to the maximum likelihood, as:

$$L^2=2\sum_{i=1}^{I}\left[C_i \times \ln \frac{C_i}{C \times P(Y=y_i)}\right] \quad (2)$$

where *C* denotes the total injury case size; C_i denotes the observed frequency of pattern *i*; $P(Y=y_i)$ denotes the probability of having the pattern *i*; and *I* denotes the total number of possible patterns in the *N*-dimensional frequency table, as:

$$I=\prod_{n=1}^{N} n \quad (3)$$

L^2 statistic is advanced on calculations especially for a large number of variables as it enables a decomposition of them into smaller components. Further, this work also incorporates other popular criteria to evaluate the LC model's goodness-of-fit for the sake of research reliability. They are the L^2 based Akaike's information criterion (AIC), the Bayesian information criterion (BIC), and the consistent AIC (CAIC). These statistical criteria measure LC's parsimony. A lower criteria value means a higher parsimony, which indicates a better model fitting. An LC model with a lower BIC value is preferred rather than one with a higher BIC value.

3.2. Data analysis example

After previously imported coded data into this analysis, the author assigned LC number from 1 to 10 (M=1, 2, …, 10, see Equation 1) to the LC model and named them model#1 (M=1), model#2 (M=2), …, and model#10 (M=10), respectively; then evaluated model#1 to model#2 through calculating their fit criteria values. The LC model fit criteria applied in this example included the likelihood ratio chi-squared statistic L^2, BIC(L^2), AIC(L^2) and CAIC(L^2), and usually a lower value of which indicated a better model fitting. The results of model fit evaluation are demonstrated in Figure 2, which indicates that the model#3 (3 LCs, M=3) has better performance (lower BIC, CAIC) than other models. In addition, model #3's *p-value* of 0.056 (good when greater than 0.05) and *Npar* value of 50 (the number of parameters) also indicate a good separation between latent classes.

According to the results, Model 3 with 3 segments provided LC-dependent univariate distributions for each variable, allowing each later class to represent a typical electrocution system pattern. The overall probabilities of falling into LC #1, LC #2, and LC #3 are 41%, 36%, and 23%, respectively. To identify the characteristics of each pattern, the researchers examined values' loadings for each LC. The loading indicates the degree of correlation between the variable values and the designated LC. In multivariate statistical analysis, some research (Stevens, 2002) preferred a cut-off of 0.4 for important loading while some other (Kline, 1994) suggested 0.3 as an acceptable threshold, irrespective of sample size. Here, this work chooses the loading of 0.37 or greater to determine a closer correlation between the variable value and the corresponding LC of model #3. In this way, the significantly related values to each of the three scenarios are identified, alphabetically listed as following three groups:

- **Scenario A**: younger (age<40) male non-electrical workers die due to indirectly contacting high-voltage power lines or powered machines/tools, usually in Summer or Winter at outdoor workplaces. The employers do not have written safety policies nor provide safety training programs. This pattern is particularly related to the residential building construction projects.

- **Scenario B**: middle-aged (age 40-64) male electrical workers die due to directly contacting high-voltage power lines or electrical components, usually in Spring, Fall or Winter weekends at outdoor workplaces. The employers have written safety policies and provide safety training programs. This pattern is particularly related to the heavy and civil construction projects.

- **Scenario C**: adolescent (age<20) male workers died due to directly contacting low-voltage electrical components or powered machines/tools at an indoor workplace. Whether the employer has written safety policies or provides safety training programs is uncertain. This pattern is particularly related to the non-residential building construction projects.

As a result, three scenarios are identified from real-world contexts. Three construction types are coincidently allocated into the three scenarios. It implies that Scenario A is highly correlated to the residential building construction projects; Scenario B is highly correlated to the heavy and civil engineering construction projects; and Scenario C is highly correlated to the non-residential building construction projects. The results can be interpreted in a tri-plot diagram (see Figure 7), showing each scenario's characteristics in a more visual manner. In the diagram, the three angels indicate the three scenarios while the distance between any two points reflects their relationship (the shorter, the closer).

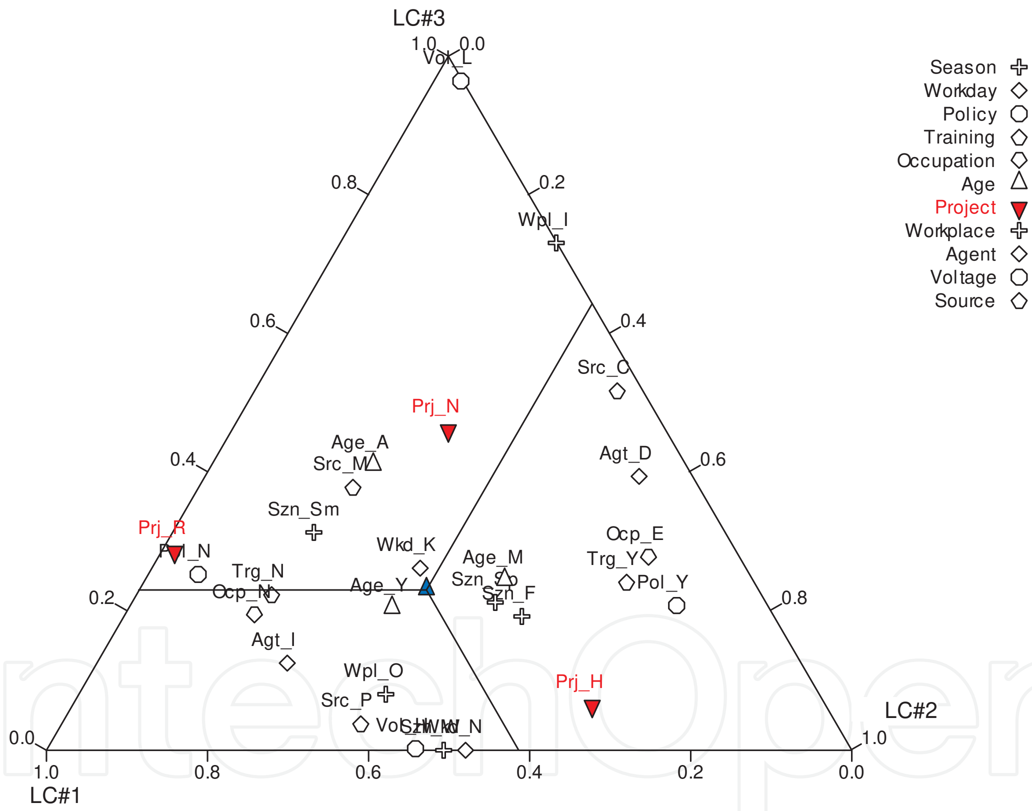

Figure 7. LC analysis triangle

4. Program development

This section introduces the program development using mobile virtual reality technology. The example for demonstration is the previously identified scenario B. Given the identification of typical workplace scenario, six training-critical points are created: the potential electrical hazardous awareness; the safe approach distance; the work condition clearance; the lockout and tag out; the suitable personal protective equipment (PPE); and the effective communication. These training points were required by OSHA regulations, National Fire Prevention Association codes (NFPA 70) and FACE report recommendations(Zhao et al., 2012). Based on the prototype simulation, a training point is linked to an event which consists of triggers and outcome animations. Taking the training point of work condition clearance for example, barriers such as waterlogging or storage boxes were added into the scenario. Users can only access the panel safely until they clear these barriers by touching them. If this training point is not completed, an electrical accident such as a shock may be triggered later and the outcome of an electrical shock will be represented via an animation (Zhao and Ye, 2012).

4.1. Design and modelling

The modeling process includes two separate parts: the 3D object modeling and 3D environment modeling. The 3D objects include buildings, machines, equipment, tools, materials, electrical components, background settings and worker actors. Most of these models were created using Autodesk's 3ds Max, such as a mobile crane and electricity transmission tower. 3D environment modeling includes designs of area terrain, sky clouds, sun point, wind, rain (if necessary), light layout, landscape as well as relative sounds. Prior complete 3D models are imported into the completed 3D working environment, the whole of which resulted in a training scenario. Each electrical hazard and its responding tasks were simulated as interactive events through coding scripts. Scenarios and events were linked by animations. The training scenarios, including 3D objects and 3D environments, and integrated training events are together comprised of a training Module. 3D characters and properties are modeled in Autodesk's 3ds Max. Scenes are designed and compiled in Torque 3D game engine. For mobility, the output is published as an Android application.

4.2. User interface design

The User Interface (UI) is designed to connect all previously developed 3D objects and the 3D environment, which can be customized for specific project. The function of UI is to display a distinct set of scenarios, which are further broken down into a series of tasks, such as:

- load the 3D environment and facility model to the user scene;
- receive user input of the 3D character with relevant behavior for the user control in the preset environment;
- load the scenarios, display 3D elements, and activate the storybook;
- track the activities that are performed during the scenario, and response timely.

4.3. Development example

The training content of this example demonstrates one of construction scenarios in which electrical accidents often occur. The designated scenario is based on the previously identified

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scenario B: middle-aged male electrical workers die due to directly contacting high-voltage power lines or electrical components at an outdoor highway construction jobsite in September. The example scenario assumes energized indoor electrical components as the hazard. In the way, the storybook is compiled as:

- Character (or avatar): a young male electrician is modeled as the character;
- Time: Sunny day with the heavy sunshine and sun glares;
- Place: an unexposed highway construction surrounded with high-voltage distribution towers;
- Properties: comprise protective equipment, heavy machines like boomed cranes, road roller, and trucks.
- Task: lifting construction materials from truck to pave the road surface.

The prototype incorporated these features into one scenario which was a road construction site with overhead power lines surrounded The scenario development included two major aspects: environment modeling and storybook coding. The environment modeling simulates construction-related objects and characters while the storybook coding linked these objects and characters with hidden electrical hazards. The modeling and coding was completed using Autodesk 3DS max (see Figure 8) and Torque 3D package.

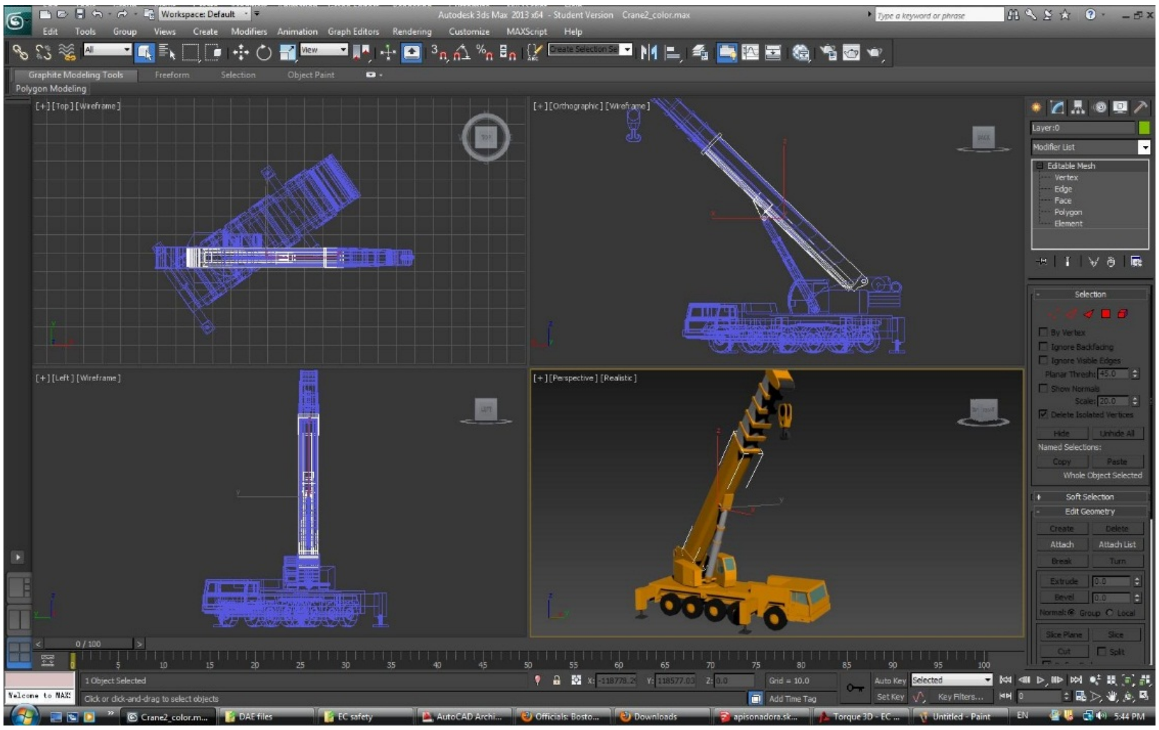

Figure 8. Elements Modelling

Simulation is processed on a module basis. Training elements are respectively simulated into virtual reality modules. Each module represents a major hazardous environment that could lead to electrocution. The working conditions, electrical hazards that workers are exposed to, and related work tasks are simulated in modules. The MVR simulations allow the users to recognize the hazards, identify them and intervene in a simulated virtual world. Trainees may participate in the safety working tasks, feel the hazards as well as its crucial outcome of failures (e.g., getting electrocuted), and hopefully transfer this experience to their real life working environment. Also, users are allowed to choose the specific module that is related to their daily work to get trained. This provides users the opportunities to choose which scenarios they would like to complete and allows them to be trained for designated working tasks or work environments.

Figure 9. User Interface Testing

The simulation storybook is presented through a thread of independent interactive events. These events are triggered by various approaches depending on the desired reaction. When the user walks through the scenario following instructions, a variety of hazard triggers will be touched and then the pre-programed reactions will be activated as responses. For examples, a touch approach is used to trigger the training event for safety emergency responses on "contact power line" when the user touches a power line. When the user goes close to the 10-feet distance line indicating the distance from the overhead power lines' upright projection allowed by safety regulations, the training element of "safe working distance and clearance" will be triggered and instructions will appear in the text panel explaining this safety regulation. These events are a mixture of animations and text used to present training contents to the user. All information expressing methods used in the scenario are aimed at increasing the learning efficiency and enhancing the training effectiveness. The learning efficiency and training effectiveness will be studied through evaluation processes in future research.

5. Merits of MVR

There are several ways to make learning more active and engaging. Training methods like on-the-job training, full scale training mock-ups, and the use of VR simulation offer more engagement. However, due to the dangerous characteristics of electricity, the on-the-job training and mock-ups can hardly allow trainees to fully rehearse electricity-related tasks, access all electrical hazards and experience possible consequences in real life. As a result, the effectiveness of these training methods might be limited. In contrast, a MVR-based training method is not constrained by these limits and instead can provide trainees full participatory experience without the safety risk from electricity.

MVR is advanced contributed to its adoptability. MVR technology provides a new perspective of safety training for dangerous hazards. A MVR-based training program has the ability to create a problem-based learning exercise in an environment that replicates the trainees' actual working environment (McAlpine and Stothard, 2003). It offers an interactive, active, and cognitive learning-by-doing experience for users (Stanney and Zyda, 2002) but without the concern for "real-world repercussions" (Eschenbrenner et al., 2008).

MVR is also advanced ascribed to the flexibility. MVR technology overcomes the training limitations on time and location and facilitates the mandatory and effective rehearsals in the virtual world. As a result, it will help establish the concepts of safety risk mitigation as habitus in workers' minds and place habitus into the context of real world practices.

Combing cloud technology, the safety training scenarios are used to be simulated in 3D interactions and on mobile devices, such as an iPad or a smartphone. The VR simulations allow the user to be exposed to the hazards within the simulated 3D environment so they can recognize those hazards, strengthen proper working memory and transfer the relative experiences into real life work or experience. Meanwhile, the cloud technology allows the user to access the training everywhere, and at any time, using any device (Chen et al., 2014). User data will be stored on remote servers and be automatically synchronized in real time with any authorized delivery devices. In this manner, users are no longer locked to a single device and do not have to transfer their data manually when switching devices.

Outside of the technology, MVR may contribute to the knowledge of safety management in terms of safety culture fostering. Literature suggests that unsafe procedures and violations by workers, such as forgetfulness, negligence and recklessness, are the primary causes leading to OSH injuries (Kletz, 2001). There is opportunity to reduce unsafe behaviors through appropriate and effective training, though, even if they cannot be eliminated completely. Goldenhar et al. (2001) highlighted that the most direct way to change statistics in human mistakes was through effective worker training. Neville (1998) suggested that effective training programs could help save large costs by preventing accidents. Effective training not only saves lives but also eliminates the extra indirect costs associated with accident investigations, insurance rates, equipment downtime and repair and productivity losses.

The MVR application may help to establish the safety culture transferring trainees' safe practices in a virtual world into their routines in real situations. In this perspective, culture is not considered a set of beliefs and values but the "whole way of life" which includes practices and routines(Zhao et al., 2014a) (Manseau and Shields, 2005). Bourdieu (2003) referred to this set of predispositions which guide improvisations in daily routines as the habitus or practical knowledge as repeated routines. One strength in understanding culture as habitus is that routines can be observed and documented, whereas values and beliefs must be inferred, making them less amenable to research. As a result, rather than formulating risk control as a break in habitus, it may prove more useful to conceive of OSH risk mitigation as a process. This process will allow people to show their own propensity toward adoption (decision-adoption process) in an appropriate way, especially when problems are encountered. Therefore, the habitus, a set of practical routines and dispositions towards certain ways of solving problems, is suggested as an innovative approach to the safety-culture-integrated OSH risk management. Combining risk mitigation as a continuous process of controls, rather than a group of static checkpoints of control, with a habitus-based process of safety training could not only mitigate OSH risk but also complement sustainable productivity and growth for the firm.

6. Conclusions

Workplace safety is paramount for all production sectors throughout the world. However, every year the number of occupational injuries attracts concerns on the safety management for every industry. Existing studies have endeavored great efforts on injury causations and found that more than half of workplace accidents are due to human errors. This chapter introduces an innovative safety management approach and the development process of such MVR-integrated application.

MVR is an adoption of virtual reality (VR) simulation on mobile/portable devices which are connected to cloud technology for end users. It allows safe simulation of real-life events in a digital environment that might otherwise be too dangerous or expensive to create (Haller et al., 1999). VR is described as a 3-dimensional world seen from a first-person view that is under real-time control of the user (Bowman et al., 2005). It also has the ability to create a problem-based learning exercise in an environment that replicates the trainee’s actual working environment (McAlpine and Stothard, 2003). Training programs via VR offers an interactive, active, and cognitive learning experience for the user (Munro et al., 2002; Stanney and Zyda, 2002). As a result, they are often used in place of on-the-job training or full size simulation. Applied to the construction industry, MVR overcomes time and location barriers for workers and provides them more flexibility to access.

MVR also benefits trainees with a participatory training environment. Such participatory training brings a real life aspect into the training in an “it can happen to you” scenario and allows the trainees to relate conditions and regulations with real life situations and a life-or-death importance (Zhao et al., 2009). The best scenario is when people do not have to consciously think about following safety procedures because it is second nature to them (Trybus, 2008). Moreover, MVR provide trainees with the ability to experiment without concern for

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"real-world repercussions" and the ability to "learn by doing." With a MVR program, the user controls the objects and couples this with information and later task-based testing, thus, an interactive and active-learning experience is created.

Most importantly, MVR simulation may contribute to building safety culture in terms of safe practical routines. Through this technology, training programs might allow construction workers to be familiar with common hazards, including dangerous electrical hazards, and to mock up relevant prevention practices without real injury repercussions. It may not only improve trainees' awareness of potential risks in a reality-based working environment, but also unconsciously influence routine behaviors as second nature, which will largely lead to the safety culture. Trainees are expected to be prepared for their future electrical tasks by rehearsing in a virtual environment. The goal of repeated rehearsal is not only to enhance trainees' professional skills but also, more importantly, to help build up their habitus for safe practices. Training goals are achieved when users complete the task repeatedly and with success. As a result, proper safety procedures and responses in the specific scenario are aimed to be enhanced and embedded in trainees' minds.

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