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'Safety Hunting': a Serious Gaming Approach for Industrial Safety Training

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Current operational safety training methods for the chemical process industry typically focus on acquiring and evaluating knowledge and technical know-how about safety measures and procedures. Although these are valuable training tools, they present certain important drawbacks in terms of availability, session time and cost, knowledge transfer evaluation and participant immersion. In this light, this study proposed and developed 'Safety Hunting', a novel Serious Gaming approach for worksite safety training in the chemical processing industry. This article introduces the game, discusses its development and reports on the evaluation of its impact as an industrial safety training tool, thus offering a methodological framework to support the research, development and evaluation of similar Serious Games. The game is staged at an international agrochemical production facility in Italy. It was tested and evaluated with Norwegian University of Science and Technology affiliates. Our results showed that learning objectives could be achieved to a satisfactory degree within a short gameplay session. Apart from enhancing knowledge and understanding about related safety procedures, playing 'Safety Hunting' also evoked feelings of confidence among participants, offering realistic and engaging simulation scenarios. These positive outcomes open interesting opportunities for further research.

1. Introduction and Research Background

Numerous accidents attributable to human error occur every year at industrial facilities, typically involving the improper execution of safety procedures. Research has shown that operational safety training for chemical facility operators is paramount for preventing and minimising accident risk (Patriarca et al., 2019). Traditionally, operators acquire safety knowledge and skills training through videos (Lanzotti et al., 2020), special seminars and courses, on-site drills (Backlund et al., 2007), individual lectures, safety cards (Chittaro and Buttussi, 2015), or through combinations of these. Despite being well-established and popular training methods, certain key challenges remain still unaddressed. First, the above conventional methods do not account for the—usually varied—initial training level of individual operators (Abed et al., 2015). Moreover, they tend to neglect evaluating the level of technical know-how gained after the training session. This is crucial for certain equipment where validation of expertise might be required to demonstrate capability to operate machinery safely (Lanzotti et al., 2020). Additionally, it is oftentimes challenging for conventional training methods to accurately emulate certain hazardous scenarios in real life as they might be either too resource-demanding or simply unjustifiably dangerous to recreate (Backlund et al., 2007). For example, conventional firefighter drills are time and cost-intensive, because large-scale sessions require numerous modular buildings to recreate different scenarios. Another shortcoming is related to the limited ability of such methods to truly resonate with the trainees, and evoke feelings of psychological pressure experienced during an actual emergency (Backlund et al., 2007). Finally, the availability of conventional safety training is rather restricted to planned training sessions, thus voluntary training at the convenience of individual operators is not an option.
In this context, gaming and simulation-based solutions offer an interesting alternative to address the challenges of conventional safety training approaches (Lanzotti et al., 2020). Serious Games *'have an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement'* (Abt, 1987 cited in Solinska-Nowak et al., 2018). Over the last years, such approaches have attracted

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significant academic interest due to their potential to effectively convey complex concepts and support learning processes in areas such as engineering, healthcare, disaster risk management and governance (Solinska-Nowak et al., 2018). They have the potential to deliver interactive and realistic experiences, which can be more engaging and easier to comprehend than traditional learning methods (Chittaro and Buttussi, 2015). Also, they offer a cost-effective, straightforward and immersive approach to simulate various scenarios for operational safety training. Importantly, Serious Games allow players to experience and train in scenarios that would otherwise be impossible to recreate in real life due to safety and resource constraints (Corti, 2006). Previous research has explored the use of Serious Games for operational safety training in the industrial and construction sectors. For instance, a Serious Gaming approach has been employed to familiarise operators with early warning indicators in evacuation scenarios involving ammonia release at a production plant (Patriarca et al., 2019). In another case, a safety training method based on digital ergonomics simulations and Serious Games was developed for operator safety at a steel sheet processing facility (Lanzotti et al., 2020). Finally, researchers proposed also a simulation-based approach for the safety training during the process of dismantling tower crane elements at a construction site (Guo et al., 2012).

Answering the call of previous researchers to expand our current knowledge of Serious Game-based operational safety training and explore further its potential in the chemical processing industry (Patriarca et al., 2019), this study proposed and developed ‘Safety Hunting’. ‘Safety Hunting’ is a novel, computer-based Serious Game for worksite safety training in the chemical processing industry. The prototype of the game was tested to evaluate its overall educational impact and effectiveness as a safety training tool. Finally, this research draws upon Project Management tools to define a streamlined framework for the design, development and evaluation of similar operational safety training games.

2. Methodology

The current study draws inspiration from an integrated framework for the design, development and evaluation of a Serious Game about cultural heritage: the FRACH model (Andreoli et al., 2017). It describes an iterative process consisting of four key phases, the Preliminary, Conceptual, Development and Evaluation, each of which is further subdivided into multiple steps. The first phase involves the preparatory work of conceptualising the main idea of the serious game and defining its target audience and learning objectives. The next three phases work in parallel, defining an iterative process concerning the design of the game mechanics, their implementation and the game trials to evaluate their effectiveness and provide feedback for further refinement (Andreoli et al., 2017).

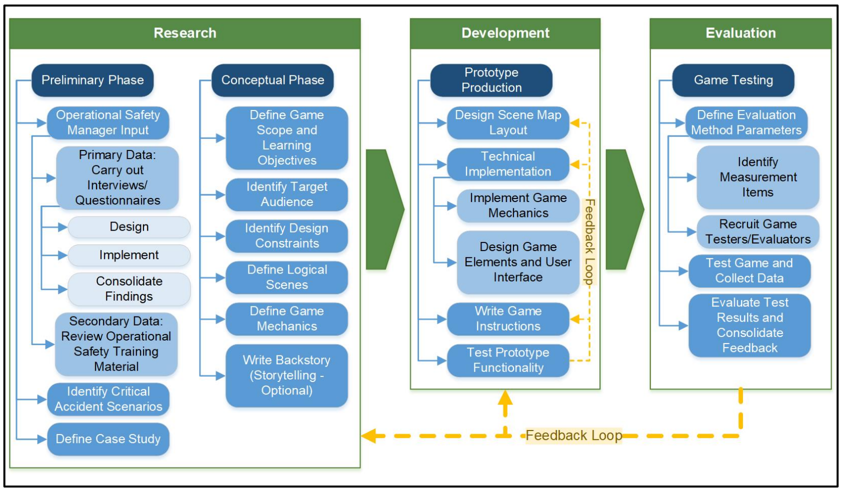

Figure 1: Workflow for industrial safety training Serious Game based on the FRACH model and WBS method

Proposing to streamline the Serious Game development framework from a Systems Engineering standpoint, this research builds upon the original FRACH model by introducing methods from Project Management, specifically the Work Breakdown Structure (WBS) (Kerzner, 2017). The WBS approach proved to be a useful conceptual tool for reviewing and (re-)organising each project phase into smaller and more manageable tasks. Thus, the different phases of the Serious Game development were restructured as presented in Figure 1. It is noteworthy that the proposed development framework has been streamlined and adapted for the development of a Serious Game for worksite safety training in the chemical processing industry, Safety Hunting. There are three main steps in the development workflow for the game, namely Research, Development and Evaluation.

It should be noted that an international agrochemical production facility in Italy was selected to provide a realistic setting and accident scenario parameters for the development of Safety Hunting in this study. This chemical processing facility handles large quantities of ammonia (NH_3) on a regular basis.

2.1 Research phase

The Research stage combines the Preliminary and Conceptual phases from the FRACH model, acknowledging their strong interdependency and addressing them in parallel. The Preliminary phase starts with obtaining input from the operational safety manager of the industry under study through primary and secondary data collection methods, aiming at delineating specific safety training practices and tailoring the game's context. Primary data collection entails designing, carrying out and consolidating findings from interviews and questionnaire surveys. For the development of Safety Hunting, a questionnaire survey was employed. Secondary data collection involves the review of any supplementary available operational safety training material. Next is the identification of critical accident scenarios by reviewing past safety reports of the industry under study and prioritisation based on HAZOP analysis and risk parameters, such as occurrence frequency and consequence severity. The Preliminary phase closes with the determination of the case studies to be used in the game, considering the scope of the safety training game. A representative accident scenario of ammonia release from the synthesis and compression equipment was selected for Safety Hunting. The Conceptual phase first defines the safety training game scope and specific learning objectives. The next tasks are the identification of the target audience and any game design constraints. Safety Hunting's goal is to enhance worksite safety in the chemical process industry by educating players about the appropriate safety procedures and associated technical skills required to effectively respond during emergencies at the facility under study. Focal points included gaining familiarity with the spatial layout of the facility, learn the safety-related tasks to be carried out during emergencies, and finally acknowledge and learn to identify risks associated with handling the hazardous materials involved in the facility's chemical processing. The target audience is facility operators, while the main game developing constraints were associated with the basic programming capabilities of the developers and software limitations in creating a user-friendly computer game. The Conceptual phase concludes with the definition of logical game scenes (e.g., levels or chapters), conceptualising the game mechanics and creating a backstory—if needed—to enhance the storytelling aspect of the Serious Game. For simplicity, the prototype of Safety Hunting was designed with a single level that plays out one accidental release scenario. A time-based scoring system was introduced to monitor and evaluate the players' performance and efficiency, while mechanics for equipping various personal protective gear (e.g., gas mask, protective suit, rubber gloves) determine the players' capacity to execute the required tasks safely through the course of the game. Player feedback is provided at the end of each playthrough (regardless of losing or winning) via on-screen messages summarising their score and offering information on any safety procedure steps or protective gear they may have missed. Safety Hunting backstory was kept to a minimum, introducing the player as a facility operator tasked with locating an ammonia release on the facility's premises, following the safety protocols, and leaving the facility without injuries.

(a) (b)

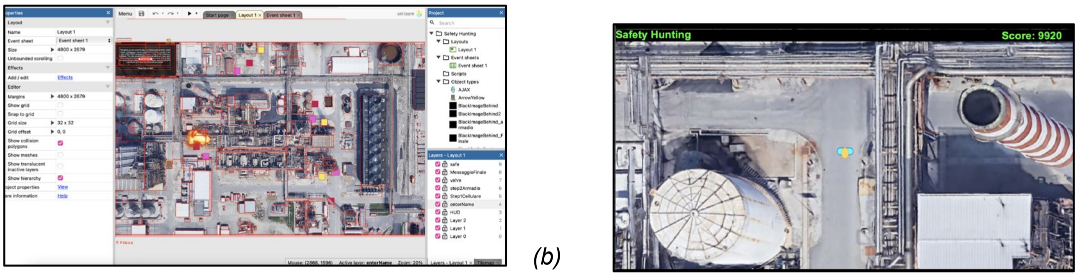

Figure 2: (a) Map layout development in Construct3 game engine | (b) Safety Hunting in-game screenshot

2.2 Development phase

Based on the decisions made during the Research phase, a prototype of the Serious Game can actually be developed in the following workflow step, the Development phase. This phase involves designing the game map layout and creating all the technical aspects of the game, such as implementing game mechanics and designing the user interface, as well as incorporating their in-game interactions. The Development phase concludes with writing the in-game instructions and finally testing the prototype for functionality issues as a computer application. After evaluating alternative options, the 'Construct 3' game engine was employed to create Safety Hunting, where all the aforementioned steps were implemented accordingly (Figure 2-a). The game prototype was then tested for functionality issues before being deployed for the educational impact evaluation (Figure 2-b).

2.3 Evaluation phase

The final phase of the Serious Game development workflow is the Evaluation. Evaluating the Serious Game's educational impact is imperative for assessing how it is received by the target audience and whether it fulfils its intended objectives as an effective learning tool. As with every evaluation process, the first task is to define the assessment criteria by identifying the measurement items and recruiting representative test subjects. To evaluate the overall impact of Safety Hunting a combination of formative assessment (i.e., utilising real-time game analytics to track player progress) and summative assessment (i.e., collecting feedback from players at the end of their game session) methods were employed. In detail, a host of parameters, such as the game score, in-game items used and time to complete each action, were recorded for each player using Google Analytics. Additionally, participants were asked to fill-in an opinion questionnaire about their user experience and the quality of the game in general. As for the test subjects, Safety Hunting was played and evaluated by engineering students from the Norwegian University of Science and Technology (NTNU), who were recruited on a volunteer basis. Although they were not employees at a chemical processing industry, arguably, their perspective was relevant for this experiment as prospective facility and industrial safety managers. Participants had not received any relevant safety training prior to the game. The final tasks in this phase are carrying out the game testing and collecting data, evaluating the results and consolidating feedback for the purposes of revisiting—if needed—the previous Conceptual and Development stages to further refine the game. Valorising one advantageous feature of single-player computer-based Serious Games, asynchronous learning, testing Safety Hunting was conducted at each participant's convenience through providing them access to the prototype application and sharing with them an online survey to collect their feedback. A notable caveat is that, due to resource limitations, the process did not involve going through multiple iterations of playing and refining the game mechanics throughout the development cycle at this stage.

3. Results

In an attempt to comprehensively assess the impact of Safety Hunting, this study examined both the educational aspect as well as the game elements. 24 study participants played Safety Hunting for at least five playthroughs each, for a combined total of 167 minutes of game time. Real-time in-game analytics were used in order to record and determine the players' learning progress over the course of their playthroughs. On the other hand, more subjective measures pertaining to the quality of their game experience were collected using a post-game test questionnaire survey. This section presents the key findings and discusses their implications.

3.1 Educational impact

In general, players' performance was improved over their playthroughs as demonstrated by the analytic data collected during their game time. In detail, even though average game scores were initially high (above 9,100 points against a maximum of 10,000), they exhibited an upward trend over the course of the playthroughs (Figure 3-a). After some possible experimentation with different—but still viable—in-game choices during their third playthrough, average game scores reached over 9,600 points at the fifth playthrough showing a considerable improvement in players' performance. This is corroborated by the marked increase in playthroughs ending with a win over those ended with a 'game over' (Figure 3-b). It is noteworthy that on their first try more than one third of the players got a 'game over', but by their fifth playthrough all players successfully beat the game.

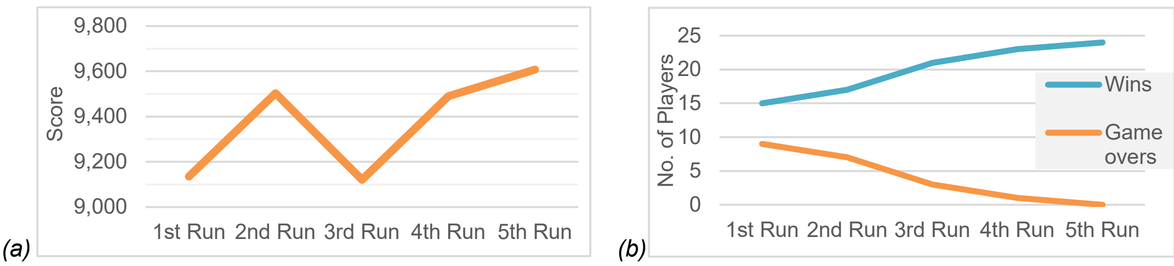

Figure 3: (a) Progression of players' average scores | (b): Progression of players' wins and losses

Furthermore, the time required players to make decisions, navigate the facility and complete in-game tasks had been significantly reduced by their fifth playthrough (Figure 4-a). Players seem to have familiarised with the map layout and got a better understanding of the safety protocol steps that needed to be executed during emergencies (e.g., locate the ammonia release, equip protective gear, shut down the system), which allowed them to manage more efficiently their in-game time. Finally, players familiarised themselves with the appropriate protective personal equipment necessary to safely carry out their tasks over the course of their playthroughs (Figure 4-b). Particularly, players needed a protective suit, rubber gloves and a gas mask to stay protected, avoiding the other three protective items that were irrelevant for their game scenario and were planted in the game as distractions. The number of players who figured out the appropriate combination of protective gear steadily increased thanks to informational messages players received in ‘game over’ screens.

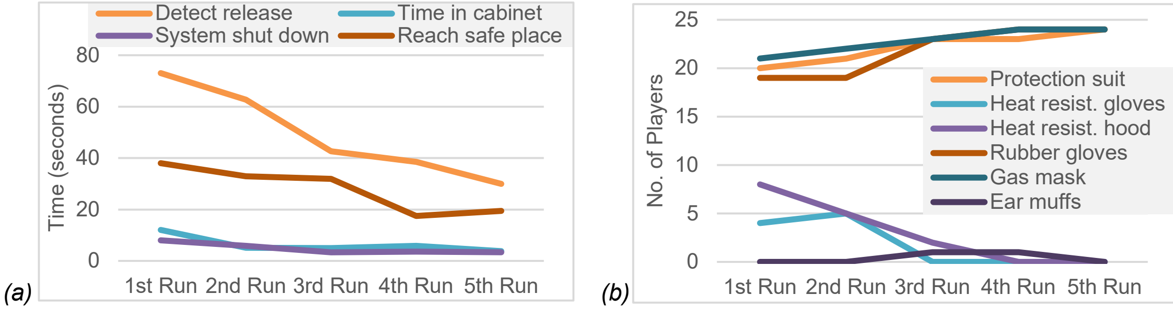

Figure 4: (a) Progression of players’ time to complete in-game tasks | (b): Progression of players’ item choices

3.2 Game experience

The results of the post-game test survey about the players’ general gaming experience revealed a positive reception of Safety Hunting (Figure 5). Specifically, more than nine out of ten players found the game to be an innovative educational tool to support operational safety training. Over 70% of respondents thought that the game included satisfactorily realistic simulated scenarios for which they became confident at encountering only after five short playthroughs. More than nine out of ten considered their overall experience immersive, and more than four fifths found the game engaging and fun. Interestingly, Safety Hunting proved to be an effective approach to motivate nearly nine out of ten players to learn more about worksite safety in the chemical processing industry. Concerning the shortcomings of the prototype, a minority (around one fourth) experienced a few technical issues, 30% found the initial instructions insufficient and about one fifth struggled with the clarity of the in-game educational feedback messages.

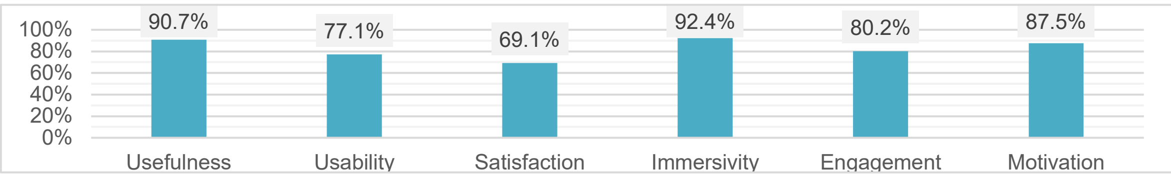

Figure 5: Post-test survey results about players’ gaming experience and game quality

4. Discussion

This study presented a comprehensive methodological framework for the design, development and evaluation of Serious Games about safety training in the chemical processing industry, inspired by the FRACH model the FRACH model (Andreoli et al., 2017) and refined through a WBS approach (Kerzner, 2017). Even though the presented workflow has been tailored for the development of Safety Hunting, a computer-based scenario simulation game, the proposed methodological framework can be adapted for other types of related Serious Games (e.g., tabletop games or gamified drills). Arguably, this streamlined workflow can facilitate future operational safety researchers and practitioners by providing a step-by-step guide to develop Serious Games.
Concerning the educational impact of Safety Hunting, our game test results revealed a notable improvement of players’ scores, time for task completion and correct choice of protective gear, over the course of just five playthroughs. Therefore, our evidence suggests that the set learning objectives and familiarity with the facility layout could be achieved to a satisfactory degree within a short gameplay session, which is in line with previous research (Chittaro and Buttussi, 2015). Of course, Safety Hunting should not be viewed as a standalone educational method, but rather as a supplementary tool that can enhance safety training alongside conventional approaches. Additionally, Safety Hunting scored considerably high in terms of a realistic game environment and accident scenarios. This is an important aspect in the industrial context, where a faithful representation of items, industrial equipment and action sequences facilitates the experiential learning process and enables an easier association of simulated scenarios with real life (Abed et al., 2015).

In terms of the practical implications of Serious Gaming approaches, this study showed that there may be significantly higher development costs for commissioning organisations compared to traditional safety training methods. However, the added benefits of adaptability to various accident scenarios, simulation of otherwise impossible conditions, and asynchronous and automated learning offered by Serious Games can in fact outweigh the initial costs over longer timeframes, as other researchers have noted (Backlund et al., 2007).

5. Conclusions

Venturing to expand our current knowledge on based on Serious Games about operational safety training in the chemical processing industry, this study proposed, developed and evaluated the novel computer game Safety Hunting. Another academic contribution of this research is that it outlined a streamlined workflow for the design, development and evaluation for similar operational safety training games. The practical implications of this work are associated with the main output: a prototype of the safety training game, Safety Hunting. Overall, the game was recognised as a useful educational tool that can support the safety training through instructing players about safety procedures during chemical accidents and motivating them to learn more about such safety protocols. In addition, the game was generally positively received as fun and approachable by non-gamers. In sum, our testing yielded encouraging results that can serve as proof of concept in further expanding the concept. Other chemical accident scenarios, involving different industrial equipment or chemical substances can be incorporated in the game as additional levels. Additional game trials with actual facility operators are needed to better appreciate the educational impact of the game on the intended audience. Finally, studies involving repeating play sessions with longer intervals can help in elaborating the long-term educational value of the approach with respect to conventional safety training methods.

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