UNIVERSIDADE FEDERAL DE PERNAMBUCO
CENTRO DE TECNOLOGIA E GEOCIÊNCIAS
DEPARTAMENTO DE ENGENHARIA DE PRODUÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO

MARCOS VINICIUS PINTO DE ANDRADE

A DATA COLLECTING FRAMEWORK FOR HUMAN RELIABILITY ANALYSIS VIA GAME ENGINE BASED SIMULATORS

Recife
2018

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Master thesis presented to UFPE for the master's degree attainment as part of the requirements of the Programa de Pós-Graduação em Engenharia de Produção.

Concentration Area: Operations Research

Advisor: Profº. Dr. Márcio das Chagas Moura.

Recife

2018

Catalogação na fonte
Bibliotecária Margareth Malta, CRB-4 / 1198

A553d Andrade, Marcos Vinicius Pinto de.
A data collecting framework for human reliability analysis via game engine based simulators / Marcos Vinicius Pinto de Andrade. – 2018.
124 folhas, il., gráfs., tabs.

Orientador: Prof. Dr. Márcio José das Chagas Moura.

Dissertação (Mestrado) – Universidade Federal de Pernambuco. CTG. Programa de Pós-Graduação em Engenharia de Produção, 2018.
Inclui Referências.
Texto em inglês.

1. Engenharia de Produção. 2. Simuladores. 3. Realidade virtual. 4. Motores de jogo. 5. Confiabilidade Humana. I. Moura, Márcio José das Chagas. (Orientador). II. Título.

UFPE
658.5 CDD (22. ed.) BCTG/2019-80

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Dissertação apresentda ao Programa de Pós-Graduação em Engenharia de Produção da Universidade Federal de Pernambuco, como requisito parcial para a obtenção do título de Mestre em Engenharia de Produção.

Aprovada em 13 de agosto de 2018.

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To my parents José Soares de Andrade and Terezinha Pereira Pinto de Andrade, that besides supporting me, gave me the example of the constant search for knowledge and self-improvement as an objective of life. I also dedicate this work to Renata Oliveira, companion and love of a lifetime, for the example of a righteous and fulfilling life.

SPECIAL THANKS

To Márcio das Chagas Moura, Isis Didier Lins, Caio Souto Maior, Erika Oliveira da Silva e July Bias Macedo, Paulo Renato Soares for the time, attention and faith in this work.

ABSTRACT

The concern about human behavior and performance have become a major issue in almost every economic activity. Human errors have been in the top list for accident causes for years, as can be found in scientific literature and media, leading sometimes to huge death tolls, material losses, and environmental damages. The lack of good quality datasets for Human Reliability Assessment (HRA) studies has been an undesirable presence in the technological and academic areas, as also is the shortage of funding for research fostering nowadays in Brazil. The above-mentioned facts are unquestionable and can be easily found in scientific literature and in the media in general. The present work intends to address this situation by proposing an alternative approach to collecting HRA data from simulator sessions. The research also takes an approach under the perspective of small research teams, generated by the shortage of funding resources, and with that in mind analyses the use of Game Engines (GE) in the creation of Virtual Environments (VE) in 3D as a streamlined and more budget-conscious approach. Game Engines are one of the most advanced technological tools nowadays, combining 3D and 2D graphic engines, programming languages, physics simulation, web interactivity, business intelligence (BI) and many more, an achievement only possible thanks to the videogame industry, a multibillionaire business that grows each year. To validate the idea an experiment was conducted with a VE entirely created with a GE for the specific scenario of refinery plant evacuation under toxic cloud release, a scenario that fits well the technique. All good practices studied, tools developed, and assets created were condensed in the form of a framework for posterior use by the scientific community in general. Also, a Bayesian Belief Network (BBN) was created with the collected data validating the tool for HRA use. The study generated valuable insights into human behavior and generated good quality datasets.

KEYWORDS: Simulator. Virtual reality. Game engines. Human reliability.

RESUMO

A preocupação com o comportamento e desempenho humanos tornou-se uma questão importante em quase todas as atividades econômicas. Os erros humanos têm estado na lista das principais causas de acidentes durante por anos a fio, como pode ser encontrado na literatura científica e na mídia, levando às vezes a enormes perdas de vidas, perdas materiais e danos ambientais. A falta de conjuntos de dados de boa qualidade para estudos de Avaliação da Confiabilidade Humana (HRA) tem sido uma presença indesejável nas áreas acadêmica e tecnológica, assim como a escassez de financiamento para pesquisas que estão sendo promovidas atualmente no Brasil. Os fatos acima mencionados são inquestionáveis e podem ser facilmente encontrados na literatura científica e na mídia em geral. O presente trabalho pretende abordar essa situação propondo uma abordagem alternativa para coletar dados de HRA em sessões de simulador. A pesquisa também tem uma abordagem sob a perspectiva de pequenas equipes de pesquisa, geradas pela escassez de recursos de financiamento, e com isso em mente analisa o uso de Motores de Jogo (GE) na criação de ambientes virtuais (VE) em 3D em uma abordagem otimizada tanto técnica quanto economicamente. Os motores de jogo são umas das ferramentas tecnológicas mais avançadas dos dias de hoje, combinando motores gráficos 3D e 2D, linguagens de programação, simulação física, interatividade web, business intelligence (BI) e muito mais, uma conquista possível graças à indústria multibilionária de videogames que cresce mais a cada ano. Para validar a ideia, um experimento foi conduzido com um VE inteiramente criado com GE para o cenário específico de evacuação de planta de refinaria sob lançamento de nuvem tóxica, um cenário que se encaixa bem na técnica e é de vital importância em um estado com uma refinaria e muitos outras instalações industriais como Pernambuco. Todas as boas práticas estudadas, ferramentas desenvolvidas e recursos criados foram condensados na forma de um Framework disponível para uso posterior pela comunidade científica em geral. Além disso, foi criada uma Rede Bayesiana (BBN) com os dados coletados que validam a ferramenta para uso do HRA. O estudo gerou insights valiosos sobre o comportamento humano em situação de evacuação de plantas através de um conjunto de dados de boa qualidade.

PALAVRAS-CHAVE: Simuladores. Realidade virtual. Motores de jogo. Confiabilidade Humana.

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LIST OF ACRONYMS

AI -	Artificial Intelligence
AR -	Augmented Reality
ASEP -	Accident Sequence Evaluation Program
ATC -	Air Traffic Control
ATHEANA -	A Technique for Human Error Analysis
AVERT -	Allhands Virtual Emergency Response Trainer
BBN -	Bayesian Belief Network
BN -	Bayesian Network
CAD/CAM -	Computer Aided Drafting and Manufacturing
CARA -	Controller Action Reliability Assessment
CNI -	National Industries Confederation
CORE DATA -	United Kingdom Computerized Operator Reliability and Error Database
CREAM -	Cognitive Reliability and Error Analysis Method
CRT -	Crew Response Tree
CSV -	Comma Separated Values
DT -	Decision Tree
EPRI-HRA -	Electric Power Research Institute E Human Reliability Analysis
ESD -	Event Sequence Diagram
FBX -	Film Box Interchange Format
FCM -	Fuzzy Cognitive Map
FLIM -	Failure Likelihood Index Methodology
FRAM -	Functional Resonance Accident Model
FT -	Fault Tree
G4L -	Games for Learning
GBL -	Game Based Learning
GD -	Game Design
GE -	Game engine
GST -	General Systems Theory
HCR -	Human Cognitive Reliability
HEART -	Human Error Assessment and Reduction Technique

HEDB -	Human Error Database
HEP -	Human Error Probability
HERA	Human Event Repository and Analysis
HFE -	Human Failure Event
HFI -	Human Factors Integration
HRA -	Human Reliability Analysis
IDA -	Information, Decision, and Action
IPSN -	Institute for Nuclear Safety and Protection
IT -	Information Technologies
JHEDI -	Justified Human Error Data Information
LISREL -	Linear Structure Relation
MTS -	Maritime Transport System
MVP -	Minimal Viable Product
NARA -	Nuclear Action Reliability Assessment
NEA -	Nuclear Energy Agency (EUA)
NPP -	Nuclear Power Plant
NRC -	Nuclear Regulatory Commission
NUCLARR -	Nuclear Computerized Library for Assessing Reactor Reliability
HEP -	Human Error Probability
PSF -	Performing Shaping Factors
QRA -	Quantitative Risk Assessment
SACADA -	Scenario Authoring Characterization and Debriefing Application
SD -	System Dynamics
SG -	Serious Gaming
SHERPA -	Simulator for Human Error Analysis
SLIM MAUD -	Success Likelihood Index Methodology, Multiattribute Utility
IT –	Information Technology
THERP -	Technique for Human Error Rate Prediction
UI -	User Interface
VR -	Virtual Reality

SUMMARY

1 INTRODUCTION

Nowadays, the concern about human behavior and performance have become a major issue in almost every economic activity. It has become a major factor for any company aiming for quality management, competitiveness increase, control of image reputation and financial losses, as well as environmental damages prevention.

1.1 DESCRIPTION OF THE PROBLEM

The intuitive notion of human factors as one of the main causes of accidents is confirmed by studies that depict worrisome numbers of human factors influence such as more than 90% of failures in the nuclear industry (REASON, 1990), 80% of failures in the chemical and petrochemical industry (KARIUKI; LÖWE, 2007), more than 75% of maritime accident (REN *et al.*, 2008), 70% of aviation accidents (KARIUKI; LÖWE, 2007), 75% of failures in drinking water distribution (WU *et al.*, 2009) and, if the failures can lead to catastrophic consequences (FRENCH *et al.*, 2011) being able to evaluate the contribution of the human factor to systems' reliability is a highly important task.

Swain and Guttmann (1983) define human reliability as the probability of an individual performs satisfactorily the requests made by a system in the appropriate time interval and does not cause damage during the actuation process. This concept remains appropriate until, however, it is necessary to have sufficient data to quantify the probability of human error through mathematical modeling. Indeed, there is a consensus in the Human Reliability Assessment (HRA) area about the lack of good datasets for human error probability (HEP) estimation, and thus finding ways to address this data scarcity has been a major concern in the research community (GROTH; SMITH; SWILER, 2014; MUSHARRAF *et al.*, 2014; ZHANG *et al.*, 2007).

Despite the importance of these studies, researchers still point out factors that make difficult undertake HRA such as:

- The scarcity of available data is an obstacle (MANCA; BRAMBILLA; COLOMBO, 2013; MUSHARRAF *et al.*, 2013);
- Difficulties and uncertainties in using data in contexts different from the ones that generated the original dataset;

- Strict access to facilities due to security reasons for data collection (CARVALHO *et al.*, 2008);
- Industrial secrecy issues, present in some activities, limiting access to some facilities.

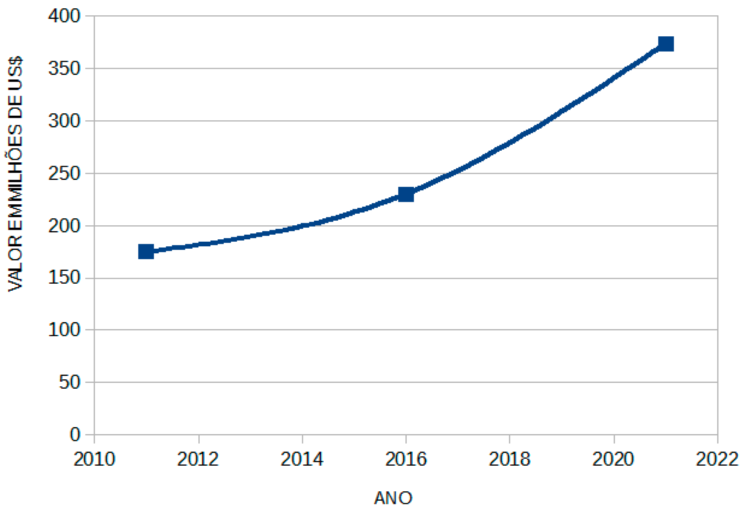
Given that, the lack of human error data continues to be an undesirable presence in the HRA research field. Thus, it is a must motivating research of alternative sources for systematic data collection beyond traditional post-training assessments, investigation and accident reports (GROTH; MOSLEH, 2012). In this context, a framework for creating immersive virtual environments (VE) to study human reactions, performance, and behavior for gathering alternative data could represent a must-have solution, deserving comprehensive studies.

In fact, simulators have been a growing trend, with many of them based on virtual reality (VR), which reduces costs and increases training efficiency. There are several training solutions using the so-called Game Engines (GE) to generate training content in the most different areas, such as the ones created by Immerse Inc. (2017). At the same time, software platforms for the assisted creation of powerful immersive applications (e.g. games, simulators, and real-time visualizations) are now at easy reach, like Unity, Unreal, Cry Engine and others (JUANG; HUNG; KANG, 2011; RUBIA; DIAZ-ESTRELLA, 2013).

For instance, in the Gas and Oil industry, Visiongain's report on the oil and gas training market for the period 2011-2021 (Figure 1) provides a growth forecast for investment in training based on dynamic platforms such as VR and Serious Games (SG) from moderate to high (VISIONGAIN, 2011). This large demand for rich content training denotes a positive environment to undertake HRA studies in virtual environments with scientific gains, optimizing costs and efforts expended if an application built for training is at the same time also used to provide HRA data.

In this research, the considered context is the evacuation planning from an oil refinery in the case of toxic substances leakage. In fact, the choice of the evacuation assessment subject is attached to the fact that chemical facilities are commonly surrounded by urban areas and, depending on the magnitude of the consequences, the number of people potentially exposed to hazard components may extrapolate facilities area reaching a great number of citizens (O'MAHONY *et al.*, 2008; SORENSEN; SHUMPERT; VOGT, 2004).

Figure 1 – Investments evolution in training using Virtual Reality (VR) for 2011-2021



Source: Visiongain (2011)

The historical side of chemical accidents has plenty of disastrous cases that required evacuation of the facilities and neighborhood. Seveso, Italy in 1976 and Bhopal, India in 1984 are classical cases of tragical consequences due to, among many other reasons, the absence of planned response measures with evacuation actions (ONELCIN; MUTLU; ALVER, 2013).

An Emergency Response Plan (ERP) has to analyze, identify, and quantify the risk in organizations as a way to reduce consequences magnitude (OLIVEIRA DA SILVA, 2017). Two major courses of action categories to be followed: either shelter-in-place or to evacuate the area. The decision is based on the quality and effectiveness of available shelters and the amount of time needed to effectively and safely evacuate the potentially exposed individuals (SORENSEN; SHUMPERT; VOGT, 2004).

The present work has a multidisciplinary approach and aims to study the creation process of VE for HRA studies based on GEs and proposes a framework for the task. For validation purposes, an experiment of HRA will be conducted using the framework in an evacuation scenario in an oil refinery, an *ad-hoc* built simulator with a Game Engine (GE) using the proposed framework and the data generated will be used in an HRA study with Bayesian Belief Networks (BBN) completing the project cycle.

1.2 JUSTIFICATION

Human data originated from Virtual Environments (VE) gives signs to be a game changer in applied sciences in general. But the creation of such tools sometimes demands specialized technicians in Game Development (DEV) and Computer Graphics (CG) tools that are not in the core knowledge area of engineers.

To make the situation more complex it has been observed a shrinking in funding for research in Brazil (ESCOBAR, 2015, 2017) making the research teams smaller with very few, or none at all, members coming from knowledge areas other than engineering. At the same time, the use of Game Engines (GE) in the creation of Virtual Environments (VE) has proven to be a solid and dependable technology backed up by the enormous commercial success of video games (COOVERT et al., 2017; JUANG; HUNG; KANG, 2011; MCMENEMY, 2007).

The literature has occurrences for the use of VEs for HRA, training and other purposes, but the creation process is quite often poorly documented. Exceptions happen when the experiment is conducted by Information Technology (IT) or electronics professionals or teams with such qualified personnel(CHA et al., 2012).

In research teams with low experience in Computer Graphics (CG), the use of GE streamlines the process of creating 3D simulators since a lot of the raw work of CG is implemented in high-level tools. The development cycle is way shorter and most of the times the application had very good graphic quality since the first releases.

Furthermore, the cost of development considerably drops, simulators based on GEs can cost up to 50 times less (HEROLD, 2014; HERSEY, 2008). Although creating a simulator with instructive and engaging scenarios is a difficult task, doing so without the use of game engines is much more complex and then costly.

In addition to these obvious advantages, simulator training decreases the wear and tear of real devices and increases their availability for production. There are reports of performance improvements of 70 to 80% and a decrease in damages to real equipment (HERSEY, 2008).

The framework is designed to be used by non-CG professionals and also is comprised of building blocks for Refinery Scenario Evacuation with 3D geometry and analytics tools and setup for scenario building and data collecting. The best practices suggested are based on the literature reviewed and, in the problems faced during scenario construction, programming and deployment.

1.3 OBJECTIVES

In this section the general and specific objectives of this work will be addressed.

1.3.1 General objectives

The present work aims at studying ways to improve the amount and the quality of the data for HRA via building GE based simulator for collecting human reliability data for emergency evacuation procedures in an oil refinery under a loss of containment of a toxic substance at gaseous phase. All good practices identified during the process will be compiled in the form of a framework together with all assets created, providing a streamlined way to other research teams build similar experiments.

1.3.2 Specific objectives

I. To research examples of good uses of Virtual Environments (VE) as data sources for HRA or human factors studies documenting their pros and cons;

II. To get acquainted with the more common and up to date knowledge for HRA in the qualitative and quantitative fields;

III. To study Game Engines (GE) and how they can streamline the creation of simulators;

IV. To create an approach based on the best practices identified and in the state of art in mathematical modeling to permit the creation of digital simulators for data collecting;

V. To compile the best practices in the form of a framework proposal for the creation of data collecting tools based on Virtual Environments (VE) for HRA;

VI. To validate the framework with the creation of a simulator test scenario for HRA using the Unreal Game Engine, feeding the obtained analytics into a Bayesian Network (BN) for conditional probabilities calculation;

VII. To start and test a basic library of reusable modules of 3D geometry, scripts, code and analytics setup for the chosen scenario type, aiming to speed up the creation of virtual environments of the same type by researchers in general;

VIII. To document the creation process of a simulator scenario via GE in a way that it can be used as a roadmap for all activities involved in simulator creation with GE;

The content delivery facet of designing applications with teaching or training purposes will not be approached at the present work despite its indisputable importance. Education and training are an obvious use for all the technology discussed in this work, but it is not an objective of the present research. Despite that, training is widely mentioned throughout this work, because such applications are becoming a standard for personnel instruction in many business areas. So, whether the simulators were built with training purposes or for HRA, the proposed framework should be of good use.

1.4 METHODOLOGY

The used methodology consisted of a two phases approach, the general approach is depicted in Figure 2.

1.4.1 Exploratory phase

Comprised a literature review and local scientific community hearings, in a search for a common ground for the HRA experiment choice. This phase was focused in finding the scenario that would be more useful for the community because the framework is intended to be reusable and extensible in future works conducted by other research teams doing works on refinery scenarios.

1.4.1.1 Related work compilation

In this phase, a comprehensive research on uses of virtual environments was made, mainly with a focus on 5 occurrences:

- Use of virtual environments on research in general, preferably for generating any kind of HRA data;
- Use of data for HRA from alternative sources, preferably digital ones;
- Use of Bayesian networks in HRA studies with alternative data sources;
- Good practices in building engaging scenarios for serious games, games in general and simulators;
- Evacuation procedures in industrial facilities.

More than 120 papers were searched that, after some primary selection, ended in almost 60 references searched through CAPES Periodicals portal. The keywords searched were:

- Virtual Environments;
- Evacuation;
- Virtual Reality;
- Human Reliability Analysis;
- Simulator.

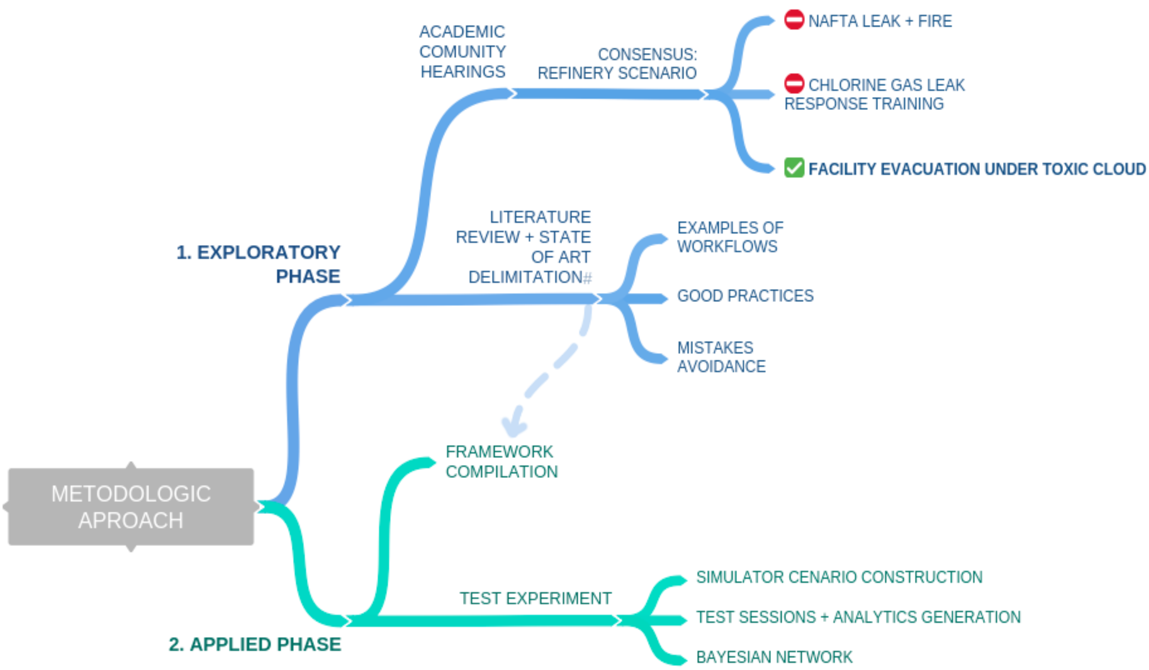
Combinations of two of the abovementioned terms were also searched, and in some cases, references present in the works were fetched for expanded research on the subject.

1.4.2 Applied phase

The applied phase consisted in a compilation of good practices for building simulators, mainly for HRA data collection, in the form of a framework, followed by the actual simulator creation and the analytics data output and analysis.

To validate the proposed methodology, an experiment was conducted with data being collected and condensed in a BBN for conclusions about how the context of the experiment is influenced by variables such as training level, scenario complexity, and visibility conditions.

Figure 2 – A general overview of the methodologic approach for the present work



Source: This research (2018).

1.5 STRUCTURE OF THIS DISSERTATION

Besides the Introduction chapter, this work has six chapters, whose contents are briefly described as follows:

Section 2: Theoretical foundations with a compilation of all the research done in the main knowledge areas that were necessary to understand the work as a whole. The main disciplines covered are HRA, Game Development and Virtual Reality (VR).

Section 3: Related work and exploratory phase with relevant cases and concepts materializations that were used as references for good practices or avoidable paths.

Section 4: Framework Creation and Simulator Design and Experiment Execution

Section 5: Analysis of Results of the experimental data and for the general and specific objectives.

Section 6: Conclusions and **Final Remarks**.

2 THEORICAL FOUNDATIONS

The present work has strong multidisciplinary characteristics and is based on three main knowledge fields: human reliability, game design, and virtual reality. Then, the following sections encompass these topics used to build de current work.

2.1 HUMAN RELIABILITY ANALYSIS (HRA): CONCEPT NA TECHNIQUES

The history of human reliability and error begins in the 1950s when H.L. Williams proposes that the reliability of the human element must be included in the reliability of the systems, and in failing to do so may turn the reliability assessments prone to not represent the reality of the arrangement properly (DHILLON, 2009).

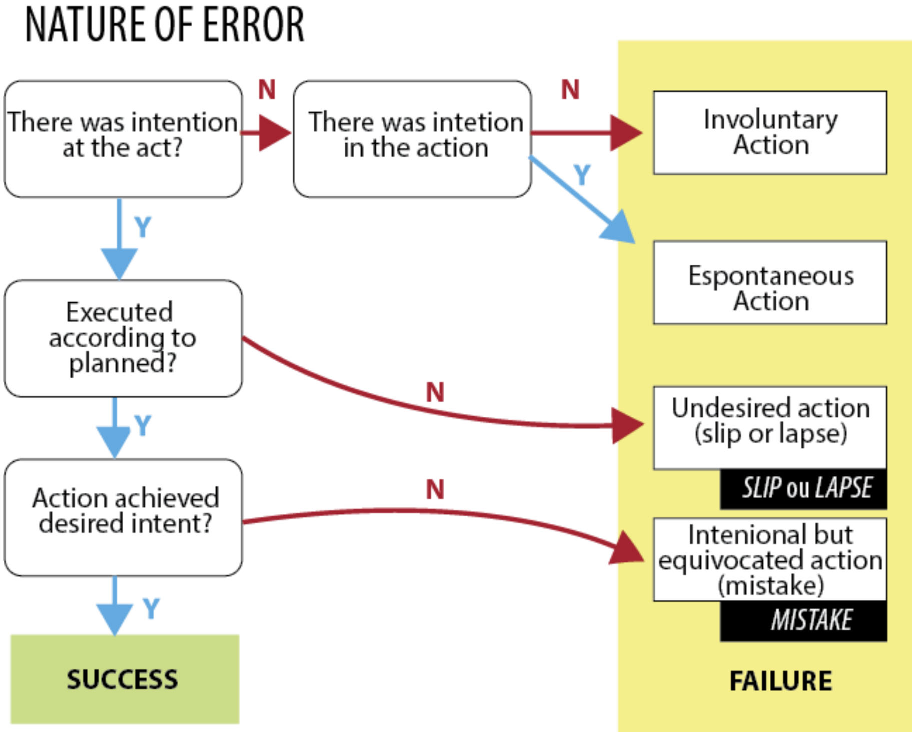
As previously stated, among the various definitions of human reliability, Swain and Guttmann (1983) define human reliability as the probability that an individual correctly and harmlessly performs an action requested by the system. These same authors also define Human Error Probability (HEP) as the quotient between the number of errors occurring in a task and the number of opportunities for the error to occur (DEACON *et al.*, 2013). The presented concepts, although apparently simple has hidden complexities, since all tasks must be enumerated, as well as all forms of error, leading to a gigantic unfolding for the total discretization of the functioning of a system (PARK; JUNG, 2007; ZHANG *et al.*, 2007).

In general, an HRA aims at identifying the tasks to be broken down in operations, weighting and modeling those that are relevant to the process and evaluating the probabilities of each occurrence (PYY, 2000). Through probabilistic (quantitative), causal (qualitative) or mixed approaches, HRA methods evaluate the human contribution to the risk of the studied activity (BELL; HOLROYD, 2009).

2.1.1 Human error

Four basic elements are recurrent in the literature on human error: Understanding, decision, performance, and the result (REASON, 1990). Failures in some of these stages or in combinations of them take names of different types of error (Figure 3). Reason (1990) proposes that a description of error to enable studies of human reliability should take into account three macro-elements: nature of the task, variables of context and mechanisms that influence the performance of the individual. The diffuse nature of these elements generates a first conclusion: error prediction studies only make sense in probabilistic contexts, as already contained in the definition of human reliability from Swain e Guttmann (1983).

Figure 3 – Adaptation flow chart of Reason (1990) on the nature of the error



Source: This research (2018).

There are several definitions of error, but it is worth mentioning one that characterizes error as a sequence of activities that do not reach the objectives for which they were idealized, excluding of course the component of chance (REASON, 1990). The definition may seem oversimplified, but it accommodates both cases in which a wrong solution was defined, as well as when protocols that would effectively solve the situation were not properly carried out (Figure 3). Errors can also be separated into omission errors that refer to non-execution of certain steps of a task and commission errors, which refer to errors made during the execution of a task (SWAIN; GUTTMANN, 1983).

Another concept that is related to the error is the definition of accidents that, according to Roberts and Perrow (1989), are unplanned and undesirable disturbances that cause material or human damages, disrupting the development of the ongoing task and impairing the perfect functioning of the system in its current or future production. Such a definition gives the measure of importance in controlling, predicting, and decreasing the probability of errors occurring.

2.1.2 Human reliability analysis techniques

HRA techniques are commonly categorized into first, second, and third generations. First-generation techniques were developed to evaluate the likelihood of human error in an equipment-like approach, having a strong reductionist tendency by breaking down the task into smaller operations, and moderating the results with conditioners called performance shaping factors (PSF). From a combination of these elements, an estimate of the human error probability HEP for that arrangement is produced (BELL; HOLROYD, 2009; DI PASQUALE *et al.*, 2013).

First-generation techniques are often criticized for poorly incorporating in their modeling the impacts of the task context, organizational factors, and especially the cognitive processes involved in human performance. Despite all criticisms, there are first generation techniques still in use in quantitative risk analysis (BELL; HOLROYD, 2009; JAMES CHANG et al., 2014).

The second-generation methods are an attempt to consider human cognitive facets involved in the arrangements in order to estimate the HEP. The studies focus more on studying factors that increase HEP, trying to replace the strongly quantitative approach with a more qualitative and causal evaluation of human error (BELL; HOLROYD, 2009; BORING *et al.*, 2010; DI PASQUALE *et al.*, 2013). Second generation methods are criticized mainly because of the lack of empirical quantitative data for its validation and development, poor human behavior modeling and strong dependence on PSF and expert judgment.

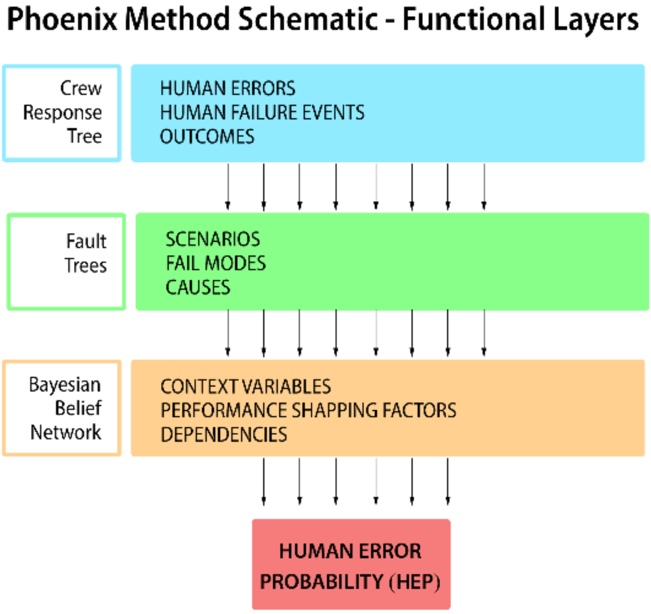
The third-generation methods of HRA are an amalgam of the previous ones, taking the best of each one of them; the quantitative approach of the first generation and the cognitive modeling of the second. As an example, we can mention the Phoenix and the Nuclear Action Reliability Assessment (NARA) and improved version of a method called HEART (JAMES CHANG et al., 2014). A Bayesian Network add-on is also used to improve or add quantitative characteristics to some methods. Through the use of empirical data, this approach attempts to join the best of both worlds, quantitative data, qualitative analysis and cognitive models (DI PASQUALE *et al.*, 2013). As an example of a third generation method worth mentioning is the Phoenix, a method that brings together a compilation of best practices in the field of human reliability, incorporating lessons learned from empirical studies and attempts to bring together the best features of the most recently developed HRA methods (EKANEM; MOSLEH; SHEN, 2015; RAMOS; DROGUETT; MOSLEH, 2016). Using a team-focused Cognitive Information, Decision and Action (IDA) model, the method also makes use of findings and operational experiences of cognitive psychology to identify possible causes of error and influencing factors during interactions of teams performing operational procedures (EKANEM; MOSLEH; SHEN, 2015).

It is a hybrid methodology with qualitative and quantitative steps. A brief overview of the method in its qualitative phase, which was considered more appropriate for the scope of this work, is presented as follows. In this step, the objective of the method is to identify events of human failure (Human Failure Events – HFE) and characterize the team and system arrangements that allow for the occurrence of errors. The procedures are divided into two fronts of approach, namely:

- Analysis and diagramming of operations with a focus on identification for further quantification of HFE indicating, where possible, the existing recovery modes;
- Creation of a human response model that connects team failure modes with context variables;
- For each HFE identified in the risk analysis, the method consists of applying three tools that constitute the qualitative approach of the method (EKANEM; MOSLEH; SHEN, 2015);
- Crew Response Tree (CRT), which is the top layer;
- Modeling of human performance in the central layer, through the use of analysis tools such as Fault Tree (FT) or event trees to create scenarios related to each HFE;
- Bottom layer PSF linked to Bayesian Belief Networks (BBN) for scenario weighting;

The diagram presented in Figure 4 illustrates the steps of the method and its interrelationship (EKANEM; MOSLEH; SHEN, 2015).

Figure 4 - The Phoenix method and its structure of qualitative analysis.



Source: Adaptation from Ekanem, Mosleh, Shen (2015).

Data analytics and Business Intelligence (BI) in general are becoming a strategic source of data in many areas (DAVENPORT, 2006). Perhaps this can represent the birth of another generation of HRA, the so-called fourth generation would be based on the predecessors approaches but doing extensive use of analytics data derived from simulators sessions with real human beings.

The technology for that is in a stable state and the abundant amount of data, even though being generated by simulator sessions, could bring these studies to another level of usefulness. Cognitive models coupled with the state of the art in mathematical approaches will be complemented with high-quality datasets tailor-made for each scenario in the study.

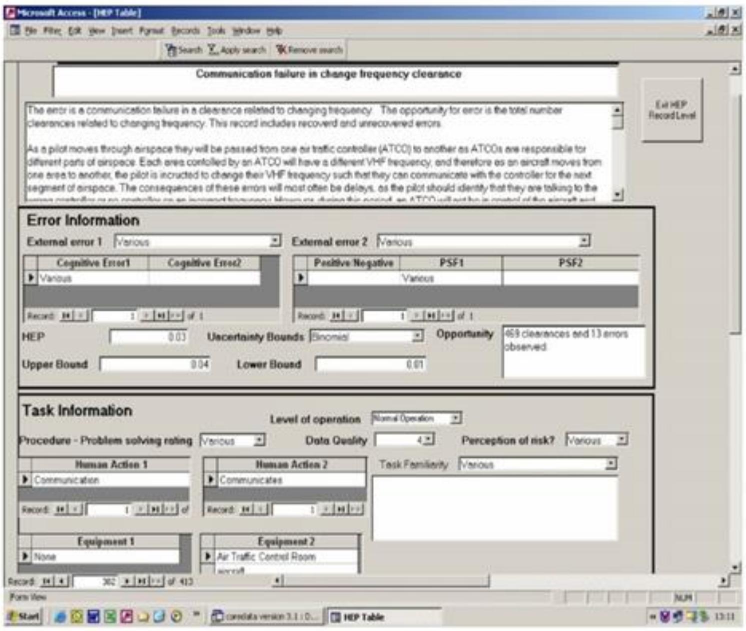
2.1.3 Human error databases

Human Error Databases (HEDB) are repositories containing descriptions of the faults that occurred in an organization for reliability estimation purposes. Well-designed HEDB also records context information and variables of the failure event environment and other conditioning elements.

A record of a HEDB contains information about the error itself and contextualization data like the size of displays, nature of alarms (sound or visual only), duration of worker shifts (JAMES CHANG et al., 2014). The better the HFE is characterized the easier will be to judge how much the data is suitable for other similar situations (JAMES CHANG et al., 2014; KIRWAN; GIBSON; HICKLING, 2008).

The CORE-DATA (United Kingdom Computerized Operator Reliability and Error Database – Figure 5) contains actual occurrence data and simulation records of various areas such as nuclear power and air traffic control, totaling 11 branches of activities. Each record contains a description of the task performed, statistical margins, PSF, and its purpose was to supply the third-generation HRA method named NARA, as well as the Controller Action Reliability Assessment (CARA), which is used in air traffic control (JAMES CHANG *et al.*, 2014).

Figure 5 - HEDB CORE-DATA registration example, with the nature of the stored data.



Source: Kirwan; Gibson; Hickling (2008).

There are also other databases such as NUCLARR (Nuclear Computerized Library for Assessing Reactor Reliability), ORE (Operator Reliability Experiments), HERA (Human Event Repository and Analysis) and also an initiative called SACADA (Scenario Authoring Characterization and Debriefing Application), which brings the interesting approach of using training data from simulators for HRA studies (JAMES CHANG *et al.*, 2014). The small size of these databases is a clear demonstration of the need for new sources of quality data (e.g. NUCLARR had 2.300 records and CORE-DATA had only 600 entries by the end of 2014) (JAMES CHANG *et al.*, 2014).-

In fact, the scarcity of data and the poor characterization of the inputted records have been pointed out by researchers as the main factor that hinders HRA (JAMES CHANG *et al.*, 2014; MARSEGUERRA; ZIO; LIBRIZZI, 2007). If the occurrence is not properly recorded, it is not possible to be sure what similarities the registered data hold with future situations in study, generating uncertainties in the estimates that are commonly compensated with more conservative postures. One possible answer would be to use data from simulator sessions to have larger and more usable samples in the HRA processes. Some works in this line use Bayesian Networks that are fed with simulation data for HRA (GROTH; SMITH; SWILER, 2014; GROTH; SWILER, 2013; MUSHARRAF *et al.*, 2014; SUNDARAMURTHI; SMIDTS, 2013).

Regarding the use of simulator data for HRA, it is necessary to cite the report of the United States Agency for Nuclear Energy (NEA), which, in 1998, included the sentences below in its chapter on the use of simulation data from a study by *Eletricité de France* (NEA/CSNI, 1998a). The study applied questionnaires to operators, who have been in a real-world situation and in simulators and concludes as follows:

> Simulators must not at all be rejected because of these restrictions. Operating problems observed on simulators can generally occur just as easily in real-life conditions. Simulators constitute an outstanding source of information. Their use should be encouraged for PHRAs (NEA/CSNI, 1998a, p. 167).

Later on, experiments confirm this fact, such as that of Quinshan in China, where a full-scale control room simulator was built to obtain human reliability data with excellent results. The data obtained when compared to those of the International Atomic Energy Agency (IAEA) validated the use of Weibull probabilistic distribution parameters provided by the agency as well as providing parameters more suitable for use in some types of operations (ZHANG *et al.*, 2007).

However, Nuclear Power Plants (NPP) are a particular case with respect to the use of simulators in HRA; little is found in scientific publications in other areas. Other exceptions to be mentioned are the Air Traffic Control (ATC), for which there are reports of use of simulators for HRA of air traffic control operators also with results being used for reliability studies (ISAAC; SHORROCK; KIRWAN, 2002), and the ingenious use of simulator data on HRA for evacuation procedures (MUSHARRAF *et al.*, 2014), which is one of the inspirations of the present work.

2.1.4 Performance shaping factors

Human performance studies have shown that the influence of the contextual conditions for a task has a greater influence on the probability of error than the nature of the task itself. This led to a greater appreciation of the elements of conditioning in the study of human performance (BELL; HOLROYD, 2009; MARSEGUERRA; ZIO; LIBRIZZI, 2007). The conditions represented by PSF vary widely, like the training level of an operator or the existence of an explanative legend for an icon in a control room computer-based console.

PSF act as multipliers for the HEPs found, in each task; after having its HEP calculated, one can have the probability adjusted through PSF adding the context information to the HEP previously calculated. An example can be seen in Table 1, used for activities when the working platforms are computer screens. Table 1 brings PSF examples for UI design, where can be seen how much HEP increases when using poorly designed elements.

Table 1 - PSF for interface design, at the right column numbers are the HEP multipliers. (2013)

Qualitative difference worst versus best	Error multiplier
Reading process variable with 45° parallax versus no parallax	13
Single click selection versus double-click selection using an icon	4
Selection using an icon versus an icon with a label and with help	7.7
All items menu versus menu with items eliminated and shortened or with gaps left	3.2
Deep menu versus shallow wide menu	4
Drag of object to be modified onto modifier function versus drag of modifier onto object	3
Small on screen keyboard with fixed position keys versus random position keys	4
8–12 digits entered in chunks of 2 from memory versus 1–3	12
Finite state automation knowledge, infrequent experience not trained, little importance and weak operational focus versus trained, frequent experience and strong operational focus	8
Un-practiced diagnoses versus practiced using on-screen procedures	3
Partial obscuration of simple interaction dialogue versus no obscuration	4

Source: Hickling & Bowie

With the evolution of system complexity increasingly including an array with large number of people, machines and software, several methods of HRA make use of PSF to adjust certain aspects of the interaction between human elements, the technological framework, the processes and environmental conditions (GROTH; MOSLEH, 2012; GROTH; SMITH; SWILER, 2014; MARSEGUERRA; ZIO; LIBRIZZI, 2007). The PSF have several functions in the HRA, serving to add negative or positive influences allowing to predict human error conditions, serving to incorporate a qualitative layer on the quantitative method (GROTH; MOSLEH, 2012).

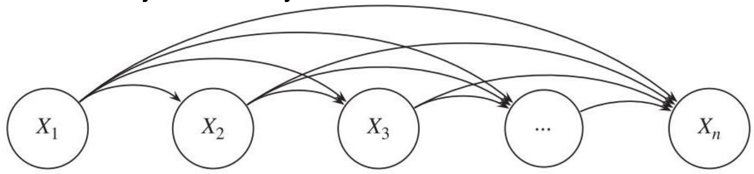
2.2 BAYESIAN NETWORKS

The use of BBNs on HRA has been subject of increasing interest in the scientific community, mainly due to their capability of mixing different data sources with a straightforward way to represent probabilistic influences or dependencies between variables. These features are making their use increase for decision support under uncertainty in many other areas such as finances, engineering, medical sciences, information technology and natural sciences (MKRTCHYAN; PODOFILLINI; DANG, 2015).

Bayesian Networks (BN) are used to represent and calculate joint probabilities in models with multiple variables and are commonly used as information processing components in Artificial Intelligence (AI) implementations, permitting the algorithm to “learn” from past events and increment the predictions as new evidence comes to light. They allow an intuitive representation of the layout of probabilities in multivariate data structures through graphs (KHAKZAD; KHAN; AMYOTTE, 2011).

BNs are composed by an acyclic graph with nodes and oriented arcs interconnecting them: the so-called Directed Acyclic Graph (DAG). Each node in the graph represents a variable and the direction of the arcs denoted by arrows represents a relationship of dependence, being the arriving node dependent on the variables of the departing ones (KOSKI; NOBLE, 2009; MARCO SCUTARI, 2015; POURRET; NAIM, 2008).

Figure 6 - Generic layout of a Bayesian Network with n random variables.



Source:*(POURRET; NAIM, 2008)*

In this case, the joint probability distribution may be represented by a BN as follows (POURRET; NAIM, 2008):

$$P(X_1, X_2, \dots X_j) = \prod_{j=1}^{n} P\left(X_j \mid parents(X_j)\right) \quad (1)$$

The conditional probability behavior of every node of the network is stored in tables called Conditional Probabilities Tables (CPT), which contain the various possible combinations of values for the conditional probabilities of the immediate predecessors of every node in the network. Then, this information coming from observed values are propagated through the network to update the probability distributions over other variables that are not directly observed (KOSKI; NOBLE, 2009; MARCO SCUTARI, 2015).

The Bayes theorem is useful to predict outcomes based on previous experiences, and it is based on the definition of the conditional probability $p(E|A)$ that is the probability of event E occurs given A occurred. For calculating $p(A|E)$ the Bayes update rule states:

$$p(A|E) = \frac{p(E|A).p(A)}{p(E)} \quad (2)$$

The idea to find a general law based on an accountable number of particular occurrences is called inductive learning and until new information appears the so-generated law carries an attached level of uncertainty inherent to its generation. The assessment is based on the idea that today events may have their outcomes predicted based on similar past events with known outcomes (KOSKI; NOBLE, 2009).

2.3 GAME DEVELOPMENT TECHNOLOGIES

The history of Game Development Technologies can be traced back to the first initiatives in the early 1990s that used game development technologies to create training applications until nowadays in an enormous evolutionary process (RAYBOURN, 2014). These streamlined tools boast high-level libraries of ready-made and interchangeable tools, which made the technological side of game development highly attractive for non-programmers.

The average user profile of game players is 35 years, with women being 43% of the total (ESA; ESA, 2015). Indeed, adults are no stranger to digital games, but the challenge is to understand what mechanisms make games so exciting and how to make use of it in other contexts, such as education and training. Furthermore, it is a so widespread technology that the idea of using Serious Games (SG) for training and benchmarking seems an obvious path to be followed.

The classification of game variants is somewhat confusing, but a good start point is the definition of Serious Games (SG) that are games built with purposes other than entertainment. Transmitting educational contents via games in a more palatable manner is called Game-Based Learning (GBL)(BECKER, 2015; DOMÍNGUEZ et al., 2013).

Games for Learning (G4L) are the particular case where the application had been specially built from scratch for the sole purpose of education. Table 2 brings a quite comprehensive, yet summarized, overview of the main game variants and the key point that help to differentiate them.

Table 2 - Game variants summarized definitions and a list with some key points that help to differentiate them.

	Game	Serious Game	Game for Learning (G4L)	Game-Based Learning (GBL)	Gamification
Basic Definition	This term includes all the other categories *except* gamification.	A game *designed* for purposes other than or in addition to pure entertainment.	A game *designed* specifically with some learning goals in mind.	The process and practice of learning using games.	The use of game elements in a non-game context.
Purpose	Can be for any purpose.	Change in behaviour, attitude, health, understanding, knowledge.	Normally connected with some educational goals.	**Not a game** - this is an approach to learning.	Often used to drive motivation, but can also be used to make something more playful and gamelike.
Primary Driver (why used)	Can be either play or rewards (or both).	To get the message of the game.	To learn something.	To improve learning.	Depending on how it's implemented, it can tap into extrinsic or intrinsic rewards (or both)
Key Question	Is it fun?	Is it engaging?	Is it effective?	Is it effective?	Business: Does it improve profits? Education: Is it effective?
Focus	Player Experience (how)	Content / Message (what)	Content / Message (what)		User Experience (how)
Budgets	Next to nothing to 100's of millions.	Next to nothing to 100's of thousands.	Next to nothing to 100's of thousands.	Usually part of institutional budget.	Next to nothing to 10's of thousands..
Business Model	User Pays	Producer Pays	Varies	Institution Pays.	Producer Pays.
Concept Catalyst	Core Amusement.	Message.	Performance or Knowledge Gap	Game is the lesson or is used as a part of the lesson.	In learning it usually impacts HOW things are taught and administered rather than WHAT is taught.
Fidelity	Self-consistent, otherwise irrelevant	Faithfulness to message essential	Faithfulness to message essential	Faithfulness to message essential	Not Applicable. If a narrative exists, it need have nothing to do with what's being gamified.

Source: http://minkhollow.ca/beckerblog/2015/06/21/games-vs-game-based-learning-vs-gamification-my-version/

The use of the so-called Game Mechanics is what makes a gameplay session different from a simple simulator session; some intensity of artificial stimuli is applied to conditionate desired behaviors. The use of these mechanics in non-game contexts is called gamification (ATTALI; ARIELI-ATTALI, 2015; DALE, 2014; ZICHERMANN; CUNNINGHAM, 2008).

Sometimes the use of these *stimuli* is a good option to bridge the difference between real-world operations and simulated ones. Literature brings cases where is perceived some degree of bias between simulated sessions and real ones (CARVALHO *et al.*, 2008; NEA/CSNI, 1998a; ZHANG *et al.*, 2007). Game mechanics elements can represent a compensatory layer bringing greater engagement or even affecting player performance to mimic adverse environmental conditions.

2.3.1 Game design

Game design is a discipline composed of several specialties: art, technology, cognitive sciences, communication, and, for educational purposes, even pedagogy (CROOKALL, 2010). Game design is the act of creating the game, defining how it works and transmitting all this information to the game creation team.

Games come from the fusion of two characteristics of human nature: the desire to play and the ability to pretend. Playing, in an open definition, can be viewed as non-essential or recreational human activities with social connotations most of the time. Related with the sense of pretending, it is an alternative reality that is different from the real world and which can be created, modified and discarded. By adding two more elements, rules and objectives, four primary elements that make up a game are created: playfulness, imaginary, rules, and goals (ADAMS, 2013).

Formally, *a game is a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome* (SALEN; ZIMMERMAN, 2004)*. Another definition worth mentioning is* from Browne and Maire (2010) stating that a game can be defined in terms of activity, rules, and outcome.

Also, there is a definition of a game that is very familiar to engineers and is one of the bases for the ideas presented in the current work; games are state machines: they store information about their current state and (if desired and designed) the past ones (EL-NASR; DRACHEN; CANOSSA, 2013; SALEN; ZIMMERMAN, 2004). Scenarios are presented to the user to whom actions or decisions are asked; this creates a loop of action (from the user) and responses (from the game) that keep the overall state of the machine changing.

In the present work, the games infrastructure was used to create a tool to systematically extract information from user and scenarios. Even though most virtual environments have the scope of actions narrower than in the “real world” situations, their development is commonly motivated once experimental environments (i.e. *in vitro*) are more expensive or not practical at all to be done (EL-NASR; DRACHEN; CANOSSA, 2013).

Another weakness pointed is that the consequences of digital simulations have a magnitude smaller than in a real-world situation, leading to less engagement in the operations by the users (NEA/CSNI, 1998b). In the field of reliability and safety engineering, this statement must be looked from a closer perspective. The magnitude of some consequences generated in real-world scenarios turns them not suitable to be simulated by some kind of physically-created special effect. Then, in these cases, digitally simulated consequences tend to have more impact than not showing any consequences at all (EL-NASR; DRACHEN; CANOSSA, 2013).

2.3.2 Game engines (GE)

Game engines consist of a set of game design tools grouped into a unique computational environment. Roughly speaking, GE could be compared to text editors, where all the necessary tools are implemented in the software environment (e.g. printing modules, spelling, and formatting). In game engines, the tools needed from the conception to the final output of an application are implemented and project-independent (JUANG; HUNG; KANG, 2011).

The first digital games had thousands of programming lines written *ad hoc* for each project and not reusable. With the evolution of the projects complexity and the massive commercial use and success of games, the idea of a group of reusable tools became mandatory due to economic and technical reasons (BISHOP e al., 1998; FERNANDES, 2010).

The various embedded features allow the creation of electronic games, simulations, or any application requiring real-time graphics, programmed environment behaviors, and user interaction. The contemporary GE have layers of hardware abstraction that allow the creation of applications for all other devices on a single platform. Users on desktop Windows PCs can develop games to run on consoles and mobile platforms (e.g. phones and tablets) and on multiple operating systems. The most common features found in GE are (DARKEN; MCDOWELL; JOHNSON, 2005; JUANG; HUNG; KANG, 2011; MIAO *et al.*, 2011):

- Graphics engine to generate two-dimensional, three-dimensional and stereoscopic graphics;
- Physics engine for simulations;
- Artificial intelligence (AI) engine for character behaviors;
- Interface for programming languages and scripts like C ++, C#, JavaScript and others;
- Multi-player network management;
- Virtualizers to simulate the various delivery platforms for prototyping.

From the solutions on the market (or in beta stage) the following GEs are noteworthy due to either technical benchmarks or the power of the company behind the project:

- Unity Engine that is one of the market leaders. It has C# and JavaScript as native programming languages and has one of the largest user databases on market. However, it has some features missing on its free version;
- Cry Engine from Crytek Gmbh (2017), with one of the best graphics quality on the market and is also an emerging marketing leader with a full-featured free version and a visual programming language called Flow;
- Ogre is a free and open source, has good graphics quality, but has a complex programming interface (TORUS KNOT SOFTWARE, 2017);
- The giant Amazon is launching Lumberyard, its own proprietary engine for game creation. The applications generated are intended to be distributed on the Amazon e-commerce platform, it is free, and it is in beta phase at the time of this writing (AMAZON, 2017);
- Autodesk, another giant in computer graphics, has also its own engine called Stingray, whose main features are unprecedented interoperability with many products of its line, such as 3ds Max, Maya, and Revit. It has a free 3-year license for students (AUTODESK, 2017).

Game engines are becoming more sophisticated and incorporating more functionality each day. The most popular versions of the market have a modular architecture that allows adding up features according to each project (MIAO *et al.*, 2011). For example, if the design needs an artificial intelligence (AI) module to simulate the behavior of a crowd, a simple addition of a module implements the new functionality. The speed, modularity, and adaptability have contributed to the wide use of GEs not only for video games but also for a variety of applications such as simulations, architecture walkthroughs, animation cinema and many other areas.
In the specific case of games for training in simulators, the use of game engines brings some advantages such as:

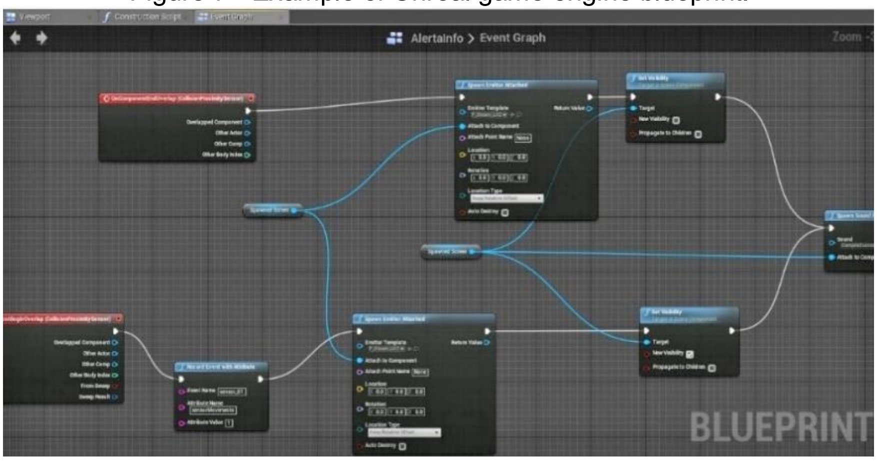
- Three-dimensional geometry of the main formats of CAD/CAM guarantees visual consistency by using data coming directly from existing projects. It is possible to transplant three-dimensional objects/entities from ProEngineer, Autodesk AutoCAD, Aveva PDMS, and others;
- Use of AI libraries to simulate interactions with teams. Several behaviors can be programmed to interact with users in the scenarios. This feature can be used to create complementary crew members on a team, a crowd evacuating a facility or a patient in an emergency room as in Chittaro and Sioni (2015);
- The possibility of interaction/integration with dedicated dynamic simulators through data exchange files, which guarantees the accuracy of the processes as in (CHA *et al.*, 2012);
- Ease of implementation of new interfaces such as virtual reality glasses, neural links and various types of interfaces. Almost all devices that lend themselves to man-system interfaces already have configurations to be used and programmed in gaming engines (BOONBRAHM; KAEWRAT, 2014).

According to Juang, Hung, and Kang (2011), the main advantages of creating simulations on GE are streamlined and facilitated development, outstanding visual quality, fast and stable physics simulation and real-time interaction.

Studies carried out for this dissertation indicated the choice of the Unreal™ game engine from the Epic Games (2017) due to its programming codeless interface and free licensing for the full version. It also has a good Analytics tool with direct interface to data analytics providers such as Google Analytics, which allows for a comprehensive visualization of data patterns, also without licensing costs.

Unreal is a mature tool that has excellent technical characteristics and great ability to work with formats coming from CAD/CAM software and 3D animation, and for extensively supporting the FBX pipeline, a file format broadly accepted by the Computer Graphics (CG) industry, around which are built interchange implementations for exchanging information and assets between CG software. Moreover, it supports the current C ++ programming language. The fact that Unreal internally uses C ++, a standard for programmers, as well as a visual flow-oriented programming interface called Blueprint (Figure 6**)** enables advanced programming of virtual environment features without the need to write any kind of code. This is perhaps the main feature that guided the choice for using Unreal in this dissertation.

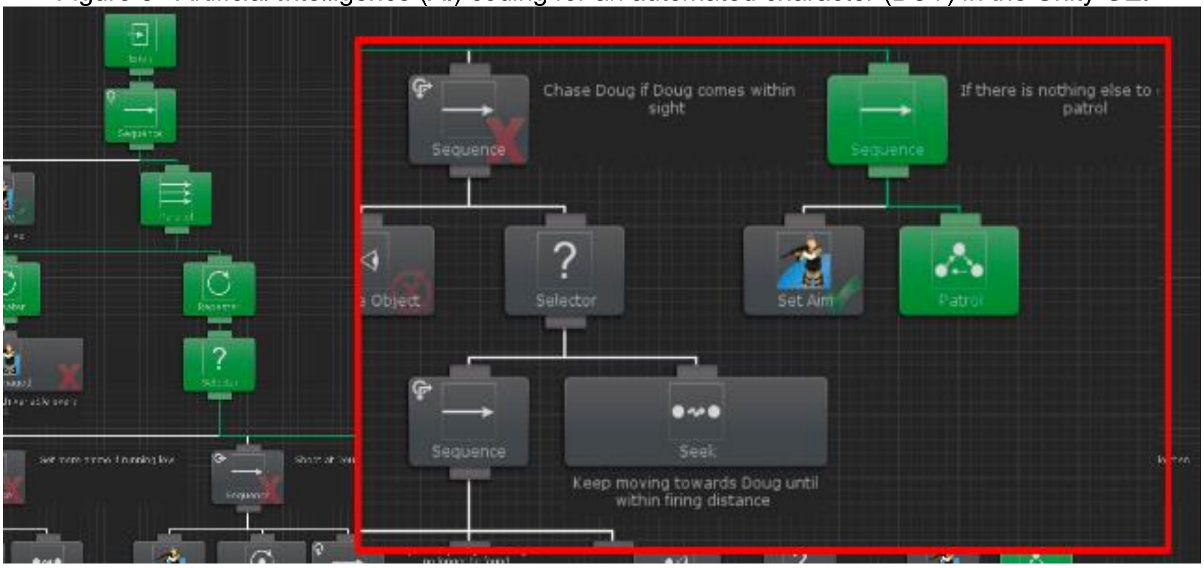
Figure 7 - Example of Unreal game engine blueprint.



Source: This research (2018) (2018).

The blueprint metaphor has many similarities with the diagrams used in engineering, which accelerates the learning process. Event trees are part of the nature of creating levels in the game and complementary behaviors can be programmed through AI blocks as in the example in Figure 8 which brings a soldier programmed to search for a certain target character. Note the high level of programming with instructions very close to the spoken language with instructions such as: “walking towards the target character if he is seen” or “Shoot when the target is at a firing range”; “if there is no visible target, follow with patrol routine”. This is a ready and reusable AI library, and the programming of behaviors is done through a block diagram, a well-known visual metaphor for engineers.

Figure 8 - Artificial Intelligence (AI) coding for an automated character (BOT) in the Unity GE.



Source: <http://forum.unity3d.com/threads/third-person-controller-third-person-ai-multiplayer-mobile-framework-out-of-beta.292541/>

When using game technologies to create the abovementioned simulators, the cost of development considerably drops, a factor perceived by the cost of the solutions: simulators based on gaming engines can cost up to 50 times less (HEROLD, 2014; HERSEY, 2008). Although creating a training application that is, at the same time, engaging is a difficult task, doing so without the use of game engines and other auxiliary technologies is much more complex and then costly.

In addition to these obvious advantages, simulator training decreases the wear and tear of real devices and increases their availability for production. There are reports of performance improvements of 70 to 80% and a decrease in damages to real equipment (HERSEY, 2008).

2.3.3 The key components of a digital game

All theory behind the process of building a game is useful to improve engagement in virtual simulated scenarios. Then, in this section, one will assume the words game and simulator will have similar meanings. From the perspective of Game

Development (DEV), the techniques are the same with distinct uses; while simulators are meant to practice and learn, games have in most cases recreational intents.

2.3.3.1 Gameplay

Although the term has a broad definition, gameplay can be defined as the set of challenges a player faces in order to achieve the objective of the game and also the actions (s)he is allowed to take as (s)he pursues this goal (ADAMS, 2013). Even in terms of simulator training, there are tasks to be executed aiming at some pre-defined objective, and rules and procedures to achieve that.

2.3.3.2 Core Mechanics

In the design of any virtual environment, one of the main tasks is to turn the general rules defined during scenario description into a symbolical and mathematical model that can be translated into an algorithm. These are the so-called core mechanics and are more specific than the rules defined as they demand quantification to work properly (SALEN; ZIMMERMAN, 2004). If a rule defines that a character in run mode will be faster than in walk mode, the core mechanics define these speeds accordingly (e.g.: 6 km/h for walking and 10 km/h for running), and perhaps for how long a character can sustain the running mode (speed) before losing stamina and be forced back to walk again to recover.

The core mechanics are the soul of any game or simulator, and are responsible for the gameplay, in terms of challenges or difficulties to player progress; goals to be pursued; consequences of every choice made; amount of realism applied to the simulations, definition of how much of scope narrowing is acceptable for the intended use. Games, in general, may be fully abstract, fully representational or any mix of the two. Making the application extremely representational may be an excessive and meaningless overhead for the development team (ADAMS, 2013) and this tradeoff is probably difficult to balance always leaving the question of how much resemblance to real-world situations is needed to have useful data.

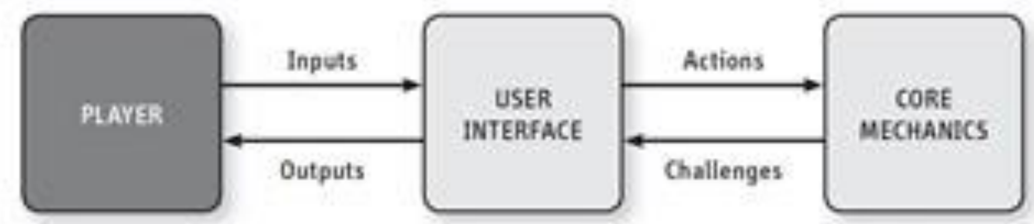
2.3.3.3 User interface (UI)

User interface (UI) is the layer between the player and the core mechanics (the game itself); it takes the challenges defined by the game mechanics and presents them in a user-friendly manner, such as graphics and sound. Moreover, UI takes the user reactions, done via any device (e.g. keyboard, mouse or joystick) and deliver them back to the core mechanics (ADAMS, 2013).

The concept of UI is familiar to everyone that used any kind of computer software, with the clear purpose to show to the user what has been done and interact as transparently as possible. The UI of games has the same functionality, but with the difference that not everything is shown to the user and, sometimes, the interactions are not fully transparent due to the challenges imposed by the core mechanics.

This controlled mediation is the key difference between games UI and conventional software ones. Figure 9 has a schematic view of the mediation done by the UI. Sometimes called presentation layer, the UI appears for the player as the game itself, is the instance where all players' actions take place, and all feedback from the core mechanics is received.

Figure 9 - How the UI mediates the core mechanics and player.



Source: (ADAMS, 2013)

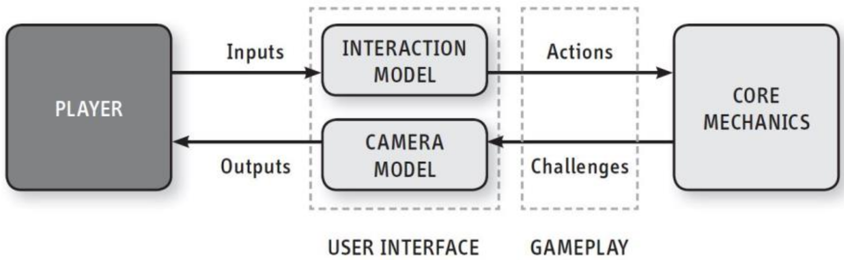
Moreover, the UI is responsible for the materialization of the game world: everything that is listened to, seen and felt is generated by the UI. Two essential features of the UI of a game are:

- **Interaction Model,** which creates the relationship between the player's inputs and the resulting actions. There are several standard interaction models like avatars and multipresence. In avatar model, the player is represented by a character inside the game, while in the multipresence the player acts from outside the game interacting at will with some parts of it(ADAMS, 2013; SALEN; ZIMMERMAN, 2004);

- **Camera model** controls the behavior of the imaginary camera that generates the point of view from which the simulated space is presented to the player. The camera models are divided into dynamic and static whether the camera moves or not during the sessions. The most common camera models used are first person and third person for 3D games, and top-down, side-scrolling and isometric for 2D scenarios(SALEN; ZIMMERMAN, 2004).

Figure 10 shows the main components of the UI and where they are placed in the structure and on what stream of information each one acts. Of course, there are digital games without graphics, but they are becoming rare.

Figure 10 - The complete layout of a digital game showing its key components.



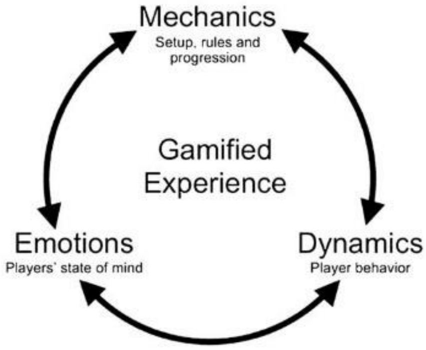
Source: (ADAMS, 2013, p. 38)

2.3.4 Gamification

Large companies have also used game elements without using video games on a variety of day-to-day tasks. There is a general acceptance of the use of game mechanisms in contexts outside games to increase participants' engagement and problem-solving skills (Figure 11) (ATTALI; ARIELI-ATTALI, 2015; DETERDING, 2012; ZICHERMANN; CUNNINGHAM, 2008).

Gartner Hypecycle of Gartner Inc. monitors the main trends of science, technology, and innovation from their earliest appearances to oblivion or arrival to the market. Figure 12 brings gamification as one of the most promising technologies for the coming years (DALE, 2014; GARTNER INC; GARTNER, 2011). The New Media Coalition, an entity that aims to promote open information about new digital media and its applications, brings visualization technologies, games and gamification in its list of the most significant technologies for the evolution of education (JOHNSON *et al.*, 2015). In fact, the Gartner Institute already in 2011 estimated that 70% of the large companies would already have at least one application of gamification deployed.

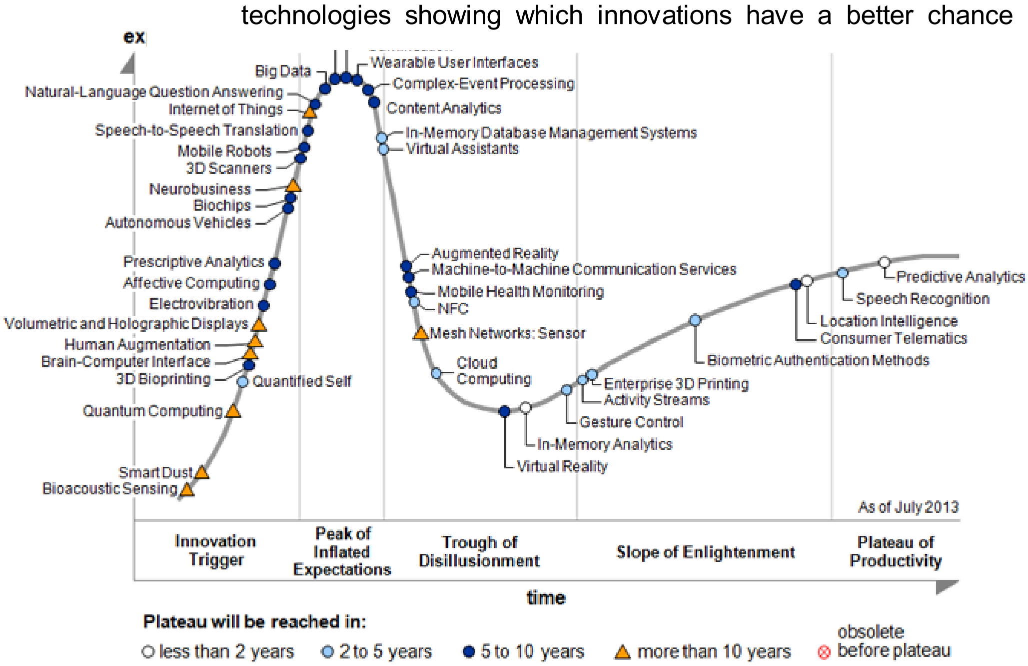
Figure 11 - Components of a gamification experience.



Source: Robson et al., (2015)

When correctly implemented, gamification generates alignment between the interests to be potentialized and the intrinsic motivations of the users, causing greater engagement, mobilization of the circle of relationships and permanence in the applications. From the moment the task or behavior is modeled as part of an environment (through the insertion of play components), behavior and posture change much faster (ZICHERMANN; CUNNINGHAM, 2008).

Figure 12 - The graphic of Gartner Inc. Gartner Hypecycle of new technologies showing which innovations have a better chance of

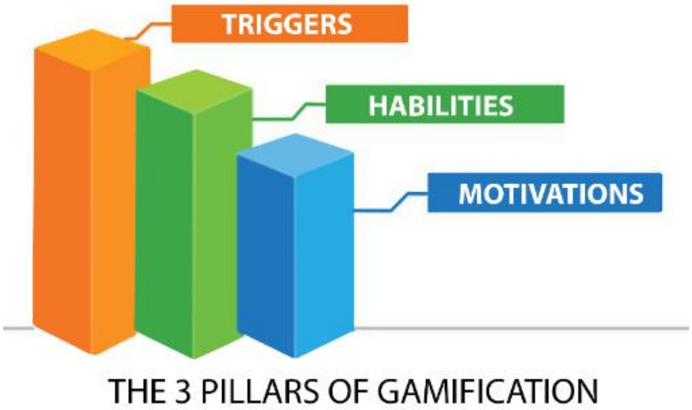


Source: (GARTNER INC; GARTNER, 2011).

Gamification refers to understand and influence the behaviors that organizations want to encourage by applying the pleasant and attractive aspects of games like fun, playfulness, and challenge (see Figure 13). At its core, the task remains unchanged, but the operator's perceptions change for the better. According to Deterding (2013), this effect is achieved through some characteristics:

- A feeling of achievement, and other deeply stimulating sensations to human beings as identification and relationship with groups, autonomy, and competence;
- A constant win situation, once the scores are progressive, there is always a positive feeling, since the player never "lose points", just stop scoring. In competitive environments not scoring, when all the opponents do, is mathematically similar to lose points, but with a better mindset;
- Visibility of status and progression, feedback is constant and always transparent; in any action, the participant has feedback whether they succeeded or not. Most of the time is very explicit how much progress is needed to achieve the desired goals or the next goal;
- Structuring tasks with challenge-oriented goal sets with gradual progression of difficulty and complexity. There is an opportunity to internalize new skills in simpler situations to be used in more complex scenarios ahead, also some autonomy to choose the paths and pace of progression;
- Cooperation vs. Competition, by intelligently assessing how much of each component of the design of a gamification environment increases the engagement of the participants stimulates feelings of participation and competence. There are reports of poorly designed competitive processes that have discouraged participants without a competitive psychological profile (DOMÍNGUEZ *et al.*, 2013);
- Freedom to fail in the game environment is the main route to learning, through test cycles, analysis of failures to feedback new approaches, which will be tested again until success in the step-in question. In the trial/error equation, fear and stress factors are removed to facilitate progression.

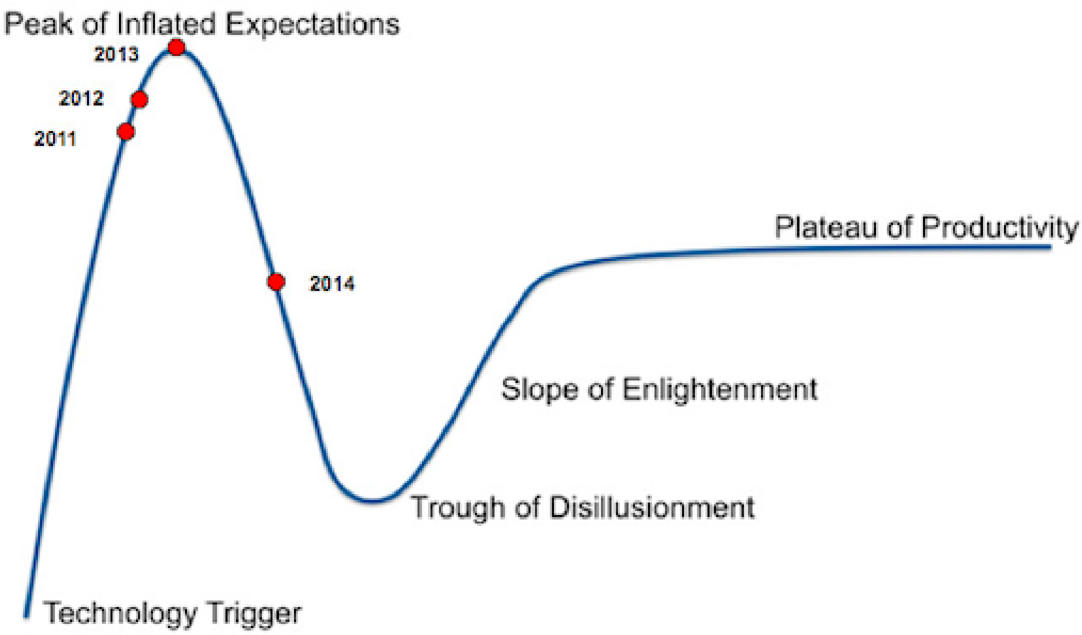
Figure 13 - The 3 pillars that comply with efficient gamification applications.



Source:(DALE, 2014)

Gamification, however, is not a magical solution. In fact, (GARTNER, 2011, 2012) predicted the failure of at least 80% of the created gamification initiatives due to failures in the implementation process. In 2014, gamification reached the path of disillusionment and from 2015 on, it stopped appearing at the Hypecycle graph; the main explanation, according to Molenaar (2014), is that the technology is becoming a widely adopted common use tool, losing its status of magic solution, with the plateau of productivity being possibly reached at the next couple of years (Figure 14).

Figure 14 - Evolution of Gamification on Hypecycle. From 2015 on it stopped to be cited.



Source: <http://edulearning2.blogspot.com.br/2014/09/gartner-hype-cycle-2014-gamification-on.html>.

Hence, there exists some difficulty in implementing a gamification action if you do not work with multidisciplinary teams and the best practices recommended, according to Dale (2014) and Raymer (2011), are:

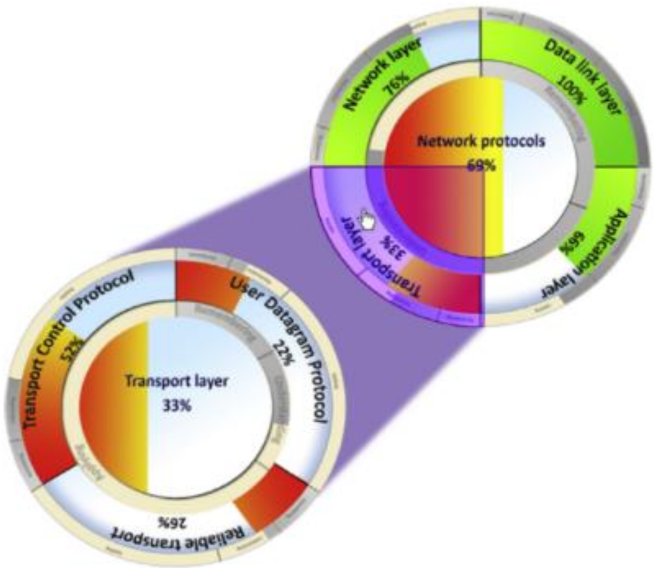
- Plan carefully before implementing, setting goals, reconciling with the company's culture or the process in question, mapping patterns of behavior to be worked or studied, not trivializing reward or feedback systems;
- Create social motivation mechanisms;
- Do not use financial rewards once they break the playfulness, the main stimulating component of a gamification implementation; financial rewards are always intuitively linked to salary, work, and obligations;
- Balancing the playful and the corporate in the visual identity of the actions of gamification, and balance the serious x fun in all visual programming;
- The process must be compatible with existing incentive programs. If there are other incentive programs being applied to the organization, the gamification implementation must not be very distant in terms of duties and rewards;
- Reward efforts, not only positive results, creating intermediary milestones to stimulate progress;
- Do not account standards below the expected, a point marked in any situation should refer to an occurrence considered satisfactory; consolation points confuse the notion of right x wrong;
- Always do some testing prior to start large-scale deployments.

2.3.5 Serious Games (SG)

The concept of serious games was created to produce advanced training tools to build decision-making capacity, improve the performance of trainees and learners. Serious Game (SG) is understood as an application that makes use of computers and advanced digital graphics for training and learning. Raybourn (2014) defines SG as the genre of games that make use of interactive digital technology for training education in public and private schools, government and military sectors, a definition confirmed by other authors (GIESSEN, 2015; LOPES; CARDOSO; 2016; RAPOSO *et al.*, 2016).

A very interesting initiative to be cited is Minović *et al.* (2014), who propose a real-time analytical tool, shown in Figure 15, that monitors the learning process on a distance learning platform. The experiment opens up a huge range of possibilities because, in addition to the records of the activities, it shows the possibility of having instant feedback to consolidate the performance and progress of participants or classes.

Figure 15 - Output from the monitoring and performance preview tool during gameplay sessions.



Source: (MINOVIĆ et al., 2014).

Figure 16 shows the Unity game engine with its analytical tool that provides, for example, frequency visualization of an event mapped on the simulation scenario, where the event occurred. In the specific case, the blue color indicates where the players passed, yellow areas represent greater circulation density and red color are areas, where the players were hit, serving to adjust project details. These tools can be very useful for HRA studies; in a simulation scenario, the locations, where errors occurred or equipment with the highest occurrence of errors could be mapped; a wide range of possibilities for presenting the data obtained within the training sessions (UNITY EUROPE, 2015; UNITY TECHONOLOGIES, 2017).

Giessen (2015) performed a study on games effectiveness and gamification in learning contexts and attested that now the question is no longer whether gamification patterns or serious games positively affect learning, but how to make it happen in the best way as well as in a predictable and replicable form. Therefore, the uses made for this analytical layer are becoming more important each year, to the point of being pointed out as one of the most influential technologies in education and training in the short and medium term (JOHNSON *et al.*, 2015; RAYBOURN, 2014).

Figure 16 - Graphical representation of the frequency of an event in the three-dimensional scenario of a game level. In this case the event of a player being hit and die in a combat scenario.

Source: Unite Europe 2015 developer conference. Available in <https://www.youtube.com/watch?v=axZJ6R8Iz8c>

In the field of training, SGs are in more advanced stages, with a long roll of suppliers in military, mining, aviation, corporate sectors, and oil and gas, focusing on training and performance evaluation for heavy construction and mining. One can cite the case of the company Immersive Tecnologies (2015), for heavy construction and mining and Simlog Inc (2015), with low-cost solutions, also for heavy construction, mining, wood extraction and logistics, all with performance analysis but without HRA tools. Another very traditional supplier is the Technologies Fifth Dimension (2015), operating mainly in mining and construction, but also has no announced features for HRA.

2.3.6 Analytics

Analytics is about perceiving and explicitating data patterns towards its use for problem-solving in business and science or to support predictions in enterprise decision management. It is rooted in statistics, data mining and visualization, operations research and programming (EL-NASR; DRACHEN; CANOSSA, 2013).

It is important to clarify that analytics is not the same thing as data analysis, which is used for individual applied instances, while analytics is about identifying and communicating data patterns. Among the several branches of analytics, are worth mentioning: marketing analytics, risk analytics, web analytics and game analytics.

Analytics is a subset and one of the main data source for Business Intelligence (BI) that uses computer-based schemes to extract information from raw data and use it for strategic or operational decisions and planning (DAVENPORT, 2006). The game applications since the earlier releases had analytical layer implemented mainly for debugging and benchmarking, but over time was perceived and developed new uses for this analytical layer, that were related to develop and measure skills and also to record and quantify user behavioral patterns (LOH; SHENG; LI, 2015).

The practice of having user data as an input for any decision-making process is a common ground nowadays projects. Analytics take this practice to a next level where streams of raw data are collected from user interaction with any artifact, processed and used as insight source (EL-NASR; DRACHEN; CANOSSA, 2013). The wide use of data-driven BI practices to support decision making processes in all levels - operational, tactical and strategic - is not historically at the core business of game development but in the past few years is becoming a standard procedure.

Quantitative data, directly sourced from analytics streams, is mixed with market reports, benchmark tests, and any other sources and fed into business intelligence or statistical models to support decision making. User-focused analytics are valuable data sources mainly due to its spontaneous nature for not being born from a question & answer process, which can be subject to biases (EL-NASR; DRACHEN; CANOSSA, 2013).

The main concepts are necessary for understanding the use of analytics in GE for HRA studies (EL-NASR; DRACHEN; CANOSSA, 2013):

- **Game Analytics**: Is the application of analytics to game or simulator research and development. Another use for the gathered data is to feed mathematical and statistical models for strategic decision making.
- **Game Telemetry**: Or just telemetry is the process of obtaining data over a distance. The analytics framework of every GE can send the collected

metrics over networks for outbound system studies. This feature is exploited at the present work, where data about every operator can be sent over the internet to an analytics provider, where its compiled for final use.

- **Metrics:** Quantitative depictions of anything that happens in the virtual environment or game. They give precise insights of a user behavior or any other event on the scenario such as response times, moving speed, idle time, total time on the system, number of doors opened, acquired equipment for a task, almost everything that happens in a Virtual Environment (VE) can be quantified via a metric for posterior analysis, times, reactions, eye gaze, choice patterns etc.

2.3.7 Game mechanics

Game Mechanics are mechanisms used to motivate and stimulate certain behaviors and may have their activity centered in the cognitive, emotional and social areas (DOMÍNGUEZ *et al.*, 2013). Some examples are progressively more difficult challenges, rewards, rankings and time constraints, user input modifications, and many more.

There are simple gaming mechanisms with big effectiveness; for example, instant feedback that informs in real-time if the player answered correctly, permitting the individual to self-assess his(her) own performance on the fly, in a highly motivating manner. For example, an experiment conducted with students used the digital gamified environment to increase learning of Information Technology (IT) basic concepts (DE-MARCOS *et al.*, 2014). A simplified list of the most commonly used game mechanics is described by Dale (2014):

- Achievements (levels, bonuses, experience scores);
- Exercises (challenges, discoveries, puzzles);
- Synchronization with social media (rankings, collaborative teams);
- Transparency in results (continuous feedback, experience bars).
- Time (regressivity, velocity).

The list is not extensive once some mechanisms can be broken down into a combination of the basic ones. When using these elements, in a gamified context, any tasks that need stimulus can have their performance improved, through balancing and in the adequacy of the used game mechanisms (ATTALI; ARIELI-ATTALI, 2015; JAGODA, 2013; ZICHERMANN; CUNNINGHAM, 2008).

2.3.8 Game-Based Learning and games for learning

Nowadays, distance-learning platforms, which were previously based on hypertexts and multimedia content, are starting to turn to digital games (ERHEL; JAMET, 2013). According to Mayer and Johnson (2010), the GBL / SG applications should have: 1) a set of rules and limiters; 2) dynamic responses to interactions, and 3) graduation in the addition of difficulties based on the results of previous interactions.

GBL applications can be quickly understood to use game technologies to actively convey content to players, allowing them to practice previously learned content in a virtual environment, where errors can be tolerated, and skills developed safely. Some authors mention another variant of GBL called Game for Learning (G4L) that are games specially created with educational purposes, while GBL is classified as the use of games in education (BECKER, 2015).

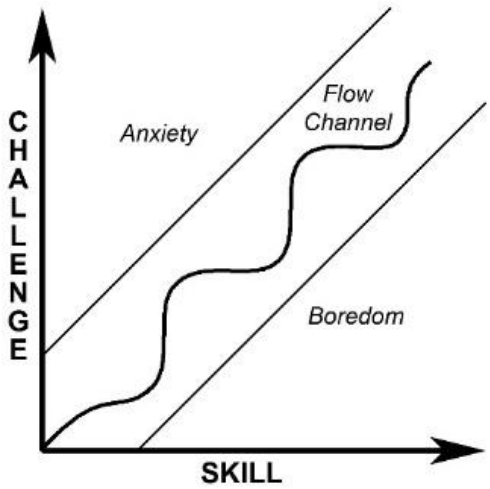
2.3.9 Flow (Optimal Attention State)

Flow is a state of concentration of satisfaction that occurs during activities that are challenging but have a level of difficulty that is matched with the competencies and abilities of the task operator (Figure 17). In this situation, the perception of time is altered (time is not perceived to pass), operations and maneuvers seem to occur effortlessly and automatically although there is a sense of voluntary control and concentration (ULLÉN *et al.*, 2012).

Several studies have proven that if challenges or tasks to be executed do not have a balanced degree of difficulty, the operator feels bored, while tasks with difficulties beyond the operator's ability generate anxiety (ABUHAMDEH; CSIKSZENTMIHALYI, 2012; ADAMS, 2013). However, in general, activities that have an obligatory character or those for which the operator does not have its own motivation, said in the jargon of games as intrinsic motivations, are seen as more pleasant, when the level of difficulty is somewhat inferior to that of skills of the operator (HARTER, 1978).

For the design of gamified environments and training, the good practice recommends carefully building the progression of challenges so that skill acquisition (learning) and difficulty grow together, constantly providing a sense of overdue challenge (Figure 17), encouraging the participant to remain engaged (RAYMER, 2011).

Figure 17 - Graphic Skill X Challenge.



Source: Raymer (2011).

Some authors like James Chang *et al*. (2014) report difficulties to make operators represent 100% faithfully the stressors present in training on simulators. Thus, Nuclear Energy Agency – NEA - CSNI (1998) recommends guidelines to operators to act as if they were in real situations. A less engaged behavior probably caused by the lack of real disastrous consequences can lead to deviations in the data obtained. Using game design elements to model engagement scenarios may be a factor to improve the quality of data obtained, especially for HRA studies.

2.4 VIRTUAL REALITY

Virtual Reality (VR) can be defined as an interactive computational simulation, which monitors the state and activities of the user, replacing or increasing the operator's senses through digital content, bringing a sense of being immersed in the simulation (MIHELJ; NOVAK; BEGUŠ, 2014). In a virtual reality environment, we will have four basic elements: virtual environment, virtual presence, sensory feedback (to the user) and interactivity (MIHELJ; NOVAK; BEGUŠ, 2014).

VR has been the object of research since its inception in the late 1980s and early 1990s, and it has always had its usability questioned mainly by the problems of resemblance with reality and high latencies in the responses. VR is becoming now a real-world tool, backed up by streamlined software and powerful hardware solutions that were physically and financially unfeasible not so long ago (MCMENEMY, 2007; MIHELJ; NOVAK; BEGUŠ, 2014).

The scientific community had never abandoned studies with VR, even with the consumer market tagging VR as an undelivered promise. However, VR now emerges based on new and more efficient technology, whether by the higher processing power of computers or by new interface solutions that make the visual, tactile or aural metaphors become less abstract for the user. Increasingly, it is becoming possible to VR applications have compelling immersion and not requiring enormous processing power to work satisfactorily (MCMENEMY, 2007).

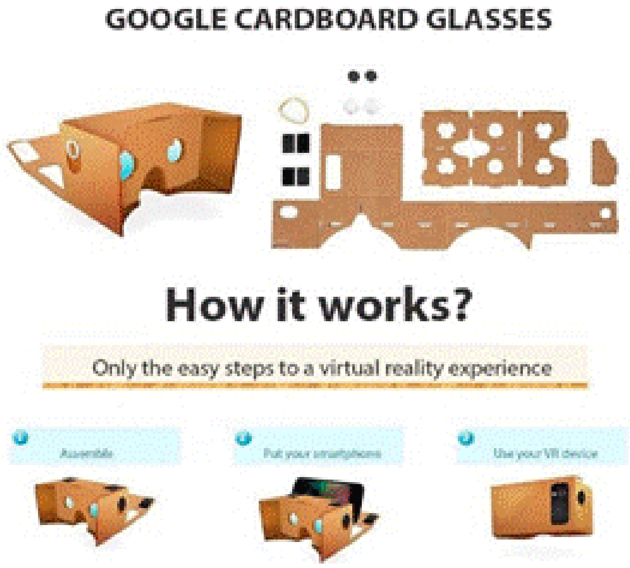
The response to interactions can be programmed to simulate the real world convincingly. With the evolution of solutions in computer graphics and large-scale processing, a greater resemblance can be achieved meaning better immersion feeling by high-quality graphics, and responsiveness (JUANG; HUNG; KANG, 2011; RUBIA; DIAZ-ESTRELLA, 2013).

Stereoscopic imaging solutions, the so-called Head Mounted Displays (HMD), facilitate the feeling of immersion. There are hundreds of solutions, several versions of low cost and low latency, some consisting of smartphones mounted on cardboard holders, the cardboard VR glasses (Figure 18), and also the more expensive ones like the Oculus Rift (Figure 19) and, the HoloLens from Microsoft (2015).

Unlike flow, where engagement occurs because the player is focused on the task, in virtual reality, multi-sense stimuli and responses to interaction requests lead to the most effective sense of immersion in the virtual environment. This perception is divided into physical and mental virtual presence and happens when users, so engaged in operations in a virtual environment, stop questioning what they are experiencing (MIHELJ; NOVAK; BEGUŠ, 2014).

In the experiment designed in this work, the simulator can be considered a VR one although the sensory feedback is not so complete, as it actuates at users' senses through digital mediation, in this specific case vision, audition, and tact.

Figure 18 **-** Google cardboard Glasses, Low-cost adaptation for smartphones to function as devices of VR



Source:<http: www.gadgets4geeks.com.au/cardboard-virtual-reality-vr-headset-kit=">

Figure 19 - Oculus DK, and a monitor showing what the user sees, attention to the head angle and the image displaying a ceiling:

Source: https://www.makeuseof.com/wp-content/uploads/2013/05/oculus-rift-review-6.jpg

For studies of HRA in simulators, the closer the real situation is from the training scenario, the more authentic will be the user's responses and, consequently, better the quality of the data. Virtual reality tools today exist in an uncountable variety of formats and costs enabling a very extensive range of applications.

2.4.1 Virtual environments

Virtual Environments (VE) are the digitally generated environment where the simulations take place; they have previously defined (programmed) laws, rules, and interrelations that govern their operation. The virtual presence consists of interacting with this environment through the mediations created by the simulation, being this the essence of virtual reality. VE can be very useful to study human behavior in many ways and are defined by their content that can be basically visual, auditory or tactile (ABU-SAFIEH, 2011; MIHELJ; NOVAK; BEGUŠ, 2014).

In a very similar real world, objects in VE have properties like shape, color, texture, temperature, and others. As it happens in natural environments, the object properties are perceived with different senses. For example, the color and reflectivity of an object are captured by the visual domain, while the texture is perceived in the visual and haptic domain of senses. The main elements of a VE are (MIHELJ; NOVAK; BEGUŠ, 2014):

- Topology: refers to the dimensions, forms, and characteristics of the environment; objects that are the entities inhabiting the environment and manipulated by the user or users;
- Intermediaries: representations of users, interfaces or avatars. Avatars are useful when you have multiple users interacting in the same environment;
- User interface elements: parts of the virtual environment created to receive inputs from the user and guide them on interactions via feedbacks of various natures (e.g. animations, sounds, and tactile feedback). The most common ones are virtual buttons, switches, and sliders.

2.4.2 Virtual presence

It can be understood as a feeling of being present in the environment and can be divided primarily into physical and mental sensations. The physical sensation of virtual presence can be artificially generated by devices for one or more senses, while the mental sensation is defined as a kind of trance in which the operator feels part of this reality (MIHELJ; NOVAK; BEGUŠ, 2014).

The individual has the senses stimulated by the various responses provided by the VE, and as it begins to interact, the mind stops to treating the surrounding stimuli as artificial despite consciousness of the user knows the environment is artificial. This kind of multifaceted sensation is difficult to achieve in other media, despite some conventional contents (e.g. TV or even books) can mentally abduct a spectator's attention, the sensorial flood caused by simultaneous stimuli generates a more engaging sensation of presence (SERRANO; BAÑOS; BOTELLA, 2016).

2.4.3 Sensory feedback

The sensory feedback is the great responsible for the sense of insertion in VE. The simulation system reads the user inputs that can be given through several devices and makes the environment respond in a convincing way. It is necessary for the system to continually update the user's positioning properties in order to maintain the resemblance of the virtual environment (MIHELJ; NOVAK; BEGUŠ, 2014; RUBIA; DIAZ-ESTRELLA, 2013).

The bigger the number of senses stimulated by the environment the better the immersion sensation. Sensory feedback may be an audio that changes the relative source location as the user moves around the scenario, objects that respond to interactions like moving or breaking as the user acts on them (MIHELJ; NOVAK; BEGUŠ, 2014).

2.4.4 Interactivity

The most open definition of interactivity says it is an active relationship between two things (SALEN; ZIMMERMAN, 2004). It is expected that, in a context of "reality", the world reacts to user interactions either by changing the characteristics of entities in a way analogous to the real world such as deforming objects at a touch or with more abstract interactions, like changing the amount of light in an environment with a gesture, or jumping to a chosen place by pointing at it (MIHELJ; NOVAK; BEGUŠ, 2014).

One important issue on interactivity is the visual metaphor by which the subject is inserted in the virtual world. It can be of first-person when the users do not see themselves, or the third person, where a representation of them in the environment, the commonly called avatars, is displayed. Many systems offer the option of switch between both instantly, which also is an item of interactivity (ADAMS, 2013).

Salen and Zimmerman (2004) bring an interesting approach to interactivity, with four models of interactivity each one with different levels of user engagement and is stated that the most engaging experiences incorporate more than one feature at a time. The so-called models are:

- Cognitive or interpretive interactivity: Is the psychological mode of participation between a person and a system. As an example, the interaction between player and an adventure game can be cited, a highly narrative style with a focus on exploration and puzzle solving, sometimes the outcomes are presented via a text interface, but the triad choice-cause-effect retains user attention despite simplified or inexistent graphic representations (MIHELJ; NOVAK; BEGUŠ, 2014; SALEN; ZIMMERMAN, 2004);
- Functional interactivity, or utilitarian participation: The functional interactions with the material components (real or virtual) of a system. The example that can be used is how responsive is the system, how accurate is the controller, is the text presented easily readable. These elements build the technical side of interactivity, how much the players feel the system as an extension of themselves (SALEN; ZIMMERMAN, 2004);
- Explicit interactivity: Also called participation with designed choices, it is the common knowledge meaning, using the joystick on a video game, navigating a hypertext novel are some examples. However, it can encompass choices, random events, dynamic simulations and any procedure programmed to interact with the user (PERERA; ALLISON; MILLER, 2012; SALEN; ZIMMERMAN, 2004);
- Beyond-the-object interactivity: Is a participation, outside the system. A good example is the phenomenon of fan universe, which extends the existence of the system outside its boundaries. This kind of interaction is being explored on transmedia products, which trespass a single medium, books who turn into movies and games with different parts of the story happening in different media (JAGODA, 2013; SALEN; ZIMMERMAN, 2004).

Carefully designed interaction experiences must also incorporate meaningful choices. When the user selects an option, and the system responds accordingly to expectations, the bonds of engagement are being created. The quality of the responses of the system is one way to rank the depth and quality of interaction. There are two levels of interaction (SALEN; ZIMMERMAN, 2004): micro and macro.

The micro level represents the sequence of continuous *ad hoc* choices the user is asked to make during a game or application, while macro level corresponds to the master plan behind the micro-choices, giving the meaning to all the actions taken by the user in the system (SALEN; ZIMMERMAN, 2004; TUCKER, 2008). Then, it makes sense to say that a big amount of effort must be placed on interaction design to improve user engagement, the main goal in any interactive system regardless of the project purpose being training, education or fun (SALEN; ZIMMERMAN, 2004).

2.4.5 Immersion

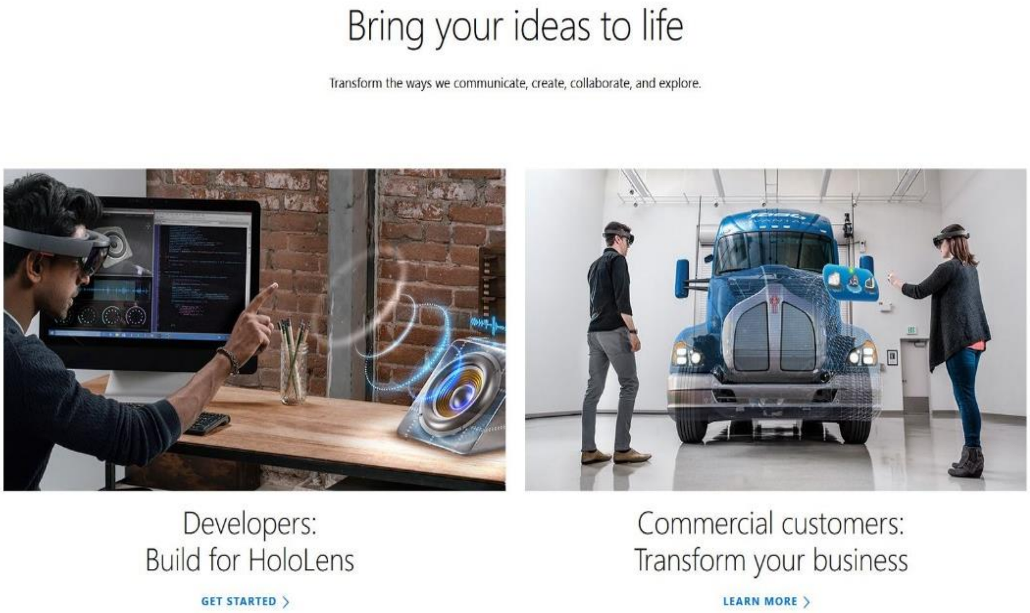
As the name suggests, immersion is the environment, where the user gets totally immersed in a simulated digital environment that, when compelling and with rich and live content, can make the user experience superlatively engaging (MIHELJ; NOVAK; BEGUŠ, 2014). When, for example, in the educational setting it can, in addition to transmitting content, develop skills, analogous to real-world experiences (BURNS, 2012; MIHELJ; NOVAK; BEGUŠ, 2014).

Immersion is one of the major factors that can reduce the distance between reactions in the real world and reactions in simulators and maybe a link to better and more representative reliability data. There is also what is called Augmented Reality (AR), where the elements of interaction are applied through semi-transparent device over the real world, using a visual and logical layer of information about our reality. For example, when looking at the window we see the weather forecast stamped on the glass. Watching the wrist gesture can activate a clock (KJELLMO, 2014; PARK; HA; WOO, 2014a).

Recently, Microsoft released the HoloLens device that promises to be a step further in AR, first by being lightweight and not using cables. Through this device, you can see 3D elements inserted in the real world, in real time and with impressive quality. The device also provides various types of interaction, from gesture to voice command.

Figure 20 one can see the product and technology presentation site (MICROSOFT INC., 2015).

Figure 20 - HoloLens's presentation Site, augmented reality device and holography.



Source: https://www.microsoft.com/microsoft-hololens/en-us.

Game technology tools can be very useful for streamlining the creation of simulators, with the set of pre-built and conFigured tools permitting concentrate team effort in the "end" areas of the project. However, interdisciplinarity remains the key to the success of the applications created. Better visual quality, resemblance, and cognitive fitness will continue to generate more attractive, and thus more effective applications that can generate datasets to be used in HRA studies.

In the present work, one will use a GE to build a simulator for HRA data extraction, the scenario will be presented in monocular 3D and the sensory paths stimulated will be vision, audition, and touch. Also will be used an analytics setup to extract data from the simulator sessions that will be used in a BBN to assess the evacuation success under certain conditions, and how the change of these context variables affect success probabilities.

In the next chapter, a pool of good practices and valuable examples of related work is compiled with the main goal of bringing insights to be used in the applied phase of the present work. Despite some inherent flaws, the works studied carry innovative and ingenious approaches and also empiric advice that were worth mentioning.

3 LITERATURE REVIEW AND EXPLORATORY PHASE

In this section, the literature review was carried out with the aim of delving deeper into the theme as well as presenting the exploratory phases of this work.

3.1 EXPLORATORY PHASE

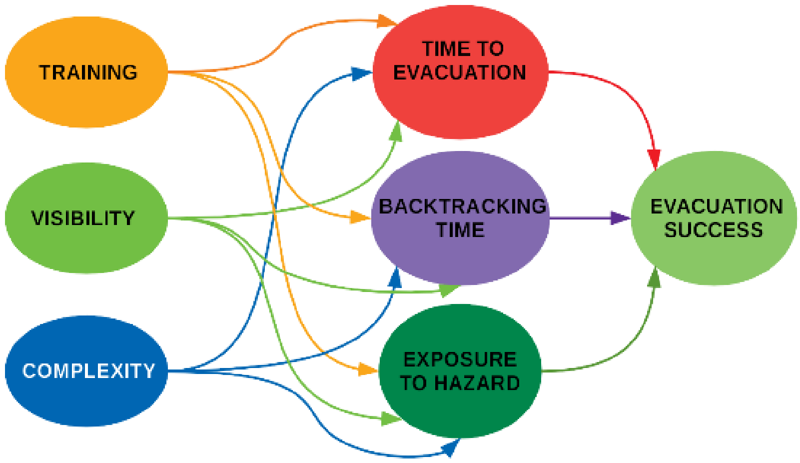
With the intention to delimitate the state-of-the-art in the area and gather good insights in the use of Virtual Environments and simulators. This phase was the starting point of the present research and consisted of a related works compilation and hearings with the local scientific community.

3.1.1 Related works found

Recent advances in VR solutions have enabled the development of immersion technologies in which users are an active part of interactive virtual environments. This evolution allowed emerging VR-based training solutions, a safe and less expensive approach of transmitting structured content, to obtain experiences that would be invariably dangerous or cost-prohibitive to reproduce in real-world (CHA *et al.*, 2012; PARK *et al.*, 2014).

Musharraf *et al.* (2014) work with a virtual training environment, called AVERT, in which it is gathered route data and routing decisions in offshore installation evacuation. The authors conclude that, although the travel times are not totally realistic, the interrelationships between virtual performances are very reliable to what is expected in a real environment. The PSF studied are training, facility complexity and visibility (see Figure 21), and the experiment was designed to gather enough data to feed the conditional probability tables for a Bayesian Belief Network (BBN), also making it possible to validate values for the PSF. The research uses a proprietary virtual environment, and there is no mention on how metrics like time to evacuation and backtracking time are measured.

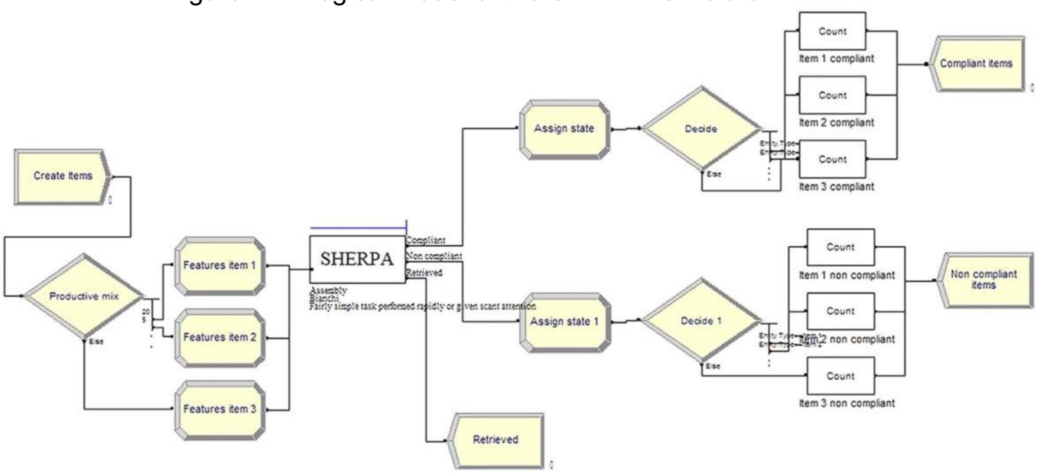
Figure 21 - Causal network with random variables (from where arrows leave) and dependent ones (the one where leads arrive). This graph called Directed Acyclic Graph (DAG) represent the causal relationships in a phenomenon.



Source: Musharraf et al. (2014).

Figure 22 shows a chart of the operation of a human behavior simulator called SHERPA with similar visual metaphor, found in the works of Di Pasquale *et al.* (2015), where human behaviors are simulated to analyze how HEP behaves with variations of PSF. Both works approach the PSF influence: one using simulated events (DI PASQUALE et al., 2015) and the other (MUSHARRAF et al., 2014) advances a little more by using real human inputs to validate pre-existent PSF via a modeled BBN.

Figure 22 **-** Logical model of the SHERPA simulator.



Source: Di Pasquale et al. (2015)

Kim, Park, and Jung (2017) work is about the classification of erroneous behaviors for HRA based on simulator data. The authors presented two ways of recording human errors to databases:

- with the list of Human Error Probability (HEP) for a given context;
- with human performance level on a given task associated with contextual information.

This classification divides the databases into HEP-based and human-performance-based databases. A classification scheme is proposed to fulfill the following requirements:

- the types of error must comprehend all possible erroneous behaviors for the control tasks in the systems;
- there must be a compatibility link between error types from the scheme in study with popular HEP databases permitting updates or validation of obtained values;
- types of errors should be mutually exclusive to avoid misinterpretation by future users.

The authors say that the cognitive process model should include the following activities: information gathering, situation interpretation, response planning and execution, and be tightly directed to the method of HRA that was defined to be used. The work brings a very useful approach that helps create a database taxonomy for classification and store logs from simulator sessions.

Chittaro and Sioni (2015) used an SG simulation in emergency preparedness for terrorist attacks in a train station. The experiment scenario consisted of a train passenger during a terrorist attack and in which several events occur, with all the wrong reactions that lead to damage shown on screen and, in case of death, the reason is explained as well as the correct procedure (Figure 23). The scenario runs on a 30-inch computer screen and interaction is done via Nintendo Wii controllers and, despite being mentioned the use of a GE, no further specification is given. Some stimuli are applied to the player in order to give the dimension of the threat involved and the seriousness of the consequences in a way similar to game mechanics. The Heart Rate (HR) and Skin Conductance Level (SCL) players are logged via an Electrodermal Activity (EDA) sensor.

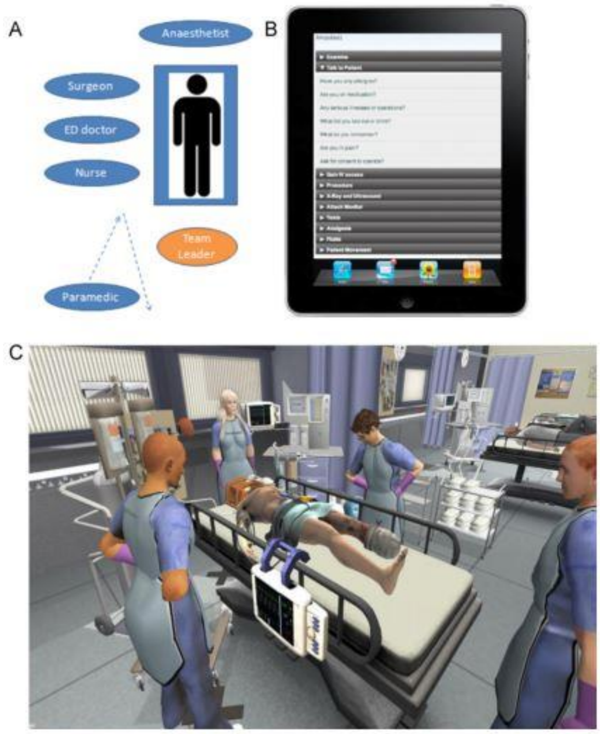
Figure 23 - Death cause informed on-screen information, and security recommendations to avoid that in similar scenarios.

Source:*(CHITTARO; SIONI, 2015)*

In Cohen *et al.* (2013, 2012), two virtual environments, one for emergencies readiness and the other for hospitals receiving victims of disasters, are created. Even though not intended for HRA, it is a good example of creating scenarios difficult to reproduce in real life even with simulated training. There is a virtual patient built as a structured data model and this automated setup controls the patient physiology within the virtual world according to defined criteria. Clinician decisions and preset timed events alter the virtual patient state accordingly. It represents a suitable idea for implementing the dynamic process simulator to a scenario without having one inside the GE. In the simulations, technical capabilities, communication skills, and team coordination are evaluated (see Figure 24).

Nyamse *et al.* (2013) bring a VR simulator of a human heart to enhance anatomy classes which, according to the author, have been suffering from various issues because of using of cadaveric materials. The article has many suggestions on user interaction and interface. The work was done in Unity game engine with an intermediate step at 3DS Max in a way like the one proposed in the present work. Recommendations are given about system performance and models optimization to guarantee minimal performance during the interactions. The same system has also a simplified version aimed at clarifying heart diseases concepts to patients.

Figure 24 - Trauma Scenario layout (A), tablet application with the menu for the trauma team actions (B), the virtual patient being treated(C).

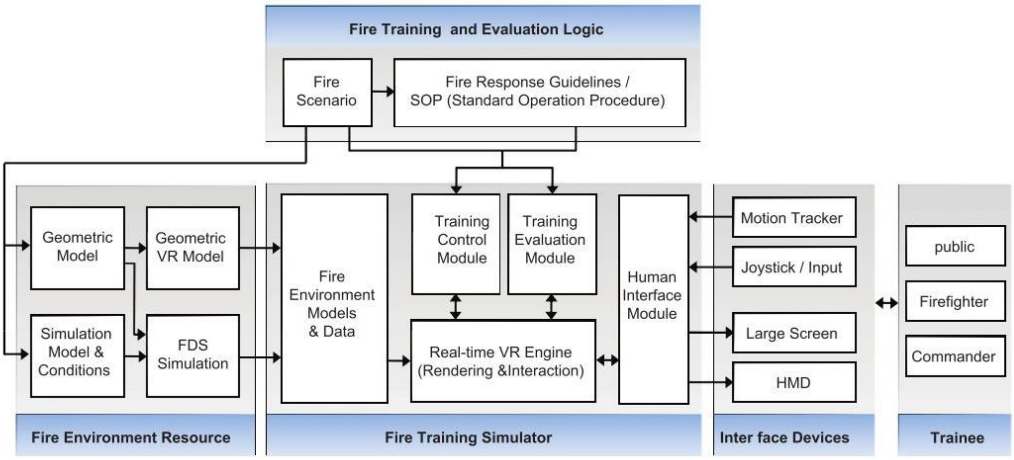


Source:*(COHEN* et al.*, 2013b)*

Kastel *et al.* (2013) reported an AR experiment in a theatrical play and provide many recommendations on how to optimize scenarios and characters for real-time performance and the use of the FBX file format pipeline for transferring data between the GE (Unity) and the modeling software (3DS Max). The experiment also depicts an ingenious way for large-scale AR and a cost-effective scheme for human motion capture from consumer grade hardware.

Cha *et al.* (2012) showed an interesting experiment for firefighters training that uses data from a Computer Fluid Simulation applied inside a Game Engine Figure 25). The experiment has many simplifications and the dynamic process simulator link is only inwards the GE. Player reactions did not generate feedback for the process simulator to reprocess the scenario logic. The host system is quite modest for the task and some performance issues were mentioned. A quick look at the pictures revealed 3D models with unnecessary details like a car’s wheels with excessive polygons. The system uses VR glasses for immersion and a joystick and motion trackers for interactions. The overall assessment of the application by professional firefighters indicates the VE for inexperienced novices and suggested some game mechanics to improve efficiency.

Figure 25 - Fire training simulator topology summary.



Source: *(CHA* et al.*, 2012)*

There have been mentions of simulator experiments in critical situations such as nuclear power generation as in Zhang *et al.* (2007) and flight control as in Isaac, Shorrock, and Kirwan (2002), with the extraction of data for HEDB or observations regarding the usability of the obtained data.

Based on the analyzed works, the panorama of GE, VR, and HRA consists of two big group groups:

- Large and expensive simulators for HRA studies (ZHANG *et al.*, 2007) or proprietary virtual training environments such as AVERT, adapted for data collection of human reliability (MUSHARRAF et al., 2014);
- Experiments with custom built virtual environments for emergency situations without HRA data.

There was great dissemination in the use of simulators outside critical areas (where the use has been more common) such as nuclear power and air traffic but always focused on training and performance evaluation. In these sectors, the use of simulators for training already seems consolidated (ADMS SIMULATOR, 2017; CHITTARO; SIONI, 2015; COHEN et al., 2013b; DAVENNE et al., 2012; TOOP, 2006). Although some of them are in early stages of development, these experiments demonstrate the great capacity of virtual environments to provide quality empirical data for HRA, and many other mathematical models, bringing powerful insights on the studied phenomena. These arguments confirm the necessity of studying the creation of Virtual Environments to collect data for HRA and also show that the focus on the creation process itself is a valuable scientific contribution. In the next Chapter, the proposed methodologic approach is described in detail.

3.1.2 Hearing the scientific community and research interconnection

The next step was to define a specific scenario to be simulated. After some investigation, the chosen scenario was an evacuation due to H_2S toxic cloud leakage scenario (hydroxy sulfide). A useful scenario that is currently the subject of studies by the optimization area at the Center for Risk Studies and Environmental Modeling (CEERMA).

This accidental scenario is one of the objects of study of Oliveira da Silva (2017), in her work that uses a Multi-Objective Genetic Algorithm (MOGA) to estimate faster and safer paths to the evacuation process. The scenarios have a realistic definition and are quite probable to happen in real life representing an outstanding opportunity to apply the framework.

Another issue worth mentioning is the existence of a Refinery Plant with characteristics very similar to the object of study in both works, representing a possibility of real utility for the researches.

Some of the results obtained with the MOGA were used as benchmarks for the simulator scenario dataset classification. Despite the diverse approaches the results were not so different as common sense should initially expect, these results are discussed in section 5. Table 3 brings a comprehensive comparison between the two works showing common points, interconnections, extensions, and differences.

Table 3 - Comparison between Oliveira da Silva (2017) and this work.

MAIN FEATURES	Oliveira da Silva (2017) WORK	THIS RESEARCH
HAZARD SIMULATION (IDENTICAL SCENARIO DESCRIPTION)	ALOHA 20 POINTS	ALOHA 176 POINTS
SPEED CHOICES	3 SPEEDS BY AREA	3 SPEEDS AT USER CHOICE
SCENARIOS SIMULATED	3	1 (H_2S LEAK)
ROUTE VARIATIONS TESTED	12 BASED ON ALGORITHM	43 BASED ON HUMAN BEHAVIOR IN SIMULATOR
TIME TO COMPLETION VALUES RANGE	27-88 min	10-62 min
INDIVIDUAL RISK CALCULATION	PROBIT EQUATIONS	PROBIT EQUATIONS
HAZARD LOCATION KNOWLEDGE	ALGORITHM KNOWS IN ADVANCE	USER DISCOVERS ON THE ROUTE
CLASSIFICATIO N OF EVACUATION STATUS	N/A	YES BASED ON TIME AND INDIVIDUAL RISK ON ROUTE
ROUTE TOPOLOGY	THEORETICAL STRAIGHT LINE LINKING NODES	REALISTIC BASED ON SCENARIO

Source: This research (2018).

The combined studies represented an opportunity to comprehensively approach a scenario and draw conclusions based on data from multiple choices, representing a rich experience for both works. The final results are discussed in chapters 5 and 6.

4 FRAMEWORK CREATION AND SIMULATOR DESIGN AND EXPERIMENT EXECUTION

This section will demonstrate the process of creating the design of the project, as well as the design process of the simulator. The experimental execution of the project will also be addressed.

4.1 APPLIED PHASE

After extensive readings, the conceptual framework was assembled, composed of 15 steps that are described in Chapter 5. The framework addresses issues specific to 3D modeling, game development and many project decisions that must be done in the early stages of any project, in which a wrong choice may imply a lot of rework afterward or a scenario with low representativeness.

In fact, a classical mistake made in the early stages of drawing is the use of over-detailed 3D meshes. Even though they look better on screen, unnecessary polygons in a mesh are a heavy burden to the system. In this case, there is a recommendation of keeping the polygon count as low as possible so that it does not become a too abstract representation.

4.2 EXPERIMENT ASSEMBLY

To validate the proposed framework, an experiment was designed and conducted, in which the chosen scenario was an evacuation procedure for an oil refinery. The scenario results treatment choice was motivated by the article of Musharraf *et al.* (2014), in which a Bayesian Network is fed with data from a virtual environment of an offshore facility called AVERT. Despite of not being a refinery scenario, the use of simulator data brings powerful insights to be used in other contexts. In Musharraf *et al.* (2014), however, very few information on the simulator itself is given, and the data collection approach is poorly documented.

Then, the experiment in this work seeks to create a VE via GE and output data similarly to Musharraf *et al.* experiment, but with the main focus on documenting the creation process. Thus, if the Musharraf *et al.* (2014) brought a pathway to use the data, the present work will present a framework to create a simulator that generates such data, extending the idea and closing the gap for HRA quantitative analysis.

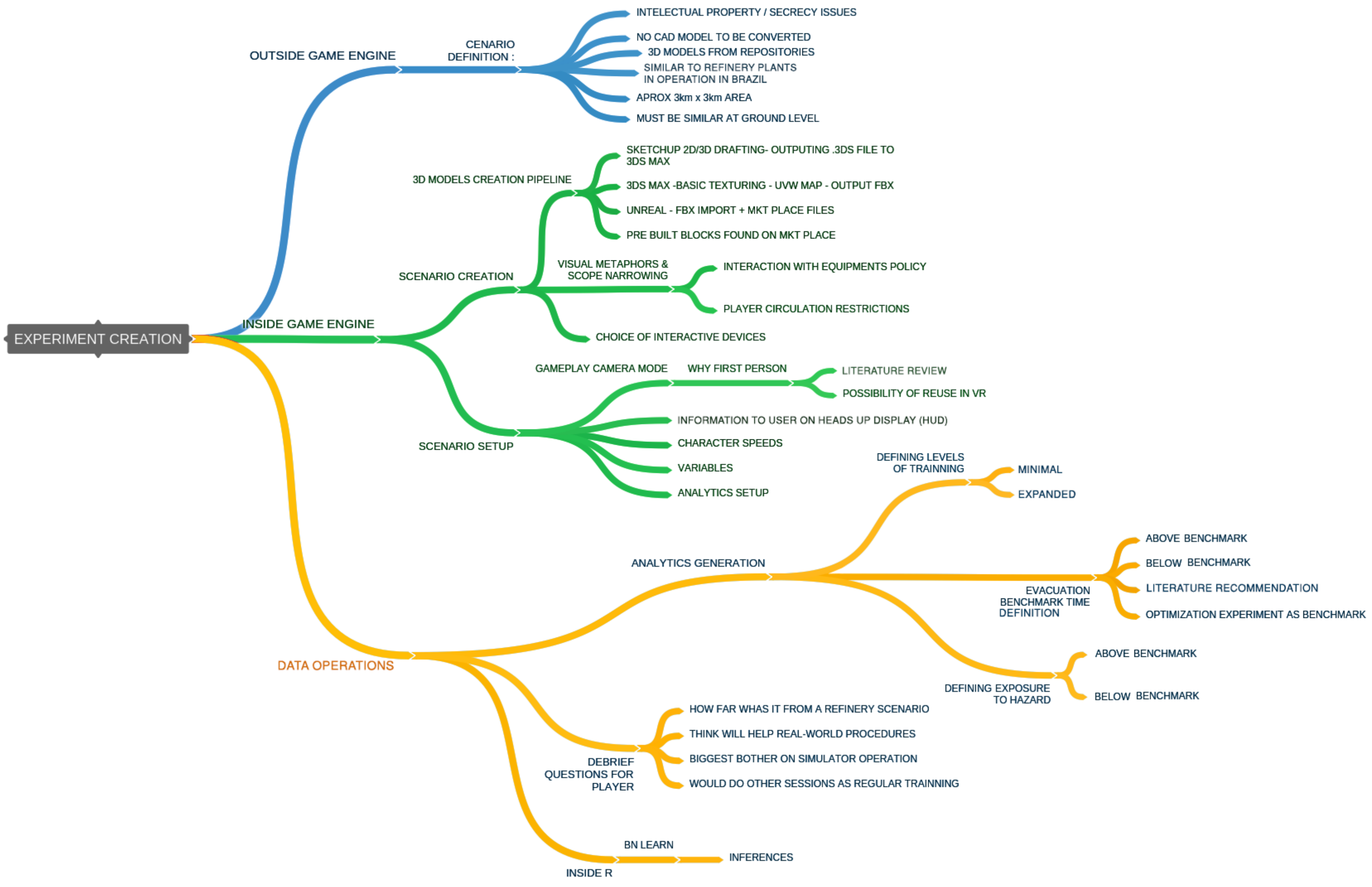
Another interesting facet of the present work is to do an interface with the work of Oliveira da Silva (2017), which developed a MOGA to obtain routes with an optimal compromise between evacuation time and individual risk using the same scenario. As a benchmark for success, the results obtained via MOGA for individual risk were used to classify the success of the evacuations operations on the virtual environment A chart with a general overview of the simulator creation process in the present research is presented in Figure 26 with all steps that were covered and decisions that had to be taken during the simulator creation.

Also, to permit comparisons between MOGA results and approaches with the ones obtained in the VE simulator, the qualitative analysis for scenario definitions were aligned with the ones developed in Oliveira da Silva (2017). This approach permitted a more streamlined VE simulator design with tested milestones since the accidental hypothesis was covered previously by Oliveira da Silva (2017).

In this experiment, a VE is defined, modeled, programmed inside the Unreal GE with analytics output and the generated data was fed into a BN for conditional probabilities calculation. There were three phases:

- The first phase, outside the GE, where the 3D modeling of the VE was carried out, consisted in the search for visual references, like photos and videos from actual refineries, to make the VE as representative as possible to a real-world scenario;
- The second phase, inside the GE, with models import and placement, game logic programming, visual metaphor definitions and scenario variations defined;
- The third stage consisted of processing the data from the VE and feeding the BN.

Figure 26 - General overview of the VE (simulator) creation process.



Source: This research (2018)

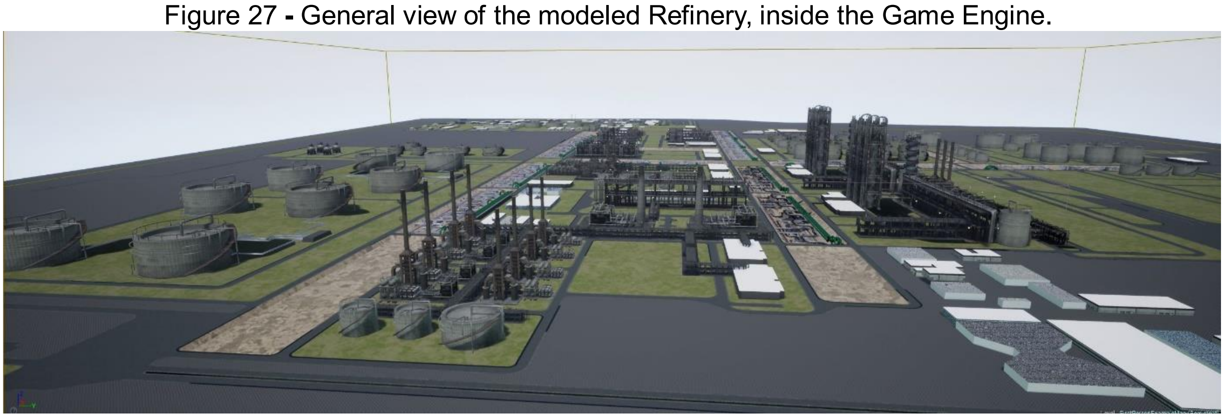
4.3 SCENARIO DEFINITIONS

A refinery scenario was chosen to serve as a model for the simulator allowing the study of the evacuation process without large-scale simulated exercises, which, despite being very important, are difficult to manage and expensive to do. Was decided then to do a plant layout based on visual research of refineries in operation in Brazil and in the state of Pernambuco, and also respecting the layout in the work of Oliveira da Silva (2017) in a way that for the users walking at the VE it will feel like a real refinery.

The first issue that appeared was that, due to intellectual property and security reasons, refineries blueprints, in general, are not public domain. Then, a Google Maps plates were created with an aerial view of refineries and, inside Sketchup, all the streets, sidewalks, blocks for the administration buildings were drawn in scale for the virtual plant.

The major concern in the case was to maintain similarity at ground level so that players walking the streets would be somewhat familiar with the surroundings. Due to the modular nature of GE, any geometry placed on the terrain could promptly be replaced, keeping very simple the process of updating and modifying geometries in the scenario (Figure 27).

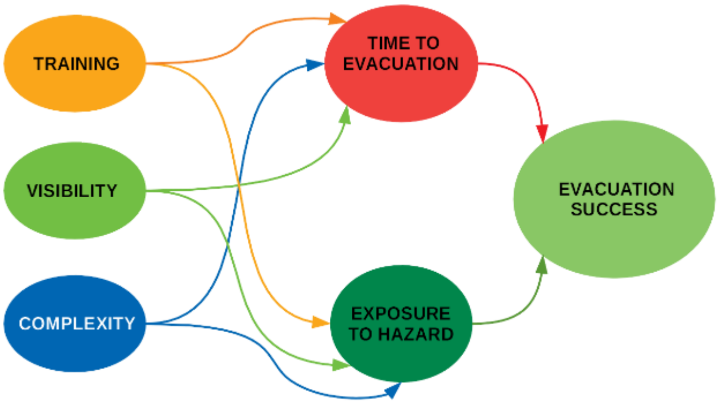
Figure 27 **-** General view of the modeled Refinery, inside the Game Engine.



Source: This research (2018).

The scenario consisted of an evacuation of the plant due to a leak that generated a toxic cloud of hydroxy sulfide (H_2S) in the Sour Water Treatment Unit. It is based on the scenario used by Oliveira da Silva (2017), a path optimization work. The main objective is to estimate analyze how context variables (training, visibility and complexity) influence the probabilities of successful evacuation under various conditions in a dependency network as can be seen in Figure 28.

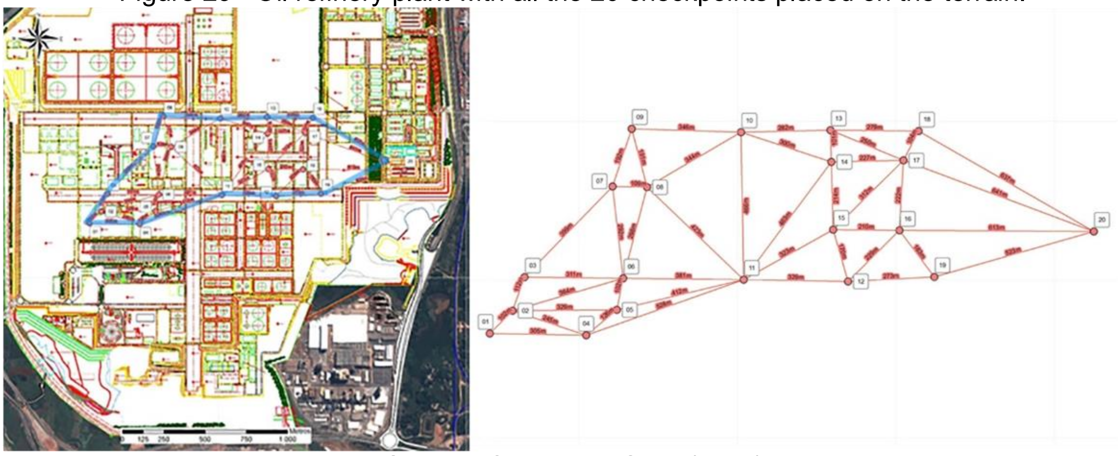
Figure 28 - The Bayesian Belief Network (BBN) for the evacuation procedures. Based firstly on training, visibility and scenario complexity.



Source: This research (2018), based in *Musharraf* et al. *2014)*.

For the present work was used a 20-point graph (Figure 29) of all possible routes, from the initial point to the final one, landmarks were placed on the terrain to be used as checkpoints for the player leaving the area. The points were not visible to the player, but each checkpoint has a control area that when trespassed by the players, records their presence and a timecode of when the sensor was triggered.

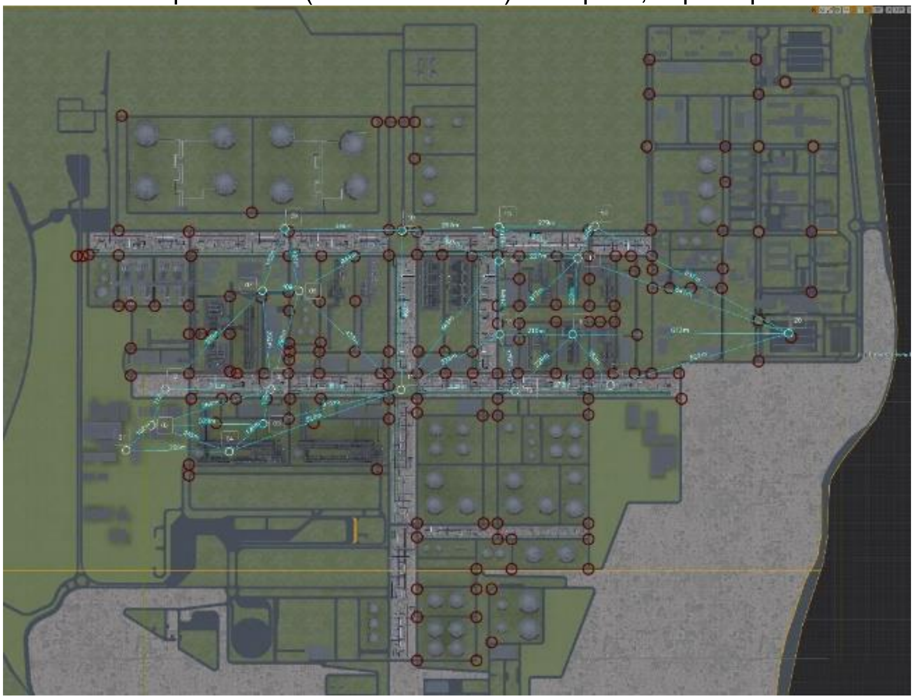
Figure 29 - Oil refinery plant with all the 20 checkpoints placed on the terrain.



Source: *Oliveira da Silva (2017)*

For auxiliary data, an extensive mesh of 166 additional smart-sensors (Figure 30) was created so that the movements of a player during an evacuation could be tracked for additional studies. Every sensor worked as a stopwatch and had internal metadata with the concentration of H_2S at its location.

Figure 30 - Smart sensors placement (small red circles) in all plant, superimposed on the original grid.



Source: This research (2018).

For computing the time spent in the whole exercise, a universal time counter is started at the beginning of the session and a lap is counted every time a checkpoint is reached. For the exercise, an average speed of 6 km/h was assumed for walking with two upper grades for fast walking and running implemented.

Initially, the optimal time estimated in Oliveira da Silva (2017) for the evacuation from point 1 to point 20 and the individual risk estimated via algorithm, was planned to be used as the benchmark for all obtained evacuation times and for all calculations of individual risk on the route. The results were grouped into two categories, above and below the benchmarked time and individual risk, being considered human failures in evacuation, times and levels of individual risk above confidence intervals for the optimal times. Afterward the benchmark time was changed to one on the simulator done by one of the volunteers that was a professional firefighter in a refinery very similar to the 3d model used, as was done in (MUSHARRAF et al., 2014).

For the visibility variable, a dynamic sun illumination system was used, fed by the hour of the day the system controlled the light intensity, color, sun and moon location making possible running the same scenario at day and night situations. No auxiliary light was provided to the player at the night session.

For user guidance about toxic areas was programmed a tactile feedback to inform the user about the hazard compound concentration in the area being passed. A force feedback event in the controller is triggered every time the toxic cloud has a non-zero value, making the joystick vibrate in the user's hand. Also, in the upper left corner of the screen, the concentration in ppm is displayed for 4 seconds.

For the complexity variable, in the three routes each user should do, two variations of complexity level were designed. The first scenario was easier to complete, and the second was a bit more complex with a part of it blocked by vehicles accidents (caused by drivers who fainted due to H_2S intoxication) to slow down the player progression. The third scenario was a night version of the first route done. For further analysis of session order influence, some sessions sets were started by the night simple session and other times the day simple was used.

All walking or running takes place in the streets and sidewalks of the plant, and in some part of the facility, pedestrian circulation was blocked. No interaction with any type of equipment is allowed so that the player really must leave the place as quickly as possible avoiding the risky areas.

All these combinations were designed with the intent to generate the Conditional Probability Tables (CPT) that will be used to feed a BBN meant to explore the influence of the PSF in the probability of successful evacuation or in the specific scenario in general. This setup will use raw data exported directly from the game engine via a JSON database file that will permit to know what path the player took, how much toxic compound he was exposed to, which were the visibility conditions and how well trained he was.

Is widely known that one of the most known signs of H_2S is the smell of rotten eggs. To simulate that in a sensory path different from visual a joystick vibration event was programmed every time the player passed through a point of non-zero concentration.

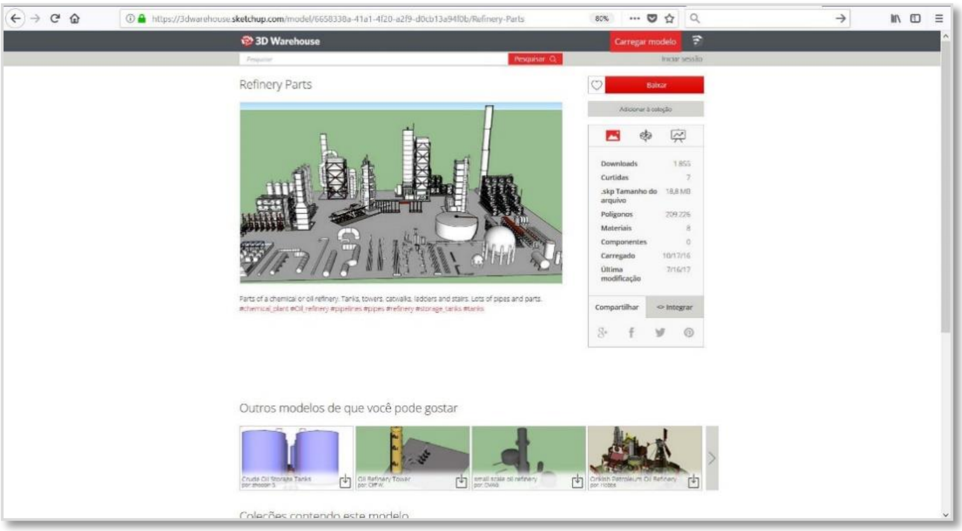
At the beginning of the simulation, a brief description of the event was introduced, and the suggested route is presented as a combination of the checkpoints. At the end of the route, all concentrations and times are used to calculate the individual risk of dying on route.

In these kinds of projects, the use geometry from CAD models of real facilities with minor modifications is commonly expected. In this particular case, such workflow was not possible due to restrictions generated by intellectual property or security reasons. Then, the general plant layout was made from researched visual references and is not totally representative of any particular refinery.

The layout was intended to be similar enough to many existing installations to permit extend conclusions drawn from the model to a real facility since common industrial plants constructive features were represented. The whole area, inscribed in a square with sides of 3.5 km, is depicted in Figure 30.

Initially, it was intended to model from scratch the main types of equipment present on a refinery, and then recombine them at the GE. A quick search on free models' repository showed an enormous number of free 3D models from sites like <https://3dwarehouse.sketchup.com> with a lot of prebuilt models for Oil and Gas in General (Figure 31).

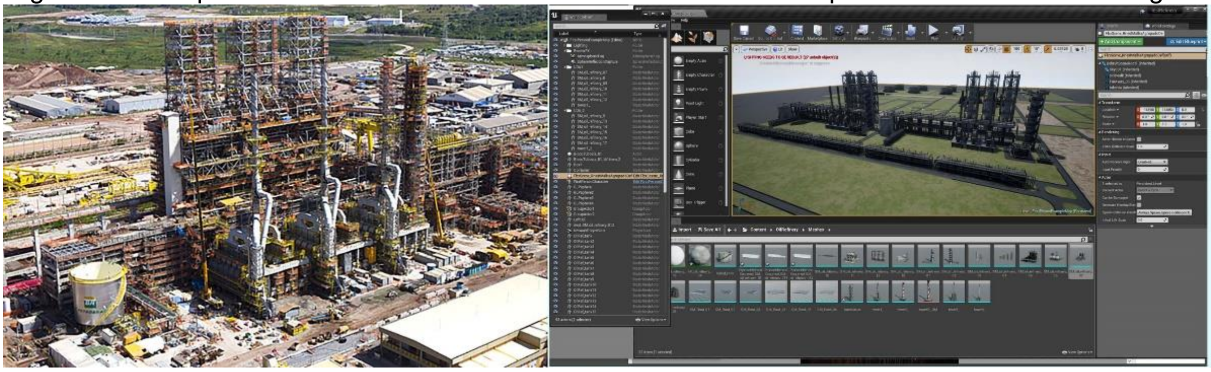
Figure 31 - The free model repository, 3D warehouse maintained by Sketchup.



Source: <https://3dwarehouse.sketchup.com>

Even though a great part of them did need some optimization inside 3DS Max before being taken to the GE, in general, they were well built, and no major flaws were found. The models were free, and their use represented a huge time saver in the process. Figure 32 brings a comparison between a photo and the model being assembled.

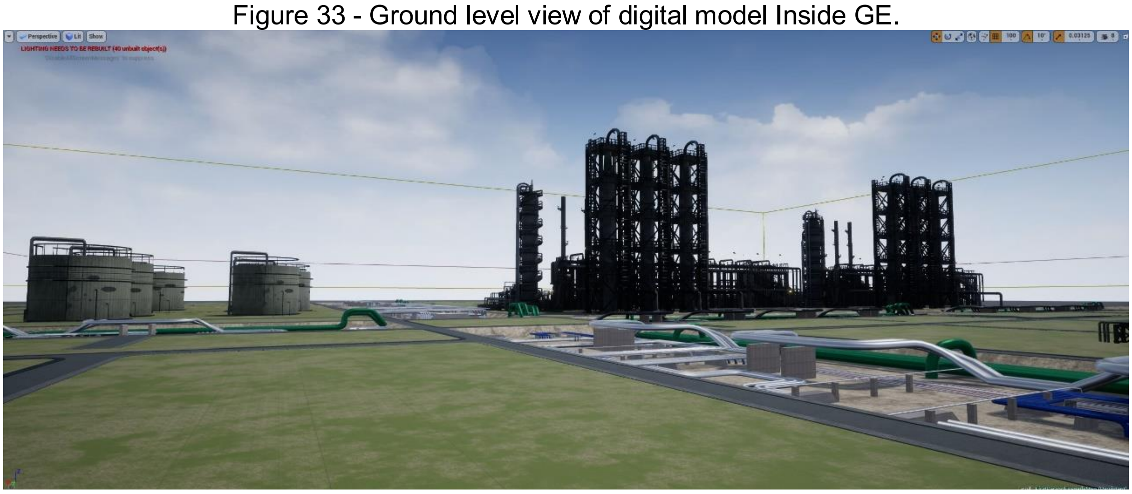
Figure 32 - The photo from the construction site and the installation represented on the Game Engine.



Source: This research (2018).

At the Unreal GE, all the created assets are imported and placed in the terrain previously modeled. All the time visual references were used to ensure the assembled facility were visually alike the real refinery (Figure 33). Moreover, refinery parts were found in Unreal Marketplace and were used to complement the scenarios. These assets were brought back inside 3DS Max, where changes were done to create new assets for specific needs on the VE. A schematic view of all interconnections and file formats is found in Figure 34.

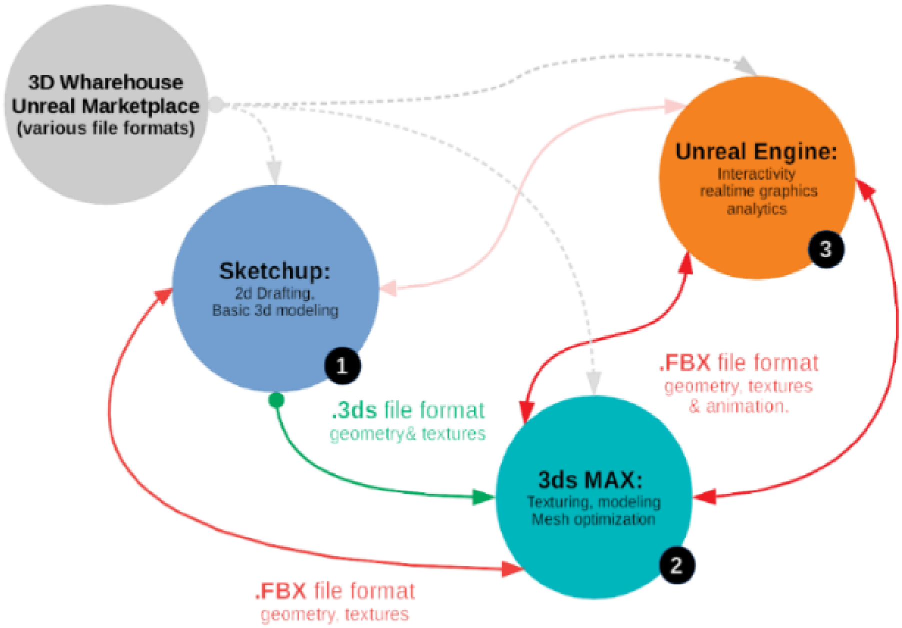
Figure 33 - Ground level view of digital model Inside GE.



Source: This research (2018) (2018).

Tests conducted revealed an excessive polygon count in assets that needed to be optimized or replaced; some of them also did not have texture maps, that are the color the 3D object display in the environment, and thus maps were created to texturize the meshes. This work of mesh optimization and texture mapping was done in 3DS Max in a way similar to other authors like Nyamse *et al.* (2013) and Kastel *et al.* (2013).

Figure 34 - The workflow for 3D modeling for game engine-based simulators. Two arrow-headed lines mean bidirectional flow. 1. Basic modeling; 2. Advanced modeling; 3. Virtual Environment.



Source: This research (2018).

4.4 VISUAL METAPHORS AND SCOPE NARROWING CHOICES

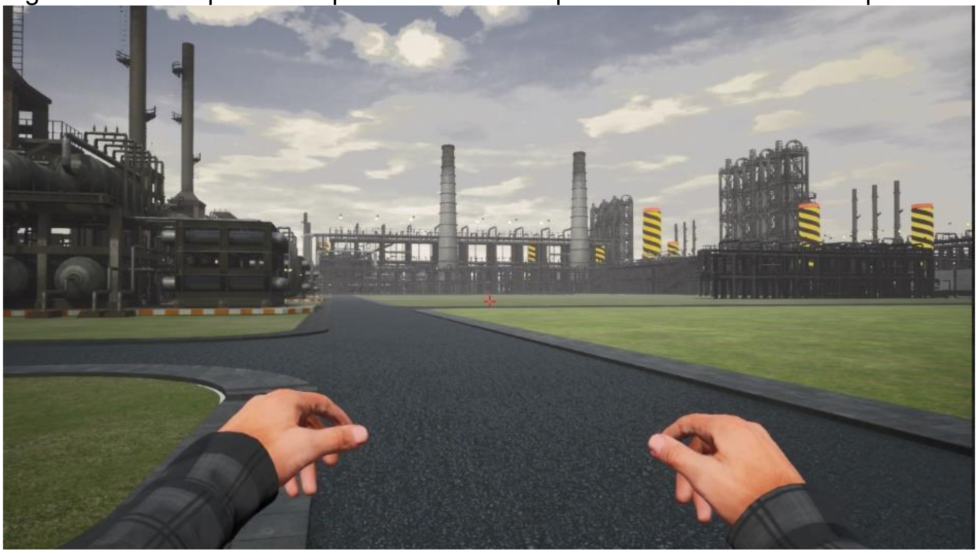
The player was allowed to walk only in the streets or sidewalks. The evacuation scenario used checkpoints to count the distances from straight lines between each checkpoint. They were not kept visible and were used for collision detection.

In a GE, if two objects have an intersection in their volumes, then a collision event may be generated. That is what the engine calls “hit”, which can be a trigger for a lot of actions, like a physical simulation of a collapsing bridge or an analytics event in coordinates XYZ. Collisions can be calculated in many ways ranging from simple bounding boxes of both objects to complex convex geometry, permitting the precision level more adequate to the scenario and system performance.

The toxic cloud will represent the worst-case scenario and no movement for the cloud was programmed. Cloud points were generated outside the game and imported with the intent to add toxic concentration metadata on top of collision detection and time data enabling to estimate hazard exposure calculation.

The model camera chosen was the first person one (Figure 35), where the player is surrounded by the scenario leaving only the upper limbs to be viewed. This visual metaphor brings good immersive sensation for the player, due to the lack of an avatar to block the user view. Although there is some questioning about the narrowing on the field of view (FOV) as in Adams (2013), the possibility of quickly adapt the scenario to a VR environment to solve the FOV issue is a good path evolution with benefits that justify this initial partial shortcoming.

Figure 35 - Example of first-person visual metaphor from the simulator experiment.

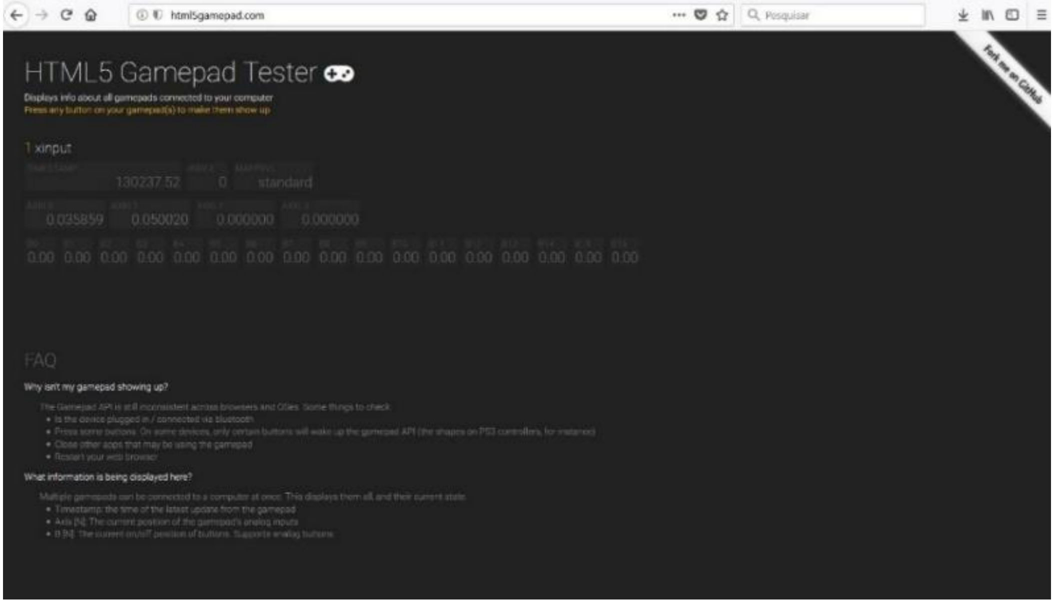


Source: This research (2018)

4.5 THE CHOICES ON INTERACTION DEVICES AND IMAGE DISPLAY

Related with interactive devices, a wired Xbox 360 joystick for development and an Xbox One wireless joystick for experiments were chosen to permit more mobility since the player can interact in a stand-up position. It is important to mention that other hardware and generic joysticks can be used, but if they are not xinput (a protocol of communication of peripherical devices from Microsoft) (Figure 36) they cannot be natively programmed with Unreal “out-of-the-box” drivers, needing extra steps to be properly calibrated and represent a pitfall to be avoided.

Figure 36 - An HTML5 site capable of giving useful information on the used joystick. Only xinput are natively supported by Unreal Engine.

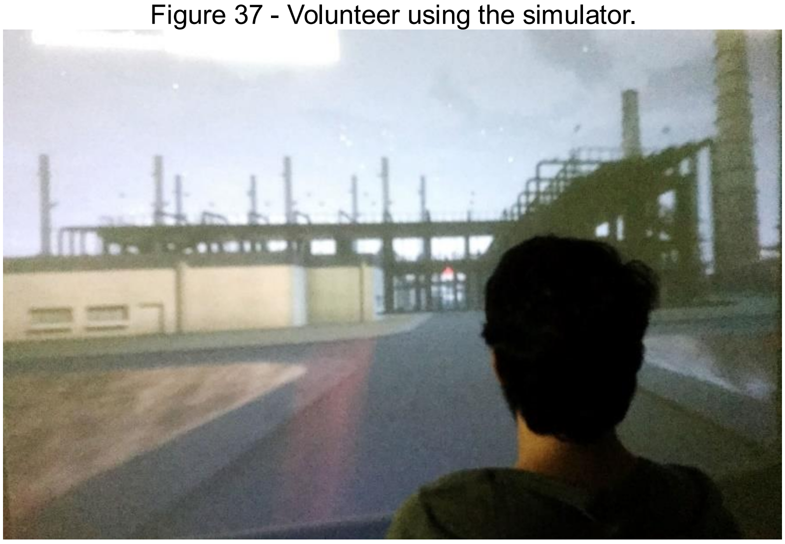


Source:< http://html5gamepad.com/>

By choosing controllers compatible with xinput protocol, the development for the joystick is easier with no additional cost. One must remember that the use of game engines to develop simulator on a small crew perspective aims to avoid low-level programming issues.

For the visual feedback, a back projection screen was used with projection in almost real size, what enabled a very good immersion feeling. Due to project scope and technical issues, the projection was not stereoscopic, even though all volunteers appreciated the size and sharpness of the image very much. Figure 37 shows how the user had almost all the field of view covered by the image.

Figure 37 - Volunteer using the simulator.



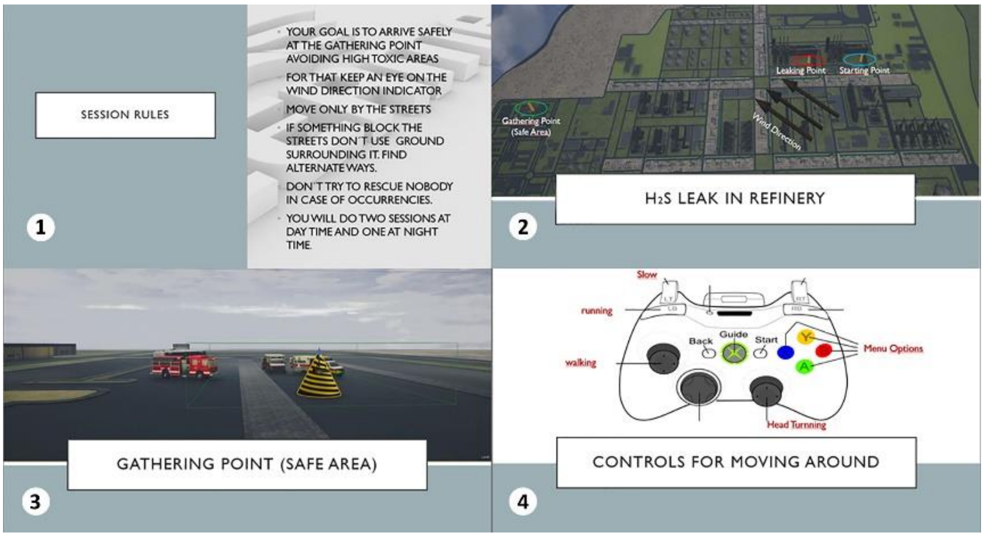
Source: This research (2018).

4.6 EXPERIMENT EXECUTION

The experiment was conducted with 15 voluntaries divided into two groups with two different training levels:

- MINIMAL: General briefing of how to orient in the facility is given (Figure 38) brings an overview picture/ map of the refinery is showed to help players o find themselves around in the plant. Another look at the map was permitted if asked in mid-session.
- EXPANDED: Identical to the past level plus: a flyby showing all the way from start to end, and for those who find necessary a five-minute walk at high speed through the plant to locate all points seen in the flyby at ground level. Basically, this training level added some time for experimentation and a guided tour around the refinery.

Figure 38 - The 4 screens presentation with basic gameplay directives, presented to the user before the session.



Source: This research (2018).

For each user, three sessions were carried out (see table 4 and Figure 39):

- Scn1: a low complexity scenario on a daylight situation;
- Scn2: a high complexity on a daylight situation with stressors like turned tanker trucks, buses on fire blocking the path forcing the user to seek alternative ways;
- Scn3: a simple scenario at night-time.

Table 4 – Scenario settings for data generation.

Scenario #	Visibility	Complexity
scn1	DAY	SIMPLE
scn2	DAY	COMPLEX
scn3	NIGHT	SIMPLE

Source: This research (2018).

For each variant, the analytics output was changed accordingly to represent the three main conditioners for the Bayesian Network as can be seen in Figure 28. For each session, a unique identification was generated permitting posterior revisions and checking.

The order in which a scenario was done variated from user to user but always beginning with a low complexity one to keep a graduation in difficulty. Additionally, this order was logged to study if there is any kind of learning curve from session to session.

Figure 39 - General scenarios layout, with differences in visibility and complexity.

Source: This research (2018).

All volunteers answered a quick survey after the experiment for impressions registering. The survey had five simple questions:

I. Do you think the scenario had some resemblance to a real-world situation? Grade from 1 to 5, being 5 the most resembling;
II. Do you think this training will help in real-world procedures? Grade from 1 to 5, being 5 the most useful;
III. What bothered you most on simulator operation? ( ) graphic quality, ( ) movement via controller, ( ) orientation, ( ) responsiveness and ( ) other (open question): Rank from 1 to 5, being 5 the most unpleasant;
IV. Would you do other sessions as part of a regular training program? Grade from 1 to 5, being 5 the most probable.

V. In which of the visibility and lighting situations did you feel most comfortable to orient yourself in the scenario: ( ) Day, ( ) Night, ( ) Indifferent

To improve data quality and bridge the gap between the simulator and reality some game mechanics were used. The first one was instant feedback, every time the player passes through a smart sensor with a non-zero value for concentration, a force feedback event was triggered, and the screen displayed the concentration on that area. Implementations like these put the user aware of how much the area is contaminated. Some players change directions immediately as they received a hazard area advice. The fact of being a tactile feedback helped to improve immersion since we are actuating in another sensorial path.

Since no competitiveness should be encouraged, no ranking or scoreboards where used, and since the player should arrive at the simulator knowing the less possible about the experiment, no social network interactions were permitted.

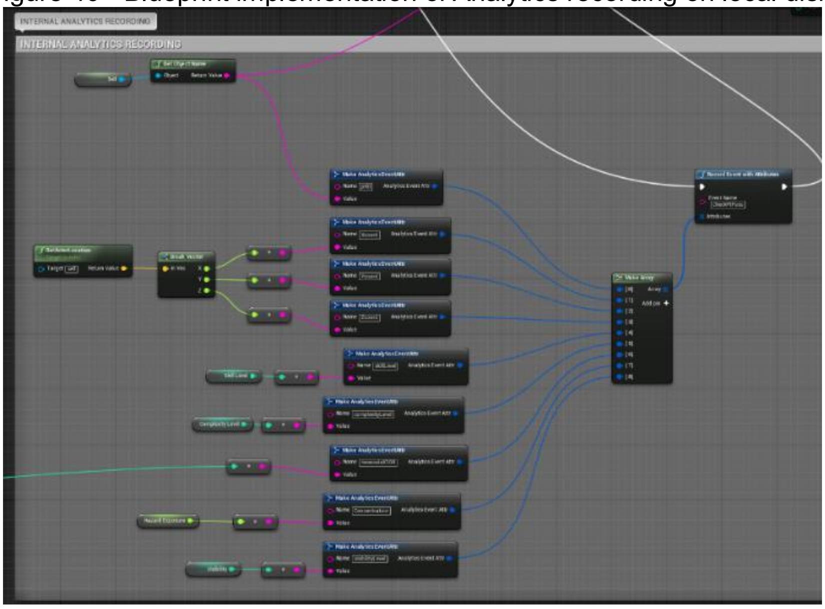
4.7 ANALYTICS SETUP AND DATA HANDLING

Two paths of output were simultaneously used for the data generated on simulator sessions:

- Telemetry via Google Analytics plugin, for real-time remote monitoring of user actions on scenario via Events and custom metrics and dimensions. In this topology, applications running all over the world can have their data seen and recorded for posterior studies. This feature was successfully implemented and tested;
- Local disk file recording, where database files containing records of all passages through the smart sensors with all study variables logged in each passage and their state throughout the role route. The files are written in *JSON* database exchange format, that can be easily read and converted to spreadsheets for posterior processing (Figure 40).

For each smart sensor, a script was created to output its coordinates that were fed into Aloha® (Areal Locations of Hazardous Atmospheres) software for estimating the gas concentration in each point. Then, a CSV file received all concentrations in each point and another specific script inside Unreal would write them to the smart sensors. This data will be present in the final report enabling the estimation of estimate the hazard exposition on the route for every session. This link Aloha – Unreal engine was done via datatables, a feature of Unreal GE used to handle external data sources, permitting the values to be updated for changing the characteristics of each scenario in an automated way.

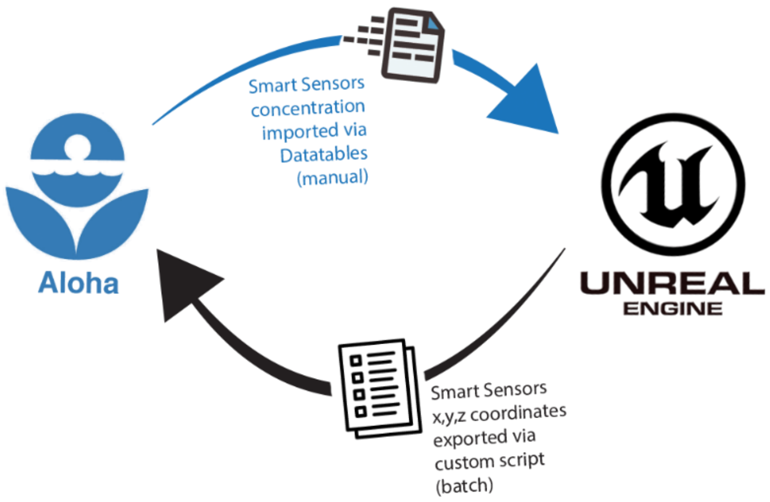
Figure 40 - Blueprint implementation of Analytics recording on local disk.



Source: This research (2018) (2018)

The Aloha® side of the framework was not possible of being done in a batch way, demanding some time to calculate all concentrations (Figure 41). Note that the process was not computationally intensive but feeding the data and storing the result was a time-consuming task. In any way, the whole calculations for 176+ points were done in a couple of days what is not prohibitive at all. Finding a way to streamline this process could be an interesting point to be studied, but it was out of scope for this work.

Figure 41 - Communication between Unreal Engine and Aloha software.



Source: This research (2018).

4.8 CALCULATING HAZARD EXPOSITION ON ROUTE

The hazard on the route was calculated via Probit equations (equation 3), that are used to estimate the probability of death for an individual exposed to hazardous substances. Probit stands for probability unit, a term attributed to C. R. Bliss, and is a binary choice model based on the normal distribution. It basically returns the probability of an answer being yes or no (ALDRICH; NELSON, 1984). It is the inverse Cumulative Distribution Function (CDF) of the standard normal distribution with mean 5 and standard deviation 1, meaning, in this specific research, the likelihood of fatalities for individuals exposed to the toxic cloud compound (ALP *et al.*, 1990; KATRINA M . GROTH, 2009; NRC, 2003).

In the present research, Probit equations will return the probability of death in an evacuation route in a toxic cloud release situation. The equation correlates this probability with toxic compound concentration and subject exposure time (GAI *et al.*, 2017). The equations most common form in this case is:

$$\mathrm{Pr} = a + b.\ln(C^n.t_e) \tag{3}$$

Where:

$\boldsymbol{Pr}$ - Probit corresponding to the likelihood of fatalities.

$\boldsymbol{a, b, n}$ - Constants related to substance toxicity.

$\boldsymbol{C}$ - Concentration in mg/m^3.

$\boldsymbol{t_e}$ - Exposure time in minutes.

The values for the constants in this equation when dealing with H_2S are:

$\boldsymbol{a} = -11.5, \boldsymbol{b} = 1$ and $\boldsymbol{n} = 1.9$ (TNO, 2005)

This set of values has been more used for contemporary authors such as Oliveira da Silva (2017) and was chosen to estimate the dose absorbed on the route, mainly because there is interest in comparing results and do some crossed analysis. Keeping the same constants used at Oliveira da Silva (2017) makes the risks on routes and times, either obtained by MOGA or done by volunteers on the simulator, a more coherent comparison.

The analytics report is a JSON file outputted straight from the GE and carries context variables like visibility, training level of the user, unique session identifier and anonymous user tagId. There was also quantitative data of the simulator session containing, for all activated sensors on route, position, activation timecode and Hydroxy Sulfide concentration.

Hence, it was quite straightforward to calculate the dose absorbed on route via a simple excel spreadsheet converted from the JSON report and estimate the hazard exposition on route. It was also possible to calculate the hazard exposition inside GE, but the external spreadsheet was preferred for being more streamlined and permitted more flexibility in forwarding data to R Studio to assemble the BBN.

4.8.1 Data classification for bayesian network creation

For the classification of each session, benchmarks were necessary to define if the session will be classified as successful or not for each one of the studied variables. For that purpose, two dependent variables will be analyzed: total time to complete the session and the individual risk in the route.

For the individual, risk were used the values reported in the Oliveira da Silva (2017). For the simulated exercise, the mean of the values on table 5 was used as a benchmark, these values were obtained via MOGA, that took in account only time an individual risk to generate the 12 solutions reported. Were considered successful evacuations done with individual risk lower than the chosen benchmark.

Table 5 - Average values calculated to determine the individual risk benchmark values for the BBN.

#	TIME	INDIVIDUAL RISK
1	31.1180	1.8000030E-06
2	30.2060	1.8000039E-06
3	29.9220	9.4186466E-06
4	29.0100	9.4186495E-06
5	28.7700	9.4187031E-06
6	88.4360	9.1200143E-12
7	87.5230	1.1509924E-11
8	38.2300	2.6470766E-10
9	37.3180	2.6656353E-10
10	35.5230	1.2985109E-07
11	34.6110	1.3091352E-07
12	27.8380	9.4500000E-06
AVG	41.5421	3.4639436E-06
STD DEV	21.9639	4.45139E-06

Source: Silva Oliveira (2017) adaptations by this research (2018).

Among the volunteers there was a firefighter that works in a refinery in Pernambuco, that is in many points very similar to the digital model created for the experiment since some of the key visuals were extracted based in photos publicly available on the media. He promptly recognized all the buildings and installations at ground level perspective, so even though he was at the MINIMAL training group his sessions were recorded as EXPANDED training that seemed more reasonable.

The firefighter performance on simulator was very good in both complex and simple scenarios, but not to the point of becoming an outlier so was decided to use his time as benchmark for the experiment following what was found in literature, similar to what was done by Musharraf et al. (2014) that used the average time of a trained crew member as benchmark time.

So, if the session had an individual risk greater than the mean of the values obtained with the MOGA or the time was superior the ones chosen as benchmarks, it will be considered failed, being logged as success otherwise. The rules generated a success percentage of 11,63% very similar to the 11% obtained by (MUSHARRAF et al., 2014).

It is important to have in mind that in real-world scenarios and dealing with real plants choosing benchmarks will be an easier task since the time from training and simulated exercises will exist or could be measured. The choice of benchmarks for this kind of work should be carefully defined and keep a close link with real-world values, in this works scope the choices were guided by the literature of previous experiments

(MUSHARRAF et al., 2014) and existing data from topologically similar plants (OLIVEIRA DA SILVA, 2017).

Table 6 – All possible states for all variables of the BBN.

VARIABLE	POSSIBLE STATES (VALUES)
EVACUATION STATUS	SUCCEED, FAIL
TRAINING LEVEL	MINIMAL, EXPANDED
COMPLEXITY	SIMPLE, COMPLEX
ROUTE TIME	BETTER_TIME, WORSE_TIME
INDIVIDUAL RISK	BELOW_RISK, ABOVE_RISK
ORDER IN SESSION	1st, 2nd, 3rd

Source: This research (2018)

Finally, all the sessions data were classified using and summarized in another spreadsheet with each row corresponding to a simulator session. Then, all conditions were recorded representing in each row one of the simulator sessions context variables like route complexity level, visibility, and user training level.

All data pertinent to the user performance will be logged, time to completion, individual risk on route, and session status (either failure or success). Then, the names for each node on the network were defined, and, in this case, the first letter of each variable is in table 7 as follows:

Table 7 **–** Variables Denomination on R.

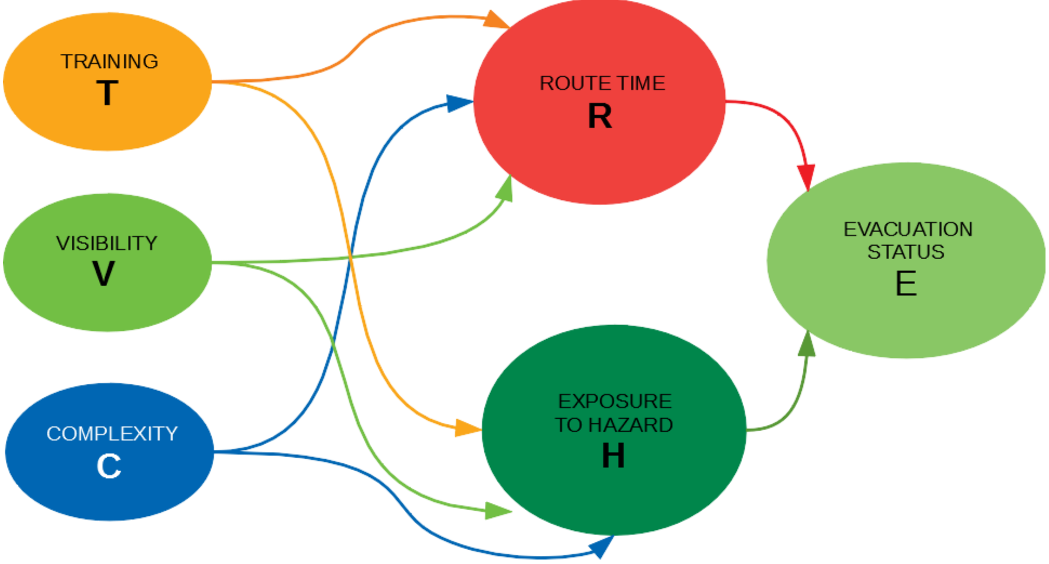
Variable	Node Denomination
Evacuation status	**E**
Training	**T**
Complexity	**C**
Visibility	**V**
Route Time	**R**
Individual Risk	**H**

Source: This research (2018)

4.8.2 The bayesian network creation and results

The Bayesian Network was assembled in R studio using the package ***bnlearn*** (MARCO SCUTARI, 2015). The process began by defining the empty acyclic graph, the command in R is: > dag <- empty.graph(nodes = c("E", "T", "C", "V", "R", "H")). Then, the arcs are added by creating the relationship of dependency between nodes. Figure 42 bring the DAG graphic representation and the main commands are transcripted in Figure 43.

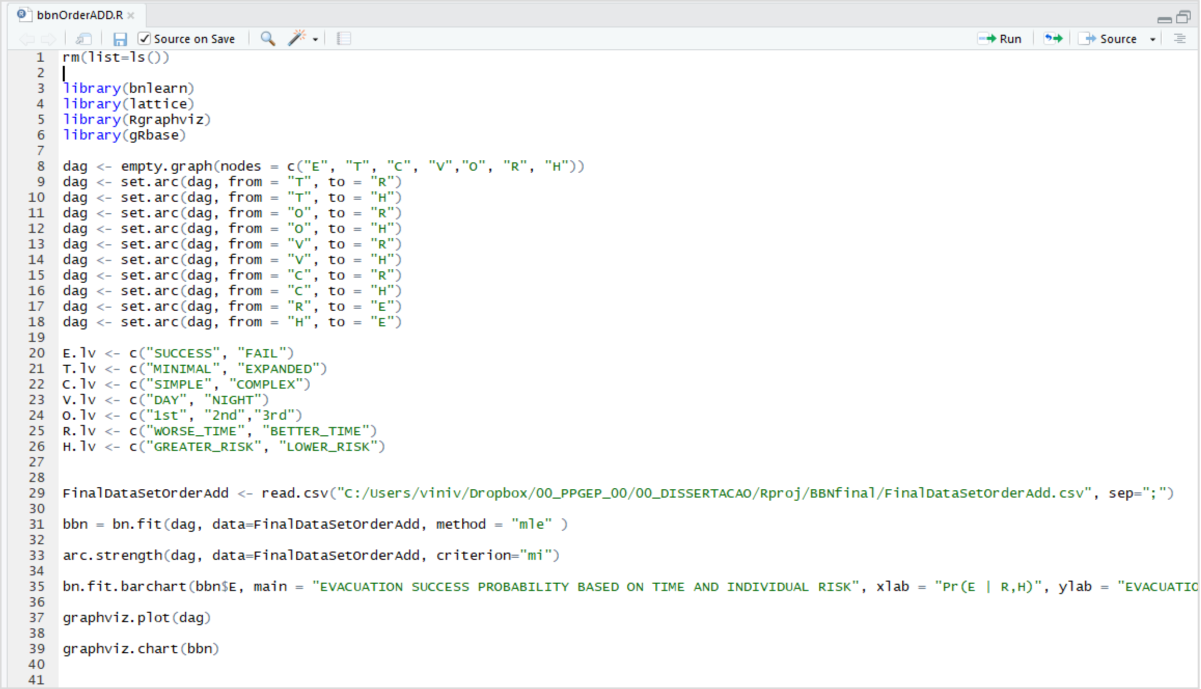
Figure 42 - Directed Acyclic Graph (DAG) with the nodes identification.



Source: This research (2018).

The basic pathway in the BBN creation is composed of, nodes creation, dependency settings and finally the dataset read to fill the structure. Through a series of commands is possible to create charts, and test how well the dataset supports the dependency relationships established by the DAG.

Figure 43 - R studio, implementation of the BBN the basic command set for each BBN assembled for experiment variations.

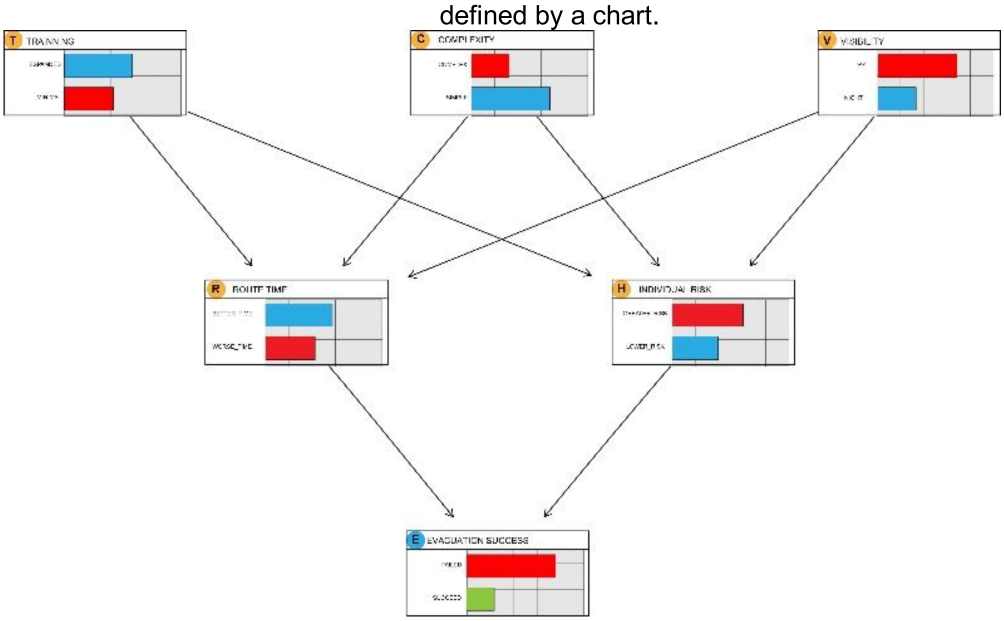



```
rm(list=ls())

library(bnlearn)
library(lattice)
library(Rgraphviz)
library(gRbase)

dag <- empty.graph(nodes = c("E", "T", "C", "V","O", "R", "H"))
dag <- set.arc(dag, from = "T", to = "R")
dag <- set.arc(dag, from = "T", to = "H")
dag <- set.arc(dag, from = "O", to = "R")
dag <- set.arc(dag, from = "O", to = "H")
dag <- set.arc(dag, from = "V", to = "R")
dag <- set.arc(dag, from = "V", to = "H")
dag <- set.arc(dag, from = "C", to = "R")
dag <- set.arc(dag, from = "C", to = "H")
dag <- set.arc(dag, from = "R", to = "E")
dag <- set.arc(dag, from = "H", to = "E")

E.lv <- c("SUCCESS", "FAIL")
T.lv <- c("MINIMAL", "EXPANDED")
C.lv <- c("SIMPLE", "COMPLEX")
V.lv <- c("DAY", "NIGHT")
O.lv <- c("1st", "2nd","3rd")
R.lv <- c("WORSE_TIME", "BETTER_TIME")
H.lv <- c("GREATER_RISK", "LOWER_RISK")


FinalDataSetOrderAdd <- read.csv("C:/Users/viniv/Dropbox/00_PPGEP_00/00_DISSERTACAO/Rproj/BBNfinal/FinalDataSetOrderAdd.csv", sep=";")

bbn = bn.fit(dag, data=FinalDataSetOrderAdd, method = "mle" )

arc.strength(dag, data=FinalDataSetOrderAdd, criterion="mi")

bn.fit.barchart(bbn$E, main = "EVACUATION SUCCESS PROBABILITY BASED ON TIME AND INDIVIDUAL RISK", xlab = "Pr(E | R,H)", ylab = "EVACUATIC

graphviz.plot(dag)

graphviz.chart(bbn)

```

Source: This research (2018).

The application is quite robust and is capable of outputting some interesting graphs for the BBN being studied, what makes the results communication a lot easier since associations of frequencies of an event with probability via visual elements like the bar are very intuitive, where the size of the bar is the probability of each variable state (Figure 44).

Figure 44 - The BBN topology of the options studied, with conditional probabilities in each node defined by a chart.



Source: This research (2018) (2018).

4.9 THE FRAMEWORK FOR HRA ON GAME ENGINE BASED SIMULATORS

The recommendations below were determined based on the compilation of the literature review and lessons learned during experiment assembly (ADAMS, 2013; EL-NASR; DRACHEN; CANOSSA, 2013; MARCO SCUTARI, 2015; NYAMSE et al., 2013). Some of the framework steps have a brief explanation pointing out why that step must be carried out. The proposed framework consists of the following steps:

- **Definition of the most probable or with most severe consequence's scenarios** obtained from the qualitative risk analysis and definition of the necessary elements for the scenarios. It is important to concentrate efforts on what data is really needed. It must be kept in mind the concept of a minimal viable product (MVP) because as soon as the first version is released, more resources tend to be allocated to the project;
- **Based on the nature of the operations involved, one must choose the type of immersion**, whether fully 3D, first or third-person, virtual reality, augmented reality or a mix of both. Keeping in mind that the more complex are the choices, the more time to finish the application it will take. If the system must interact with the outside world, augmented reality must be considered. If it is a simple interface testing and validation for control room operations, a 2D application will be more than enough.
- **Definition of visual metaphors for man-system interactions.** This feature is directly connected to the number of animations and custom programming needed for the simulator work. A lever activation, a closing tap, can be simplified by, for example, a mouse-click, or a joystick button press, that will close/open the tap or actuate at the lever. Sometimes, they might be enough for the scenario, avoiding complex animations and programming of unnecessary interactions and responses. But if the time taken on an action or a specific procedure must be judged, the animations and reactions to interaction must be as representative as possible to their real-world counterparts;
- **Creation of 3D or 2D elements whether for total immersion augmented or mixed reality;** here the general law is reuse, avoid to 3D model again what has been already done, a good look in some free repository of 3D

models can save many hours of work, saving effort to other parts of the project. Converting CAD models from engineering department may be a good choice if it is possible to do so keeping the polygon count low, the golden rule of any real-time graphics application (JUANG; HUNG; KANG, 2011);

- **Insertion of all elements created in the game engine**;
- **Programming of environments in the game engine and its interrelationship;** things like how the physics simulation will work, how much time can the player/user carry a weight, how much gas can be inhaled before the player dies, for how much time can the breath be held underwater;
- **Intra-game programming of the "laws" that will govern the operation of scenarios**; Ex: laws of physics, interface with external dynamic simulators for processes non-programable in the game engine, artificial intelligence, and others;
- **Definition of the events and variables to be implemented**;
- **Definition of the metrics to be collected**; Response times, number of retries before success, any event of interest must be defined in advance to be tracked and measured;
- **Definition of the database structure**; mainly the datatypes of each metric, the numbers will be integer, float or binaries, strings will differentiate upper/lower case, a two-state variable must be represented by strings or by booleans. Avoiding by all means to have a useless or hard to process dataset being outputted from the simulator;
- **Definition of the game mechanics for application in the sessions;** what constraints will be applied to the scenario, there will be a fixed time for a task, there will be some kind of biasing to user inputs to simulate fatigue or dizziness? All these decisions will make the data from the simulator scenario of better quality by bringing situations closer to real-world ones;
- **Interviews with post-session participants and/or review of recorded sessions**; information on how well the scenario performed for the users, any inconvenience perceived, suggestions and general impressions should be registered;
- **Use of the data in the quantitative tool chosen for the project with the**

necessary adjustments;

- **Analysis of the results by comparing them with the values obtained from standard values of available databases**.

Some of the steps will be very accelerated when the building blocks developed in this work are used. These assets are part of the framework representing a valuable toolset for HRA studies in refinery context.

5 ANALYSIS OF RESULTS

The data was collected in three opportunities consisting of all day long simulator sessions.

5.1 SAMPLE DESCRIPTION

The sample was composed of 15 volunteers from UFPE university, coming from graduation and post-graduation courses. The gender proportion is approximately 60% male and 40% female, no prior selection was done, and all students that attended the experiment were used. The total amount of collected samples was 43, not the expected 45, due to the interruption of exercise caused by motion sickness. The main dependent variables studied by the experiment via the BBN are time to evacuation and individual risk on the completed route. A descriptive statistic of the results is in table 8.

Table 7 - Descriptive statistics for dependent variables obtained from the 15 volunteers sample, that generated 43 data points.

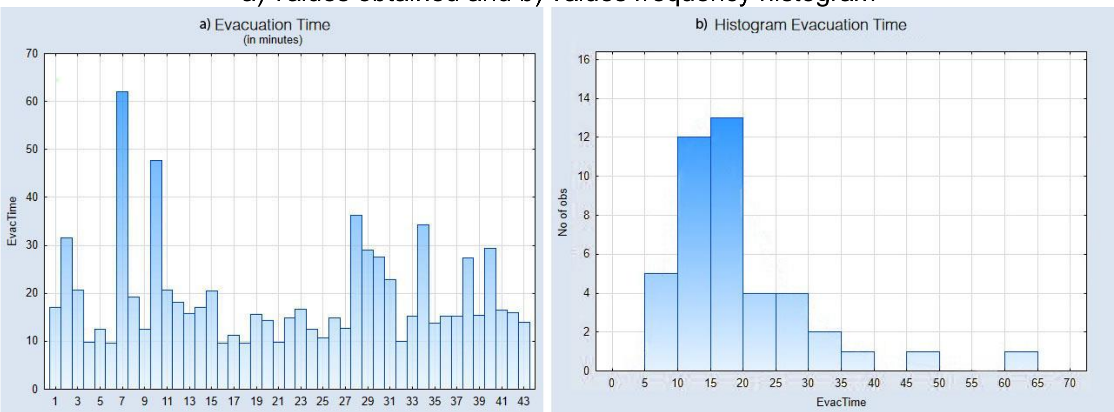
Statistics	**Evacuation Time (min)**	**Individual Risk ($year^{-1}$)**
Minimal Value	9.63	8.49E-20
_25th%	12.57	9.91E-10
Median	15.57	1.44E-04
_75th%	20.75	2.67E-02
Maximal Value	62.08	7.19E-02
Mean	19.21	1.35E-02
Standard Deviation	10.66	1.97E-02

Source: This research (2018).

A more comprehensive description of the dependent variables results is found in Figure 45 and Figure 46, with bar plots and a frequency histogram, showing tendencies and dispersion of the values. The evacuation times are in almost their totality in an interval of two standard deviations (SD) above and below the mean, and the 75% percentile is really close to the mean and inside the interval of one SD.

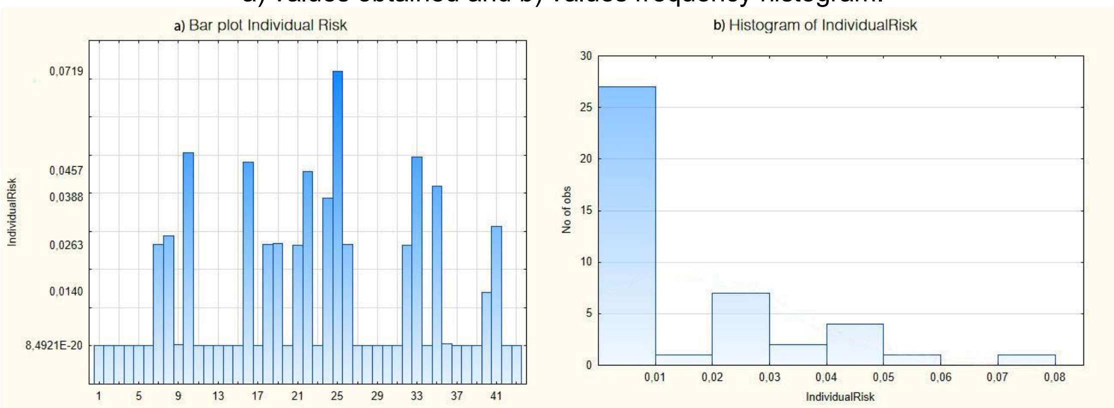
It must be taken into account that very few, or sometimes none at all, constraints were applied to the path subjects could choose in the evacuation. Then, it was expected a high variability in the results given the huge combination of possible paths and walking speeds. However, the data ended up being very well concentrated for a real-world based scenario, where 75% of the pedestrian did the way in a time not greater than 10% of the average evacuation time.

Figura 45 - Dependent variables: Time to evacuation, the experiment results.
a) values obtained and b) values frequency histogram



Source: This research (2018)

Figure 46 - Dependent variables: Individual risk, the experiment results.
a) values obtained and b) values frequency histogram.



Source: This research (2018)

The overall success percentage was 11.67%, which was calculated based on a criterion that considered the total time of evacuation coupled with individual risk exposure. In other words, if the route chosen by the volunteer took more time to evacuate the plant than the benchmark time established in section 4.8.1 (the firefighter evacuation time) or the final individual risk was higher than the average individual risk obtained by the MOGA in Oliveira da Silva (2017), the session was considered a failure, being successful otherwise. The complete dataset from the experiment can be seen in table 9.

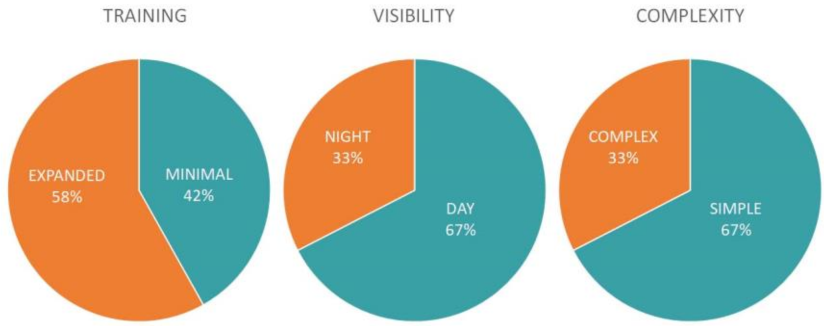
Table 8 - Final simulator sessions results.

ID #	TRAINING	VISIBILITY	ORDER IN SESSION	COMPLEXITY	TIME (MIN)	TIME STATUS	EXPOSURE	EXPOSURE STATUS	ABSORBED DOSE	STATUS
1	MINIMAL	DAY	1st	SIMPLE	17.06667	WORSE	1.61697E-11	BELOW	19,235.17	FAILED
1	MINIMAL	DAY	2nd	COMPLEX	31.63333	WORSE	9.91195E-10	BELOW	36,342.99	FAILED
1	MINIMAL	NIGHT	3rd	SIMPLE	20.71667	WORSE	7.75886E-12	BELOW	17,275.18	FAILED
2	EXPANDED	DAY	1st	SIMPLE	9.78333	BETTER	8.49214E-20	BELOW	1,752.55	SUCCEED
2	EXPANDED	DAY	2nd	COMPLEX	12.55000	BETTER	1.45113E-04	ABOVE	390,869.48	FAILED
2	EXPANDED	NIGHT	3rd	SIMPLE	9.63333	BETTER	1.44510E-04	ABOVE	390,448.75	FAILED
3	MINIMAL	DAY	1st	SIMPLE	62.08333	WORSE	2.66185E-02	ABOVE	2,120,169.71	FAILED
3	MINIMAL	DAY	2nd	COMPLEX	19.26667	WORSE	2.88872E-02	ABOVE	2,196,978.59	FAILED
3	MINIMAL	NIGHT	3rd	SIMPLE	12.43333	BETTER	2.90363E-04	ABOVE	469,554.43	FAILED
4	MINIMAL	DAY	1st	SIMPLE	47.66667	WORSE	5.05748E-02	ABOVE	2,843,920.03	FAILED
4	MINIMAL	DAY	2nd	COMPLEX	20.75000	WORSE	1.54653E-08	BELOW	57,752.04	FAILED
4	MINIMAL	NIGHT	3rd	SIMPLE	18.08333	WORSE	4.15913E-06	ABOVE	169,935.67	FAILED
5	EXPANDED	DAY	1st	SIMPLE	15.86667	BETTER	2.09492E-05	ABOVE	243,591.19	FAILED
5	EXPANDED	DAY	2nd	COMPLEX	16.98333	WORSE	2.54029E-12	BELOW	14,716.04	FAILED
5	EXPANDED	NIGHT	3rd	SIMPLE	20.58333	WORSE	2.34637E-10	BELOW	28,881.33	FAILED
6	EXPANDED	DAY	1st	SIMPLE	9.68333	BETTER	4.81893E-02	ABOVE	2,778,245.10	FAILED
6	EXPANDED	DAY	2nd	COMPLEX	11.21667	BETTER	1.44412E-04	ABOVE	390,380.62	FAILED
6	EXPANDED	NIGHT	3rd	SIMPLE	9.63333	BETTER	2.66185E-02	ABOVE	2,120,169.71	FAILED
7	EXPANDED	DAY	1st	SIMPLE	15.56667	BETTER	2.68732E-02	ABOVE	2,128,918.53	FAILED
7	EXPANDED	DAY	2nd	COMPLEX	14.30000	BETTER	2.01563E-04	ABOVE	425,904.59	FAILED
7	EXPANDED	NIGHT	3rd	SIMPLE	9.71667	BETTER	2.62797E-02	ABOVE	2,108,477.27	FAILED
8	EXPANDED	DAY	1st	SIMPLE	14.95000	BETTER	4.57482E-02	ABOVE	2,709,956.59	FAILED
8	EXPANDED	DAY	2nd	COMPLEX	16.71667	WORSE	1.49456E-12	BELOW	13,653.69	FAILED
8	EXPANDED	NIGHT	3rd	SIMPLE	12.56667	BETTER	3.87604E-02	ABOVE	2,507,368.77	FAILED
9	EXPANDED	DAY	1st	SIMPLE	10.66667	BETTER	7.18923E-02	ABOVE	3,396,168.98	FAILED
9	EXPANDED	DAY	2nd	COMPLEX	14.86667	BETTER	2.66984E-02	ABOVE	2,122,918.90	FAILED
9	EXPANDED	NIGHT	3rd	SIMPLE	12.70000	BETTER	8.92738E-05	ABOVE	345,386.11	FAILED
10	EXPANDED	DAY	1st	SIMPLE	36.25000	WORSE	3.29111E-07	BELOW	912,839.52	FAILED
11	EXPANDED	DAY	1st	SIMPLE	29.05000	WORSE	4.34316E-10	BELOW	31,829.55	FAILED
11	EXPANDED	DAY	2nd	COMPLEX	27.60000	WORSE	3.13497E-09	BELOW	43,941.14	FAILED
11	EXPANDED	NIGHT	3rd	SIMPLE	22.85000	WORSE	3.55301E-08	BELOW	66,938.56	FAILED
12	MINIMAL	DAY	2nd	SIMPLE	10.05000	BETTER	2.63675E-02	ABOVE	2,111,512.69	FAILED
12	MINIMAL	DAY	3rd	COMPLEX	15.23333	BETTER	4.93956E-02	ABOVE	2,811,581.54	FAILED
12	MINIMAL	NIGHT	1st	SIMPLE	34.28333	WORSE	1.72225E-05	ABOVE	232,839.89	FAILED
13	MINIMAL	DAY	2nd	SIMPLE	13.78333	BETTER	4.17786E-02	ABOVE	2,596,281.16	FAILED
13	MINIMAL	DAY	3rd	COMPLEX	15.25000	BETTER	5.55249E-04	ABOVE	561,898.08	FAILED
13	MINIMAL	NIGHT	1st	SIMPLE	15.16667	BETTER	5.94055E-12	BELOW	16,619.80	SUCCEED
14	MINIMAL	DAY	2nd	SIMPLE	27.41667	WORSE	2.37018E-07	BELOW	95,174.32	FAILED
14	MINIMAL	DAY	3rd	COMPLEX	15.40000	BETTER	1.49224E-10	BELOW	26,914.42	SUCCEED
14	MINIMAL	NIGHT	1st	SIMPLE	29.33333	WORSE	1.40347E-02	ABOVE	1,629,338.75	FAILED
15	EXPANDED	DAY	1st	SIMPLE	16.45000	BETTER	3.13171E-02	ABOVE	2,276,660.83	FAILED
15	EXPANDED	DAY	2nd	COMPLEX	15.96667	BETTER	5.69015E-09	BELOW	48,593.31	SUCCEED
15	EXPANDED	NIGHT	3rd	SIMPLE	13.91667	BETTER	9.78965E-12	BELOW	17,869.91	SUCCEED
	REFINERY STAFF MEMBER BENCHMARK TIME								SESSIONS SUCCESS %	11.63%
									AVG MOG Exposure*	3.46E-06
									AVG MOG Time*	41.54000
									*Source: Oliveira da Silva (2017)	

Source: This research (2018), MOGA data from Silva Oliveira (2017)

Then, the proportion of success had a value compatible with other experiments like Musharraf et al. (2014) that also was about 11% showing a good alignment between the dataset of the present experiment and previous works. Due to the absence of some of the volunteers, the *a priori* probability for training level did not end up being exactly 50% each. Some volunteers did not show up for experiment and one had nausea during the experiment forcing to interrupt the sessions sequence and the final share was approximately 42/58%. The share for the Visibility and Complexity PSF was about 1/3 to 2/3 each as can be seen in table 11 and Figure 47. The CPT for the independent nodes is used as the *a priori* probabilities for the BBN. It is calculated by the conventional frequentist approach, i.e., dividing the event frequency by the total number of occurrences. Since these numbers are part of the experiment design these values were easy to obtain.

Figure 47 - The independent variables distribution.



Source: This research (2018).

5.2 DATA ANALYSIS

The R Studio's bnlearn package was adopted and performed all these calculations based on the network topology and the inputted dataset (MARCO SCUTARI, 2015). It is interesting to mention that building a BBN from CPTs can be a very useful approach if one intends to explore variations on the probabilities of events and how they propagate along the network. The package also can calculate all the conditional probabilities by combining the described net topology presented in past sections in Figure 42 and the dataset (table 10) in a more straightforward approach since it demands no additional calculations of CPTs.

Table 10 is an extract of the actual dataset that is inputted to R studio, and it was obtained straight from table 9 by hiding the undesired data and outputting a CSV file and adding a custom header identifying to what node the column belongs. This procedure is necessary since the bnlearn package checks all data columns against the structure to assure all nodes described in the DAG are present in the dataset.

The objective of this kind of experiment is to analyze the influence of the context variables (T, C, V) in the overall success of the operation showing how the dependent variables (R, H) are influenced by those PSF (MARCO SCUTARI, 2015; MUSHARRAF et al., 2014). The CPTs for the dependent nodes are calculated by the direct application from the dataset interpretation; the results are condensed in Table 10, Table 11 and Table 12.

Table 9 - Extract from the dataset with all sessions ready to be inputted at R Studio.

T	V	C	R	H	E
MINIMAL	DAY	SIMPLE	WORSE_TIME	LOWER_RISK	FAILED
MINIMAL	DAY	COMPLEX	WORSE_TIME	LOWER_RISK	FAILED
MINIMAL	NIGHT	SIMPLE	WORSE_TIME	LOWER_RISK	FAILED
EXPANDED	DAY	SIMPLE	BETTER_TIME	LOWER_RISK	SUCCEED
EXPANDED	DAY	COMPLEX	BETTER_TIME	GREATER_RISK	FAILED
EXPANDED	NIGHT	SIMPLE	BETTER_TIME	GREATER_RISK	FAILED
MINIMAL	DAY	SIMPLE	WORSE_TIME	GREATER_RISK	FAILED
MINIMAL	DAY	COMPLEX	WORSE_TIME	GREATER_RISK	FAILED
MINIMAL	NIGHT	SIMPLE	BETTER_TIME	GREATER_RISK	FAILED

Source: This research (2018).

Table 10 - *A priori* probabilities of the independent variables.

A PRIORI TABLES		
TRAINING	MINIMAL	0.42
	EXPANDED	0.58
COMPLEXITY	SIMPLE	0.67
	COMPLEX	0.33
VISIBILITY	DAY	0.67
	NIGHT	0.33

Source: This research (2018).

Table 11 - Conditional Probabilities Tables for the Evacuation Time

CPT FOR EVACUATION TIME								
TRAINING	MINIMAL				EXPANDED			
VISIBILITY	DAY		NIGHT		DAY		NIGHT	
COMPLEXITY	SIMPLE	COMPLEX	SIMPLE	COMPLEX	SIMPLE	COMPLEX	SIMPLE	COMPLEX
TIME WORSE	0.666666667	0.5	0.666667	0	0.222222	0.375	0.25	0
TIME BETTER	0.333333333	0.5	0.333333	0	0.777778	0.625	0.75	0

Source: This research (2018).

Table 12 - Conditional Probabilities Tables for the Evacuation Individual Risk

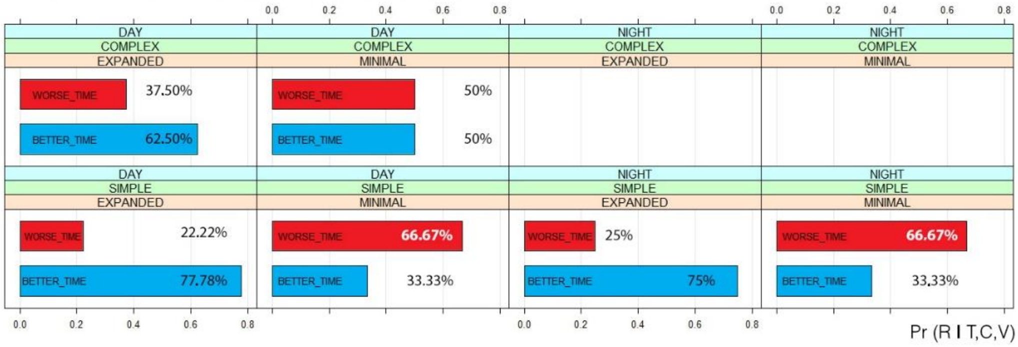
CPT FOR INDIVIDUAL RISK								
TRAINING	MINIMAL				EXPANDED			
VISIBILITY	DAY		NIGHT		DAY		NIGHT	
COMPLEXITY	SIMPLE	COMPLEX	SIMPLE	COMPLEX	SIMPLE	COMPLEX	SIMPLE	COMPLEX
RISK ABOVE	0.666666667	0.5	0.666667	0	0.666667	0.5	0.625	0
RISK BELOW	0.333333333	0.5	0.333333	0	0.333333	0.5	0.375	0

Source: This research (2018).

For example, to study the influence of training (T) on evacuation time (R) in daylight, Figure 48 first row is used. Both cells containing DAY/COMPLEX are compared and the differences in time are credited to the training level (MUSHARRAF et al., 2014). In this case, the times below benchmark were about 50% (for T: minimal) and passed to 62.50% (for T: expanded) representing an increase of 25%.

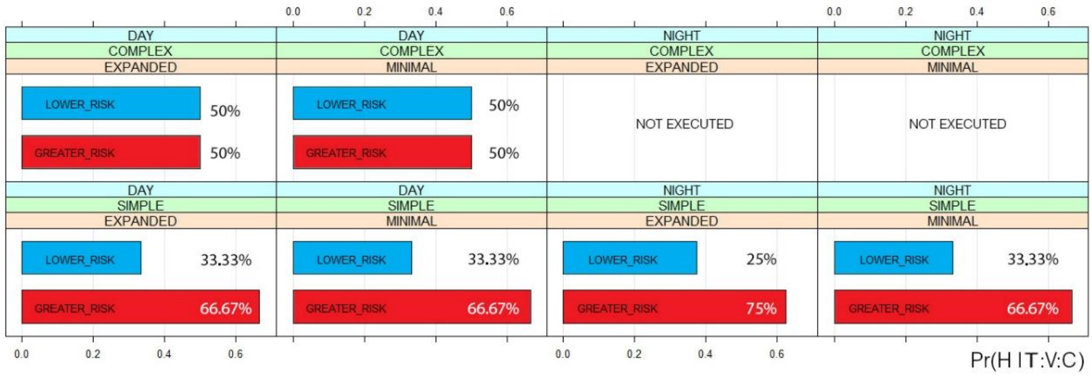
This type of analysis was done for all possible combinations and are transcripted in the next sessions. The charts are a more intuitive way to deal with all the combinations in a multivariate system, with both numeric and visual feedback. This kind of tool may seem not very necessary in small nets, but, as topology grows in complexity, such tools become very useful. Figure 49 presents the results for the individual risk, Table 13 and Table 14 compile all the conclusions.

Figure 48 - The BBN for the dependent variable time to route completion (R) and how it variates as training level (T), route complexity (C) and visibility (V).



Source: This research (2018).

Figure 49 - The BBN for dependent variable Individual Risk (H) and how it variates as training level (T), route complexity (C) and visibility (V).



Source: This research (2018).

5.2.1 Training effect over evacuation time and individual risk

For the time variable, the expanded training scheme increased 25% the occurrence of times lower than the benchmark complex scenarios at daytime. In daytime simple scenarios, the increment was 134% and of 125% for night time simple ones. As for the individual risk variable, in the case of nighttime simple scenario expanded training caused an increment of 33.33% in the occurrence of individual risk values below the benchmark, having no influence in the other scenarios (day/complex, day/simple).

5.2.2 Visibility effect over evacuation time and individual risk

For the time variable, daytime operation increased by 3.71% the probability of occurrence of times lower than the benchmark simple scenarios with expanded training. In simple scenarios with minimal training, no difference was registered related to visibility and since no night time complex scenarios were conducted, no further conclusions are possible.

Again, for the individual risk variable, in the case of simple scenario with an expanded training level, there was an increment of 33.33% in the occurrence of individual risk below the benchmark, having no influence in the simple/minimal scenarios. For complex scenarios, no further studies were possible since no nighttime complex scenarios were carried out.

5.2.3 Complexity effect over evacuation time and individual risk

For the time variable, simple scenarios in daytime evacuations with volunteers with minimal training brought an increase of 50% the occurrence of individual risks lower than the benchmark, and the increment was of 24.45% for daytime evacuations for subjects with expanded training combination. Since no session was carried out in nighttime complex scenarios, no further conclusions are possible.

As for the individual risk variable, in the case of daylight scenario with minimally trained subjects, complex scenarios generated an increment of 50% in the occurrence of individual risk below the benchmark happening the same for the expanded training, daytime combination, this can be attributed to scenario design and learning curve issues from session to session. For complex scenarios, no further studies were possible since no night time complex sessions were carried out.

Table 13 - Influences on the time to evacuate refinery.

TRAINING EFFECT SCENARIO	MINIMAL X EXPANDED INFLUENCE	VISIBILITY EFFECT SCENARIO	DAY X NIGHT INFLUENCE	COMPLEXITY EFFECT SCENARIO	SIMPLE X COMPLEX INFLUENCE
DAY/COMPLEX SCENARIO	EXPANDED TRAINING INCREASED IN 25% OCURRENCE OF TIMES BETTER THAN BENCHMARK	SIMPLE/EXPANDED SCENARIOS	DAYTIME SCENARIOS GENERATED 3,71% MORE EVACUATION TIMES BETTER THAN BENCHMARK	DAY/MINIMAL SCENARIOS	SIMPLE SCENARIO MADE 50% MORE PROBABLE ROUTE TIMES BETTER THAN BENCHMARK
DAY/SIMPLE SCENARIO	EXPANDED TRAINING INCREASED IN 134% THE PROBABILITY OCURRENCE OF TIMES BETTER THAN BENCHMARK	SIMPLE/MINIMAL SCENARIOS	NO DIFFERENCE	DAY/EXPANDED SCENARIOS	SIMPLE SCENARIO MADE 24.45% MORE PROBABLE EVACUATION TIMES BETTER THAN BENCHMARK
NIGHT/SIMPLE SCENARIO	EXPANDED TRAINING INCREASED IN 125% OCURRENCE OF TIMES BETTER THAN BENCHMARK	COMPLEX SCENARIOS	NO COMPARATION POSSIBLE SINCE THERE WERE NO COMPLEX NIGHT SCENARIOS	NIGHT CENARIOS	NO COMPARATION POSSIBLE SINCE THERE WERE NO COMPLEX NIGHT SCENARIOS

Source: This research (2018).

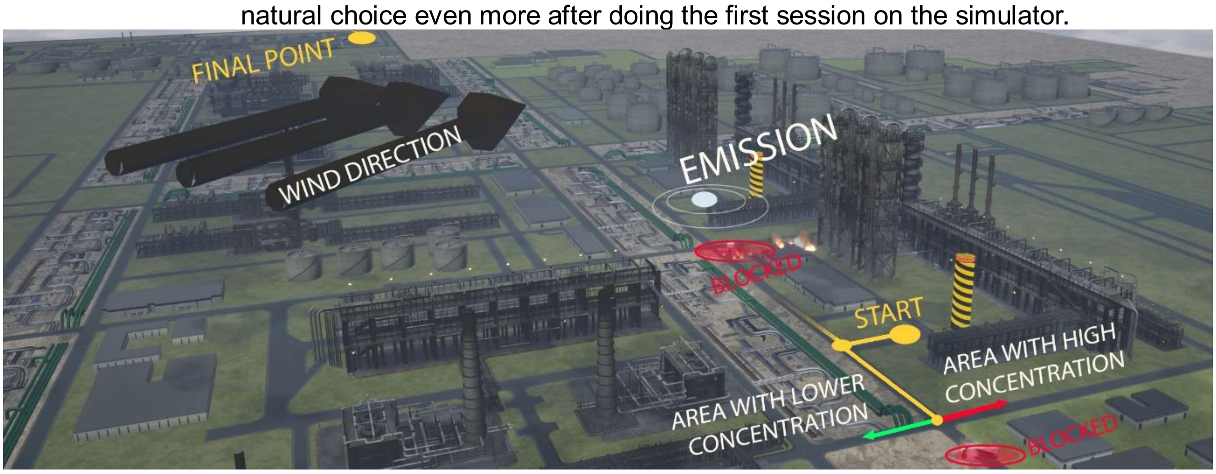
Table 14 - influences on individual risk during evacuation.

TRAINING EFFECT SCENARIO	MINIMAL X EXPANDED INFLUENCE	VISIBILITY EFFECT SCENARIO	DAY X NIGHT INFLUENCE	COMPLEXITY EFFECT SCENARIO	SIMPLE X COMPLEX INFLUENCE
DAY/COMPLEX SCENARIO	NO DIFFERENCE	SIMPLE/EXPANDED SCENARIOS	DAYTIME INCREASED IN 33,33% OCURRENCE OF RISK LOWER THAN BENCHMARK	DAY/MINIMAL SCENARIOS	COMPLEX SCENARIO INCREASED IN 50% OCURRENCE OF RISK LOWER THAN BENCHMARK
DAY/SIMPLE SCENARIO	NO DIFFERENCE	SIMPLE/MINIMAL SCENARIOS	NO DIFFERENCE	DAY/EXPANDED SCENARIOS	COMPLEX SCENARIO INCREASED IN 50% OCURRENCE OF RISK LOWER THAN BENCHMARK
NIGHT/SIMPLE SCENARIO	EXPANDED RAISED BY 24,24% THE PROBABILITY OF RISK HIGHER THAN BENCHMARK	COMPLEX SCENARIOS	N/A	NIGHT CENARIOS	N/A

Source: This research (2018).

The above-mentioned results draw attention for a paradox, where complex scenarios yielded better results than simple ones. A possible explanation can be found in the design of the complex scenario, in which blocked roads took the user to a point where a right or left decision should be taken. Due to the wind indication, almost all users turned right, going upwind to a path with lower concentration points, what might have reduced the absorbed dose on the route, and thus decreased the individual risk (Figure 50).

Figure 50 - The complex scenario layout where can be observed that lower concentration areas are a natural choice even more after doing the first session on the simulator.



Source: This research (2018).

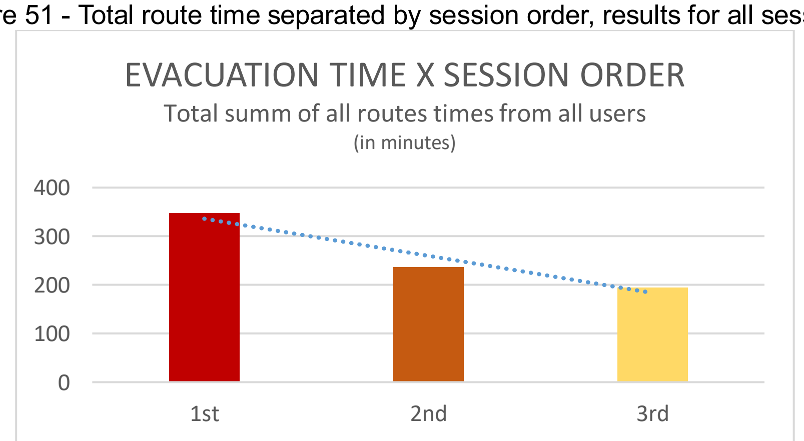
In a more comprehensive study, all user paths can be retraced from the smart sensors coordinates collected by the analytics as subjects triggered them. In the present case, this process was skipped due to the existence of experiment notes reporting the fact, but such data can solve various doubts on how each simulator session happened.

5.2.4 The learning curve influence

As it has been said, during the simulator session, a strong influence of the learning curves was observed. Given that, an additional datapoint was recorded for each user session, containing the order of that session in the total of 3 executed for each subject.

The order of the starting session was varied, beginning with the simple/day scenarios and other times with simple/night situations. The total sum of the time of all first sessions for all users was calculated as well as for the second and third sessions. Figure 51 shows the total sum of the three times, and as it can be easily seen, users improved their time from session to session, since the scenario was identical with the conditions that changed from session to session were not strong enough to overcome the effect of the learning curve.

Figure 51 - Total route time separated by session order, results for all sessions.

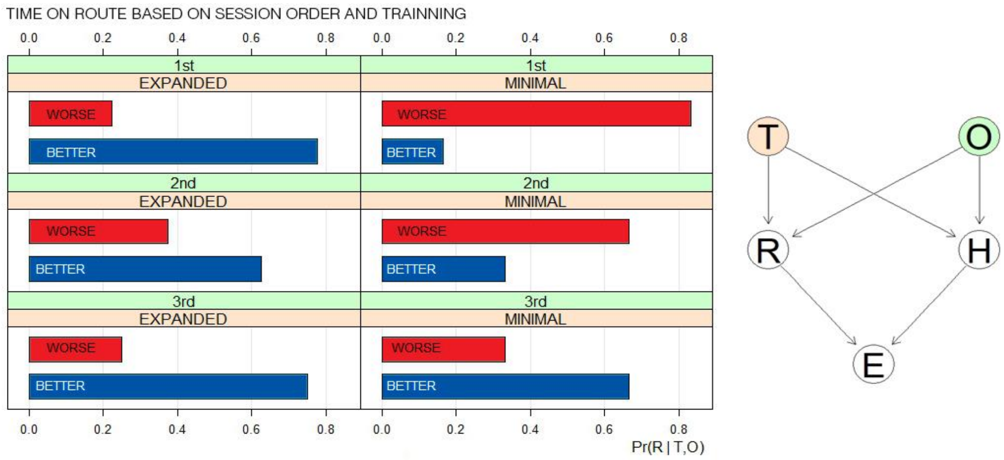


Source: This research (2018).

This was one of the most important lessons learned in the experiment: one must design each session in a way no past experience should influence the following sessions if this is not a desirable issue. The learning ability of subjects should not be underestimated and since the events in virtual environments are experienced in a way very similar to the real world, the learning process tends to be more effective (MANCA; BRAMBILLA; COLOMBO, 2013).

For example, the complex scenario design had to be neutral in the sense that every obstacle had at least two ways out, one leading to a more contaminated area and the other to lower toxic concentrations areas. These interferences were placed at the beginning of the route. The users passed the obstacles and quite often find their way back to the path they did in the previous sessions. The representation of this is found in Figure 52, which is a parallel study with a smaller BBN with only training (T) and session order (O). In Figure 52, it is possible to notice that this effect was clearly perceived in the volunteers with the minimal training level, probably because the insufficient training level leaves more room for improvement in performance.

Figure 52 - A study with a small BBN with training (T) and session order (O), at right the BBN topology. It is easy to see the time improvement on the second column to the right in the probability of occurrence of times better than the benchmark.



Source: This research (2018).

5.3 POST-SESSION SURVEYS

As it was said before, a survey was sent to all volunteers to collect post session impressions about the experiments. The results of the survey brought important insights into user experience. In fact, most users found the scenario realistic, useful for training and stated they would do regular sessions as part of a long-term training program (Figure 53).

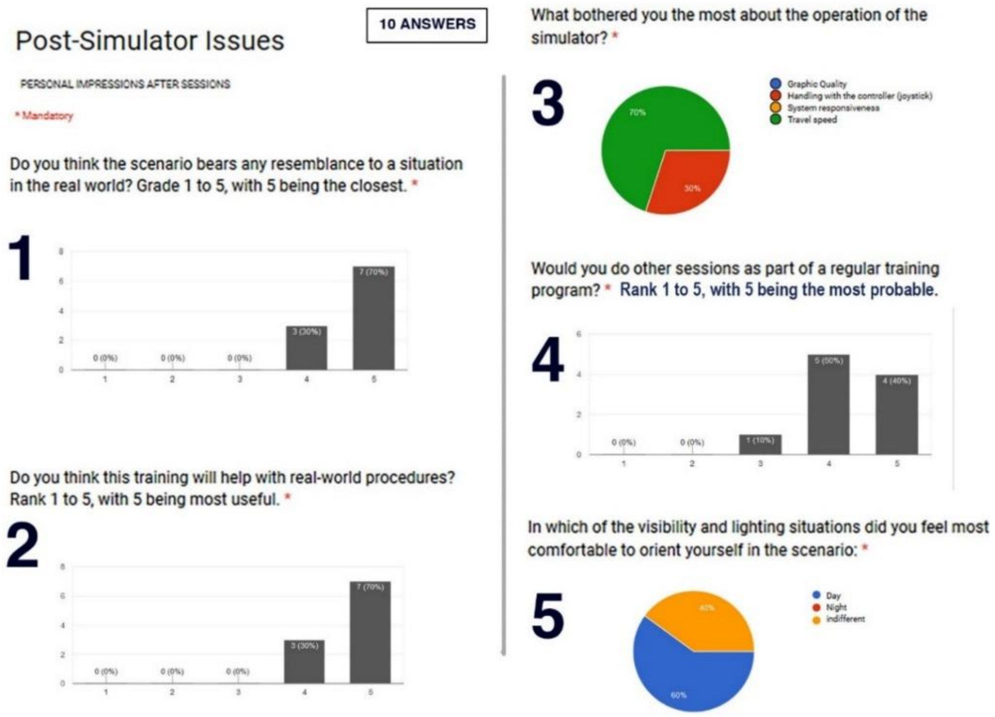
The night-time activities were said to be less straightforward than the day-time ones, partially contradicting findings from Musharraf et al. (2014) and from the present work (section 5.2.2) both with mixed and unexpected results. Indeed, Musharraf et al.

(2014) showed route times that got 17% more probable of being worse than benchmark as should be expected, but strangely the backtracking time got a 20% probability boost of being lower than or equal to the benchmark what represents a performance improvement at nighttime (backtracking is the time spent returning and seeking another path, an issue not studied at the present work).

All these findings strongly suggest the need for a closer look at the day/night influence on evacuation time, and both works evidenced strange gaps that need a closer look to be filled. It must be noticed that, in the present work, the simulator sessions happened at day-time, mostly in a period from 8 am to 18 pm. Running simulator sessions with night visibility during the actual night in the real world may be a path to be explored.

The two emerging complaints were about the use of a joystick and the speed of motion, which for being realistic made the session last sometime about half an hour each, an issue that bothered the users in general.

Figure 53 - Survey Results, from 13 volunteers 10 answered.



Source: This research (2018).

6 CONCLUSIONS AND FINAL REMARKS

Throughout the work, results for proposed objectives, both general and specific are identifiable: the framework proposal, the experiment assembly, the BBN setup, the use of a GE in an HRA experiment, the database taxonomy and almost all the other specific objectives.

This section intends to formalize the results for the general objective and emphasize two of the specific ones that are not identifiable in the work despite being fully accomplished during the research development. Also, at the end of this chapter, some very interesting notes based on observations during experiments, are registered, together with some suggestions for future works.

6.1 ABOUT THE PROPOSED OBJECTIVES

The virtual environment scenario and the analytics setup were capable to provide useful and relevant data for HRA via a BBN. The simulator was completely built from scratch with no code programming at all, what is good if one has in mind the perspective of small engineering teams building their own data gathering tool for HRA studies; then, the general objective of studying, proposing and validating new data sources, was fully achieved.

6.1.1 The uses of virtual environments for HRA study (objective I)

From the researched literature, scenarios were identified and summarized in Table 15. they can benefit from data sources originated on digital simulators. some of them have already digital simulator initiatives, while others do not, representing a vast territory for research and new implementations.

Table 15 – Scenarios for HRA studies identified in the researched literature. Military applications are not included

Scenario	Tasks	References
Offshore Scenario	Evacuation, maintenance, operations, firefighting	(CHA et al., 2012; MANCA; BRAMBILLA; COLOMBO, 2013; MUSHARRAF et al., 2014)
Nuclear Power Plants	Control room	(PARK et al., 2004; ZHANG et al., 2007)
Refinery	Operations, Evacuation, Control Room	(CRICHTON; FLIN, 2001; PRASAD; GAIKWAD, 2015)
Transportation	Driving	(BA et al., 2016; DARKEN; MCDOWELL; JOHNSON, 2005; DAVENNE et al., 2012)
Accident Response	First Response, Catastrophic Scenarios	(CHITTARO; SIONI, 2015; COHEN et al., 2013b, 2012)
Air Traffic Control	Control Room	(SHORROCK; KIRWAN, 2002)
Transports Maritime	Maritime operations	(UNG, 2015)
Transports Rail systems	Driving, automation systems interface	(VISIONGAIN, 2011; WILSON et al., 2005)
Surgery	Surgery room, general operations	(ARORA et al., 2011; CUSCHIERI; HANNA; FRANCIS, 2001)
Software development	Programming, User Interface	(AARDALSBAKKE, 2014)

Source: This research (2018).

6.1.2 About reusable building blocks (objective VII)

A reasonable amount of building blocks was built or gathered, making it possible now to create new refinery scenarios, being easily repurposed, and the complete refinery can have the concentrations of hazardous components easily changed for different studies via reprogramming the smart sensors that can be repositioned at will. The smart sensor can have new functionalities added with minor tweaks in the Blueprint scripts, making it not so reusable and repurposable, but extendable as needed for different scenarios.

All the assets created will be published for full access of the CEERMA Research Center representing an enormous time saver in digital simulators creation for oil refinery scenarios. There is the intent to publish all data from the simulator Refinery Digital Twin publicly available for comparisons with other experiments via the datasets originated by the game engine.

6.1.3 Summarizing other objectives achieved

Objective II - To get acquainted with the more common and up to date knowledge for HRA in the qualitative and quantitative fields – Achieved at 2.1.2 ;

Objective III - To study Game Engines (GE) and how they can streamline the creation of simulators - Achieved at 2.3.2 ;

Objective IV - To create an approach based on the best practices identified and in the state of art in mathematical modeling to permit the creation of digital simulators for data collecting – Achieved at 4.9;

Objective V – To compile the best practices in the form of a framework proposal for the creation of data collecting tools based on Virtual Environments (VE) for HRA – Achieved at 4.9;

Objective VI – To validate the framework with the creation of a simulator test scenario for HRA using the Unreal Game Engine, feeding the obtained analytics into a BBN for conditional probabilities calculation – Achieved at 4.

Objective VIII - To document the creation process of a simulator scenario via GE in a way that it can be used as a roadmap for all activities involved in simulator creation with GE – Achieved at 4.

6.2 OBSERVATION NOTES DURING EXPERIMENT

Since all data was being recorded by the analytics rig, the researcher was freed from tasks such as dealing with stopwatches, notes on paths taken and others. This represented a very good opportunity to observe patterns in behavior and choices.

- First and the most important, people took very seriously the exercises just for the sake of doing it right, and most of them changed direction in toxic areas seeking a safer path. This brings good prospects for future studies since demonstrates how exercises are taken into serious account, even though the consequences were far lower than in the real world.
- Different from the MOGA, all users were instinctively single objective oriented towards safety. Some volunteers initially inquired about the time taken to complete exercises by their predecessors in a somewhat

competitive approach, but when they were debriefed and knew the trade-off for speed was health (individual risk), all of them tried to do a safer path at the cost of time.

- Volunteers did not tend to use landmarks as orientation strategy for the first time. The minimal training subjects had this notion, but quite often people got lost due to not being able to know where they were and where they should go. Some of them when got back to the starting point began to look at known landmarks to better navigate the plant.
- A tendency to repeat a successful way was observed. Even though it is not the best, it was very common a play safe approach to orientation at the cost of time and even safety sometimes. Despite that, a strong intent was perceived to review what was done to improve in the next session if the results were not perceived as satisfactory; this will be discussed later.
- A big difference was perceived in time between the first and the subsequent sessions. Even though the scenarios changed in complexity and visibility, lessons learned in the first run were promptly incorporated.

There were two occurrences of nausea in subjects, a male, and a female. In both cases, it happened after almost an hour in the simulator. This is a well-known fact in the literature as can be found in Adams (2013) and Mihelj, Novak and Beguš (2014). There are various possible explanations; one is related to the differences in focal planes of objects in real-world and in the VE, and another explanation is related to the fact that the eyes see motion, but the body does not feel it; researchers believe in the hypothesis that this conflict of sensation makes the organism assume it must have been exposed to some sort of intoxication or poisoning leading to nausea and the will to leave the environment (MIHELJ; NOVAK; BEGUŠ, 2014; PALMER, 2014). It is a common issue in head-mounted displays (HMD), but the big back projected screen may have caused it too, perhaps due to the oversized and closely-looked projection covering almost entirely the volunteer field of view.

Virtual environments proved to be an outstanding tool for data collecting, despite all the scope narrowing choices used at the project. Moreover, despite in a virtual reality, a lot of issues related to human factors showed up in the exercises: lack of attention, impatience, disorientation (volunteers really got lost in the plant), impulsive decisions and all kind of phenomena that makes humans so unpredictable could be observed, and, most important, measured and recorded in real time.

The comparison with the Oliveira da Silva (2017) work, that raised many doubts in the beginning, ended up being a very rich and worthy exercise. The times calculated via algorithm laid in the range of 27-88 minutes approximately and the ones from the simulator ranged from 10-62 minutes. A Mann-Whitney U Test was performed yielding a z of about 4.31 with a p-value of 0,000016, showing that are samples with different distributions as expected.

It is interesting to point that all times remained in the timespan of one to one and a half hour that is the time a human can survive a 200ppm concentration of H_2S. In the plant, the mean values for concentration were about 44ppm and only 8 in 166 smart sensors had a concentration above 200ppm, so all times were in the range of acceptable exposure time to H_2S concentrations in the plant, showing a somewhat homogeneity of findings.

It is worth mentioning a big difference between data generated from each approach: the MOGA process knows in advance the concentrations in all the points of interest, but the humans had to go to the places and “feel” the signs to guide themselves in the evacuation process. The proximity of result may mean that all the assumptions in the MOGA process were, in some amount, a good approximation of reality. The effects of the learning curve from session to session were also impressive. Then, special attention must be paid to this issue, trying to mitigate it, if undesired, or potentialize it in the case of training applications.

This work was generated from the profound wish to contribute to a wider acceptance of digital simulated environments as a serious research tool. A primary bottleneck identified and addressed in this work was that researchers, interested in using this new approach could not start experimenting with the technology if they did not have a large knowledge of computer graphics.

It is very important to register that while the present work was being concluded, informally a research team member of CEERMA needed to do an experiment with LPG spheres leak inspection. The researcher was able to setup a simple experiment in five working days using the framework. This is a good sign of how the framework may be useful for the scientific community.

The fact that the results in this work carry so many issues related to human factors is an excellent indicator of how useful this approach can be as a day to day tool. The use of such tools should be extended for researchers in areas that do not belong to Technology Information or Computer Graphics.

For future works, it would be very interesting to have the following features as object of study:

- Multiplayer scenarios for inter-person and crew coordination observation (CHITTARO; SIONI, 2015; COHEN et al., 2012);
- Augmented reality for onsite simulations layers in plants (KASTEL et al., 2013; MANCA; BRAMBILLA; COLOMBO, 2013);
- Live link with dynamic simulators (e.g. Aloha, Ansys, etc.) for over-time scenario variation (CHA et al., 2012; MANCA; BRAMBILLA; COLOMBO, 2013);
- Improvements in interaction features such as hand and position tracking leading to more natural behavior of users in the VE (BOONBRAHM; KAEWRAT, 2014; LIAROKAPIS et al., 2014; PARK; HA; WOO, 2014b) ;
- Further analysis of what caused motion sickness on volunteers (PALMER, 2014);
- Psychological profiling techniques based on simulator data (MUSHARRAF et al., 2017).

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