AMERICAN UNIVERSITY OF BEIRUT

A DIGITAL FRAMEWORK FOR INTEGRATING CONSTRUCTION SAFETY TRAINING WITHIN LOCATION-BASED SCHEDULES AND MATCHING TRAINED WORKERS WITH ACTIVITIES' SAFETY NEEDS

by

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submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
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AN ABSTRACT OF THE THESIS OF

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Title: A Digital Framework for Integrating Construction Safety Training within Location-Based Schedules and Matching Trained Workers with Activities' Safety Needs

The construction industry is unarguably one of the most dangerous industries contributing to a high percentage of work-related injuries and fatalities. The reasons behind such a dangerous working environment include but are not limited to unforeseen site-related hazards, lack of proper safety awareness and training, lack of proper safety planning, and the varying background and cultures of construction personnel. Several studies have focused on mitigating such dangers by studying the contributing and influencing factors. Other research efforts have focused on developing advanced digital frameworks and gaming tools to help train construction personnel. However, none of the previous works have developed an integrated and unified safety management framework that combines safety training, production planning, and construction resource allocation to promote safety on construction sites. As such, this research aims at creating a digital safety management framework that integrates safety training in location-based schedules then allocates safety trained workers to the tasks. The objective of this study is thereby three-fold: (1) pinpointing and adding safety-dependent activities and respective information onto location-based schedules, (2) adopting game engines as digital tools to assess and train construction workers on safety-related matters, and (3) designing two resource allocation methods to match trained workers with activities according to predefined safety-related criteria. Components of the complete framework were implemented for a case study project in Lebanon and results highlighted its potential in generating better safety-oriented project schedules and matching trained workers with activities' safety needs for the purpose of enhancing safety on construction jobsites.

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ABBREVIATIONS

AA	Assessment Activity
AS	Allocation Score
CLT	Cost of Lost Time
D	Duration
E	Total Number of Workers
Ex	Experience
F	Number of Fatalities
FR	Probability of Fatal Injuries
FRS	Fatal Risk Score
HLBS	Hybrid Location-Based Schedule
HW	Hourly Wage
IRR	Index of Relative Risk
LBS	Location-Based Schedule
LBSMF	Location-Based Safety Management Framework
LPR	Location Physical Risk
LPS	Last Planner System
LRL	Location Risk Level
LRLM	Location Risk Level Matrix
MDAFW	Mean Days Away From Work
ND	Normalized Duration

NEx	Normalized Experience
NF	Number of Non-Fatalities
NFRS	Non-Fatal Risk Score
NLRL	Normalized Location Risk Level
NSS	Normalized Safety Score
P	Probability of Non-Fatal Injuries
PR	Production Rate
R	Risk Score
SAM	Safety Allocation Metric
SAS	Safety Aware Schedule
SS	Safety Score
TA	Training Activity
TRS	Total Risk Score
WWP	Weekly Work Plan

CHAPTER I

INTRODUCTION

A. Research Background

The world we live in today is one where uncertainty is nested within it. Construction projects are known to face uncertainties throughout the project's life time (Ballard and Howell 1998). While some might think that uncertainties only revolve around weather conditions, workflow, and resource availability, uncertainties from safety hazards in construction should not be excluded nor neglected. The problems related to the health and safety of workers in construction are being addressed today with a higher priority than in the past (Gao et al. 2017). According to the Occupational of Safety and Health Administration OSHA, 4674 worker fatalities were reported in all industries in the year of 2017. The construction industry alone accounted for 20.7% of the reported fatalities, which equals to 971 fatalities in 1 year. Similarly in 2015 and 2016 in the UK, the percentage of fatalities in the construction industry out of all fatalities in all industries was equal to 29.8%, which is the highest percentage among other contributing industries (Gao et al. 2017).

To mitigate safety related hazards, the construction industry relies on two main aspects of safety management; training and planning. Training has been recognized as being an important pillar of successful project management (Oakland and Marosszeky 2017). Practitioners in the construction industry use several training methods in order to decrease the frequency of encountered safety hazards. In practice, most construction firms use traditional tools such as classroom lectures, brochures or handouts, presentations, and video animations (Gao et al. 2019).

Workers in traditional training programs have a passive role, since these tools are not engaging. Traditional methods were found to be unsuitable for low literacy workers or workers working in a country having a different language than their native one (Gao et al. 2017, 2019). To overcome the limitations of such traditional techniques, researchers in the past decade have focused on the development of computer aided technological training tools. Most researchers have used serious game engines such as Unity and Torque 3D to develop interactive training programs for safety inspectors or workers (Greuter and Tepe 2013; Guo et al. 2012; Hafsia et al. 2018; Li et al. 2011, 2012). Moreover, virtual reality and augmented reality are also being used in such training tools. VR and AR can offer users a more immersive experience, which allows them to better understand, visualize and communicate with the virtual environment (Fang et al. 2014). These two technologies can deliver better and more realistic location based information (Li et al. 2018).

As for safety planning, many researchers have developed safety planning frameworks and digitized safety planning tools. Researchers first used 4D models to integrate safety tasks with the construction process. As BIM became more popular, researchers integrated BIM with safety planning to automate the safety constraints identification process. Some researchers used artificial intelligence and BIM to automatically detect any unprotected openings in the building model (Qi et al. 2014; Zhang et al. 2013; Zhou et al. 2013). Saurin et al. developed a framework that integrates safety planning with production planning. Saurin et al. integrated safety constraint-identification and removal to the lookahead planning phase (Saurin et al. 2004). Moreover, to better understand the safety risks which may occur in tasks, several researchers have developed quantitative analysis methods to measure the level of risk in each task. Furthermore, Yi et al. developed a quantitative approach to measure the degree of danger of each task based on several factors. These factors range from environmental risks such as high speed winds and rain to task related risks such as the number of incidents in scaffolding tasks (Kyoo-Jin and Langford 2006).

However, the mentioned researches were all linked to the CPM planning technique only. Location-Based Management System (LBMS) is a relatively new scheduling method which is similar to the Line-of-Balance (LOB) technique but with several modifications (Seppänen 2013). LBMS uses a location breakdown structure in order to schedule activities in their respective locations. Hence, it doesn't only use floor 1 for example, but it also divides the floors into several working areas (Kenley and Seppänen 2010). The advantages of using LBMS is that is visually shows buffers between tasks, workflow continuity, and forecasts activity progress to warn about any possibility of cascading delays or clashes (Kenley and Seppänen 2009). Despite the ongoing research in LBS, no research has yet studied the safety management aspect of LBS.

The overarching goal of this research is to enhance and integrate construction safety training and production planning in construction. This research proposes a Location-Based Safety Management Framework (LBSMF) which integrates production planning and scheduling, safety training, and resource allocation into a unified framework. The LBSMF contains three connected components which are developed in this research. The LBSMF is integrated into the Last Planner System to integrate the framework into the planning phases. Within the LBSMF, a Hybrid Location-Based Schedule (HLBS) which adds safety assessment and training activities to the LBS, and uses a developed equation to quantify the Location Risk Level (LRL) or the level of danger for each activity in each location. The HLBS is digitized through a coded tool which also color codes the activities depending on their corresponding LRL. The second component aims to enhance safety training by developing a location-based safety assessment and training system using game engines. The developed training material is based on two factors which were found to have a direct effect on worker's safety behavior which are safety knowledge and experience, and risk perception. Each worker obtains a Safety Score (SS) after going through the training program. Finally, a Resource Allocation system is developed which introduces two allocation methods. The first sets safety as the main property for resource allocation where it compares the SS of each worker with the LRL and allocates each worker to the activity based on this comparison. The second method uses an algorithm to integrate worker's experience and SS to know which worker is more fit for the job relative to the other workers rather than to a fixed criterion. Moreover, the second method also uses the SS and LRL to notify planners which of the activities has workers who need more safety monitoring and inspection. Hence, the proposed LBSMF allows planners generate a safer schedule by allowing them to visually perceive dangerous activities, properly schedule training sessions to train workers in, and allocate workers based on safety criteria.

B. Research Objectives

The overarching objective of this research is to enhance construction safety through the development of a Location-Based-Safety Management Framework (LBSMF). To achieve this objective, this research pursued three main sub-objectives. Each of these sub-objectives is considered to be a Safety Screen which ensures that the project schedule becomes safer after passing through each one of them. The first screen is created by developing a LBS where dangerous activities can be visually seen by planners. The second screen is achieved by assessing and training workers in a virtual and interactive training program. The third and final screen aims to allocate workers based on their safety training output and the level of danger of the activity they are allocated to. To develop this framework, this research pursued the three aforementioned sub-objectives as follows.

- Develop a Hybrid-Location-Based Schedule (HLBS).

This objective aims to transform the safety training session into a scheduled task which is added as a predecessor for each task on the schedule. The training task were represented on the LBS with a production rate and buffer. The tool also uses a developed equation in this research which quantifies for each activity the Location Risk Level (LRL) which allows us to know the level of danger of each activity in each location. The HLBS allows planners to check who needs to be trained, how long the training takes, and what resources are needed to complete the training.

- Develop a game engine-based assessment and training tool for LBMS.

This tool is presents two programs which all workers are required to pass through. The first is an assessment program which is used to identify each worker's safety performance. The second program is the training program which is used to train workers on safety hazards and measures. The tool is a location-based tool since it trains workers on the upcoming location's safety hazards rather than on the entire construction site.

- Integrate safety training with resource planning.

The research proposes two different allocation methods to support planners in deciding which workers should be allocated to a given activity. The first allocation method is a safety-oriented method which uses a developed safety criterion that links the obtained SS with the activity's LRL. The second method uses a different approach to balance between worker's skill and safety performance. This method allows planners to know which workers are more fit in comparison to others, and it also identifies which activities require more safety monitoring and inspection.

C. Thesis Structure

This thesis is divided into seven chapters. The introduction is the first chapter which includes the research background, problem statement, and the research objectives. The second chapter provides the relevant literature review needed to carry on this research. The third chapter discusses the methodology of this research and the proposed framework. Chapter 4 and 5 respectively present the development of the proposed framework's components and its implementation on a case study. Finally, Chapter 6 includes the conclusion of this research and the proposed ideas for future work.

CHAPTER II

LITERATURE REVIEW

A. Location-Based Management System

The Location-Based Management System (LBMS) is one of the most recently developed scheduling techniques (Seppänen 2013). To overcome the limitations of the Line of Balance which was limited to repetitive tasks, Mohr developed a location-based schedule which was based on location rather than work quantities (Mohr 1991). Seppanen et al. developed the LBMS which further enhanced the location-based schedule developed by Mohr. The LBMS included a location breakdown structure which divided working locations into sub-areas. Moreover, the LBMS developed techniques to allow for buffers between tasks, to achieve for continuous flow, and to alert of any clashes or cascading delays (Kenley and Seppänen 2010).

To develop a location-based schedule, the first step is to develop a location breakdown structure which informs us where and which tasks should be executed. After that, quantity take-offs for each location is calculated along with the required resources, and the duration of the task is obtained (Seppänen 2009). Moreover, three types of buffers are included in LBS which are time, space, and plan buffers. These buffers are placed between successive tasks to mitigate any variability and any risk of cascading delays (Frandson et al. 2015).

B. A Systemic Training Model

Recently, organizations have been directing their focus more and more towards proper employee training. The training process is no different in the process of planning normal work activities. The widely used training model is made up of four main phases as shown in Figure 1.

The first phase is the Assessment Phase, which is the phase where managers are required to identify the purpose of the training program. This includes the identification of the current skills of employees and the gap they have between their current skills and the organization's future plans and goals.

The second phase is the Planning/Design Phase. During this phase, managers and planners answer two main questions; where the training takes place, and when it takes place. Moreover, other variables are quantified such as the number of people who require this training, and what resources such as money and equipment are needed to perform this training.

The third phase is the Implementation Phase. This is the execution part or the delivery of the actual training. Training might be delivered on site or at the office. Training techniques vary from one program to another. Training can be delivered in the form of presentations, meeting talks, brochures, serious games, and case studies.

The fourth and last phase is the Evaluation Phase. This is a critical step in the process which allows for continuous improvement of the program or Kaizen. Trainees' feedback are gathered through surveys and interviews which help trainers in identifying weaknesses and gaps in the training program (Oakland and Marosszeky 2017).

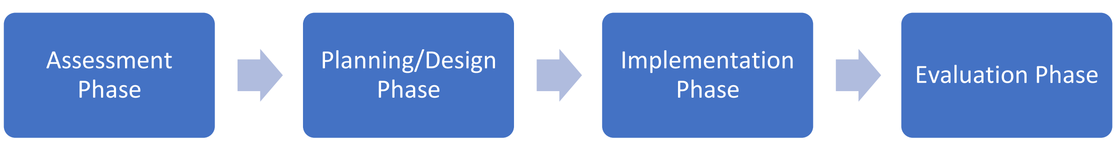

Figure 1 - A Systemic Model of Training

C. Serious Games Safety Training

Several researches have shown the effect of proper safety training on the safety climate and behavior of workers. One research compared the performance of workers in using PPE and in accessing heights before and after proper training. The results showed that after training, worker's understanding and use of PPE increased from 65% to 96%. As for accessing heights, the worker's score increased from 51% to 93% (Lingard 2001). Another research indicated that an increase in management safety efforts such as training would increase worker's safety knowledge (Hallowell et al. 2019). Moreover, according to workers, the most importance factor that enhances their safety performance is proper training (Jannadi 1996).

In the past decade, researchers have progressively focused on integrating construction applications with serious game engines especially for developing safety training programs. Researchers used simulation software such as Stroboscope and VitaScope to study and visualize construction operations (Khoury et al. 2007). While simulation software offer a better experimental environment, serious game engines offer a more interactive training environment. This section provides a thorough literature review of safety training programs using serious game engines. The review starts with the researches from the year 2009 and then continues year by year till the most recent researches in 2020.

Zhao et al. developed a safety training program using the Torque 3D game engine. Their researchers were the first to develop a VR safety training program that dealt with electrical safety hazards on construction sites. The program trained heavy machinery drivers on working in close proximity to electrical structures such as electric poles and overhead powerlines (Zhao et al. 2009). Another research by Lin et al. also used the Torque 3D game engine to develop a safety training program. This research however focused on more general safety violations rather than on specific task related ones. The game allows users to play the role of safety inspectors and to go through a construction site while pointing out safety hazards using a mouse click (Lin et al. 2011; Son et al. 2011). Dickinson et al. used the Microsoft XNA Studio 3.1 to develop a safety training program for trench construction. The game trains users on the risks of falling into a trench, trench collapse, and construction sequence (Dickinson et al. 2011). A more general safety program was developed to assess safety hazard identification on several different construction operations. The researchers used the Unity game engine to develop a 4D construction environment which embedded MCQ that users have to answer regarding several animated tasks (Li et al. 2011). Also, in 2011, a research was developed proposed the concept of Building Interactive Modeling. The research proposed a gaming environment using Second Life, which trains students on several aspects of construction. Students can learn through interactive gaming about BIM, safety hazards, and construction processes (Ku and Mahabaleshwarkar 2011).

In 2012, Lin et al. developed a training program for workers with low English proficiency and literacy. The program trained workers on falling hazards in construction sites using six different case studies which were animated in a game engine (K.Y et al. 2012). Another research published in 2012 developed a training program which included safety inspection training during different construction phases (Yuan-Ling et al. 2012). Later in 2013, Greuter et al. developed a game under named “Trouble Tower” to train students on safety hazard management. At each stage of the game, students would face a safety hazard where they needed to apply safety measures to mitigate any injuries to workers (Greuter and Tepe 2013). In 2014, Fang et al. introduced a research which coupled BIM and game engines to develop a training environment for crane operators. The research also used wireless ultra-bands in order to track workers position in the construction site, and to represent it inside the virtual training environment (Fang et al. 2014).

Other researchers focused on developing a classroom teaching environment for construction safety training. They used the Second Life platform to develop a safety training program containing three modules. The first module is titled “Cooperative Distributed Safety Learning”, and it brings students along with their instructor into a VR classroom to learn about safety measures and procedures. The second module is titled “Hazard Inspection and Safety Cognition”, and this module acts as a test to what students have learned in the first module. Students are asked to identify safety hazards in the construction site, as well as answering questions inside the gaming environment. The instructor then checks and evaluates the students' performance and answers in their test. The last and third module is titled “Active Safety Game-based Learning”. This module is divided into two parts. The first involves students individually performing certain tasks to learn about what safety hazards might occur during practice. As for the second part, it involves several students cooperatively performing tasks in the same environment to better understand work conditions (Le et al. 2014). Dawood et al. the OpenSim platform to develop a 4D training environment for workers. Workers were trained on identifying safety hazards as the building progressed with time (Dawood et al. 2014). Another research that tackles aims to train workers on electrocution hazards on construction site was developed. The researchers used the Torque 3D engine to develop a road construction environment where heavy construction machinery is used near electrical power lines. Workers can navigate freely in the construction site and each time they come close to a safety hazard a warning message is triggered. After that, users are asked to perform one or more tasks where their acquired knowledge of safety hazards is tested (Zhao and Lucas 2014).

In 2015, Le et al. developed a research similar to the one developed in 2014, but with a different approach. The research used the Build AR Pro 2 platform to develop a VR and AR mobile based safety training program. The program had a similar approach to that presented in the 2014 research by Le et al in terms of the module of the training framework. However, in this research technological advances such as mobile based VR and AR were used (Le et al. 2015, 2014; Pedro et al. 2016). Li et al. introduced a training program using the Unity game engine which focused on safety precast concrete installation. The program aimed to train installation workers on safety measures while placing precast units without negatively influencing their productivity (Li et al. 2015). Hilfert et al. developed a game using the Unreal Engine 4 which enhances worker's awareness on heavy machinery movement in the construction site. Users are asked to carry objects from one location on the site to the other while taking into account heavy machinery movement to avoid any collisions (Hilfert et al. 2016). Park et al. used serious games and VR technologies to introduce the concept of Interactive Building Anatomy Modeling (IBAM) system to university students. The proposed system allows students to interact with a BIM model and to select any of its building elements. Once they selected a building element, they can learn about the material used and the execution process of the element (Park et al. 2016). Houa et al. used the Unity game engine to develop a training frame work for workers in the oil and gas industry. Workers can use the proposed framework to train on pipe assembly while complaining with safety measures (Hou et al. 2017). Another research used VR to contextualize reported OSHA case studies in a built environment (Peña and Ragan 2017).

Previously, Khoury et al. developed three algorithms that used several location aware technologies to present information regarding building elements in the construction site. The studies' results prove the applicability of these technologies and that they can also be used for safety purposes (Khoury and Kamat 2009a; b). Hafsia et al. focused on developing a practical training program for workers. Their research used serious game engines to develop a training environment for formwork fixing. Using VR technology, workers have to set up a formwork panel taking into consideration assembly steps and safety measures (Hafsia et al. 2018). Other researchers focused on natural safety hazards such as earthquakes. Using the Unity game engine, they developed a training program for earthquake safety hazards and measures in hospitals (Feng et al. 2019). Vahdatikhakia et al. developed a construction heavy machinery driving simulator for training workers using the Unity game engine. The researchers used a road pavement and compacting process as their case study. Workers in the virtual environment were modeled as agents to represent human behavior as close as possible. Also, they used GPS technology to integrate workers' location into the virtual environment. Moreover, trainees driving the compactor for example had to execute their job while maintaining a planned production rate, and while taking into consideration agent behaviors and safety measures (Vahdatikhaki et al. 2019).

Liang et al. also used the Unity game engine but to tackle a different safety problem. The training program focused on training underground or mine workers to identify loose rocks that had a potential of falling on them (Liang et al. 2019). Zhang et al. developed a VR game using Unity to educational purposes. The developed game allowed students to go through a building site and to measure distances, add buildings, and change material and building sizes. The research showed that students felt they had a better understanding of their designs once they visualized and manipulated it in a VR environment (Zhang and Chen 2019). The most recent research that worked on integrating construction applications with serious game engines was published in 2020. The research aimed to compare safety training programs using 360-degree panorama images coupled with augmented reality with virtual reality. Research showed that students favored the real images as the images gave them a more realistic feeling. However, experienced practitioners didn't find any difference between using real site images or VR. Moreover, students indicated that VR scenes are easier and user friendly than real images when identifying safety risks. On the other hand, the research suggests that VR can be used to train students in a less crowded and chaotic environment, while real images can be used to test and train the safety knowledge of experienced practitioners to challenge their knowledge (Eiris et al. 2020).

All previous studies proved the effectiveness of using serious game engines over traditional training tools. The research conducted by Lin et al. showed that 100% of participants answered “Yes” to whether the game motivated them to refresh their knowledge on safety topics. Moreover, 80% of participants gave a score of 5 and 20% gave a score of 4 to assess how much the game increases their learning interests. When asked if the learning experience was facilitated by the game, 100% of the respondents answered by “Yes” (Lin et al. 2011). A similar assessment of a developed safety video game showed that 81% of participants answered “Yes” to whether the game facilitated the learning experience. Also, 86.5% answered “Yes” to whether the training method was more enjoyable than traditional training tools (Yuan-Ling et al. 2012). Another study showed that 80% of participants thought that the training program developed using the Unity game engine was more useful than traditional training tools (Li et al. 2015). Furthermore, a framework for safety integration with construction developed using serious game engines scored a 4 out of 5 on the ability to effectively transfer knowledge to users (Pedro et al. 2016).Table 1 shows which game engines were used to develop the previously mentioned researches.

Table 1- The Game Engines Used in the Literature

Authors	Year	Title	Game Engine
Dong Zhao, Jason Lucas, Walid Thabet	2009	Using Virtual Environments to Support Electrical Safety Awareness in Construction	Torque 3D
John K. Dickinson, Paul Woodard, Roberto Canas,Shafee Ahamed,	2011	Game-based Trench Safety Education: Development and Lessons Learned	Microsoft XNA Game Studio 3.1
Kihong Ku, Pushkar S. Mahabaleshwarkar	2011	Building Interactive Modeling for Construction Education in Virtual Worlds	Second Life
Ken-Yu Lin, JeongWook Son, Eddy M. Rojas	2011	A Pilot Study of a 3D Game Environment for Construction Safety Education	Torque 3D
JeongWook Son, Ken-Yu Lin, and Eddy M. Rojas	2011	Developing and Testing a 3D Video Game for Construction Safety Education	Torque 3D
Heng Li, Greg Chan, Martin Skitmore	2011	Visualizing Safety Assessment by Integrating the Use of Game Technology	Unity
Sidney Newton, Russell Lowe, Rosamond Kember, Rui Wang and Stephen Davey	2013	The Situation Engine: A Hyper-Immersive Platform for Construction Workplace Simulation and Learning	Cry Engine 3
Nashwan Dawood, Geoff Miller, João Patacas, Mohamad Kassem	2014	Combining Serious Games and 4D Modelling for Construction Health and Safety Training	OpenSim
Quang Tuan Le, Akeem Pedro, Chan Sik Park	2014	A Social Virtual Reality Based Construction Safety Education System for Experiential Learning	Second Life
Dong Zhao, Jason Lucas	2014	Virtual Reality Simulation for Construction Safety Promotion	Torque 3D
Quang Tuan Le, Chansik Park, Akeem Pedro	2015	A Framework for Using Mobile Based Virtual Reality and Augmented Reality for Experiential Construction Safety Education	BuildAR pro 2
Heng Li, Miaojia Lu, Greg Chana, Martin Skitmore	2015	Proactive Training System for Safe and Efficient Precast Installation	Unity

Thomas Hilfert, Jochen Teizer	2016	First Person Virtual Reality for Evaluation and Learning of Construction Site Safety	Unreal Engine 4
Lei Houa, Hung-Lin Chib, Wernhuar Tarngc, Jian Chaid, Kriengsak Panuwatwanicha, Xiangyu Wangd	2017	A Framework of Innovative Learning for Skill Development in Complex Operational Tasks	Unity
Idris Jeelani, Kevin Han, Alex Albert	2017	Development of Immersive Personalized Training Environment for Construction Workers	Unity
Zhenan Feng, Robert Amor, Vicente Gonzalez, Michael Spearpoint	2019	An Immersive Virtual Reality Serious Game to Enhance Earthquake Behavioral Responses and Post-earthquake Evacuation Preparedness in Buildings	Unity
Faridaddin Vahdatikhakia, Khaled El Ammarib, Armin Kassemi Langroodic, Seirgei Millerd, Amin Hammade, Andre Doreef	2019	Beyond Data Visualization: A Context-Realistic Construction Equipment Training Simulators	Unity
Cheng Zhang, Bing Chen	2019	Enhancing Learning and Teaching for Architectural Engineering Students Using Virtual Building Design and Construction	Unity
Zhipeng Liang , Keping Zhou, Kaixin Gao	2019	Development of Virtual Reality Serious Game for Underground Rock-Related Hazards Safety Training	Unity
Ricardo Eiris, Masoud Gheisari, Behzad Esmaeili	2020	Desktop-Based Safety Training Using 360-degree Panorama and Static Virtual Reality Techniques: A Comparative Experimental Study	Unity

D. Safety Planning

Many researchers have focused their efforts on developing safety planning framework to enhance construction safety. Kartam et al. developed a computerized tool which integrated safety planning with the Critical Path Method (CPM). The tool is equipped with a database of safety regulations for specific construction activities obtained from the CSI. The tool takes as input the CPM network of the project and automatically links the required safety regulations to each of the tasks on the network (Kartam 1995).

Saurin et al. developed a framework that integrates safety planning with production planning. Saurin et al. integrated safety constraint-identification and removal to the lookahead planning phase. At this level, the author divided safety constraints into 5 categories which are; Training, Safeguards, PPE, Design, and Space. As for the short-term planning phase, all previously mentioned safety measures would be discussed and reevaluated in daily or weekly meetings (Saurin et al. 2004).

Choe et al. integrated safety planning with 3D and 4D BIM models to better visualize the process. The researchers assessed the level of danger of each activity per day and calculated the total risk score for each day. The risk scores are then integrated into the 4D model where risky activities are colored coded according to their risk level (Choe and Leite 2017).

E. Computer-Aided Safety Planning

Several tools were developed using computer software and programming languages to enhance construction safety planning. Benjaoran et al. developed a 4D CAD tool that integrates safety measures into construction planning. The tool takes that 3D model as input along with the construction schedule build on MS Project. A built-in algorithm checks the construction stage and adds the required safety activities to the schedule. Safety activities that are automatically added are slab guardrails erection and removal and scaffolding inspection (Benjaoran and Bhokha 2010). Another application of 4D was used to visualize the construction process of metros. The tool used 4D to visualize the construction process while detecting any delays that might occur due to safety incidents. Such safety incidents are not limited to work space clashes between workers and heavy machinery, but also incidents due to excavation soil failures and stresses are also warned about (Zhou et al. 2013). BIM was also integrated with algorithms to automatically detect specific safety hazards in the model. Qi et al. developed a tool where the BIM model can be imported into, and an algorithm would check if there are any openings in the slab which are larger than the specified criteria. If the algorithm detects an opening larger than the specific value the opening would be color coded in the model (Qi et al. 2014). An ontology-based safety planning tool was also developed using BIM. The tool uses a database of safety knowledge about masonry work and automatically matches them with the building elements. The output would be a summary of safety hazards and recommendations for each element (Zhang et al. 2015a). Virtual prototyping was integrated with BIM to simulate the construction process and identify safety risks and hazards before construction. The proposed model also used the tool in order to train workers after they have went through the construction simulation (Guo et al. 2013). 4D and BIM were also coupled together to develop useful tools for safety management. A more general tool was developed to manage four aspects of construction: resource and cost management, structural safety analysis of temporary structures, site conflict management, and schedule management (Zhang and Hu 2011).

As for the aspect related to safety, the tool analyzes the scaffolding systems for any design errors and unforeseen safety risks within the design (Zhang and Hu 2011). Zhang et al. developed a tool that automatically checks the BIM model for any openings in the slab and free slab edges. The tool then adds safety guards to the slab's perimeter and places a plank over a the slab openings (Zhang et al. 2013, 2015b). Moreover, a framework was developed that automatically checks and warns about safety hazards related to temporary structures. The algorithm within the framework detects and warns about any safety hazards that might occur and gives suggestions to overcome them (Kim et al. 2016).

F. Safety Planning Tracking and Inspection

Li et al. developed a framework that is based on proactive behavior-based safety management. The construction site is built in Unity 3D, and location tracking systems are used on workers in the actual construction site. The location of each worker is inserted into the Unity model where a check is done if the worker is near a high-risk safety zone. If the worker is near this zone, a signal is sent to his hat and an alarm goes off to warn him (Li et al. 2015). A new approach was developed which used GIS along with a building's 3D model to simulate and manipulate construction processes. The model takes advantage of GIS for example by detecting low lighting areas of the construction site (Bansal 2011). This approach allowed the researchers to detect dangerous areas in terms of visibility. In a different approach, Mneymneh et al. developed a computer vision machine learning algorithm which is able to detect whether workers on site are wearing their hard hats or not (Mneymneh et al. 2019).

G. Factors affecting Construction Safety

In the attempt to mitigate safety hazards, several researchers have focused on developing mathematical models to link and predict safety climate, safety behaviors, and injuries based on different factors. Safety Climate has been defined as the perception or understanding of the organizational safety policies and procedures which the employees have towards their work environment (Choi et al. 2017; Newaz et al. 2019). Researchers defined safety behavior as the worker’s behavior that is supported and encouraged by safety and health requirements which mitigate accidents and injuries (Panuwatwanich et al. 2017). Also, Abbas et al. suggested that the years of experience of a worker may have a significant effect on his risk perception and thus on his safety performance (Abbas et al. 2018). Fang et al. studied the relation between different personal traits of workers and safety climate. The research used factors such as marital status, number of family members to support, education level, and safety knowledge. The findings of the research showed that individuals who are older, married, or have more family members are more likely to have a positive appreciation of the safety climate. Moreover, workers who have more years of experience and a higher level of education tend to have a positive perception of the safety climate (Fang et al. 2006).

In a similar study, Zhou et al. used Bayesian networks to develop relations between safety climate factors and personal traits with safety behavior. Personal traits included in the study were work experience, education, and drinking habits. The study showed that although higher work and education experience have a positive effect on safety behavior, other factors such as management commitments and workmate’s influence had higher effects. However, the most optimum way to increase safety behavior is by a joint strategy of enhancing all mentioned traits (Zhou et al. 2008). Patel et al. used 10 safety climate factors to predict the safe behavior of workers. The study showed that competence and individual perception of risk were found to be crucial for the prediction of safety behavior (Patel and Jha 2016). Another research studies the effect of several features including economic features, self-esteem, and experience on safety behavior. The study showed that the more experience a worker has the more aware he is regarding safety requirements. Another factors which was identified to have a negative effect of safety behavior is self-esteem. The research found that worker’s tend to prove that they are “tough guys” which puts them in many different unsafe situations (Choudhry and Fang 2008). Beus et al. studied the effect of psychological traits on the safety of the workplace. The first factor that the research studied is extraversion which is defined as the individuals who are outgoing, spontaneous, and bold. The study showed that individuals who carry this trait are more likely to engage in unsafe behaviors in the attempt to compete with others and to achieve their goals in all ways possible. Another personality trait which the research addressed is conscientiousness. Individuals who are described as such are responsible and prefer to follow rules and avoid risk. These individuals aim to complete their tasks while taking into consideration higher order goals such as safety. Thus, this trait is proven to be negatively associated with unsafe behavior. Neuroticism is a trait which describes people who are not emotionally stable and tend to have high levels of anxiety and stress. It was found that people with this trait are more likely to perform unsafe behaviors (Beus et al. 2015). Other researchers used artificial neural networks to predict safe work behavior based on 10 safety climate factors. Among these factors, the research identified individual traits such as personal appreciation of risk and the competence of workers. The research ranked personal appreciation of risk as the fourth contribution factor to safe behavior, while competence was ranked ninth (Patel and Jha 2015). Mohammadfam et al. used Bayesian networks to study the relation between organizational and personal factors and safety behavior. The research also showed that safety knowledge plays a crucial role in predicting safe behavior (Mohammadfam et al. 2017).

Esmaeili et al. used linear models to predict the type of injury that might occur given the circumstances of the work. Predictor variables were conditions such as working in swing area of a boomed vehicle, use of nail gun, wind, and working on trench. The type of injuries varied from not fatal to not severe to mild and fatal. The developed prediction model showed to have a valuable usage for practitioners to forecast different types of injuries (Esmaeili et al. 2015). In a similar approach, Boateng et al. used artificial neural networks to predict the levels of safety performance on construction sites. The model used as input the number near misses, incidents, and fatalities. Jitwasinkul et al. used Bayesian networks to study the relation between different organizational factors on safe work behavior. Factors such as communication, management commitment, reward, and empowerment were included in the model. The model would then predict if the work behavior is at risk depending the values of the mentioned factors (Jitwasinkul et al. 2016). Other researchers studied the effect of job stressors such as safety equipment, supervisor support, co-worker support, job certainty, and job control on safety behavior and accidents (Leung et al. 2016). Guo et al. focused on the effect of the social support aspect of safety climate on safety behavior. The research found that social support has both direct and indirect effects on safety behavior where social support can mitigate unsafe behavior by providing a communication channel between individuals. The study highlighted on the importance of communication and guidance between supervisors and co-workers for the lack of which can cause unsafe actions (Guo et al. 2016).

H. Gaps in the Literature and Contributions

Despite the advancements in research, the literature still has several gaps. Although researchers have advanced and developed several tools and frameworks for safety training and planning, and production planning in general, no research was found which integrated safety training into scheduling especially with Location-Based Schedules. Previously developed frameworks and tools either linked safety databases with to BIM models or CPM networks, but none developed such methods for LBS. Moreover, researchers have developed several equations to quantify the level of danger of activities, but none have developed equations to be used in LBS. Furthermore, researchers visualized activity danger levels within BIM models but none developed a “Safety Aware” schedule where planners can directly notice dangerous activities and use this information in planning.

Workers are usually allocated to activities in a way to increase productivity or optimize the project’s cost. However, no research was found which developed a resource allocation system which integrates safety training into the allocation process. Thus, no research developed a safety requirement specific to each activity in order to decide whether the worker is qualified to be allocated to this activity based on this requirement.

Researchers have developed several serious games for construction safety using game engines. Despite all developed researches, none have developed a location-based safety trainer which trains workers based on the activity’s execution location. Moreover, no research was found that develops an assessment program within this trainer to assess workers’ safety performance. Furthermore, researchers have identified several personality factors which have a direct effect on the safety behavior of workers. No research was found which used these factors in the developed training scenarios to enhance these traits in workers.

CHAPTER III

METHODOLOGY

Design Science Research (DSR) is the research methodology for this study. In construction management DSR can be a proper tool when building problem-solving artefacts that tackle real problems. It is considered constructive research that connects research and practice (Rocha et al. 2012), which this is the objective of this paper. This research used Unity 3D; a professional game engine, to develop a practical tool to enhance construction safety training. On the other hand, the programming language Python along with its scientific and numerical libraries such as SymPy and Matplotlib were used to develop a safety planning tool. Both tools are integrated to develop a unified safety planning and training tool.

After developing the digital LBSMF, the framework was implemented and tested on a case study project. Also, a survey was conducted to study the effectiveness of the training and assessment tool developed in Unity. Figure 2 below visually shows the research methodology.

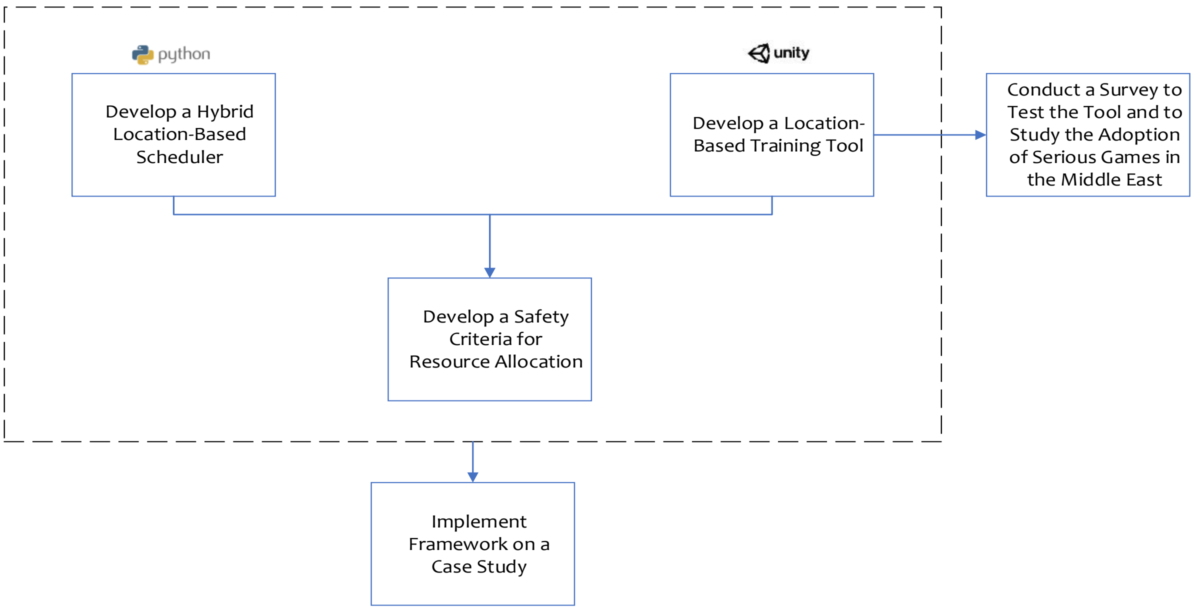

Figure 2 - Research Methodology

A. The Location-Based Safety Management Framework

The Location-Based Safety Management Framework (LBSMF) shown in Figure 3 is divided into three main components. The first component is the Hybrid Location-Based Schedular, where the term hybrid indicates that this schedule is an integration between a production and safety schedule. This component generates a Hybrid Location-Based Schedule (HLBS) which automatically adds a safety training activity as a predecessor for each activity in each location. Then, this schedular calculates for each activity in each location a Location Risk Level which indicates how dangerous this activity in each location really is. After obtaining the LRL, the scheduler color codes each activity based on its LRL values, and then it would generate a Safety Aware Schedule (SAS) which can directly and visually show the level of danger of each activity.

The second component is the Activity Safety Trainer which is divided into two programs. The first program is the Assessment Program which is used give a Safety Score (SS) to each worker based on their safety knowledge and risk perception. This program is implemented before the very first start date of the activity and is repeated as necessary. The second program is the Training Program which is used for safety training and revision sessions to prepare workers for what dangers they might face before entering a new working location. This program takes place before the start date of each activity in each location.

The last component is the Worker Allocator which is a safety criteria-based allocation system. This component contains two allocation criteria or methods. The first method is based only on a safety criterion which compares the LRL of a given activity with the SS of the worker. Both the LRL and the SS were developed in such a way to range between 0 and 70 to have them on the same grading scale. The second method allows planners to balance between the worker's experience and SS by using an algorithm which integrates them to get an Allocation Score (AS). The computed AS informs planners of the most fit workers for the given activity. Moreover, the second method notifies the planners if there are workers who have been allocated to the activity but do not meet the safety requirements of the first method to indicate that this activity requires more safety monitoring and inspection. In both cases, planners are able to know if the worker is qualified from a safety perspective or from both experience and safety perspectives to work on this activity. If not, planners have the choice to either allocate him onto another activity which he is qualified to be allocated on, or they can allocate him to his original activity but they have to re-train him and increase safety monitoring and inspection for the activity.

The LBSMF would provide a safer project planning and execution by using the three aforementioned components. These components represent three Safety Screens to ensure the safest possible project planning and execution. The first screen is the predecessor training activity and the Safety-Aware Schedule (SAS). This component allows planners to always be aware of the importance of implementing safety training activities and of the dangers in each activity by providing a color-coded SAS. The second screen is the training program itself which ensures that workers receive their training in an interactive, engaging and effective environment. The final screen is the allocation component which allows us to qualify workers who are fit for the given activity from a safety standard, and it also notifies us about activities which require more safety monitoring and inspection.

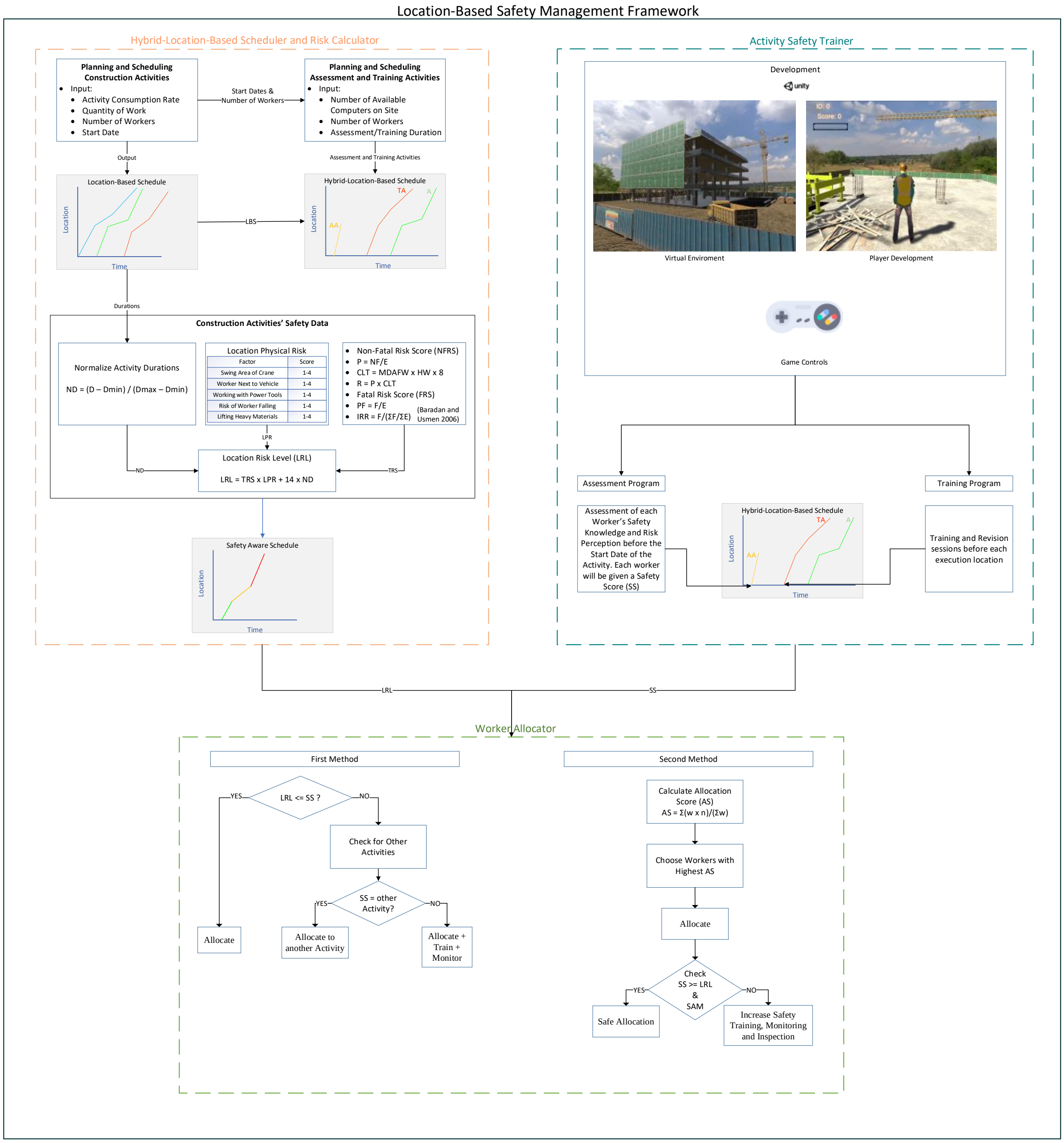

Figure 3 - The Location-Based Safety Management Framework

B. Integrating the Framework within the Project Phases

The proposed framework is integrated within the Last Planner System (LPS). The LPS is used because it divides planning into several phases which makes it simpler and clearer to integrate the framework into.

1. The Last Planner System Planning Phases

The Last Planner System is developed by Glenn Ballard and Greg Howell to enhance production planning and control (Ballard 2000). The LPS is divides planning into four main phases. The difference between each phase is the type of planning and level of detail of planning being done. The four phases are; the Master Scheduling phase, the Phase Scheduling phase, the Lookahead Planning phase, and finally the Weekly Work Plan phase (Samad et al. 2017). This research aims to integrate the proposed LBSMF into the Lookahead and Weekly Work Plan phases.

The Lookahead planning phase spans over a six-week time frame. During this planning phase, planners break down activities into processes and operations to generate a detailed execution schedule (Tommelein and Ballard 1997). Moreover, all activities pass through a screening phase in order to identify and remove constraints. The objective behind this phase is develop the execution schedule and to shield it by making all activity requirements and prerequisites available ahead of time (Hamzeh et al. 2015).

As for the Weekly Work Plan (WWP) phase, at this level all activities should have been made ready for execution to start. During the WWP, execution starts and by the end of the week several metrics are evaluated to measure different aspects of planning (Hamzeh et al. 2012).

2. The LBSMF within the Last Planner System

The proposed LBSMF adds to the Lookahead planning phase several procedures as seen in Figure 4. From weeks 6 to 4, planners have to develop the LBS and the HBLS by calculating the LRL. Also, during this time, the development team should be developing the assessment and training scenarios in Unity to make all training related procedures and material ready, hence removing the safety assessment and training constraints. In the LPS, planners usually start to assign resources and allocate workers in activities from week 4 onwards (Hamzeh et al. 2012). The LBSMF uses the Assessment Program to decide whether a worker is qualified to be allocated to the activity or not. Hence, from weeks 4 to 1, planners have to execute the Assessment Program to be able to allocate the workers to their activities. The Training Program should take place during the week before the activity's execution to minimize the period between training and execution.

By the end of the WWP, planners usually assess and evaluation their planning and performance by calculating several metrics. During the WWP, safety monitoring, inspection, and evaluation should be performed for all ongoing activities.

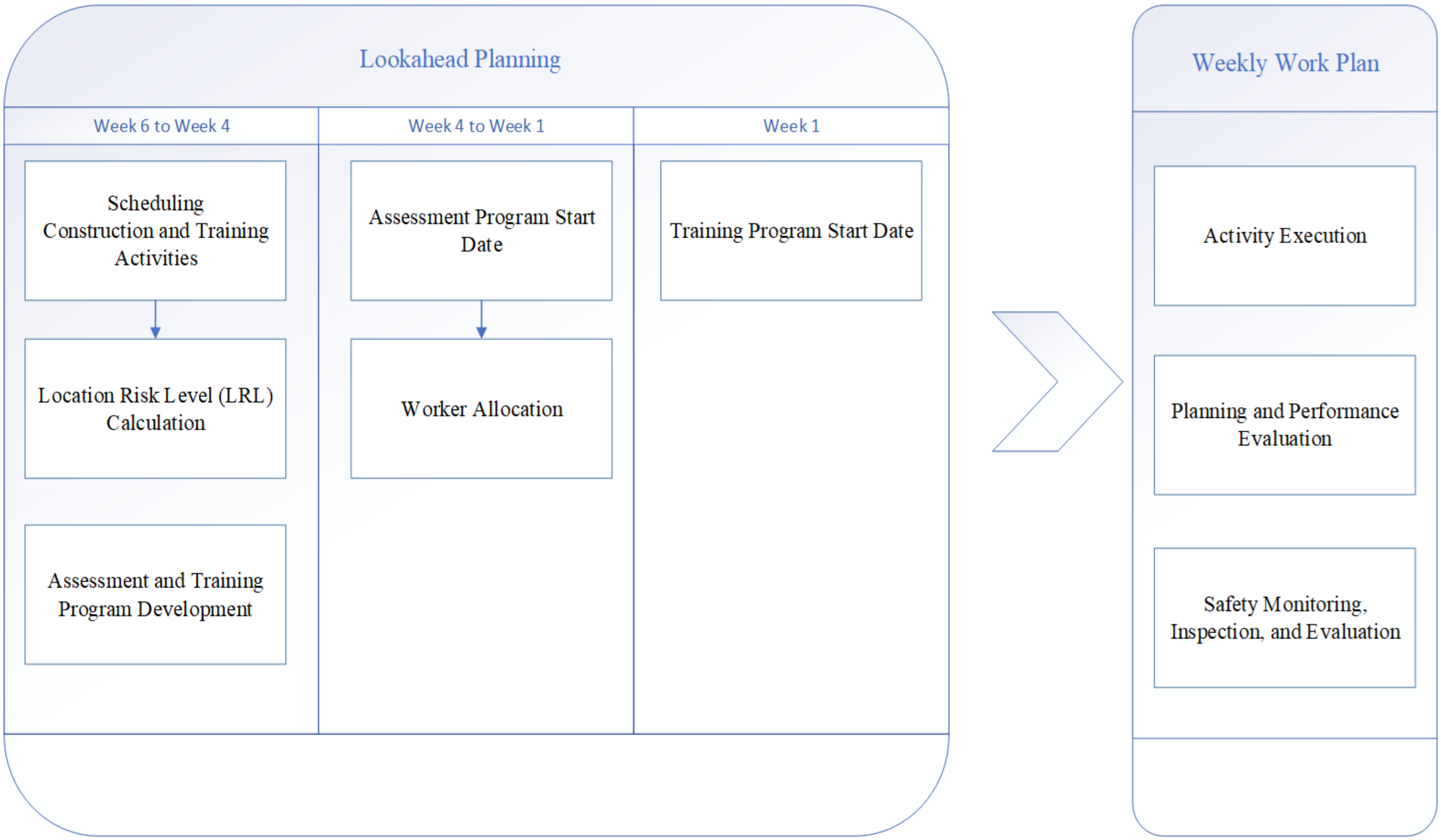

Figure 4 - The LBSMF TimeLine

CHAPTER IV

FRAMEWORK COMPONENTS DEVELOPMENT

A. Hybrid Location-Based Scheduler

This component is divided into two modules or two sub-tools. The first part of the tool is used to generate the HLBS, while the second is used to generate the Location Risk Level of each activity and then color code activities based on their LRL values.

The HLBS is composed of two main phases; the Planning Phase of the training activities, and the generation of the Location Risk Level Matrix. During the Planning Phase and in addition to the scheduling of work activities, planners identify who needs training, how long the training takes, and how much resources are needed such as the number of available computers (Oakland and Marosszeky 2017). Moreover, planners are able to visually identify dangerous activities on the schedule which allows them to also identify which activities require more intensive training.

The HLBS contains two main features. The first feature is the ability to schedule normal work activities denoted by A, and training activities denoted by TA. The second feature is to integrate location risk levels into the schedule and give it a color coding depending on the level of danger or risk of this activity.

1. The Planning and Scheduling Module

The purpose behind this planner is to represent safety assessment and training by a training activity (TA) and an assessment activity (AA), and schedule them on the project's location-based schedule. During this phase, planners are required to identify who needs training and how long the training takes. The first step was to develop the LBS. In order to generate a LBS, singularity functions were used to mathematically model and visualize all tasks on the schedule. Singularity functions are discrete mathematical functions which were developed between the years 1919 and 1927 (Lucko and Su 2014). Singularity functions were first used in the structural analysis of beams (Lucko 2007). In 2007, Lucko was able to give a mathematical representation of tasks in Linear Schedules using singularity functions. Equation (1) shows the general form of singularity functions.

$$\langle x-a\rangle^n = \begin{cases} 0 \ for\ x<a \\ (x-a)^n \ for\ x \geq a \end{cases} \tag{1}$$

In singularity functions, x is defined as the variable under consideration, and in the case of schedules, x represents the time axis. The letter a represents the activation point of the function. It is described as an activation points because these functions act as a switch, where they are turned on and off depending on the values of x and a. Finally, n is the exponent of the function and it controls the shape of the function. When n is equal to zero, the functions yield a step function, and when n is equal to 1, the functions yield a sloped or linear function.

Sympy and Matplotlib were used in Python for this part. To represent an activity on a location-based schedule, the production rate of the activity should be calculated in order to calculate its duration. The production rate is simply the time required to train one worker and it can be obtained using Equation (2).

$$PR = Training\ Duration\ per\ Worker + Setup\ Time\ per\ Worker \tag{2}$$

The duration of training per worker is obtained from the duration allocated to each training model in Unity, the setting up time is the time needed to setup the computer and the training program after each worker.

Afterwards, Equation (3) was used to calculate the Training Activity Duration (TAD). The ratio of the number of workers to the number of available workstations or computers indicates the number of batches that workers are trained in. The percentage of re-training is the assumed percentage of workers which might need a second round of training in order to obtain the desired level of knowledge. Planners are required to input the number of workers allocated to a given activity in addition to the mentioned parameters.

$$TAD = (PR\ x\ \frac{Number\ of\ Workers}{Number\ of\ WorkStations})\ x\ Percentage\ of\ Re - Training \quad (3)$$

After obtaining the LBS and calculating the TAD, the TA is ready to be modeled and added to the LBS. Each task on the schedule is represented as TAi-l, where *i* denotes the activity's label, and *l* denotes the activity's location. For example, AAi is the assessment activity of activity *i*. To represent the TA on the schedule, each task has to satisfy the following criteria.

$$Start\ Date\ of\ TAi - l\ >\ End\ Date\ of\ TAi - l - 1 \quad (4)$$

$$End\ Date\ of\ TAi - l\ \leq\ Start\ Date\ of\ Ai - l - 1\ - 3\ days \quad (5)$$

The Assessment Activity (AA) is generated in the same way as the TA in terms of its duration and production rate. However, the only difference is that the AA is situated in the Lookahead planning phase which requires it to have a different scheduling criterion as seen in Equation 6.

$$End\ Date\ of\ AAi\ \leq\ Start\ Date\ of\ Ai - l1\ - D\ days \quad (6)$$

Equation 6 shows that the AA should finish before the start date of the activity in its first execution location by a certain amount of days denoted by D. D would then range from 20 to 40 days depending on the Lookahead planning duration.

After calculating the start and end date of the TA and AA using the above equations, the tool is able to generate the first part of the Hybrid-Location-Based Schedule (HLBS) which clearly and accurately models and represents each activity along with its corresponding TA and AA.

2. *The Location Risk Level Module*

After obtaining the HLBS, planners are now able to calculate the Location Risk Level (LRL) for each task. The LRL is used to develop an allocation criterion based on which workers are assigned to their tasks. The equations used to calculate the LRL were obtained from three different studies and integrated to develop the LRL for LBS. To calculate the LRL, we have to first calculate a Non-Fatal-Risk-Score (NFRS) which gives us a risk level for a location based on the probability of occurrence of non-fatal incidents. The second Score we have to calculate is the Fatal-Risk-Score (FRS) which gives us a risk level based on the probability of occurrence of fatal incidents in a given task.

The planner starts by calculating the NFRS. The following set of equations are used to calculate the NFRS (Baradan and Usmen 2006).

$$P = \frac{NF}{E} \tag{7}$$

$$CLT = MDAFW \times H.W \times 8 \tag{8}$$

$$R = P \times CLT \tag{9}$$

In Equation 5, P is the Probability of Occurrence of a Non-Fatal Incident, NF is the number of non-fatal injuries per task, and E is the total number of workers per task. In Equation 6, CLT is the Cost of Lost Time, MDAFW is the median days away from work, and H.W is the hourly wage of the worker. Finally, in equation 7, R is the Risk Value of the task. Finally, to obtain the value of the NFRS, Table 2 was used.

Table 2 - Non-Fatal Risk Score

R	**NFRS**
≥ 0 & <10	1
≥ 10 & <20	2
≥ 20 & <30	3
≥ 30 & <40	4
≥ 40 & <50	5
≥ 50 & <60	6
≥ 60	7

After obtaining the NFRS, the second step is the calculation of the FRS. The following equations are used to calculate the FRS (Baradan and Usmen 2006).

$$FR = \frac{F}{E} \tag{10}$$

$$IRR = \frac{FR}{\left(\frac{\sum F}{\sum E}\right)} \tag{11}$$

FR is the Fatality Rate of the task, F is the number of fatalities in the task, and E is the total number of workers in the task. In equation 9, IRR is the index of relative risk, $\sum F$ is the total number of fatalities in all tasks, and $\sum E$ is the total number of workers in all tasks. The following table was then used to obtain the FRS.

Table 3 - Fatal Risk Score

IRR	FRS
≥ 0.01 & ≤0.24	1
≥ 0.25 & ≤0.49	2
≥ 0.50 & ≤0.74	3
≥ 0.75 & ≤0.99	4
≥ 1.00 & ≤1.24	5
≥ 1.25 & ≤1.49	6
≥ 1.50	7

After both the NFRS and the FRS have been calculated, the Total Risk Score (TRS) is obtained by the addition of the two scores.

$$TRS = NFRS + FRS \tag{12}$$

Although the TRS takes into account the number of fatalities and injuries in a given task, the equations used to calculate it do not take into consideration the dangers in each location the task passes through. Esmaeili et al. listed several 22 factors which may cause severe injuries to workers (Esmaeili et al. 2015). These factors are related to site logistics, type of equipment used, and the type of work being performed. This research uses five of these factors to calculate a Location Physical Risk (LPR) for each location. The five chosen factors where those that the research found to be the most significant in terms of representing the safety hazards. The Location Physical Risk which has a value ranging from 1 to 4 as shown in Table 4.

Table 4 - Location Physical Risk Factors

Factor	Score
Swing Area of Crane	1-4
Worker Next to Moving Equipment	1-4
Working with Power Tools	1-4
Risk of Worker Falling or Falling Objects	1-4
Lifting Heavy Material	1-4

Moreover, Yi et al. developed a risk quantity equation which multiplies the previously calculated risk score by the duration of each task (Kyoo-Jin and Langford 2006). The researchers suggested that as the time that the worker spends in a certain activity increases, the probability of the occurrence of a safety hazard increases. However, since the durations of the activities can differ considerably making it difficult to set a value range for the LRL. To overcome this issue, this research first normalizes the values of the durations using Equation (12) in order to get a Normalized Duration (ND) ranging from 0 to 1. However, by doing so, the activity which has the minimum duration would have a ND of 0 and thus multiplying the TRS by it would yield a non-logical LRL of 0. To overcome this issue, the terms of the LRL equation is divided into two parts, one part which takes into consideration the level of injuries, fatalities, and LPR of the activity, and the second part takes into consideration the effect of the duration. This research assumes that 80% of the LRL is obtained from the level of injuries, fatalities and LPR, while

20% of the LRL is obtained from the duration. Thus, the LRL would range from 0 to 70, where 56 points are allocated to the TRS and the LPR, while 14 points are allocated to the duration of the activity.

$$ND = \frac{D - Dmin}{Dmax - D\,min} \quad (13)$$

$$LRL = TRS \times LPR + 14 \times ND \quad (14)$$

After obtaining the LRL for each task in each location, the values are represented and sorted into a Location Risk Level Matrix (LRLM) as shown in Table 5. The tool assigns a color to each activity in each location on the schedule depending on its LRL value. The tool assigns three colors; Green for activities with low LRL values (less dangerous), Orange for activities with medium or average LRL values, and Red for activities with High LRL values (most dangerous). The value ranges for each color code are shown in Figure 5.

Table 5 - Location Risk Level Matrix

Activity \ Location	**L1**	**L2**	**…**
A	LRL	LRL	LRL
B	LRL	LRL	LRL
C	LRL	LRL	LRL
...	LRL	LRL	LRL

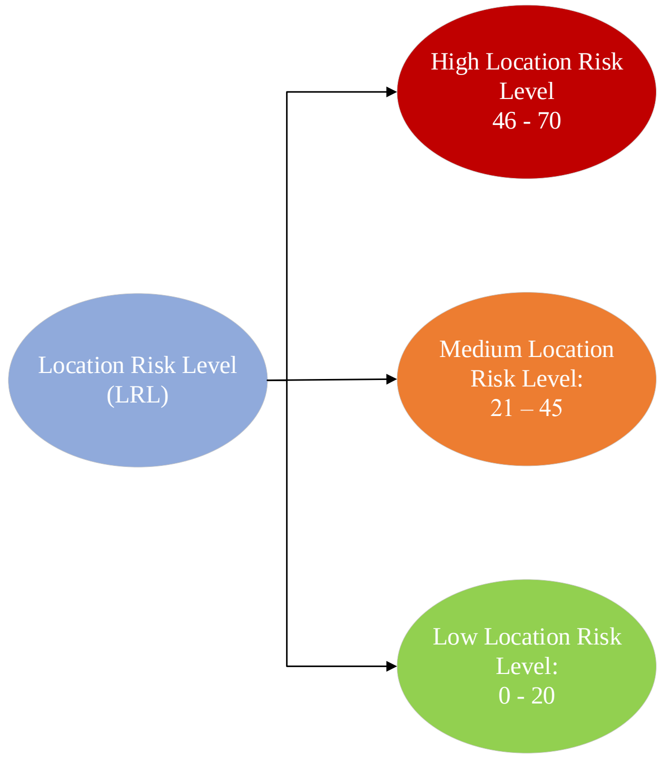

Figure 5 - Location Risk Level Color Coding

B. Activity Safety Trainer

This research uses Unity, a professional game engine, to develop a location-based training and assessment tool. The tool is divided into two modules. The first module is the safety assessment of workers which takes place before the start of the activity in its first execution location. This module aims to assess the worker's safety behavior which is needed to decide whether he is qualified to be allocated in this activity or not. The second module is the safety training module. This module takes place in succeeding locations including the first location, so that workers can refresh their memory on safety measures before entering a new location. The training tool uses as-built 3D models of the project to ensure that workers are trained on the exact location they will work in. However, this research only focuses on the assessment and training of concrete related activities.

All safety related measures, equipment, and PPE which were used in the training and assessment program were taken from the OSHA manuals.

1. User Interface

The Activity Safety Trainer contains two programs, the Assessment Program and the Training Program. The UI was developed in a way where the user chooses the desired program at first as seen in Figure 6. Figures 7 shows that if the user chooses the Assessment Program, the user then has to choose the required activity he wishes to perform the assessment on. On the other hand, Figures 8 and 9 show that if the user chooses the Training Program, he first has to choose the required activity and then the required execution location he wishes to train on.

Figure 6 - Activity Safety Trainer UI

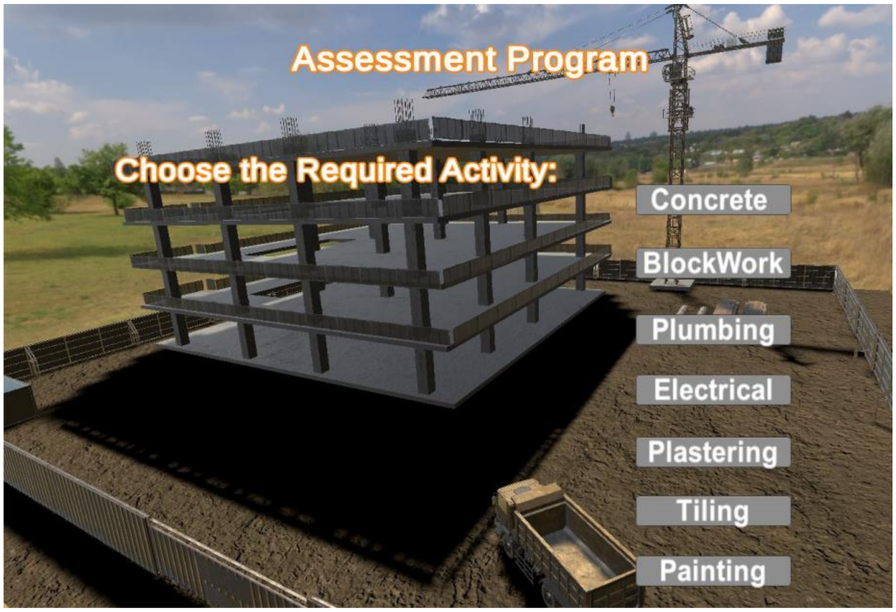

Figure 7 - Assessment Program UI

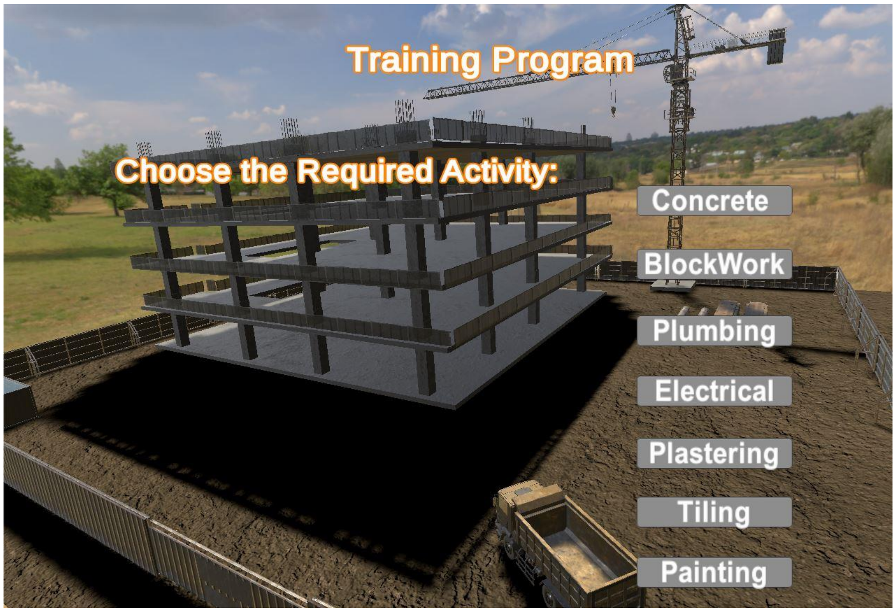

Figure 8 - Training Program UI

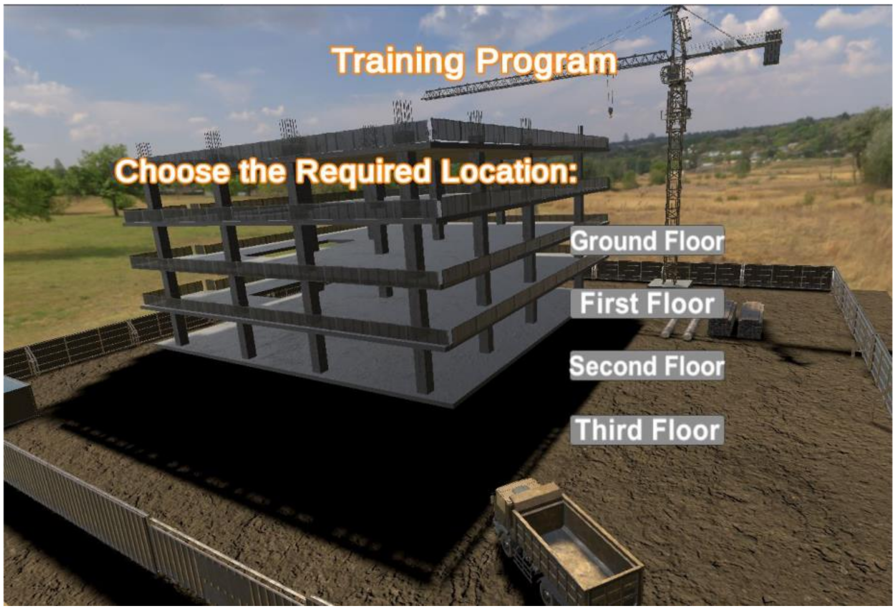

Figure 9 - Training Program UI

2. Gameplay Controls

The developed serious game covers different scenarios which enhances worker's safety knowledge and risk perception. Some scenarios are developed in different ways than others, and hence require a different type of gameplay controls. Game controls were developed in a way to be simple and easy to use by all workers regardless of their age and gaming skills. In the assessment program, certain scenarios are question-based scenarios where the user uses the mouse to press the button which indicates the right move or answer. Other assessment scenarios are played from a third person view where workers have to use the up and down arrow keys to move forward and backward respectively, and they have to use the right and left arrow keys to turn around or rotate. In these scenarios, workers are also required to use the mouse to point and click safety hazards and missing measures. In the training program, the user has to only use the arrow keys to navigate through the site to learn about the safety hazards and measures.

3. *The Virtual Environment*

The project used in this research is a four-story residential reinforced concrete building. The building's 3D model and site logistics were all built in Unity. The research makes use of the rendering power of game engines by producing a realistic high definition as built virtual. Figure 10 shows the concrete structure of the building in Unity, and Figure 11 shows the level of realism of the materials used in developing this game. The workstation used to develop this game is a laptop with 16GB of RAM and a NVIDIA GeForce GTX 1050 Ti graphics card.

Figure 10 - The Virtual Construction Site

Figure 11 - Game Graphics

4. Personality Factors in Game Development

As previously mentioned in the literature review section, Table 6 lists personality factors which have a direct effect on the safety behavior of workers. This research integrates two of these factors in the development of assessment scenes to enhance these factors in the workers. The two used factors are Safety Knowledge and Experience, and Risk Perception. The scenarios were developed in such a way that 60% of which are focused on Safety Knowledge and Experience, while the remaining 40% is focused on Risk Perception. In the Assessment Program, the score is also divided in the same way. Scenarios which focus on Safety Knowledge and Experience are those related to workers identifying missing PPE and safety equipment. On the other hand, the scenarios which focus on Risk Perception develop dangerous incidents to check if the worker would notice or perceive them as being dangerous. Figure 12 shows an example of how scenarios are developed for each case.

Table 6 - Personality Factors

Factor	Effect on Safety Behavior	References
Safety Knowledge & Experience	Positive	(Fang et al. 2006) (Zhou et al. 2008) (Patel and Jha 2016) (Choudhry and Fang 2008) (Patel and Jha 2015) (Mohammadfam et al. 2017)
Conscientiousness	Positive	(Beus et al. 2015)
Risk Perception	Positive	(Patel and Jha 2016) (Patel and Jha 2015)
Extraversion	Negative	(Beus et al. 2015)
Anxiety and Stress	Negative	(Beus et al. 2015)
Self Esteem	Negative	(Choudhry and Fang 2008)

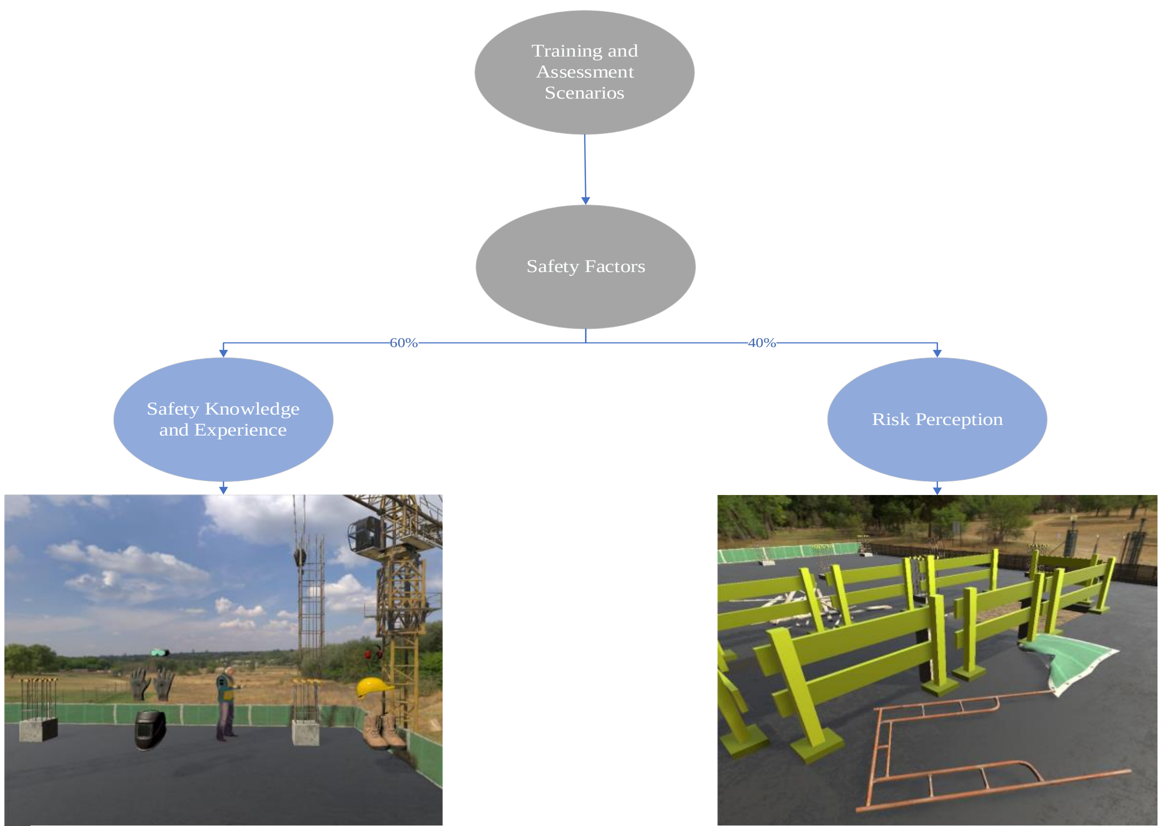

Figure 12 - Personality Factors in the Game

5. *Assessment Program*

The assessment program aims to test the worker's safety traits and to allow planners to know whether this worker is qualified to work in the given activity from a safety perspective. To achieve this objective, the worker went through a series of scenarios in the developed serious game where at the end he obtained a Safety Score (SS) which ranges from 0 to 70. The worker starts with a score of zero and as he progresses through the game the score increases or even decreases in some instances depending on his performance. This score was then compared with the LRL to know whether the worker is safety ready to work in this activity or not.

All developed scenarios are related to safety hazards and measures for concrete activities such as column reinforcement. These scenarios vary in terms of their requirements and their location in the project. The developed assessment program contains seven scenarios which workers have to pass through in order to obtain their SS.

The first and second scenarios take place on the ground floor and they aim at assessing the worker's risk perception. In these scenarios, the worker was asked if he the workers in the scene are under any kind of safety danger. If he answers with a yes indicating that the workers are in danger, he points to and click on the object causing that danger. If he answers with a no, then workers in the scene would get injured by the undetected danger. In the first scenario, a worker is standing with his back turned to the crane which is carrying and moving column rebar. In the second scenario, one worker is standing under a pile of rebars lifted by the crane. Figure 13 shows the second scenario before the worker chooses the answer, and Figure 14 shows how the worker would get injured if the user did not notice the lifted materials above the worker. As for the third scenario which takes place on the last floor, a worker is seen carrying a 12-meterlong rebar next to another worker. This carrying method is not supported by safety provisions for two workers should be lifting the long rebar each holding it from one side to avoid hitting another person. Thus, if the user fails to perceive the risk of carrying a long rebar alone, the worker in the game hits his coworker and injures him as seen in Figures 15 and 16.

Figure 13 – Second Assessment Scenario (1)

Figure 14 - Second Assessment Scenario (2)

Figure 15 - Third Assessment Scenario (1)

Figure 16 - Third Assessment Scenario (2)

In two other scenarios, the game was developed in a different approach. In scenarios four and five which take place on the first and last floor, the user navigates through the site using the arrow keys and clicks on any position where he finds a missing safety measure. For example, in the fourth scenario, the worker should point to missing rebar caps over some columns and formwork and scaffolds thrown on the floor near the slab's opening. Also, in the fifth scenario, the user has to notice missing safety guard rails around the slab's opening, missing safety nets around the slab edges, and a worker wearing a normal head cap instead of his hard hat. Figures 17 and 18 show some of the missing safety measures from the fourth and fifth scenarios respectively.

Figure 17 - Fourth Assessment Scenario

Figure 18 - Fifth Assessment Scenario

The sixth and seventh scenes are similar in terms of their scope. Both scenes are used to assess the worker's knowledge of the PPE that should be used. In these two scenes as seen in Figure 19, the user has to choose the PPE that the worker in the scene should be wearing while performing his job. The worker in the game is wearing some of the PPE and some PPE options are not necessary for the job at hand, so the worker loses points if he chooses all the available PPE selection.

Figure 19 - Sixth Assessment Scenario

6. Training Program

As previously mentioned, the Activity Safety Trainer is divided into two main programs; the Assessment Program and the Training Program. Before the start of the activity in its very first execution location, the worker first goes through the Assessment Program to obtain a SS. After that, the worker goes through the Training Program before the start date of the activity in each location. This process allows us to continuously prepare and train workers for what danger they might face before going through another working location or zone.

The Training Program was developed in a way that would be understandable by all workers despite their age and education level. Some workers might not know how to read or they read and speak a different language than the one the game uses. For this reason, the training game environment was built in a way that uses visual aids to teach workers on what is right and wrong, and what is safe and not.

As aforementioned, the Training Program trains workers based on the upcoming execution location of the activity. This section provides an example of the training of the concrete activity in the Ground Floor location. In the game environment, the user uses the arrow keys to navigate a virtual worker in the Ground Floor area. While navigating through the location, the user is able to see workers performing their tasks while neglecting some safety measures. For example, Figure 20 shows a worker fixing the wooden formwork of a concrete column. However, since the worker is not wearing all the appropriate PPE, the user should notice a red “X” sign over the worker indicating that he is in violation of the safety measures. Next to this worker, the user is able to see a worker who has a green check over him and wearing all the required PPE. Moreover, Figure 21 shows that the user would also see that the worker in the game also threw all the nails on the ground next to him which might cause injuries to others if they stepped on them. While walking through the Ground Floor location, the user would notice that a worker is carrying materials and walking in the path of a reversing truck. Figure 22 allows the workers to learn that they should not walk near a moving vehicle especially when it is moving backwards. Furthermore, the user would also notice that a worker is cutting formwork under the crane which is considered to be a dangerous zone to work under. As shown in Figure 23, the user would also be able to visually learn that working under a crane is not safe.

Figure 20 - PPE Training Scenario

Figure 21 – Nails Safety Training

Figure 22 - Surrounding Safety Training

Figure 23 – Crane Safety Training

C. Allocation Methods

After both tools have been developed, the integration of both can be implemented. This part of the tool is a rule-based system for worker allocation, which compares the LRL of an activity with the SS of each worker in the crew. If the SS is greater than or equal to the LRL, then the worker is qualified to be allocated to the required activity. However, if the SS is less than the LRL, planners have two options. The first option would be to check if they could allocate him to another activity if his metrics qualify him to. On the other hand, the second option would be to re-train this worker and allocate him to his original activity while increasing safety monitoring and inspection for the given activity.

This research develops two methods for resource allocation. The first method allocates workers to activities based on a safety criterion only. The second method allocates workers to activities based on an integration between the worker's experience in an activity and his safety performance.

1. Safety Allocation Plan

This allocation method focuses on allocating workers based on only a safety criterion. The worker's experience does not affect the allocation outcome. This method is used to ensure that workers who are qualified from a safety perspective are allocated to activities. Planners might use this method when dealing with a dangerous project and safety is the main goal.

This method is a simple comparison between the LRL of an activity obtained from the Hybrid-Location Based Scheduler, and the SS of the worker obtained from the Assessment Program. In this method, the LRL and SS are grouped into three level groups. The first group is for values ranging from 0 to 20 which includes activities with a low LRL indicating the less dangerous activities, and it includes low SS indicating workers with a bad safety performance. Similarly, the second group is for values ranging from 21 to 45, and the third group is for values ranging from 46 to 70. Once the LRL of a given activity is calculated and the SS of a worker is obtained, the system checks to which group does the SS belong. If the SS belongs to a group higher than or equal to that of the LRL, then the worker can be safely allocated to the activity. If not, then the worker's SS is less than the LRL which indicates that he is not qualified to be allocated in this activity. Figure 24 summarizes the developed safety criteria and allocation plan.

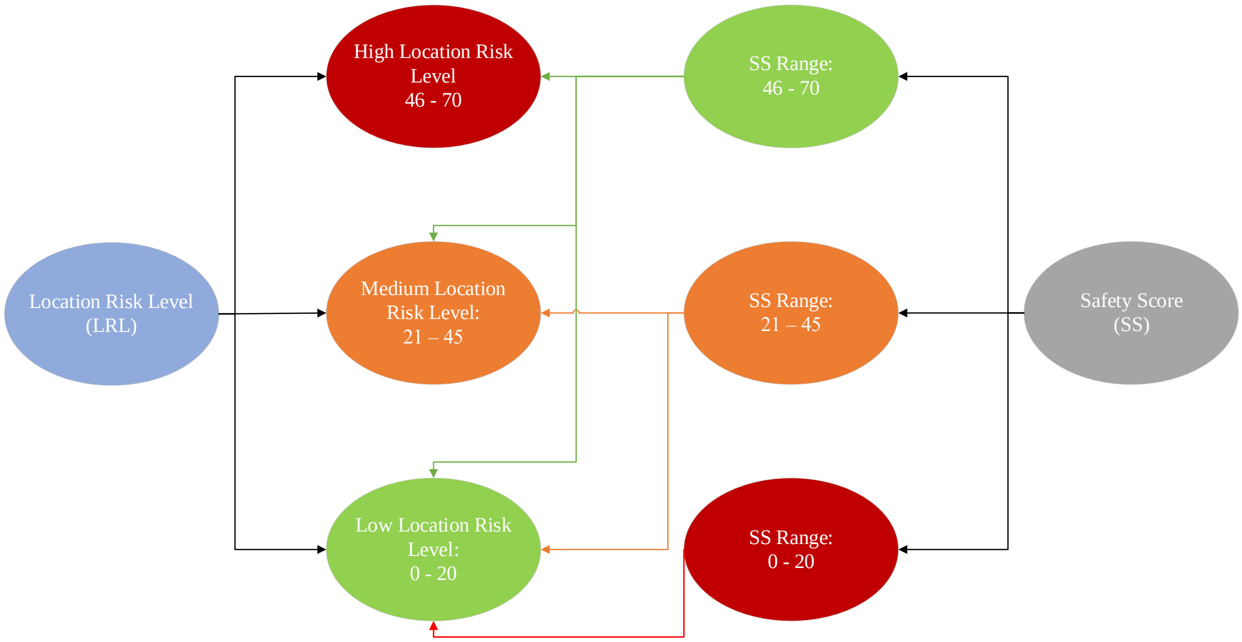

Figure 24 - Allocation Safety Criteria

2. *An Integrated Allocation Plan*

The proposed LBSMF gives planners the option to choose whether they want to allocate workers based on a safety requirement only, or they want to balance between the worker's experience and safety performance or SS in order to know which workers are more fit for the job.

Previous researchers have developed allocation methods which take into consideration several parameters into consideration. Stobrawa et al. used three competences which are performance, experience, and level of practice to decide which worker is best fit to be allocated to a given task. Each of these competences are normalized to obtain a value between zero and one. After obtaining these values, the shown algorithm in Equation 14 is used to obtain an allocation score for each worker (Stobrawa et al. 2019).

$$a_{e,t} = \frac{\sum w_c.n_{c,e}}{\sum w_c} \qquad (14)$$

In Equation 14, $a_{e,t}$ is the obtained allocation score, w_c is the weight assigned to each competence which is a user defined parameter, and n is the normalized value of each competence. For example, assuming we have to allocate two workers to a given task or activity having two competences. The weight of the first competence is equal to 1, while the weight of the second is equal to 3. The value of competence one for the first worker is $n_{1,1} = 0.6$, and for competence two is $n_{2,1} = 0.4$. The second worker's competences are $n_{1,2} = 0.5$ and $n_{2,2} = 0.9$. Using the algorithm in Equation 14, the following allocation scores would be obtained:

$$a_{1,1} = \frac{w_1 * n_{1,1} + w_2 * n_{2,1}}{w_1 + w_2} = \frac{1.8}{4} = 0.45$$

$$a_{2,1} = \frac{w_1 * n_{1,2} + w_2 * n_{2,2}}{w_1 + w_2} = \frac{3.2}{4} = 0.8$$

Based on the obtained allocation scores $a_{1,1}$ and $a_{2,1}$, we can clearly see that the best decision would be is to allocate the second worker since his allocation score is closer to 1.

This algorithm was applied in this research to develop another allocation criterion which takes two competences into consideration; the Experience (Ex) of the workers in a given activity, and his SS. An Allocation Score (AS) is calculated for each worker using Equation 14. Equation 14 requires that the Experience and the SS would be normalized. Therefore, their values were normalized using Equation 12 to obtain a Normalized Experience (NEx) and a Normalized Safety Score (NSS). The AS was then used to decide who among the workers are the best fit of the given activity. Workers having an AS close to one are considered to be the most fit, and workers having lower AS are either be allocated to a different activity or re-trained to increase the SS and thus their AS. This method allows planners to balance their allocation decisions between the worker's skill and safety performance.

As an example, assume we have two workers where we want to decide who is more fit to be allocated to the given activity. The first worker has a NEx value of 0.4 and a NSS value of 0.7. The second worker has a NEx value of 0.7 and a NSS of 0.6. Assuming that the weight of the experience is equal to 4 and that of the safety is equal to 3, the AS for both workers are as follows:

$$AS_{1,1} = \frac{w_1 * n_{1,1} + w_2 * n_{2,1}}{w_1 + w_2} = \frac{3.7}{7} = 0.52$$

$$AS_{2,1} = \frac{w_1 * n_{1,2} + w_2 * n_{2,2}}{w_1 + w_2} = \frac{4.6}{7} = 0.65$$

The results show that based on our decision criteria which has a stronger weight on the experience rather than on safety, the second worker is more qualified or fit than the first. The planners thus have a decision to either allocate both or to allocate whoever the AS is closer to one.

After selecting the fittest, the worker's SS are used to indicate how many workers of those who were selected as the fittest are safety ready. This can be made easy by calculating a Safety Allocation Metric (SAM) which is the ratio of the number of workers who obtained a qualifying SS over the total number of workers employed. After obtaining these metrics, planners have two indicators to the level of danger of each activity; the LRL, and the SAM. This method then allows planners to allocate workers even if their SS doesn't qualify them, but planners now are aware of the potential risks of this allocation and are able to implement better safety monitoring and inspection for the given activity.

CHAPTER V

FRAMEWORK IMPLEMENTATION AND RESULTS

A. Project Data

This research uses a project case study to implement and investigate the effectiveness and the applicability of the proposed LBSMF. The selected project is a four-story residential building in Lebanon built in 2012 by EEC, a Lebanese contracting company. The obtained data from the project is the start date of the activities, work quantities for each floor, consumption rate of each activity, and the number of workers allocated to each activity. The activities were grouped into 7 main trades; Concrete, Block Work, Plumbing, Electrical, Plastering, Tiling, and Painting. This research uses LBS which require activities to be scheduled by locations. However, the project at that time did not use LBS, and so this research used the provided data to develop a LBS for the given project. For simplicity purposes, the location breakdown structure was limited to the floors of the building as shown in Figure 25. The provided project data can be seen in Table 7.

Table 7 - Project Data

Trade		**Consumption Rate (man-hours per unit)**	**No. of workers**	**GF**	**First**	**Second**	**Third**	**Units**
Sequence	**Name**			Quantity	Quantity	Quantity	Quantity	
1	**Concrete**	**0.0892**	**15**	150	150	150	150	m3
2	**Block Work**	**0.4791**	**10**	460	460	460	460	m2
3	**Plumbing**	**0.0133**	**8**	12	12	12	12	units
4	**Electrical**	**0.0143**	**8**	11	11	11	11	units
5	**Plastering**	**1**	**12**	960	960	960	960	m2
6	**Tiling**	**1.5625**	**6**	750	750	750	750	m2
7	**Painting**	**1.25**	**6**	960	960	960	960	m2

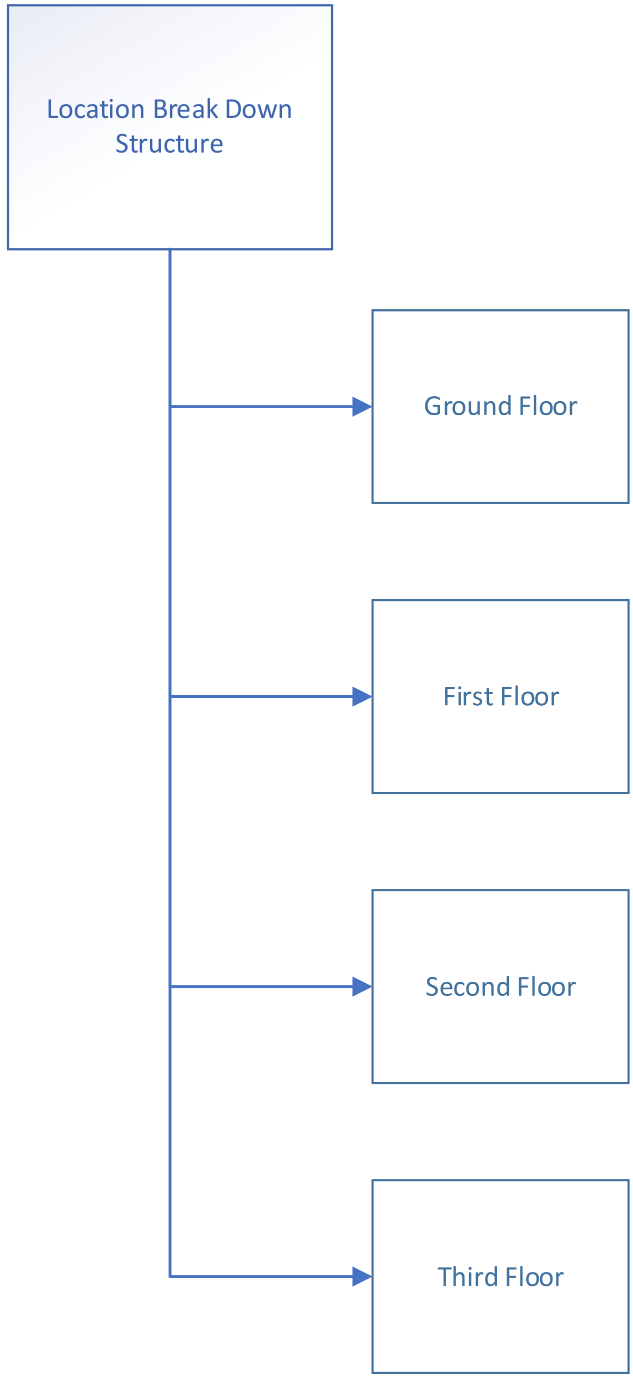

Figure 25 - Project Location Break Down Structure

B. Hybrid-Location Based Scheduler Implementation

This research uses a cases study project data to develop the HLBS and calculate the LRL. This research develops the schedule as planned by the providing contractor without any optimization of modification.

The set of input data that the Hybrid-Location Based Scheduler requires is easy to obtain. To schedule the provided activities or trades in Table 7, the user first has to enter the project start date in DD/MM/YYY format, the number of activities, and the number of locations. After doing so, the tool requires the scheduling data of each trade. The data required by the tool to generate the schedule are those provided in Table 7. The user enters the consumption rate of the activity which is then used along with the number of workers per activity and the quantity of work in the given location to calculate the duration the activity in each location. As for the training data, all the user is required to input is the number of available workstations or computer for training, and the duration of the assessment and training program. By inputting these data, the tool is now able to generate the HLBS including all assessment, training, and production activities.

To calculate the LRL, the tool prompts the user to input several safety-related information. The first safety related input for each activity is the LPR. Moreover, the tool was first designed in a way that the user has to enter the number of non-fatal and fatal injuries for each activity. However, after performing some investigation regarding the practicality of such input, it was found that few contractors would have this data especially in Lebanon where the case study is being implemented. To overcome this issue, the user can either enter these number if they have them or can opt for the default data provided by this tool. The default data was taken from Baradan et al. which contains a list of different construction activities along with their non-fatal injury rates, fatality rates, Mean Days Away From Work (MDAFW), and Hourly Wage (HW) (Baradan and Usmen 2006). The default safety related data obtained from Baradan et al. are listed in Table 8.

Table 8 - Project Safety Data

Activity	Non-Fatal Injury Rate	MDAFW	HW ($)	Index of Relative Risk (IRR)
Concrete	0.056	9	20	3.78
Blockwork	0.038	9	17	0.88
Plumbing	0.030	8	20	0.66
Electric	0.025	9	20	1.24
Plastering	0.026	10	17	0.01
Tiling	0.028	8	18	0.01
Painting	0.026	8	15	1.07

1. *Location Risk Level Validation*

After inserting the required safety data, the tool is able to calculate the LRL for each activity. This research uses a modified risk equation to take into account location specific data. Hence, it is required to validate the output of this equation in terms of how accurately it quantifies the danger of each activity. For this reason, the maximum LRL value of each activity was compared to the Risk Score of the activity calculated by Baradan et al. (Baradan and Usmen 2006). However, the Risk Score ranges from 0 to 21, while the LRL ranges from 0 to 70 making it difficult to compare them as is. For this reason, we first normalized the values of the Risk Scores and the LRL, and then compare them. Table 9 shows the comparison between the normalized Risk Score and the normalized LRL and also color codes both values to see if they both fit the same color-coding criteria this research is using.

Table 9 - LRL Validation

Activity	Risk Score	LRL	Normalized Risk Score	Normalized LRL
Concrete	21	55	1.00	1.0
Electric	14	25	0.61	0.47
Painting	13	27	0.56	0.42
Blockwork	11	25	0.44	0.36
Plumbing	10	24	0.39	0.34
Plastering	3	8	0.00	0.00
Tiling	3	8	0.00	0.00

As noticed from Table 9, both the Risk Score and LRL gave the same danger order to the activities, and they fell into the same color-coding criteria. Moreover, when comparing their normalized values, all values were almost equal to each other. This indicates that it is safe to use the proposed LRL equation to quantify the level of danger of the activities.

2. *Project Hybrid-Location Based and Safety Aware Schedule*

After inserting all the required project data, the tool is now able to generate two types of Location-Based Schedules. The first is the HLBS which shows the assessment, training, and production activities. Since the Assessment Program is situated in the Lookahead planning phase, the assessment activities are scheduled to start 20 days before the activity's start date. After that comes the training activity which is planned in the week before the start date the activity. Figure 26 shows the HLBS of the project used in this research. The second LBS is the

Safety Aware Schedule (SAS) which only shows the normal LBS but activities are color coded depending on their LRL values as seen in Figure 27.

The HLBS clearly and visually allows planners to schedule, track, and notice the assessment and training activities as well as the production activities. Moreover, the SAS allows planners to directly notice which activities are dangerous by simple inspecting the schedule. As seen from the HLBS, the start date of the project is on the fifth of May 2012, and the project's end date is on the twelfth of November 2012, making the total duration of the project to be equal to 191 days. The SAS clearly shows that the Concrete activity is the most dangerous while the Plastering and the Tiling activities are the least dangerous. Moreover, it can be also noticed that the Blockwork activity in the first location is less dangerous than in succeeding location due to the difference in the values of the LPR.

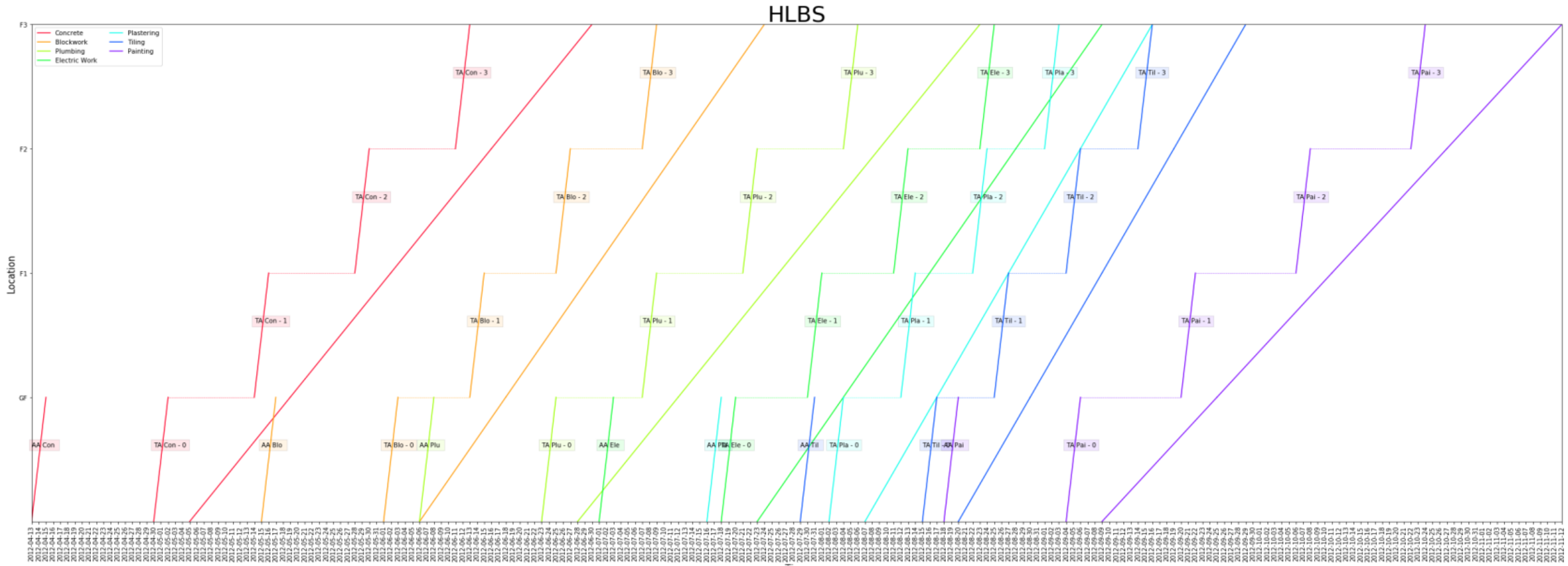

Figure 26 - Project's HLBS

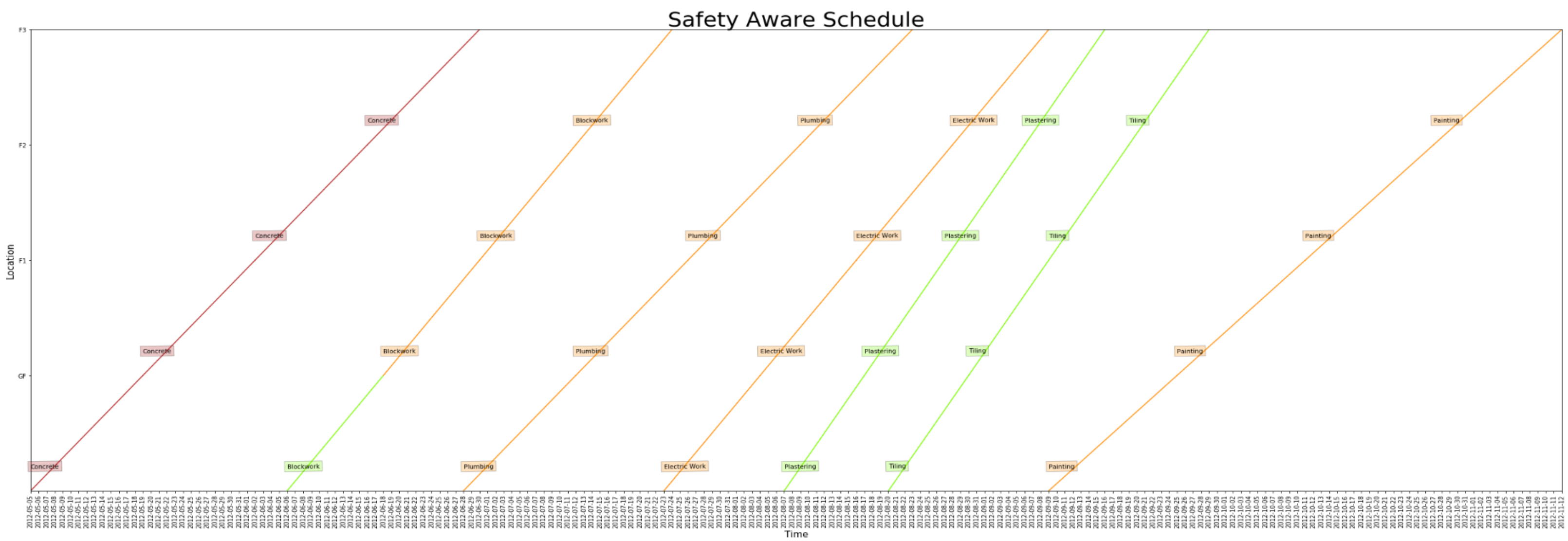

Figure 27 - Project's SAS

C. Activity Safety Trainer Testing

1. *Survey Design*

The scope of this research includes conducting a survey to evaluate the effectiveness and the level of realism of the training tool developed in unity, and to study the potential usage of serious games in the Middle East region. The survey was developed using Google Forms and consisted of 12 questions. The questions focus on evaluating the developed safety program in Unity in terms of its ability to increase learning interest, mimic construction site activities, and to show the applicably of such methods in the Middle East region. The survey was developed using Google Forms. Answers to the questions vary in form as some questions have a linear answer scale from 1 to 5, while other questions have a direct Yes or No answer. To perform this survey, the developed safety training program was tested on 25 construction workers. Workers were then asked to fill the survey on Google Forms.

2. *Survey Analysis and Results*

The survey was conducted on 25 workers where their ages ranged from 20 to 60 years old. Workers where then grouped into three age groups as shown in Figure 28. The workers' experience in construction also ranged from 1 year to almost 40 years. The experience was also grouped into three groups as shown in Figure 29.

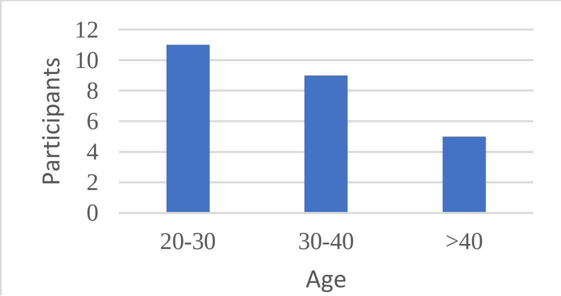

Figure 28 – Participants Age Groups

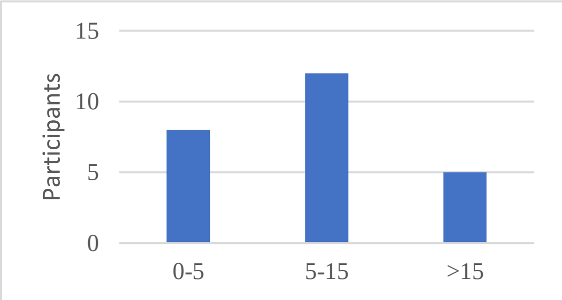

Figure 29 – Participants Years Of Experience

The workers were first asked to insert the Safety Score (SS) they got while testing the safety training program. As shown in Figure 30, 56% of workers acquired a SS between 30 and 50 which is a medium SS range, while the other 44% acquired a score between 50 and 70 which is a high SS range. Despite having workers with very few years of experience, or workers with a high age which might affect their computer skills and thus their performance in the program, no worker got a score in the low score range between 0 and 30. This result might indicate the effectiveness of the use of serious games in safety training where workers were motivated to increase their training score. This can be supported by the fact that when asked if the game increased their motivation for learning, 56% of the workers answered with a 5, 40% answered with a 4, and only 4% answered with a 3 as shown in Figure 31. This shows that 96% of the workers found that serious games do in fact have a positive effect on increasing their interest in learning. Moreover, another feature which increases workers' scores is that the game was developed to have simple game controls so that workers with no experience with computers would be able to easily go through the training program. 72% of workers scored the game's controllers a 5, and the remaining 28% scored the game's controllers a 4, indicating that all workers found the controllers to be easy to learn and use.

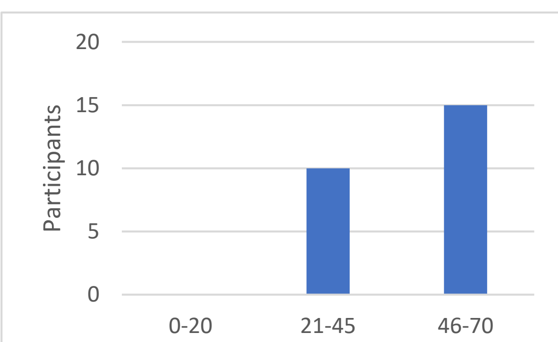

Figure 30 – Participants Safety Scores

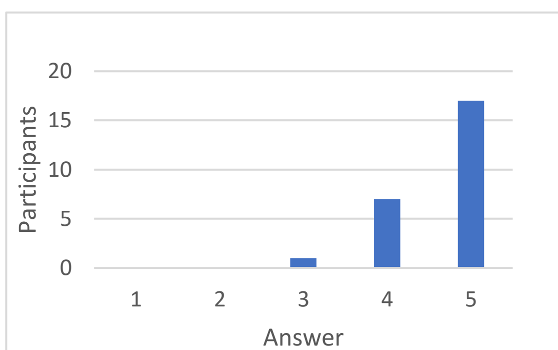

Figure 31 - Results For Motivation For Learning

Furthermore, all participants found that the game helped them in refreshing their safety knowledge. Figure 32 shows that when workers were asked whether the game increases their risk perception skills, 64% if the workers answered with a 5 and the remaining 36% answered with a 4. Also, when asked about the degree in which the obtained SS reflected their safety knowledge and risk perception, 68% of the participants answered with a 5, 28% answered with a 4, and the remaining 4% answered with a 3 as shown in Figure 33. This shows that 96% of the participants found that the SS truly reflect their safety awareness and knowledge, and their risk perception.

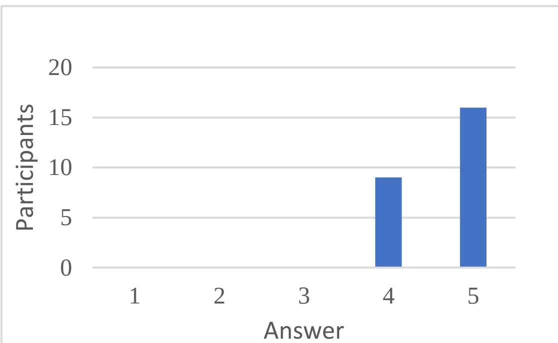

Figure 32 – Results For Risk Perception

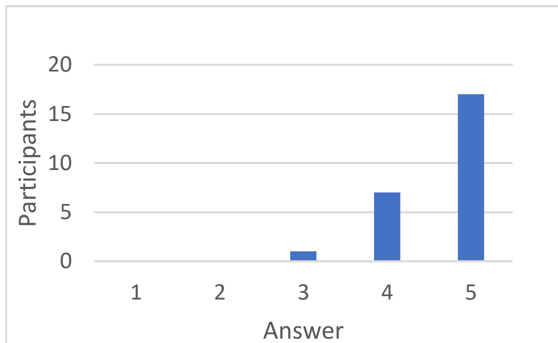

Figure 33 - SS Reflection

When asked about the level of realism in which the program mimic construction activities, 96% of the participants answered with a 4 or 5 indicating that the program realistically reflects construction activities.

Finally, the survey also investigated whether serious games can be adopted and used in the Middle East region. The participants were asked whether they preferred being trained using traditional methods such as presentations, videos, and handouts, or using serious games. 92% of the participants preferred training using serious games while only 8% preferred the traditional methods. Also, 92% of the workers thought that serious games can be implemented in the

Middle East. As shown in Figures 34 and 35, both results indicate that the construction sector in the Middle East is ready to implement a digital transition in its safety training methods.

Figure 34 – SG vs TM

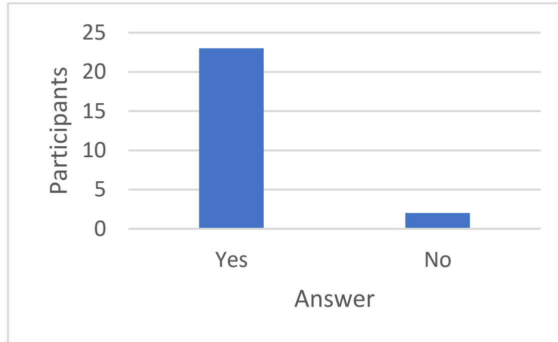

Figure 35 - SG Implementation In The Middle East

D. Worker Allocation

Since the survey was conducted on workers working in concrete related activities, this section discusses the implementation of the two proposed worker allocation methods for the concrete activity which requires 15 workers.

1. Safety Allocation Plan Implementation

This method only compares the SS of the workers with the LRL in order to decide whether the workers are qualified to be allocated to the concrete activity or not. Table 10 shows the SS of 15 workers along with the comparison between each of their SS and the LRL of the concrete activity which is equal to 55.

Table 10 - Construction Workers' SS

Worker	SS	LRL	Status
W1	61	55	OK
W2	61	55	OK
W3	58	55	OK
W4	53	55	NOT OK
W5	69	55	OK
W6	50	55	NOT OK
W7	53	55	NOT OK
W8	44	55	NOT OK
W9	32	55	NOT OK
W10	44	55	NOT OK
W11	50	55	NOT OK
W12	42	55	NOT OK
W13	54	55	NOT OK
W14	49	55	NOT OK
W15	42	55	NOT OK

As seen in Table 10, among all the twelve workers, only five of which had obtained a SS which directly qualifies them to be allocated into the concrete activity. However, most of the SS of the workers are close to the LRL 55, which allows planners to take the decision in re-training them and implementing another assessment session. The benefit of using the LBSMF is that the Assessment Program is located in the Lookahead planning phase which is well before the start of the activity, planners have enough time to invest in training the workers to achieve the required SS and this the needed number of workers.

For the given case study, the HLBS should be reconfigured to add another Assessment Activity to ensure that the workers increased their SS to the required value. The second Assessment Activity could either be implemented directly after the first or it could be implemented after a week which would be on April 22 2012. Moreover, the survey conducted on the Activity Safety Trainer showed that the developed serious game program increased worker's interest in learning and in achieving higher SS. Thus, if planners implement another assessment round, workers should be motivated to increase their SS.

2. Integrated Allocation Plan Implementation

This method allows planners to choose which workers are more suited to be allocated to a given activity based on their experience and SS. Moreover, after allocating the workers, this method also notifies planners if the given activity requires more safety monitoring and inspection.

To demonstrate this method, the data acquired from the 25 participants who tested the Activity Safety Trainer were used. For the given project data, the concrete activity required 15 workers to achieve the planned production rate. Table 11 shows the SS, normalized SS (NSS), Experience in years (Ex), the normalized Experience (NEx), and the Allocation Score (AS). This method allows planners to choose the weight they want to assign to each competence. In this implementation, the competence of the experience was set to 3, while that of the SS was set to 4, indicating that safety is more important in the allocation criteria.

Table 11 - Integrated Allocation Method

Worker	SS	NSS	Ex (yrs)	NEx	AS	LRL	SS Qualification
W3	61	0.783784	40	1	0.918919	55	OK
W4	61	0.783784	35	0.871795	0.838791	55	OK
W15	58	0.702703	20	0.487179	0.568001	55	OK
W7	53	0.567568	20	0.487179	0.517325	55	NOT OK
W11	69	1	5	0.102564	0.439103	55	OK
W9	50	0.486486	15	0.358974	0.406791	55	NOT OK
W23	53	0.567568	10	0.230769	0.357069	55	NOT OK
W13	54	0.594595	7	0.153846	0.319127	55	NOT OK
W17	44	0.324324	13	0.307692	0.313929	55	NOT OK
W12	61	0.783784	2	0.025641	0.309945	55	OK
W19	32	0	20	0.487179	0.304487	55	NOT OK
W25	54	0.594595	6	0.128205	0.303101	55	NOT OK
W24	50	0.486486	8	0.179487	0.294612	55	NOT OK
W14	44	0.324324	11	0.25641	0.281878	55	NOT OK
W6	53	0.567568	5	0.102564	0.27694	55	NOT OK
W5	53	0.567568	3	0.051282	0.244889	55	NOT OK
W18	49	0.459459	4	0.076923	0.220374	55	NOT OK
W20	42	0.27027	8	0.179487	0.213531	55	NOT OK
W10	41	0.243243	7	0.153846	0.18737	55	NOT OK
W8	42	0.27027	5	0.102564	0.165454	55	NOT OK
W16	38	0.162162	7	0.153846	0.156965	55	NOT OK
W1	46	0.378378	1	0	0.141892	55	NOT OK
W21	32	0	6	0.128205	0.080128	55	NOT OK
W22	32	0	6	0.128205	0.080128	55	NOT OK
W2	32	0	1	0	0	55	NOT OK

The table shows that workers W1 and W2 have a AS which is the closest to one, indicating that they are the best fit for this allocation. Workers W3, W4, and W5 have acceptable AS which is greater than 0.5. The remaining ten workers are those having the relative highest AS. Hence, we can notice that the fittest workers are from worker W3 with an AS of 0.91 to reach worker W6 with an AS of 0.27. After that, it was noticed that 5 out of the selected 15 workers have a SS higher than activity's LRL which is equal to 55. Thus, the SAM is equal to 33% which is considered a significant SAM. If planners decide to go with this allocation method, then they now know that this activity requires a higher level of safety monitoring and inspection since it has a high LRL and a significant SAM. Moreover, the SAM serves as an indicator to the crew's overall safety performance and hence a crew having a high SAM should perform better in terms of safety accidents.

CHAPTER VI

CONCLUSION AND FUTURE WORK

A. Conclusion

The proposed LBSMF is developed to enhance construction safety and to reduce the number of injuries and fatalities among construction workers. The framework integrates safety training into the Last Planner System planning phases to ensure that safety is considered a prerequisite and a constraint that should be identified and resolved. In this context, the LBSMF constructs three Safety Screens that to ensure that activities are safely planned and executed. The framework starts with the planning screen which ensures that planners implement safety assessment and training activities. Moreover, the first screen allows planners to visually notice dangerous activities on the schedule which allow them to constantly be aware of the risks which might occur. The second shield is the training itself which takes advantage of game engines to properly and effectively train workers on safety measures. The research showed the high effectiveness of this screen by testing it on 25 construction workers. The final Safety Screen is the allocation methods proposed by this research which allow planners safely allocate workers to activities.

The implementation of the LBSMF showed that the generated HLBS would facilitate the planner’s job in making sure safety training is considered an obligation and a predecessor for production activities. The HLBS allows planners to easily schedule the assessment and training activities early on in the process. Moreover, the proposed scheduling tool allows planners to easily and with few inputs to calculate the LRL of each activity. The proposed LRL equation was validated from previously developed risk equations in the literature. The LRL equation was found to be safe and accurate in estimating the level of danger of each activity in each location. To make planners more aware of the safety dangers, the tool also generates a Safety Aware Schedule which allows planners to visually notice the dangers in activities by color coding each activity depending on its LRL values. Using this tool, users are able to quickly and visually notice which activities and in which specific execution location do they need more safety monitoring and inspection.

The developed game engine-based tool for safety assessment and training also showed its effectiveness in enhancing construction safety. Survey results showed that workers in the Middle East are ready to have such methods deployed in construction projects. Moreover, the developed serious game increased the workers' interests in learning and thus they were more motivated in learning about safety and in increasing their generated Safety Score.

Finally, the developed allocation system was proven to be useful and practical in terms of aiding planners in the resource allocation process. Although the first method showed that only 5 out of the 12 workers were qualified to work in the concrete activity, the structure of the LBSMF gives time to planners to invest in the unqualified workers by retraining them to achieve a desirable SS. When this method was applied to the given case study, the results showed that the majority of the workers required another assessment round in order to develop the required SS. Thus, another assessment program should be added to the schedule in the Lookahead planning phase. The second method was used to aid planners in seeing which workers were more fit for the job and allowing them to decide further allocation decisions. This method allowed us to integrate the skills of the worker represented by the years of experience he has with his safety performance represented by the generated SS. Moreover, the second method uses a developed metric to aid the LRL in tracking whether the activity is dangerous or not. The developed Safety Allocation Metric (SAM) used alongside the LRL gives a clear indication to the level of risk and injuries which might be encountered while executing the given activity. Using such methods would allow planners to balance between productivity and safety, and to know which activities require more safety monitoring and inspection.

B. Future Work

The proposed LBSMF integrates various concepts, systems, and digital tools in the attempt to enhance construction safety. Despite these integrations and advancements, the developed framework can still be further developed in future work and research. Regarding the Location Risk Level equation, future work will focus on developing a more specific risk equation for location-based schedules. The equation should take into consideration more location specific hazards and schedule data such as congestion for example. As for the developed serious game, future work will first focus on the application of augmented and mixed reality in construction training. Moreover, factors affecting the training score or the developed Safety Score will be studied in order to enhance worker's SS. Furthermore, more research will be done to study the social, cultural, technological, and economical barriers of implementing digital serious games in the Middle East region.

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APPENDIX A

SURVEY

Construction Safety Training Survey

This survey is part of a master's thesis at the American University of Beirut (AUB).

You are kindly asked to answer the following 11 questions.

Thank you for your time and help!

1. What is your age?

   ____

2. How many years of experience do you have?

   ____

3. What Score did you get in the game?

   ____

4. How much does the game increase your interest in learning?

   1 ○ 2 ○ 3 ○ 4 ○ 5 ○

5. How realistic did you find the game to be in the way it reflects construction activities?

   1 ○ 2 ○ 3 ○ 4 ○ 5 ○

6. Is the game visually appealing to you?

   1 ○ 2 ○ 3 ○ 4 ○ 5 ○

7. Are the game controls user-friendly and easy to use?

   1 2 3 4 5

○ ○ ○ ○ ○

8. How much does the game score reflect your safety performance?

1 2 3 4 5

○ ○ ○ ○ ○

9. Is the information in the game clear?

1 2 3 4 5

○ ○ ○ ○ ○

10. Do you prefer this method or the traditional methods such as meetings, presentations, and brochures?

○ Serious Games

○ Traditional Methods

11. Did you find the game helpful in refreshing your safety knowledge?

○ Yes

○ No

12. Do you believe this method can increase your risk perception of safety hazards?

1 2 3 4 5

○ ○ ○ ○ ○

13. Do you think such methods can be implemented in the Middle East?

○ Yes

○ No