Towards a Parametric and Context-realistic Compaction Training Simulator

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Disclaimer

This report presents the design-oriented work of the author as part of the Engineering Doctorate program he followed at the University of Twente. It should be highlighted that during this period the author has collaborated with a number of researchers from the BMS and ET faculties. While the candidate has contributed to the development of the VR-based training simulator that has supported many applications (i.e., compaction training, assessment of situational awareness, technology assessment, and compaction planning tool), the candidate only claims original conceptual contribution for the development of the simulator as the training tool. The conceptualization, method development and design of the experiment of the other three applications belonged to the collaborator. More specifically, Dr. I. Friso-van den Bos made the most contributions to the situational awareness application, ir. Denis Makarov was responsible for technology assessment application, and finally, ir. Andre Revollo Dalence was in charge of the compaction planning tool application. For these applications, the candidate worked closely with the aforementioned researchers to ensure that the developed simulator can serve the required functionalities. To this end, the disclaimer has to be made that the candidates only claim contributions to the implementation and development of these applications and not to the conceptualization and design. Therefore, the aforementioned researchers reserve the right to report their respective novel contributions in other scientific outlets.

Executive Summary

Virtual reality (VR) has been used for training in many industries and it already became a popular platform for education. VR provides a highly interactive environment that offers a unique opportunity to develop skillsets that are otherwise difficult, unsafe or costly to acquire in the real-world settings. VR-based training simulators have long been used in the construction sector for the training of equipment operators as well as workers. There are already advanced commercial simulators that support excavation, crane, and grading operations. There are also several simulators that are designed to sensitize general construction labor to safety rules and regulations. Trainees use these simulators to navigate in the VR environment and perform certain tasks that are designed to hone craftsmanship, dexterity, productivity, and safety skills.

Despite the growing popularity of training simulators, there are a few limitations that cast a shadow on the wide-spread applicability of them in the industry. (1) there are currently no training simulators for the asphalt paving operations. This is a major oversight because road construction constitutes a considerable portion of all civil engineering projects and hot mix asphalt is the dominant material in our roads. Besides, the proper compaction of asphalt is highly complex and requires very rigorous training and practice. Conventional training is very costly given the cost of equipment, material and space needed for training; (2) Existing simulators function based on pre-defined scenarios that are predominantly designed by developers with little to no affinity with paving operations. This reduces the applicability of simulators for a wide range of scenarios for which trainees need to be prepared; (3) Scenarios are commonly not realistic and fail to represent uncertainties and variabilities inherent in construction projects.

Based on the above problem, this design research intends to develop a framework for parametric and context-realistic compaction training simulators that can offer customizable and highly realistic training scenarios. To this end, a design research methodology was pursued wherein the stakeholder analysis was used to determine the functional requirements of the training simulator. Based on these requirements, an elaborate framework was developed to base a compaction training scenario on (a) actual data from real projects, and (b) inputs from the instructors that define the parameters of the training environment on the specific needs of target trainees. The framework was then implemented in a prototype system. In the developed simulator, the instructors can input the data from the actual construction site to represent the realistic cooling behaviour of the asphalt. They can also define the core parameters of the scene, such as the type of road, number of lanes, thickness, weather condition, number of required compaction passes, and the compaction temperature window. The developed prototype was tested in a number of cases to assess its usability, applicability and scalability.

The results of the validation suggest that the context-realistic and parametric training simulator has a great potential for progressing the training conventions in the road construction industry. The simulator is also found to be highly versatile, with applications that go beyond training and education. It is shown that the simulator can be used for project review (i.e., quality control), project planning, and Virtual Prototyping.

Table of Contents

List of Acronyms

GUI	Graphical User Interface
HTTPS	Hypertext Transfer Protocol Secure
JSON	JavaScript Object Notation
EngD	Engineering Doctorate
UML	Unified Modeling Language
VR	Virtual Reality
AR	Augmented Reality
SE	Simulation-based Education
ISTE	International Society for Technology in Education
3D	3 Dimensional
AI	Artificial Intelligence
RE	Requirement Engineering
SDLC	Software Development Lifecycle
ABS	Agent-based Simulation
VP	Virtual Prototyping
ASPARi	Asphalt Paving Research and Innovation
LOD	Level of Detail

ix

Table of Figures

x

List of Tables

Chapter 1. Introduction

1.1. Background

Road construction is a very intricate operation, where operators of the heavy equipment (i.e., rollers and pavers) need to account for a wide variety of parameters to develop efficient compaction strategies (i.e., determining when to start and end the compaction pass, the number of required passes, the length of one compaction pass, and the distribution of compaction task between multiple pieces of equipment) (Arbeider 2016). This is mainly because the hot mix asphalt layer needs to be compacted to a certain extent (through the back-and-forth movement of rollers) at a specific range of temperature. Compaction done below or above the temperature thresholds or insufficient compaction passes detrimentally impacts the overall quality of the asphalt layer both in the short and long term. Given the complex cooling behavior of the asphalt, challenges of just-in-time delivery of asphalt to the site, complicated coordination of a multi-equipment team, and sensitivity of the compaction strategy to multiple factors (e.g., asphalt mix type, layer thickness, road geometry, type of road, etc.), developing an efficient compaction strategy is very challenging and requires careful planning and execution. That is why it is cardinal for operators of asphalt equipment to be well-trained and sensitized to the delicacies of efficient compaction strategies (Beuving and Luby 2016).

Conventionally, construction training programs mainly consist of two parts: theoretical and practical (Vahdatikhaki et al. 2022). In theory sessions, trainees are familiarized with the required background knowledge about rules/regulations and safety considerations, and they learn about theoretical aspects relevant to compaction (e.g., types of mixtures and properties of the compactor). These sessions are commonly

delivered in a classroom context. Practical training, on the other hand, aims to help trainees develop the skillsets and dexterity required to operate heavy construction equipment using actual machines/equipment. Although practical sessions take place under heavily controlled and regulated settings (to reduce risk and cost), they are still significant safety, cost, and effectiveness concerns.

Safety is an issue because working with real equipment may lead to dangerous circumstances that trainees are not yet skilled enough to deal with (Vahdatikhaki et al. 2022). Practical training can also be uneconomical because of the hourly rate of the equipment. Besides, given that many of the influential parameters are explicit and not directly discernable by operators (e.g., temperature), and given that due to cost concerns the time allotted to each trainee is limited, on-equipment training has a limited capacity for sensitizing trainees to the significance and contributions of different decision-making parameters.

A substitution for on-equipment education is Virtual Reality (VR) training simulators that can complement on-equipment training. In VR training, trainees use VR headsets and controllers to operate a piece of equipment in a realistic virtual world. These simulators have high potential because of their relatively low cost, unlimited scalability, timesaving, and more importantly, safety. VR simulators have been used effectively in the construction industry for some years now.

1.2. Design Problem

The current VR training simulations have a few major problems: (1) they are mostly static (i.e., not reflecting the mobility and human/equipment traffic on the construction site) and therefore unrepresentative of the complex context oof construction sites, (2) they have limited and often pre-defined training scenarios. This means the training simulators have little flexibility to account for the wide variety of training curriculums

and working conditions on the site. Therefore, they cannot be easily tailored to the specific needs of trainees based on their skill level. Additionally, the pre-defined scenarios are commonly developed by programmers who have no to limited knowledge about construction operations. On the other hand, educational experts and trainers have limited knowledge about the technical aspect of simulator development. This creates a disconnect between the education content developer and the platform developer. This disconnect can result in inconsistent and sub-optimal training; (3) to the best of the author's knowledge, there are currently no available training simulators for paving operations, although training simulators are available for crane, excavation, and grading operations.

1.3. Design Objective

Based on the above-mentioned problems, this design project aims to develop a framework for a parametric and context-realistic compaction training simulator. It is called context-realistic because several features and characteristics of the simulated world will be based on real data. This real data is captured from construction sites using sensors. Some examples of these types of sensed data are vehicle speed, asphalt temperature, the impact of weather conditions on temperature, and equipment dimensions. Also, a parametric simulator means that the scenarios are not rigid and predefined. Instead, instructors can generate specific scenarios considering the particular needs of the target trainees.

"Context-realism" and "parametric-ness" are the two features that set the final product of this assignment different from the existing alternatives. Together, these two features can narrow two major gaps in road construction education. The main one is the gap between theoretical education and on-the-job training by bringing the real working

context into the classrooms. Second, the disconnect between simulator developers and instructors in construction can be addressed.

1.4. Project Client and Requirements

This project is funded by NWO in collaboration with the Department of Educational Science (OWK) and the Department of Construction Management and Engineering (CME) of the University of Twente. Therefore, the primary beneficiaries of the final design project are (1) researchers from the OWK group, who pursue a realistic VR-based training simulator that allows them to assess the impact of using VR in the development of Situational Awareness (SA) of trainees. The disclaimer has to be made that while the evaluation of the impact of the simulator on SA is out of the scope of this project, it is essential the developed platform can support this evaluation by ensuring VR-readiness (i.e., the possibility to support the use of VR goggles in the simulator); (2) researchers from the CME group, who are interested in utilizing the developed simulator as a Virtual Prototyping (VP) platform that allows them to assess and evaluate the effectiveness of different operator support systems first in the simulator. They are also interested in the context awareness of the simulator because this would allow them to build a virtual replica of the actual projects in the simulator. Such virtual replicas can be used for planning, training, and project review purposes. Again, while the validation of the effectiveness of the simulator as a VP is out of the scope of this research, it is imperative that the system can be used for this purpose; (3) instructors at SOMA college, i.e., the largest construction equipment training school in the Netherlands. The simulator is expected to address their training needs. To this end, inputs from instructors are of paramount importance to determine the parameters of parametric training scenarios.

5

Based on the discussion with the above potential end-users of the system, the following high-level requirements are identified. The training simulator should:

1. Offer the possibility to develop various scenarios based on the training needs of target trainees;

2. Be able to use real construction data to develop context-realistic scenarios. As mentioned above, this feature has applications beyond training, and it can be used to also support road construction planning and review;

3. Support the use of virtual reality headsets that can be used to facilitate perceptive and cognitive skills that are necessary for obtaining SA;

4. Be realistic in terms of driving experience and appearance;

5. Offer clear metrics for the assessment of trainees' performance;

6. The simulator can be used as a virtual prototyping platform to experiment with new technological ideas in a safe environment.

1.5. Outline of the EngD Report

The remainder of this report is organized as follows. Chapter 2 describes the theoretical background. Chapter 3 presents the overall design methodology. This is followed by a stakeholder and requirement analysis of the proposed system in Chapter 4. Next, Chapter 5 elaborates on the proposed framework for the compaction training simulator. Chapter 6 presents the implementation of the training simulator. The case studies conducted for the validation of the framework are presented in Chapter 7. Finally, the discussion and conclusions of the project are presented in Chapter 8.

Chapter 2. Theoretical Background

This section presents the theoretical background for the situational awareness dimension of the training simulator. The section intends to explain and justify the choice of VR-based training simulator for the SA assessment.

2.1.   Situational awareness

Operators need to be able to deal with variations, uncertainties, risks, and even hazards in their daily jobs. This requires them to develop a strong sense of what is going on around them. This so-called situational awareness (SA) helps them to take decisions and to take appropriate actions that enable them to control and direct the situation (Endsley, 1995). SA involves being aware of what is happening around you to understand how information, events, and your own actions will affect your goals and objectives, both now and in the near future (Bolstad, Endsley, & Cuevas, 2014). The most common definition is provided by Endsley (1995, p. 36), who defined SA as: "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future". In her definition, Endsley distinguishes three hierarchical levels of SA: perception, comprehension, and projection. The first level of SA is the perception of the status, attributes, and dynamics of relevant elements in the environment (e.g. speed of the road roller; characteristics of the asphalt (e.g., temperature, cooling rate); and atmospheric conditions (e.g., temperature, humidity, wind). The second level of SA is about the comprehension of the situation. The person has specific goals that need to be achieved, and at level 2 he or she considers how each of the elements perceived at level 1 contribute to achieving the intended goals. The person connects those data points to form a holistic pattern or picture of the situation. For example, the roller

operator oversees the situation and decides whether the road construction process is going according to plan and if possible deviations are still within the set margins of error. The third level of SA is the ability to predict or foresee how the situation might develop in the (very) near future. In the case of the roller operator that could be foreseeing how the changing weather conditions might affect the cooling rate of the new asphalt, which in turn might require the operators to adjust their speed or distance relative to other moving equipment accordingly.

2.2. SA Training

Because SA is normally acquired on-the-job, and develops as the workers get more work experience, it has largely remained beyond the scope of formal training and education (Aboagye-Nimo & Raiden, 2016; Gherardi & Nicolini, 2002; Kamoche & Maguire, 2011). However, with technology such as Virtual Reality (VR) training, it becomes possible for students to experience real-life working situations in a safe, controlled, virtual environment in which they can train their SA. This project focuses on the design and development of a VR-based training for the acquisition of SA in the context of vocational training of students in the field of asphalt paving operations.

In order to train SA, students need to be exposed to situations that come close to real job situations, so they must look credible, authentic, realistic, and also sufficiently reflect the complexity of the real situations. In vocational training, and in particular in vocational engineering education it is often difficult to provide students with trainings and training materials that provide them with opportunities to apply and train their knowledge and skills in realistic environments that accurately reflect the real job's complexities. Sometimes there is a lack of environments that offer a realistic experience of the work place, in which the students can apply and train their knowledge and skills, and where they can even safely try out different behaviors and see how they

work out. Sometimes, the schools cannot offer realistic opportunities for learning and training, because the equipment involved is too big, too costly to use, too complex, too impractical (one cannot build a motorway, just for the sake of training), or too dangerous to use in school settings. A possible solution can be offered by using computer technology, such as Virtual Reality (VR) training.

Mikropoulos and Natsis (2011, p. 769) describe Virtual Reality (VR) as "technologies that support the creation of synthetic, highly interactive three dimensional (3D) spatial environments that represent real or non-real situations." The 3D virtual worlds in VR are distinguished from other types of media through immersion and presence. In general, immersion is seen as the product of technology that produces multimodal sensory input (Mikropoulos & Natsis, 2011; Slater & Wilbur, 1997; Wang, Petrina, & Feng, 2017). However, Witmer and Singer (1998) view immersion as a "psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences" (1998, p. 227). Many other authors refer to this psychological immersion as 'presence', the psychological perception of being "there," within a virtual environment in which the person is immersed (Calleja, 2014; Riva & Waterworth, 2014; Wang et al., 2017; Witmer & Singer, 1998).

This sense of presence is an important prerequisite for the acquistion of SA in virtual training environments. Clifford and his colleagues (Clifford, Khan, Hoermann, Billinghurst, & Lindeman, 2018; Clifford, McKenzie, Lukosch, Lindeman, & Hoermann, 2020), studied the acquisition of situational awareness of fire fighters in 2D and 3D (VR) training environments. Their studies showed that the 3D-VR environment was associated with higher levels of presence experienced by the users and was more effective in terms of acquistion of SA as compared to the 2D training environments. In

the literature, several characteristics of 3D VR environments are identified that appear to stimulate the level of experienced presence, including representational fidelity (or realism) and learner interaction. Representational fidelity refers to characteristics such as a realistic display of the environment (including perspective, texture, and lighting), smooth view changes and motion, and the natural, realistic way objects in the environment behave and respond to user actions. Learner interaction includes characteristics such as that learners can undertake embodied actions in the virtual world, for example they can navigate through that world, manipulate objects and the environment. Dalgarno and Lee (2010) conclude that these 3D virtual learning environments can have five specific learning affordances in terms of learning outcomes or benefits: spatial knowledge representation, experiential learning, engagement, contextual or situated learning, and collaborative learning, all of which are important in the acquisition of SA

2.3. Pedagogical framework

Very few studies about the use of VR in the design of educational virtual environments have a clear pedagogical model underlying the environment (Mikropoulos & Natsis, 2011). Fowler (2015) argues that the design of learning systems should be driven by pedagogical rather than technological consideration. The training of which the current project is part, is based on pedagogical principles derived from socio-constructivism (Bandura, 1997; Bruner, 1961, 1987; Piaget, 2001); Vygotsky, 1978, 1994). In the socio-constructivist learning philosophy, students are encouraged to be active participants in their learning, to self-regulate their learning process and to construct complex knowledge and skills through experimentation, reflection, and social interaction. According to Jeffrey (2006), constructivist learning is characterized by teaching focused on development of personal relevance making, student ownership of

knowledge and competence acquisition, and control of learning processes. Three essential strategies are often employed to create a constructivist learning environment intended to support the development of competence in students (West et al., 2012; Wright et al., 2013). First, learners are engaged in authentic tasks. Authentic tasks are 'real world' or contextualized tasks that are personally relevant or interesting to the learner (Duderstadt, 2008; West et al., 2012). Second, learners are encouraged to actively construct their understanding and create their own representations, instead of receiving information from a teacher (Crawley et al., 2007; Dyer et al., 2009; Wright et al., 2013). Third, learners are given the opportunity to engage in discussion, collaboration, and reflection (Dyer et al., 2009; Schön, 1995; Wright et al., 2013). For the students to train SA in these authentic circumstances, it is necessary that the VR training incorporates all three of the above-mentioned parameters.

2.4. Didactical framework

The didactical framework is based upon the principles of constructive alignment (Biggs, 1996; Biggs & Tang, 2011), the Four Component Instructional Design model (4C/ID; van Merriënboer 1997), and Fowler's (2015) stages of learning. Following constructive alignment, three elements of instruction, learning goals/outcomes, learning activities, and assessment should be aligned with each other, so that goals are assessed, teaching activities contribute to realizing the goals, and assessment measures the extent to which the goals are attained (Biggs, 1996; Biggs & Tang, 2011). According to the 4C/ID model for complex tasks by Van Merriënboer (1997), students should be presented with simplified, but nonetheless whole tasks, along with careful design of how the information is presented. Third didactical framework is based on Fowler's (2015) work. In this article, Fowler demonstrated how his learning stages framework that he proposed in 1999 together with Mayes (Mayes & Fowler, 1999), can be

combined with Bloom's (revised) taxonomy, and Conole et al's (2004) mini learning activities in order to form the pedagogical foundation on which a VR training can be built. In this framework, a learning experience is characterized by three stages: conceptualization, construction, and dialogue. In the conceptualization stage, learners are introduced to the training and the training scenarios. The scenarios include information about the context in which tasks have to be performed, the task conditions, the achievement goals. In the construction stage, learners deepen their understanding by exploring, investigating, manipulating, or questioning the new concept or skill. This stage is the actual experience in the VR environment in which the learners deals with situations and tries to achieve the missions and/or goals specified in the scenario. This requires interactivity. The learners' actions now drive the flow of information. In the *dialogue* stage, learners may test their emerging understanding by discussing it with others. A common way of doing this is by using debriefings. According to Gardner (2013), debriefing provides opportunities for exploring and making sense of what happened during an event or experience, discussing what went well and identifying what could be done to change, improve and do differently or better next time. A helpful tool in debriefing is the use of video playback. Video playback allows participants to see how they performed rather than how they thought they performed, and it might also help to reduce hindsight bias in assessment of the scenario (Fanning & Gaba, 2007).

2.5. Assessment

Many scholars agree that standard assessments fail to accurately measure complex competences (e.g., SA). Assessment of complex competences should be formative and based upon authentic and complex tasks (Binkley et al., 2012; Voogt & Roblin, 2012). Formative assessments are considered a diagnostic instrument and a powerful

way to make the students' learning visible which in turn can contribute to the capacity building of students and teachers. Using formative assessment in authentic and complex tasks implies that the assessment procedure needs to be integrated in the VR training and this requires an innovative type of assessment that blends VR and the assessment of SA in the VR training.

A widely used method of measuring SA during training situations is the Situation-Awareness Global Assessment Technique (SAGAT) (Endsley, Selcon, Hardiman, & Croft, 1998), which focuses on extracting operators' explicit knowledge through probes during the training. In this method, trainee has to answer questions about the current situation in the training exercise. For example: What is the current speed of your roller? A drawback of SAGAT is that it might be hard for people to put their knowledge in words. In the case of experience operators this might be because their knowledge is mainly tacit; in the case of student, thinking about and answering the questions may cause a cognitive overload. Lo, Sehic, Brookhuis, and Meijer (2016) argue that it is therefore important to not only focus on the answers to probes, but also to assess the operators' decision making and performance (e.g., how well the road construction tasks are managed and if and how the goals are achieved).

2.6. Pedagogical and didactical design requirements for the VR training of SA

The preparation of the students before they enter the VR training environment, but also possible assessment, debriefing, and relection activities after the students leave the VR environment are beyond the scope of the current project. Yet, the VR environment plays a central role in the training, and it is strongly connected with the activities before and after using the VR application. In order to be integrated in training program with

the pedagogical and didactical specifications described above, the VR environment needs to:

- expose students to situations that come close to real job situations, that is, look credible, authentic, realistic, and also sufficiently reflect the complexity of the real situations,

- allow students to undertake embodied actions (e.g., can navigate through that world, manipulate objects and the environment),

- require students to carry out simplified, whole tasks,

- give students feedback in the sense of showing the results and consequences of their actions and performance

- offering flexible scenarios that can be adjusted (by the instructor/teacher) to the competence level and needs of the individual students

- offering opportunities to include or facilitate SA assessment

- allow assessment of the operators' decision making and performance

- offering functionality to make video recordings of task performance in VR (to facilitate reflection, debriefing, coaching and assessment activities afterwards)

Chapter 3. Design Methodology

To pursue the objective of this project, the design research methodology shown in Figure 1 was followed. In general, the methodology consisted of three main phases, namely, stakeholder analysis, framework development, and implementation and validation.

In Phase 1, the researcher tried to capture the expectations of different stakeholders to determine the main functional requirements of the framework. During Phase 2, the functional requirements were used as the departure point to develop a framework for the parametric and context-realistic compaction training simulator. Finally, the developed framework was implemented in a prototype and applied in a number of case studies to assess the functionality and usability of the simulator from the users' perspective. Each of these phases is explained in more detail in the following sections.

3.1. Stakeholders and Requirement Analysis

During this phase, first, the main stakeholders of this design were identified. Then, through rounds of interviews, their core needs were captured. This was a set of open semi-structured interviews with instructors from SOMA, and researchers at OWK and CME units. Interviewees were asked to openly talk about different scenarios in which they want to use the simulator.

After determining the needs of different stakeholders, a workshop with five instructors was held at SOMA college to identify the parameters that need to be considered for the customization of training scenarios, as shown in Figure 2. This workshop had the setup shown in Table 1.
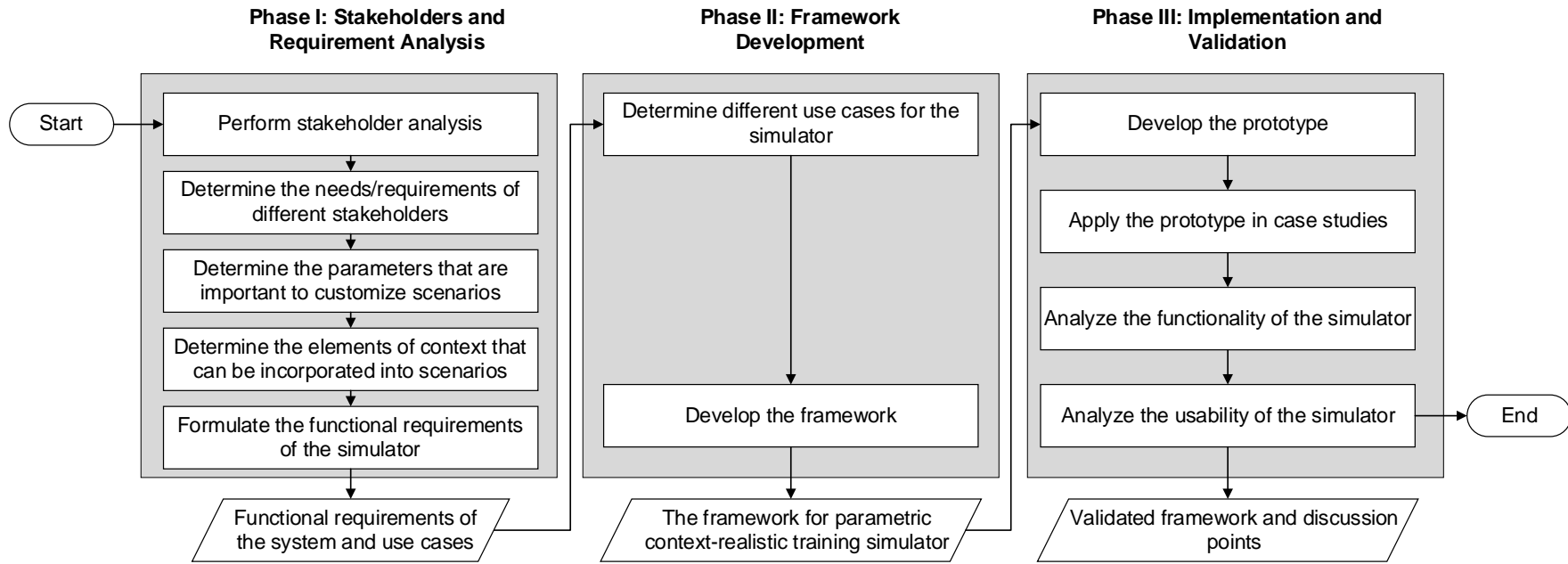
Figure 1. Design research methodology

11
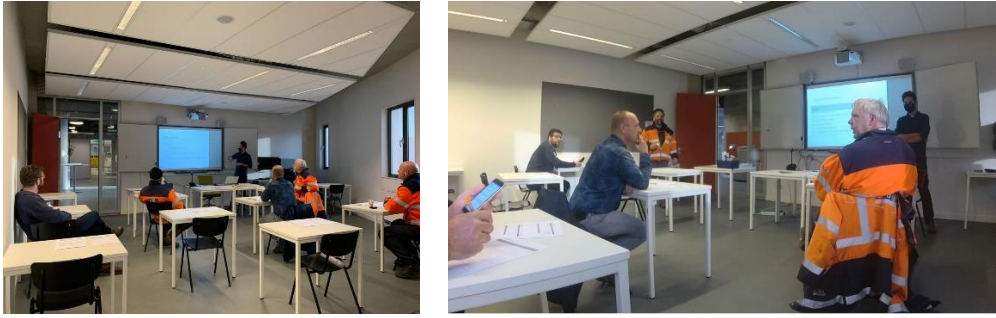
Figure 2. Workshop with instructors at SOMA college

Table 1. Workshop setup

Step	Explanation	Duration
Introduction	The EngD trainee presents the purpose of the workshops	10 min
Extracting Parameters	All participants write down their idea on the given paper and present it to the others	30 min
Setting Priorities	All the presented parameters will be graded by all participants	10 min
Break	-	15 min
Discussion of priorities	Parameters that have high and mid priority will be discussed. All participants identify different states of the given parameters and indicate what are their effects on the task.	30 min

As shown in the table, first the purpose of the workshop was explained to the participants. Then, the form shown in Table 2 was distributed among the participants to identify the core parameters of the training scenarios. To help participants better understand the scope of expected parameters, a few parameters that the researcher found relevant, through his judgment, were already put into the form. Given that the participants had to also prioritize the identified parameters later, the fact that the researcher included a few parameters as the starting point in Table 2 does not introduce any bias, because the participants could potentially give low priority to these parameters.

Table 2. The form used for the identification of parameters

Parameters		Explanation
Identified by researcher	Road Geometry	Ability to define the shape of the road
	Ambient temperature	Ability to set the temperature of the surrounding environment
	Weather	Ability to set the weather condition
	Asphalt type	Ability to set the type of the asphalt
	Traffic condition	Ability to define the volume of traffic on the adjacent road
	Number of rollers	Ability to decide the number of rollers which should be assigned for the task
Identified by instructors		

Once all participants, filled out Table 2, all the identified parameters were unified and synthesized on the board. Then, the participants were asked to use Table 3 to prioritize the parameters, including those pre-identified by the researcher. The result of this step was the list of prioritized parameters.

Table 3. The form used for the prioritization of parameters

Parameters	Priority Low ↔ High				
	1	2	3	4	5
Road Geometry					
Ambient temperature					
Weather and time of day					
Asphalt type					
Traffic condition					
Number of rollers					

After a short break, the participants were asked to have an open discussion about the parameters that were identified in the previous step. The discussion revolved around identifying the potential range of values for the given parameters and the impact the parameters would have on the training scenario. The results of this discussion were summarized by the researcher in the format shown in Table 4. Ultimately, this step resulted in a set of parameters that can be used in the user interface of the training simulator to build a custom training session for target trainees.

Table 4. The form used for the discussion about the parameters

Parameters	Range	Impact
Road Geometry	Road types	
Ambient temperature	Min and max temperature	
Weather and time of day	Ambient weather condition	
Asphalt type	The type of asphalt mix from a list	
Traffic condition	Surrounding traffic condition	
Number of rollers	Min and max number of rollers	

Next, researchers from the CME group were asked about the component of the context that can be captured from real projects. The reason why this investigation was limited

to CME participants is that only the researcher from the ASPARi unit of the CME group knew about the type of data that can be captured from the actual construction site using sensors.

Once the needs of different stakeholders, parameters, and elements of context were known, these were translated into a set of functional requirements that the system needs to meet. This was done through a detailed analysis of the needs and the expertise/background of the research in VR development. The details of this phase are presented in Chapter 3.

3.2. Framework Development

Once functional requirements were identified, the development phase began. In this phase, functional requirements were translated into a set of technical use cases. A use case defines different ways in which users interact with a design system in order to perform certain tasks. The guiding factors in the determination of the target tasks were the functional requirements. So, basically functional requirements were classified into a set of well-defined tasks/functions that define how users should interact with the system. The reason why functional requirements were classified is that not all functional requirements need to have a dedicated use case. Sometimes, a single use case can address several functional requirements. For instance, the two functional requirements of (1) the instructors should be able to input the parameters of the training scenario, and (2) instructors should be able to use the actual temperature data to mimic the cooling rate of the asphalt in the simulator, can be both incorporated in the user input use case. A Unified Modeling Language (UML) use case diagram was used to identify the interaction between the user and various functions of the system.

Upon the determination of use cases, the framework was developed. Use cases were used as the starting point for the determination of various modules of the system. The details of this development are presented in Chapter 4.

3.3. Implementation and Validation

In the last phase of this project, the developed framework was implemented and then tested in a number of case studies. The implementation was done by developing a working compaction training simulator using Unity 3D. The implemented simulator had the core functionalities identified in Phase 1. Different case studies were needed because the simulator needed to be tested for different intended use cases. In general, the training simulator was tested for its applicability for (1) compaction training, (2) technology assessment, (3) situational awareness, and (4) compaction planning. For each one of these use cases, a dedicated workshop was set up to allow a number of participants (novice and expert) to experiment with the simulator. At workshop sessions (i.e., compaction training, and technology assessment), a dedicated questionnaire was used to get feedback from the participant and assess the fitness of the simulator for the given purpose. In these cases, System Usability Scale (SUS) (1996) and NASA TLX (Hart 2006) were used as inspiration for the assessment of some aspects of the simulator.

Table 5 presents the questionnaire used for the assessment of the simulator as a training tool. In this workshop, 5 instructors and 34 trainees were exposed to the training simulator. The instructors were asked to first develop a custom scenario using the scenario builder and then complete one training session. Trainees, on the other hand, were just asked to follow a uform training session. At the end of each session, participants, instructors, and trainees were asked to fill out the questionnaire. As shown in Table 5, the simulator was assessed in 24 criteria, which were classified into 4

categories. The respondents were asked to rate the extent to which they (dis-)agree with each statement using a Likert scale of 1 (completely disagree) to 5 (completely agree). It should be highlighted that some of the questions could only be answered by instructors who used the simulator for the scenario development too.

As will be later explained in Chapter 6, one possible application of the simulator is virtual prototyping. In this application, the simulator is used as a platform for professionals to experiment with and provide feedback for potential new technologies that can be used to further enhance the operational quality of compaction, before it is actually implemented on the actual equipment. Table 6 presents the questionnaire used for the assessment of the simulator as a technology assessment tool. As shown in this table, the fitness of the simulator for this application can be assessed using different criteria. In this validation, 50 participants used the simulator and filled out the questionnaires. 14 Of these participants were considered to be inexperienced, i.e., still in training and with no practical experience. The remaining 36 participants were professional operators.

Validation of the simulator as a tool for testing and training Situation Awareness was conducted in a series of experiments with various target groups. A first experiment aimed to investigate sources of variability in performance, specifically for answering SA queries that participants were presented with at the end of a simulation. This experiment was conducted with 40 students who were enrolled in a program containing road construction modules. A second experiment was conducted to benchmark SA performance using similar queries. For this purpose, the performance of asphalting professionals was compared to that of students and that of laymen. Finally, the training of SA using the simulator was validated in a quasi-experimental training study in which four classes from vocational education participated in three quasi-experimental

conditions: a condition that received training with feedback sessions by their teacher containing video playback (1 class), a condition that received training with feedback sessions but no video playback (1 class), and a condition that only participated in the training sessions with the simulator, but no feedback sessions (2 classes). For each of the studies, qualitative and quantitative data were analyzed and used to further develop the SA queries and feedback.

Finally, the validation session about the compaction planning used the questionnaire shown in Table 7. In this session, three planners were asked to use the training simulator as a medium to visualize the results of their compaction planning. More details about the content of the session will be provided in Chapter 6. It should be noted that because this application would require the integration of the simulator with an Agent-based Simulation (ABS) simulation model, as will be explained in Section 4.1, the questionnaire refers to the integrated model, which encompasses the simulator and ABS model. This application was validated by three expert planners who tried to use the simulator as a planning tool in a case study project.

Table 5. The questionnaire used for the validation of the simulator for compaction training use case

Category	Criterion	Statement	Target participant	Response
Customizability	Comprehensive	The simulator can be used to build different work scenarios	Instructors	
	Adaptable	The system can cover different difficulty levels for a scenario		
	Complete	The simulator covers my training wishes and expectations		
	Fit for assessment	The simulator can be used to assess all trainees at different levels		
Realism	Engaging	I felt stimulated by the virtual environment	Instructors &Trainees	(1) Completely disagree
	Auditory realistic	I correctly identified sounds within the virtual environment		
	Intuitive Control	The controllers were intuitive		
	Responsive	The virtual environment was responsive to my actions		(2) Disagree
	Visually realistic	The visual aspects of the virtual environment involved me		
Usefulness	Informative	The simulator helped to get familiarized with the paving operation	Instructors &Trainees	(3) Neutral
	Substitutive	The simulator can substitute practice with actual rollers		
	Safety training	The simulator was able to sensitize me to the safety rules		
	Preparative	The simulator helped me prepare for real operations		
	Skill assessment	The simulator can be used to assess my students' skills	Instructors	(4) Agree
	Detection	The simulator can help identify focus points for improvement		
	Recommendable	I recommend my colleagues use this simulator for education		
	Complementary	The simulator complements theoretical or practical education		(5) Completely Agree
Usability	Easy to use	I thought the scenario builder was easy to use	Instructors	
	Easy to learn	The scenario builder was easy to learn		
	Trustable	I feel confident to use the scenario builder		
	Reusable	I think that I would like to use the simulator frequently	Instructors &Trainees	
	Comprehensible	I found the visuals in the simulator easy to understand		
	Standalone	The simulator can be used without the support of a technician		
	Reliable	I feel confident to use the simulator		

Table 6. Questionnaire for the assessment of the simulator as a virtual prototyping platform

Criterion	Statement	Response
Adequate	VP is an appropriate medium to evaluate/compare different operator support solutions	(1) Completely disagree (2) Disagree (3) Neutral (4) Agree (5) Completely Agree
Preparative	VP helps you prepare for future work with the real machine	
Realistic	VP represents the scene and equipment in a realistic manner	
Work analysis	VP can be used to explore and evaluate different working scenarios	
Communication value	VP can be used to express your wishes, expectations, and suggestions about operator support solutions	
Planning value	VP can be used to test your compaction strategy before actual projects	
Development tracking	VP can be used to assess your skills and progress (as a training tool)	
Education value	You recommend using the VP platform to your peers for education	
Technology assessment	You recommend using the VP platform for the evaluation of new technologies	
Formative	The VP platform provides sufficient feedback on your performance	
Easy to use	The use of all control elements (wheel, pedals, and buttons) is easy	
Enhancing Control	VP platform can be more realistic with the use of additional joysticks & VR goggles	
Enhancing Audio	VP platform can be more realistic with the use of additional sound accompaniment	

Table 7. Questionnaire for the assessment of the simulator as a project planning platform

Category	Criterion	Statement	Response
User-friendliness	Ease of use	How easy is it to use the integrated model?	(1) Absolutely useless (2) Not useful (3) Neutral (4) Somehow useful (5) Very useful
Usefulness	Comprehensive	How useful is it to simulate the whole process (Transportation, Paving, Compaction)?	
	Visualization	How useful is it to visualize the strategy in a virtual reality environment?	
	Feedback	How useful is it to receive operational quality feedback?	
	Standardization	How useful is the integrated model to standardize current planning practices?	
Versatility	Versatility	How useful is the integrated model to assess different planning strategies?	
Awareness	Awareness	How useful is the integrated model for better showing the consequences of compaction strategies in operational quality?	
Teamwork	Teamwork	How useful is the integrated model to enhance coordination and collaborative work?	

Chapter 4. Stakeholders and Requirement Analysis

As mentioned in Chapter 2, the core objective of this phase of the project was to identify the core requirements of the design. To this end, the first stakeholder analysis was performed. Then, the needs of different stakeholders were investigated. This was followed by the identification of parameters and context elements, as explained in Chapter 2. Finally, all the inputs were translated into a set of functional requirements.

4.1. Stakeholder Analysis

In general, 5 main stakeholders were identified for the system, namely: (1) *Trainees* who interact with the simulator for training and improving their abilities. They receive feedback from the system after each session; (2) *Instructors* who use the system to run a training session and assess students by monitoring their results; (3) *Training Schools* who use the simulator in their training curriculum in order to make training more effective; (4) *Researchers* employ the simulator for their research in educational science or construction management; (5) *Government and contractors* who benefit from the simulators because it can ultimately contribute to improving the quality of the roads, and reducing job site accidents. Table 8 presents a detailed analysis of these stakeholders in terms of their roles, interests, and impact. Based on this analysis, the main, i.e., high-impact, stakeholders of the compaction training simulator are the instructors and university researchers (i.e., OWK and CME units). As mentioned in Chapter 1, these stakeholders were interviewed to identify the high-level needs/requirements of the system.

Table 8. Identification of stakeholders

Stakeholder	Role	Interest	Impact
Instructors	They use the simulator in the classroom, customize it to cover different scenarios, and use it to assess students	a user-friendly interface for modifying scenarios, realistic control, flexibility to modify scenarios	**High impact** because the main objective of the project is to provide flexibility for teachers to enhance training. If teachers are not satisfied, the project fails
Trainees	They are supposed to practice with the simulator as part of their study and get feedback from the system	User-friendly interface, realistic representation of actual operations, useful feedback on their performance	**Low Impact** because although they are the main beneficiary of the simulator, it is mainly the instructors who would determine what scenarios are the best for training and what constitutes a realistic representation
Operators	Operators use the simulator to experience different types of new technologies that can be used in the road construction	User-friendly interface, realistic representation of actual operations, useful feedback on their performance	**Low Impact** because they are commonly the subject of studies that will be conducted by researchers. Therefore, they have little say in what elements need to be present in the simulator. This would have been drastically different if the simulator was supposed to be also used for on-the-job training
Researchers	They define scenarios for testing their hypothesis and utilize the simulator to run a workshop. They contributed to designing the simulator by providing requirements	Flexibility in the simulator, recording the performance of the participant for further analysis	**High impact because** while they are not end-users, their needs shape the scope of the simulator
Government & contractors	Increasing quality of asphalt. increasing safety at sites. reducing the cost of operations	Effective training simulator that can sensitize the next generation of operators to safety, productivity, and quality requirements of paving operations	**Low Impact** because they are the secondary beneficiary of the simulator. Their interests are satisfied when the simulator indeed addresses the needs of training schools and research units.

4.2. High-level Stakeholder Needs/Requirements

Based on the interviews, the high-level requirements of the compaction training simulator are identified. Based on these requirements, the training simulator should:

1. Offer the possibility to develop various scenarios based on the training needs of target trainees;

2. Be able to use real construction data to develop context-realistic scenarios. As mentioned above, this feature has applications beyond training and it can be used to also support road construction planning and review;

3. Support the use of virtual reality headsets that can be used for SA assessment;

4. Be realistic in terms of driving experience and appearance;

5. Offer clear metrics for the assessment of trainees' performance;

6. The simulator can be used as a virtual prototyping platform to experiment with new technological ideas in a safe environment.

4.3. Identification of Influential Parameters

As explained in Chapter 2, a group of five instructors was interviewed to identify the core parameters of the building various training scenarios, using the workshop setting explained in Section 2.1.

Based on the discussion with the instructors, the parameters shown in Table 9 are identified. The priorities given to each parameter by all instructors collectively are also presented in Table 9. As shown in this table, the highest-priority parameters include weather conditions, asphalt type, number of rollers, drum water system, and road gradient.

Table 9. The form used for the prioritization of parameters

Parameters		Priority Low ↔High				
		1	2	3	4	5
Identified by researcher	Road geometry			X		
	Ambient temperature			X		
	Weather and time of day					X
	Asphalt type					X
	Traffic condition		X			
	Number of rollers					X
Identified by instructors	Drum water system					X
	Asphalt layer thickness				X	
	Road profile					X
	Asphalt delivery temperature			X		
	Multi-layer asphalt behavior				X	

To further elaborate on why these parameters are important and what ranges need to be considered, Table 10 was filled together with all instructors as explained in the previous chapter.

Table 10. The form used for the discussion about the parameters

Parameters	Range	Impact
Road Geometry	[Crossing, roundabout, transverse joint]	Affect the compaction strategy (e.g., where to start, in which direction to compact, how to distribute and coordinate compaction tasks between several rollers, etc.)
Ambient temperature	[-10°, 50°]	Affects the cooling rate of the asphalt
Weather and time of day	[Sunny, Rainy, Windy, Snowy, Foggy]	Affects the cooling rate of the asphalt. Also, rain, snow, and fog reduce the sight distance. On colder days, the compaction window is smaller. If the wind is strong, the direction of the wind has an influence on the direction of compaction. Also, the amount of daylight impacts the safety of the work
Asphalt type	[Stone mastic asphalt, Porous asphalt]	Affects the type of roller needed for compaction, the cooling rate of the asphalt, the compaction window, and the number of compaction passes
Traffic condition	[no traffic, light traffic, heavy traffic]	Affects the accident risk
Number of rollers	[1, 3]	Affect the compaction strategy (e.g., where to start, in which direction to compact, how to distribute and coordinate compaction tasks between several rollers, etc.)
Drum water system	[On and Off]	Water on the drum has the lubrication role to prevent the asphalt from sticking to the roller drum. On the other hand, by applying water to hot asphalt, the cooling of the asphalt is accelerated and thus the compaction window decreases
Asphalt layer thickness	[3 cm, 5 cm, 9 cm]	The asphalt thickness has an impact on the type of roller needed for compaction, the cooling rate of the asphalt, and also the length of the road that needs to be compacted per delivery
Road Profile	Possible cross-section of the road	The cross-section profile of the road is important to ensure the safety of the road and also the water drainage
Asphalt delivery temperature	[120°, 180°]	If the asphalt arrives too hot, the rollers need to wait. On the other hand, if the asphalt temperature is low at the arrival, the compaction needs to start quickly. This also has an impact on how much distance is needed between rollers and the paver
Multi-layer asphalt behavior	[1, 2]	In the case of multi-layer asphalt compaction, there is always the risk of the upper layer sliding away. Also, this has an impact on the proper connection between the asphalt layers

It is noteworthy that the priorities given to each parameter are primarily from the perspective of the instructors and thus only account for their desirability for education/training purposes. Nonetheless, not all the parameters are equal in terms of

the development effort required to include them in the simulator. For instance, while it is relatively easier to include ambient temperature, the representation of multi-layer asphalt behavior is very complex. Therefore, the researcher has used his professional judgment to consider the development effort needed for each feature. In the end, the instructors' priorities are concurrently considered with the required development effort to determine parameters that are going to be included in this project. This will be explained in Section 3.5.

4.4. Identification of Elements of Context

As mentioned in Chapter 2, the core elements of context that need to be included in the simulator were determined in consultation with CME researchers from Asphalt Paving Research and Innovation (ASPARi) research unit. ASPARi researchers have previously presented their methodology for a context-realistic training simulator (Vahdatikhaki et al. 2019). While an in-depth discussion of these elements is considered out of the scope of this research and interested readers are referred to the previously published paper (Vahdatikhaki et al. 2019), a brief discussion is presented in this report for completeness.

Figure 3 presents the high-level categorization of context data that can be incorporated into a construction training simulator. Briefly, context-realism is defined as the alignment between the real and virtual world in terms of (1) environment, (2) actors/materials, (3) operations, and (4) products. Environment represents the surroundings of an operation, including buildings, urban furniture, etc. Actors and materials include agents that make an operation possible, e.g., rollers, pavers, and asphalt. Operation is about the realistic presentation of how the operation takes place, e.g., the realistic behavior of a roller that is controlled by the scene and not by the

trainee. Finally, the product is about the changes that are brought to the composition of the scene due to the operation, e.g., a change in asphalt layer thickness.
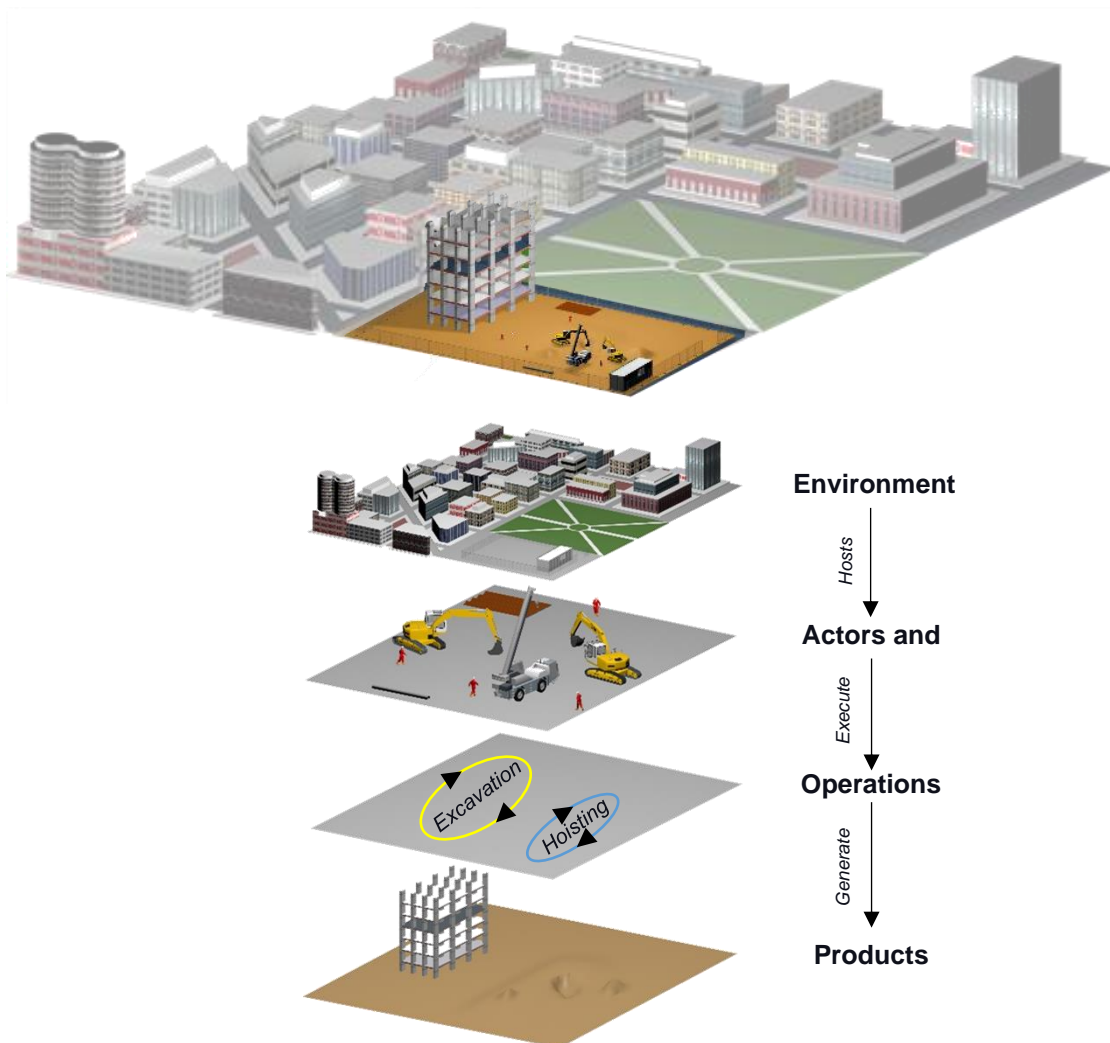

Figure 3. Categorization of construction site's context (Vahdatikhaki et al. 2019)

In terms of required context elements in this project, while the ultimate goal of ASPARi researchers is to bring all these core elements into the training simulator, for this specific project the focus is placed on the representation of (1) real-time asphalt temperature based on actual project data, and (2) the movement of the paver. So, basically, the initial temperature of the asphalt at the delivery and the rate at which asphalt cools down can be determined based on the sensory data collected by ASPARi researchers. To this end, the simulator should be able to read the temperature data file and translate it into the temperature behavior of the asphalt in the training scenario.

Similarly, the training simulator should be able to read the motion data of the paver, which is collected from actual projects using GPS, and translate it to the movement of the paver in the training scenario. This would ensure that the inherent variability in the temperature profile of the asphalt and also the interruption to the motion of the paver introduced by the back-end logistic is realistically represented. This would help trainees hone their skills to cope with these variabilities.

4.5. Determination of Functional Requirements

Based on the requirements discussed in Sections 3.2, 3.3, and 3.4, the functional requirements of the compaction training simulator are developed using the technical knowledge of the EngD researcher, as shown in Table 11. As mentioned in Section 3.3, not all requirements are the same in terms of the required development efforts. Therefore, the EngD researcher combined the priorities provided by instructors with his assessment of required development effort to prioritize functional requirements. Accordingly, each functional requirement was rated either as a must-have or a good-to-have function. During the development phase, the focus was first placed on the implementation of must-have functions. After the implementation of all the must-have functions, the good-to-have functions were implemented in the remainder of the project time based on the priority scores given by the instructors. Please note that the limited timespan of the project did not allow the implementation of all the good-to-have functions. The discussion of which functional requirements have been implemented and which have not will be provided in Chapter 8.

With the functional requirements known, the next chapter will present the use cases and the framework for the compaction training simulator.

Table 11. List of functional requirements of compaction training simulator

ID	Functional Requirements	Keyword	Priority
FR.1	The simulator should allow trainees to perform a compaction session	Training	Must-have
FR.2	The System should provide a scenario builder module to customize paving operation. The ability to specify values for the following parameters is required: (1) Shape of the road, (2) Weather condition, (3) Type of asphalt, (4) Thickness of asphalt, (5) Number of rollers, (6) Practice duration, (7) Number of compaction passes, and (8) Compaction temperature window	Scenario builder	Must-have
FR.3	The system should provide a road designer module to sketch the shape of the road for operations	Road designer	Good to have
FR.4	The roads designer should support having a slope on the roads	Road slope	Good to have
FR.5	The Cross section of the road in the scene should be realistic, as shown below:	Cross-section realism	Good to have
FR.6	Enabling/disabling water on drums should be visualized and the impact on the asphalt should be simulated	Asphalt realism	Good to have
FR.7	The simulator should provide a realistic control mechanism	Controller realism	Must-have
FR.8	The simulator should monitor and record details of the performance of users and store them for data analysis, including: (1) Compaction map, (2) Distance between compactor and paver, (3) Speed, (4) Shoulder check and gaze direction, (5) Trajectory tracking	Data collection	Must-have
FR.9	The simulator should emulate the movement of a second roller like it is operated by a real person for scenarios that have more than one roller	Second roller AI	Must-have
FR.10	The simulator should provide a dashboard in the cabin of the roller to check and change the status of the roller, in terms of (1) Vibration function, (2) Water tank status, (3) Fuel tank status, (4) Oil level status	On-board screen	Must-have
FR.11	The simulator should provide a tutorial for the users	Tutorial	Must-have
FR.12	The simulator should notify students when they make a mistake	Mistake notification	Good to have
FR.13	The simulator should support a VR headset for the assessment of situational awareness	VR support	Must-have
FR.14	The simulator should share the player's view on a big screen in the classrooms for all people in the room	Share screen	Must-have
FR.15	The simulator should record the performance of students and provide a video playback feature to go through step by step in training sessions	Video playback	Must-have
FR.16	In the case of the availability of multiple screens, the system should use them as mirrors (in non-VR mode)	Multiple displays	Good to have
FR.17	The environment in the simulator should be dynamic and includes moving entities (people, vehicles)	Environment realism	Good to have
FR.18	The simulator should provide realistic sounds	Sound realism	Good to have
FR.19	The simulator should use realistic 3D models and enough details in the surrounding environment	Visual realism	Good to have
FR.20	The environment should be based on sensed data for temperature and vehicle movement	Context-realism	Must-have
FR.21	The simulator should support the visualization of the simulated and planned projects	Project planning	Must-have
FR.22	The simulator should support the application for virtual prototyping	Virtual prototyping	Must-have

Chapter 5. Framework Development

This chapter presents the developed framework for the compaction training simulator. The first step in the development of the framework is the identification of use cases that addresses the functional requirements presented in Table 11. Next, the use cases are used as the beacon for the development of the framework.

5.1. Use cases

As mentioned in Section 2.2, a use case represents the specific manner in which the users interact with the system in order to perform a task. Therefore, a use case includes actors. i.e., users, tasks, and the interaction between the actors and tasks. Table 12 shows the main six use cases that need to be supported by the training simulator. A detailed description of each use case is presented below.

Table 12. List of different use cases for the training simulator

ID	Use Case	Actor(s)	Associated Requirement(s)
UC.1	Generate a customized training scenario	Instructors, Researchers	FRs. 2, 3, 20
UC.2	Design and Implementation of tutorial/quiz	Trainees, Operators	FR. 11
UC.3	Perform a training session in the simulator	Trainees, Operators	FR. 1, 4~7, 9, 10, 12, 16~19
UC.4	Review the performance of trainees	Trainees, Operators, Instructors	FRs. 8, 14, 15
UC.5	Evaluate Situational Awareness	Instructors, Researchers	FR.13
UC.6	Visualize simulated/planned projects	Planners, Researchers	FR.21
UC.7	Support virtual prototyping	Researchers, operators	FR.22

1) **Scenario Generation:** as shown in Figure 4, in this use case, instructors and/or researchers s interact with the training simulator to build a custom training scenario through modifying the parameters discussed in Section 3.3. Also, since the simulator is expected to be context-realistic, the users should be able to import the actual temperature and equipment movement into the scenario.

   This use case would require the development of a scenario builder module that can receive the parameters of the scenario form the user through a user interface and then build a custom training scenario as an output.
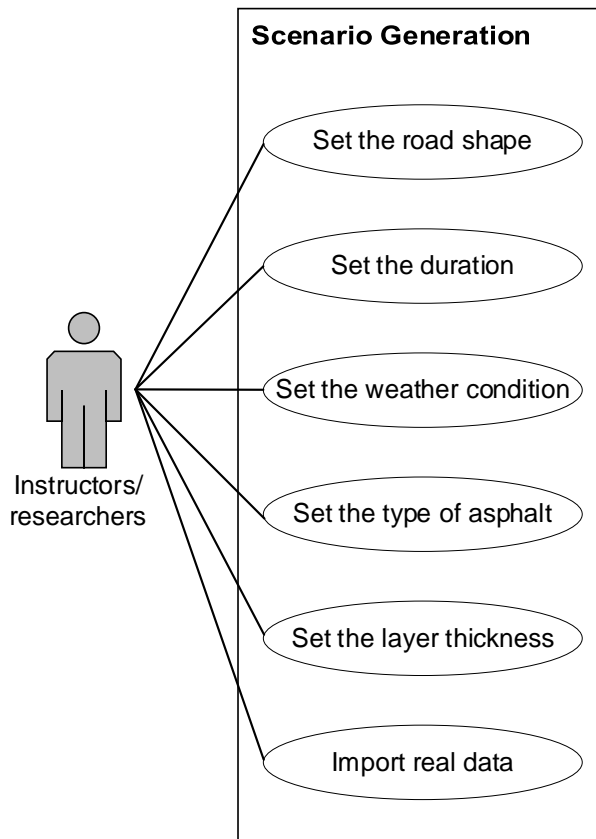
Figure 4. Use case diagram for scenario generation

2) **Tutorial/Quiz Design and Implementation:** Before the training session begins, the simulator provides a set of tutorial content to familiarize the student with the control mechanisms of the simulator. Figure 5 presents the diagram for this use case. Also, in case the simulator is used for research purposes, e.g., assessing SA, specific and custom-made quizzes can be provided to the trainees/operators to assess their departure point knowledge about the subject of the research. The quizzes and specific tutorial materials need to be designed/programmed specifically for each type of research. In other words, the simulator does not provide a specific module for the design of tutorials/quizzes, and these needed to be hard-coded in the system for every specific research goal.
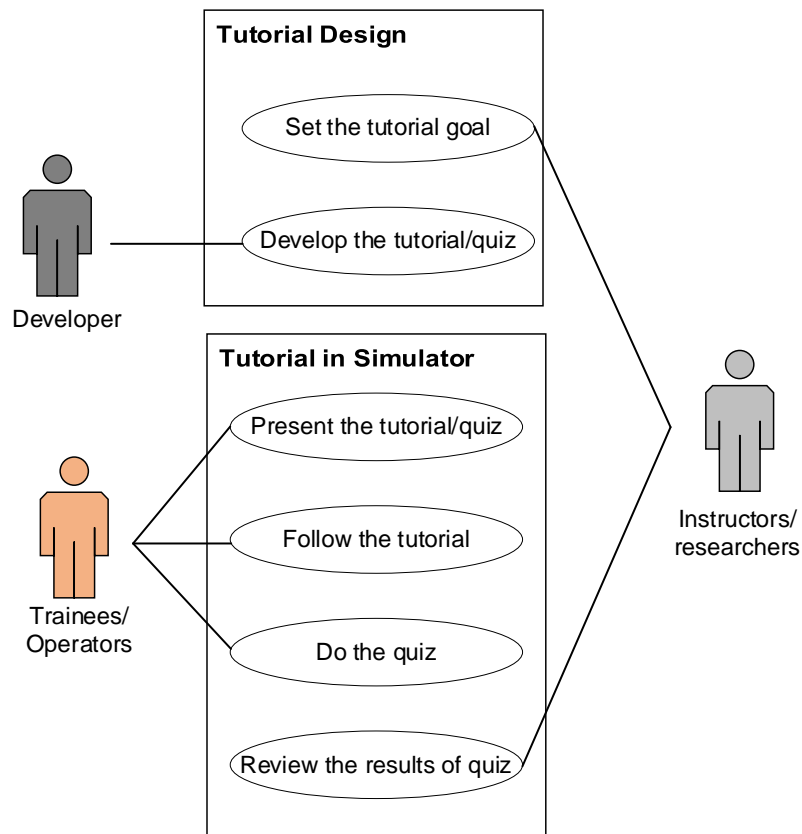
Figure 5. Use case diagram for tutorial/quiz design and use

3) **Training Session:** as shown in Figure 6, in this use case, trainees/operators will start a training session and log in with his/her credentials. Then, the control devices (steering wheel, joysticks, pedals, etc.) are used to move the roller and perform the compaction of the asphalt layer. During this operation, required operator support information (e.g., a map visualizing the number of compaction passes performed on different parts of the asphalt mat) can be provided to the trainee/operator upon request. The trainee/operator can use the keyboard to choose the kind of operator support information (e.g., no information at all, only the temperature data, the priority map, etc.) he/she wants to use. Also, information about the equipment status can be provided upon request. If the trainee/operator makes a mistake (e.g., collides with other equipment) the simulator provides a warning. As the roller moves on the asphalt, the trainee/operator can see changes to the asphalt layer in terms

of the number of compaction passes and changes in the temperature. Finally, in case there are other rollers in the scenario, the trainee/operator can see the movements of the other equipment.
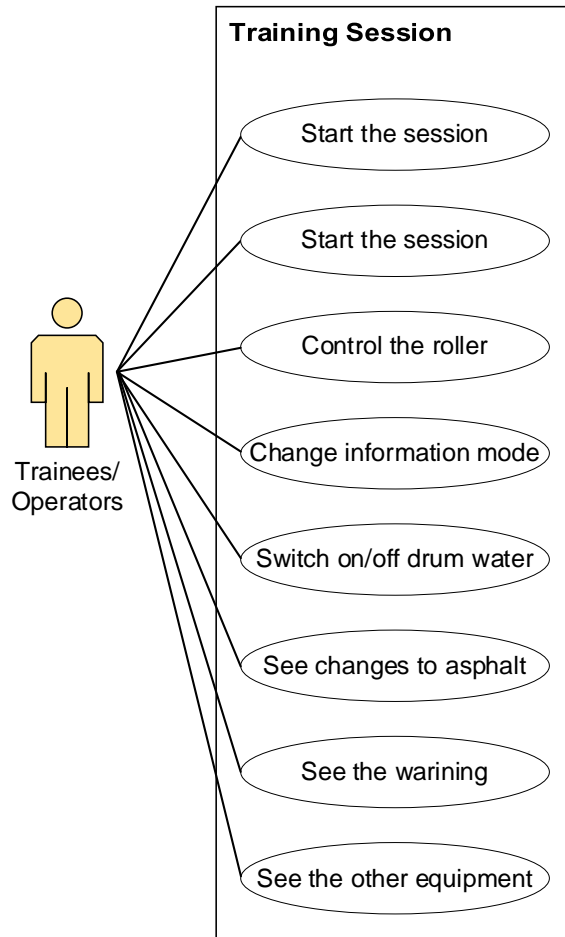

Figure 6. Use case diagram for the training session

4) **Performance Review:** The next use case concerns the use of the simulator for the review of the training session completed by trainees/operators, as shown in Figure 7. For this purpose, the simulator should be able not only to record the entire session but also to analyze the performance of the trainees/operators in terms of several performance metrics. These metrics include the map about the degree of compaction at different parts of the road, the average distance between the roller and the paver, average speed, and shoulder check. The simulator should be able to playback the entire performance of the trainees/operators on demand and present this on the big screen in the classroom setting.
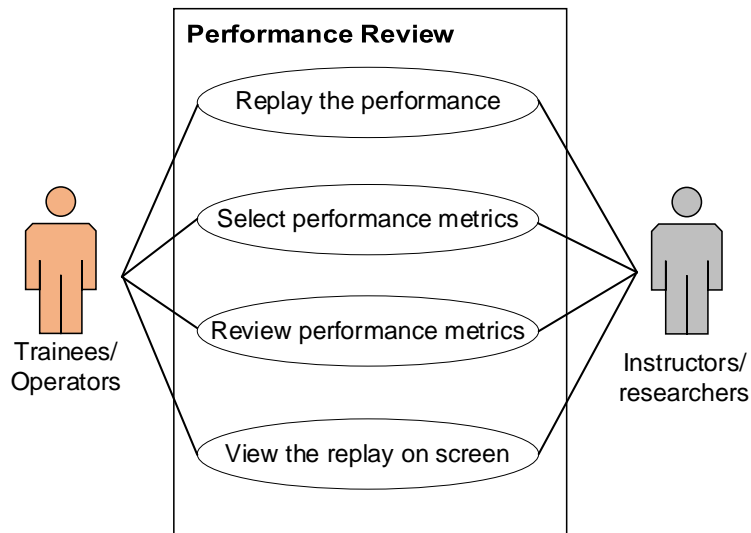
Figure 7. Use case diagram for performance review

5) **Situational Awareness Evaluation:** A specific use case demanded by researchers from the OWK group was the support for the evaluation of SA. This case study required the trainees/operators to use VR headsets and pay attention to their surroundings while operating, as shown in Figure 8. Therefore, in this use case, the researchers would define the core subject of situational awareness evaluation and the specific metrics that need to be tracked during the operation. The developer, then, uses this information to develop (1) the elements required for the presentation of specific context elements (i.e., safety cones, road barriers, heavy rain, etc.) required for the evaluation of SA, and (2) metrics required for the assessment of SA. Closely linked Use Case 3, SA evaluation requires pre- and post-training tests. Therefore, the researchers can go through Use Case 3 to develop specific quizzes/tests needed for the SA assessment and implement them here.
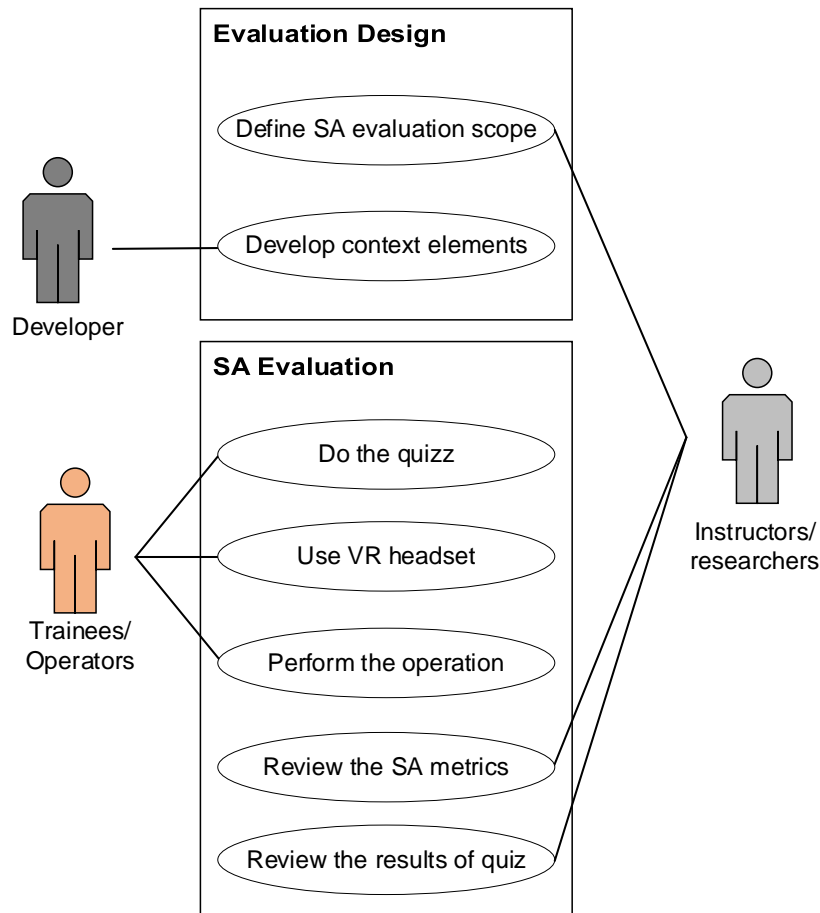
Figure 8. Use case diagram for SA evaluation

6) **Project Planning:** As mentioned in Section 3.2, one high-level requirement from the CME researchers was the ability of the simulator to support the visualization of planned/simulated operations. Basically, this use case would require the simulator to be able to use inputs from the operation planners and visualize the entire operation. As shown in Figure 9, in this use case researchers or project planners provide the details of the planning data into the simulator, and then the results are visualized. It is noteworthy that it is not the function of the simulator to convert the planning parameters into detailed operational parameters (e.g., motions of the rollers). This task is done by a detailed ABS model that is specifically designed for this purpose. Instead, the simulator is only expected to provide functionality for the visualization of the results coming from the ABS model. Once the planned project is visualized, the research/planner can use the same performance metrics

mentioned in Use Case four to assess the fitness of the plan. Please note that in this specific use case, the functionality of the simulator changes from an interactive platform, where a human agent controls a roller, to a visualization platform, which only replays the data from a simulation model.
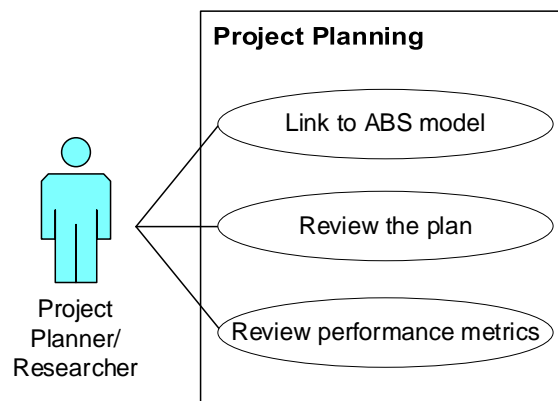

Figure 9. Use case diagram for project planning

7) **Virtual Prototyping:** The final use case for this simulator addresses the last requirement mentioned in Section 3.2, which is about virtual prototyping. In this use case, the simulator should support experimentation with new technological ideas. To further elaborate on this point, CME researchers have been actively developing new ideas for operator support systems that can help roller operators perform compaction more efficiently. However, the implementation and testing of these ideas on actual compaction projects proved to be very difficult mainly because operators are not willing to take the risk of experimenting with still unproved technologies. This introduces a major challenge in the development of operator support systems. However, the training simulator can be used as a virtual prototyping platform where the operator can comfortably test new technological ideas without the fear of the implications on their operation. As shown in Figure 10, in this use case, the researchers develop the concept of the new technological solution and ask the developer to implement it in the simulator. Operators can use

the training simulator to complete a task. At the end of the session, the researchers can review the performance of the operators and compare the performance before and after the user was exposed to the new technology.
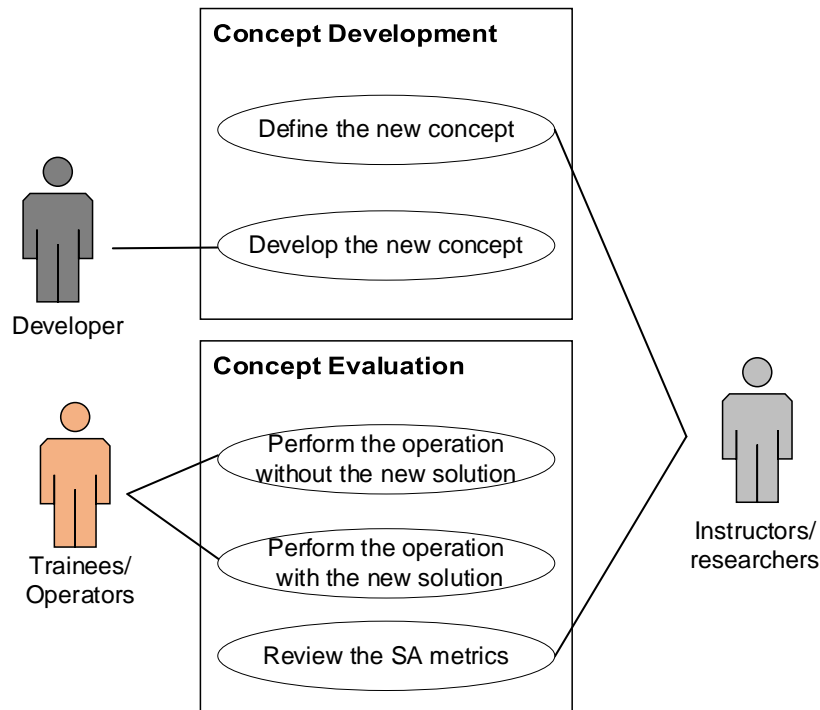

Figure 10. Use case diagram for project planning

As mentioned before, the above use cases are defined based on the high-level requirements of the stakeholders and also the expected functional requirements. These use cases define the scope of the training simulator and guide the development process, as will be explained in the next section.

5.2. Framework for the Compaction Training Simulation

Figure 11 presents the overview of the proposed framework. As shown in this figure, the framework consists of 5 main modules that will be utilized by instructors/researchers, developers, and trainees/operators to execute the use cases presented in Section 4.1. The 5 modules include, (1) Scenario Generator module, (2) Dynamic module, (3) Control module, (4) Information module, and (5) Visualization module. The remainder elaborate on this framework.
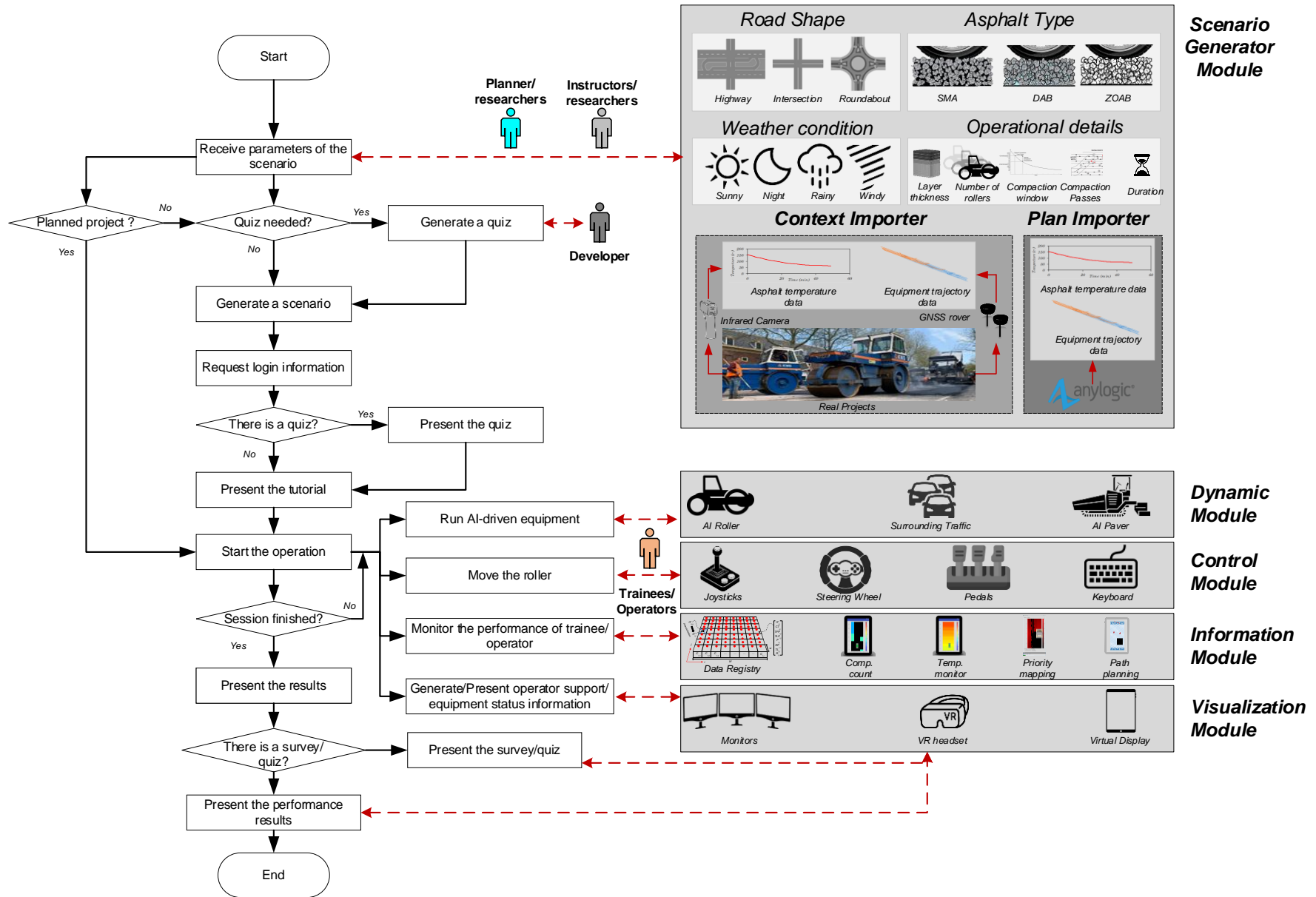
Figure 11. Proposed framework for parametric and context-realistic compaction training simulation

5.2.1. Scenario Generator Module

As shown in Figure 11, the framework starts by requiring the user, i.e., instructors/researchers, to define the core parameters of the training scenario. As discussed before, a scenario is defined in terms of the preferred road shape, asphalt type, weather conditions, and operational details. Road shape can be a choice from any of common road parts such as straight stretch, intersection, or roundabout. Ideally, it should also be possible to combine different road parts to make complex and compound roads, but as will be discussed in the next chapter, this feature was not implemented in this research. This is primarily because, from the training perspective, each type of road part requires a specific and distinctive compaction strategy that trainees need to be familiarized with separately. Learning about these strategies for each road type can be enough content for a training session and therefore training in the compound road may not have much merit (or practical relevance) in the scope of one training session. Nevertheless, this feature can be useful for expert operators/project planners who may want to use the simulator for the purpose of planning upcoming complex projects.

The next parameter of the scenario is the asphalt type. Different types of asphalt require different compaction strategies in terms of vibratory compaction, number of compaction layers, etc. Therefore, it is important for the asphalt type to be specified and then communicated to the trainee/operator. Please note that the selection of the asphalt type is more relevant from the standpoint of the compaction strategy and not specifically for the purpose of accurate visualization. It is important to highlight that the accurate visual representation of the asphalt type increases the computational cost of the simulator and imposes a high computing power requirement. As a result, although high visual fidelity is found to be appealing, bearing in mind the afore-mentioned trade-

37

off, this research found the added value of accurate visual representation marginal at this stage of development. Needless to say, in the future development of the simulator into a commercial unit, this assessment can change.

Weather condition is the next parameter that needs to be defined. The time of the day and precipitation condition is a significant determinant of asphalt cooling behavior. Consequently, it is important to specify the weather condition and capture its impact on the asphalt cooling behavior. The cooling behavior of the asphalt is commonly a non-an exponential decay function, as shown in Figure 12. The impact of weather conditions and time of the day on asphalt cooling can be captured from statistical historical data or literature, as shown in Figure 13. As will be explained in Section 4.2.4, each cell of the asphalt will cool down based on its randomly generated initial temperature, weather condition, and time of the day.
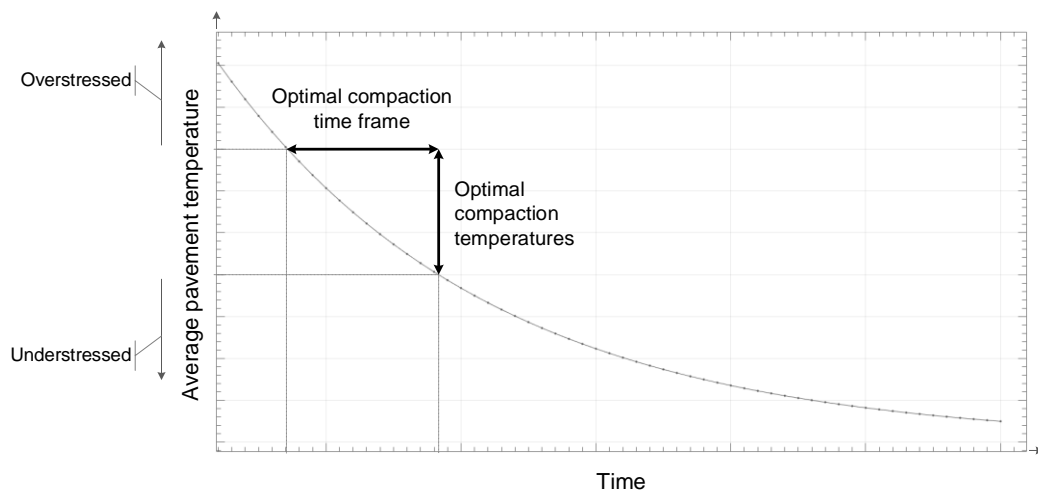

Figure 12: Example of the cooling curve of an asphalt mixture (adapted from Timm et al. 2001)
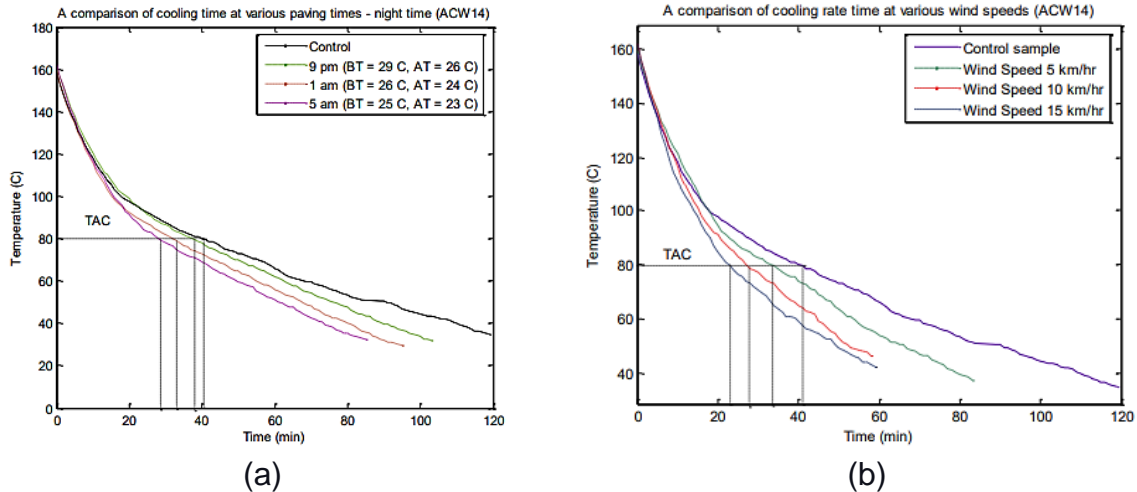
Figure 13: Example of the impact of (a) time of the day, and (b) wind speed on asphalt cooling rate (adapted from Hashim et al. 2015)

Next, the operational details of the scenario need to be specified. This includes the determination of layer thickness, the number of rollers (i.e., single-roller compaction or multiple-roller compaction), the compaction window, the number of required compaction passes, and operation duration (or alternatively size of the road). Layer thickness has an impact both on the visual representation and the required compaction strategy. The number of rollers would determine whether the trainee/operator is solely responsible for the entire compaction or whether he/she needs to collaborate with other rollers. It is important to mention that in the case of multiple-roller compaction, the supporting rollers are driven by the Artificial Intelligence (AI) agent. In other words, these rollers are controlled automatically by the simulator following an agent behavior, as will be explained in Section 4.2.2. The compaction window refers to the temperature range at which asphalt can be best compacted, as shown in Figure 12. In order to achieve quality compaction, operators should strictly refrain from compaction of the asphalt layer if the temperature is above or below this range. Therefore, it is important for the scenario designer (i.e., instructors/researchers) to specify the compaction window. This can be done by simply inputting the upper and lever temperature threshold in the scenario generator. The number of required compaction pass also

needs to be specified. This has significant implications on how much time trainees/operators would have in each session as they are expected to properly compact all parts of the asphalt within the compaction window. Finally, duration simply specifies the designated time for the training session. This can be specified either directly through capping the training session or by mentioning the size of the road (e.g., the length of a straight segment).

The next input in the scenario generator module is the context data. This is an optional input and scenario generators will decide whether they want to use data from the actual project or they want the simulator to simulate the equipment movement and asphalt temperature. In case, the designer decides to use data from the actual project, it is important that the equipment motion data has the right structure. In other words, the location of the paver and rollers need to be specified in terms of the time series coordinates and the time stamp. The simulator then converts the coordinates to the local coordinate system of the VR environment. As for the temperature data, the input should be in form of an asphalt cooling curve shown in Figure 12. A more detailed discussion of how this conversion is made can be found in the proposed framework by Vahdatikhaki et al. (2019).

Finally, as mentioned in Section 4.1, it should be possible to generate a scenario based on a simulated/plan project. In this case, the simulator will receive all the afore-mentioned parameters from an ABS model. As mentioned in Section 4.1, it is important to note that in case information is imported from a simulation model, and since the use case is no longer about training, no equipment needs to be controlled by a human operator. In other words, in this use case, the simulator is an interactive environment and it becomes only a visualization platform.

Once the user defines the parameters of the scenario, the simulator proceeds to generate the scenario based on the inputs. As shown in Figure 11, in case data is imported from a simulation model, the framework directly proceeds to the visualization step. In case, the simulator is supposed to be used for SA assessment, the developer will generate the specific quizzes designed by OWK researchers and add them to the beginning of the scenario. It should be highlighted that since this project is only providing the instrumentation for SA assessment, the discussion of the analysis components and the SA-related quizzes is out of the scope. The product of this research is only supposed to provide support for this type of study. In all cases, except visualization of the planned project, the simulator would, then, require the trainees/operators to log in using their ID. If there is a quiz in the scenario, the users need to take the quiz before the start of the training session. The final step before the commencement of the training session is the tutorial. The developer has developed a static and text-based tutorial that explains how the control mechanism of the simulation functions. In case trainees/operators are already familiar with the simulator, they can skip the tutorial.

Once the tutorial is completed, the simulator proceeds with the training or visualization session. During the training session, the following four modules, namely, Dynamic, Control, Information, and Visualization modules, work in parallel to allow trainees/operators to interact with the training scenario. Each one of these modules is responsible for a specific form of user-simulator interaction. The delineation of these specific responsibilities will be provided in the following four sections.

5.2.2. Dynamic Module

The dynamic module is responsible for the representation of elements of a dynamic site. This includes the automatic control of rollers (in multiple-roller operation), the

surrounding traffic, and the paver. In the case of surrounding traffic, simple car traffic libraries can be used to generate surrounding traffics of different densities. As for the roller and paver, the agent behavior models shown in Figure 14 can be used to mimic the behavior of these pieces of equipment. It should be noted that these agents are only used if the context data about the rollers and pavers from the actual site are not used. These models were derived from the work done by CME researchers (Revollo 2021). This project only implemented the model presented in the afore-mentioned research. Therefore, a more detailed account of how these agents function can be found in the work of Revollo (2021). In simple terms, the paver moves in a straight line (or around the roundabout) as long as there is asphalt in the hopper. When the hopper is empty, the paver stops and waits for the next truck to arrive. The truck arrives to the site based on a fixed and pre-defined rate. As for the roller, it first positions itself at the beginning of the designated area and then waits until the paver is at a minimum distance from the roller and the temperature is within the compaction window. When these conditions are met, the roller keeps compacting a predefined length for as long as the conditions are still valid.
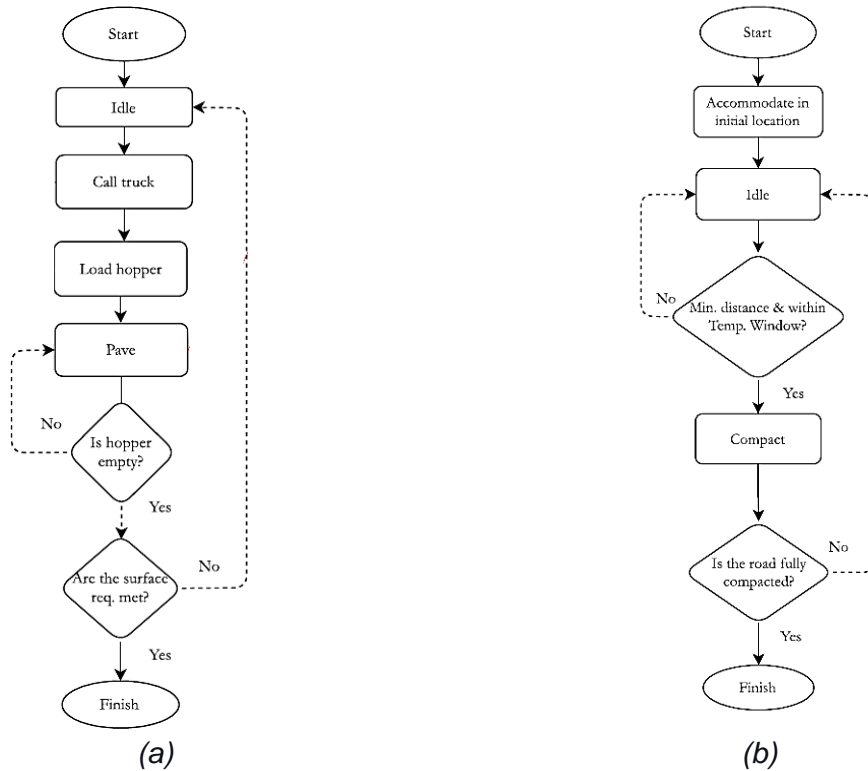
Figure 14: Agent model for (a) paver, and (b) roller (adapted from Revollo 2021)

5.2.3. Control Module

The next module in the simulator is the control module. As the name suggests, this module is responsible for controlling the roller in the VR environment. The controllable elements include the speed and heading of the roller, breaking, switching between different information display modes (will be explained in the next section), switching the water on drum function on/off, and switching the drum vibration on/off. This will be done through a joystick, gaming steering wheel, gaming pedal set, and keyboard. It should be highlighted that some commands can have redundancy in the sense that they can be controlled both by the keyboard and the joystick.

5.2.4. Information Module

As mentioned earlier, it is important that the performance of the trainee/operator is monitored and analyzed in the simulator. Besides, it is important to be able to provide the user with relevant information about the operation and the status of the equipment. These tasks are assigned to Information Module. Therefore, this module is responsible

for the provision of different types of information on the virtual displays placed inside the virtual roller cabin, as shown in Figure 15.

Before elaborating on the type of information provided to the users in this simulator, the core principle behind the modeling of the asphalt layer needs to be explained first. In essence, the virtual asphalt layer is presented in the same fashion compaction operator support systems collect information from the actual asphalt layer, which is explained in the work of Makarov et al. (2021a). Briefly, the virtual asphalt layer is a rasterized representation of the actual asphalt layer. In this form of representation, the asphalt layer is a cell grid in which each grid holds, records, and visualizes distinct information, as shown in Figure 16.
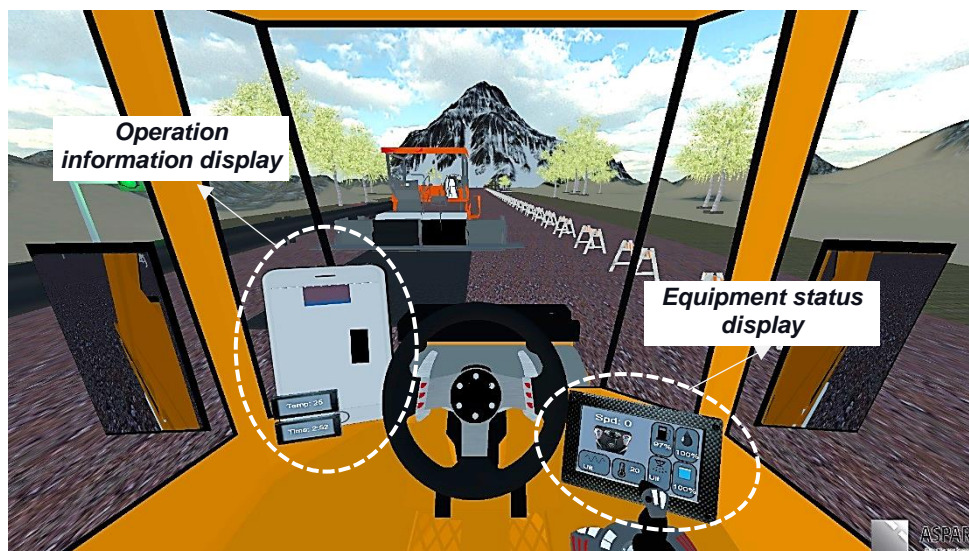

Figure 15: Placement of information displays inside the virtual cabin

As shown in Figure 16, each cell represents a part of the asphalt layer and manages an array of information about the status of that part. The main pieces of information assigned to each cell include the initial temperature, i.e., the temperature right after the asphalt comes out of the paver, the real-time temperature, temperature at first and last passes, number of passes, number of remaining passes, and time left for compaction. In the generation of these pieces of information, the simulator makes use of the user

inputs about the cooling curve, the initial temperature, number of designed compaction passes. Based on these input data, the current temperature of each cell is determined by considering the initial temperature and calculating the time since the cell appeared on the asphalt until now. With this information, the current temperature can be found using the cooling curve, i.e., Figure 12. To count the number of passes on each cell, a simple collider is used to detect any contact between the roller drum and the cell. Each contact is considered to be a pass. The number of remaining passes can be determined by calculating the difference between the target number of compaction passes and the compaction passes made at any point in time. Finally, the time left for compaction can be determined by considering the compaction window, the current temperature, and the cooling curve.
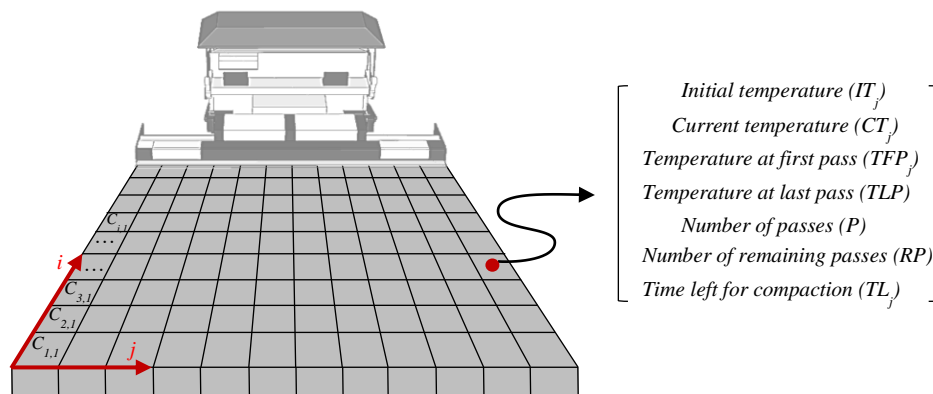

Figure 16: Schematic representation of asphalt layer rasterization in the VR environment (adapted from Makarov et al. 2022)

As explained in the work of Makarov et al. (2021a), pieces of information shown in Figure 16 are integrated to provide three modes of support for trainees/operators, namely (1) Descriptive guidance, (2) Semi-prescriptive guidance, and (3) Prescriptive Guidance. It should be highlighted that the EngD researcher in this project does not claim contributions to the conceptual/theoretical development of these support modes, as this was mainly done by other researchers in the ASPARi unit. However, the

implementation of these support modes inside the training simulator was done by the EngD researcher. While a detailed description of each support mode can be found in the work of ASPARi researchers, a brief description of each mode is presented here for completeness.

1) **Descriptive Guidance:** As shown in Figure 17, descriptive guidance mode provides a temperature plot and compaction plot to the trainees/operators, who can use this information to develop a compaction strategy. The trainees/operators can consider part of the asphalt that is within the compaction window and can decide about the length and start point of the next compaction pass based on the number of compaction passes that have been made so far. It should be considered that descriptive guidance mode only visualizes the current temperature and compaction passes in a plot, and therefore does not apply any additional processing to the raw data. As a result, it can be understood as a support mode that only describes the current state of the asphalt, and thus the name Descriptive Guidance.
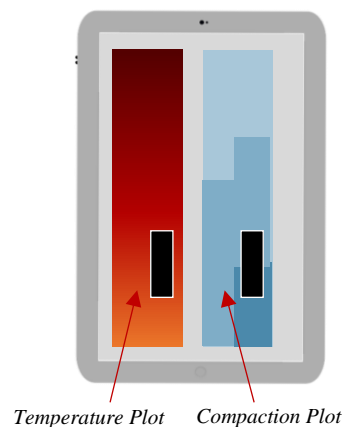

Temperature Plot   *Compaction Plot*

Figure 17: Schematic representation of Descriptive Guidance mode (adapted from Makarov et al. 2022)

2) **Semi-prescriptive Guidance:** This mode of guidance integrates pieces of information about the compaction window, the current temperature, and the

remaining number of compaction passes to assess the compaction priority of each cell ($R_{i,j}$). Compaction priority represents the degree of urgency attached to each cell with respect to how much time is left for that cell to still be compacted. This priority index is calculated using Equations 1 to 3 and ranges between 0 (lowest priority) and 1 (highest priority) (Makarov et al. 2021a). The priority map plot, shown in Figure 18 visualizes the priority index of each cell using a heatmap.

$$R_{i,j} = CP_{i,j} \times TP_{i,j} \qquad\qquad \text{Eq. 1}$$

$$CP_{i,j} = \begin{cases} \dfrac{PD - P_{i,j}}{PD} & PD \geq P_{i,j} \\ 0 & PD < P_{i,j} \end{cases} \qquad\qquad \text{Eq. 2}$$

$$TP_{i,j} = \begin{cases} 0 & TL_{i,j} > t_c \\ \dfrac{t_c - TL_{i,j}}{t_c} & 0 < TL_{i,j} \leq t_c \\ 0 & TL_{i,j} = 0 \end{cases} \qquad\qquad \text{Eq. 3}$$

Where:

$R_{i,j}$: Priority of cell i and j
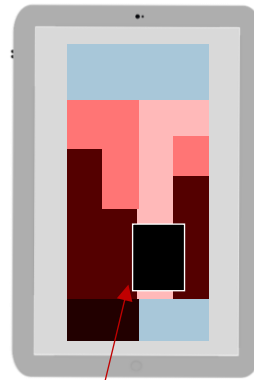*$CP_{i,j}$: Compaction priority of cell i and j*
$TP_{i,j}$: Temperature priority of cell i and j
PD: Desired number of compaction (number of roller passes)
$P_{i,j}$: Compaction achieved at cell i and j (number of roller passes)
TC: Maximum possible compaction time
$TL_{i,j}$: Time left for compaction of cell i and j

Priority Index

Figure 18: Schematic representation of Semi-prescriptive Guidance mode (adapted from Makarov et al. 2022)

1) **Prescriptive Guidance:** As the name suggests, this guidance mode prescribes a specific trajectory to trainees/operators and requires them to follow this

trajectory, as shown in Figure 1. The detailed description of how this trajectory is determined is out of the scope of this research and can be found in the research of Makarov et al. (2022). However, for completeness, a brief explanation is provided here for completeness. The trajectory planning is essentially done in two steps. Firstly, the length of the compaction section, i.e., *L* in Figure 19, is determined in such a way that (a) all the cells in this section can be compacted fully within the right compaction temperature window, and (b) after the completion of compaction in this section there is a section of equal (or greater) length available ahead of this section so that the compaction can continue uninterruptedly. Second, once the length of the compaction section is determined, a typical compaction trajectory, i.e., the red line in Figure 19, is mapped to the size of the compaction section. This calculation process would require all pieces of information presented in Figure 16 to determine the appropriate compaction length.
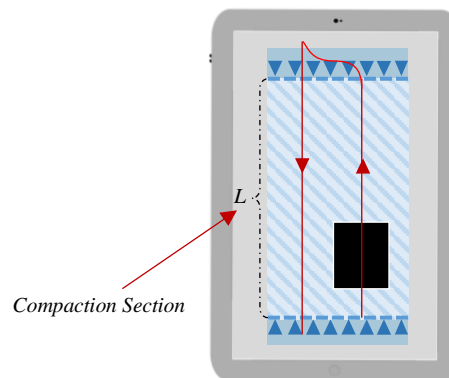

Figure 19: Schematic representation of Prescriptive Guidance mode (adapted from Makarov et al. 2022)

The equipment status display, shown in Figure 15, presents information about the speed, fuel level, water level, oil level, ambient temperature, vibratory compaction state (i.e., on/off), and drum water spray state (i.e., on/off). The presentation of this information to trainees/operators is an integral part of SA assessment.

48

5.2.5. Visualization Module

The module responsible for the visualization of the scenario to the users is called the visualization module. Essentially, this module enables the users to choose from the multi-screen setup or VR headset setup, as shown in Figure 20. In a Multi-screen setup, one or several displays are used to immerse the user in the VR environment. In a VR headset setup, the users are required to wear a headset and navigate the scene through head movement. It should be noted that even in the VR setup, the view of the operator is projected on a screen in order to enable instructors/researchers to observe the performance of trainees/operators. The main advantage of a VR headset would be that because it allows for head tracking, the gaze direction of the users can be traced. This can be very well used in SA assessment research where it is important to monitor how the user pays attention to the surroundings of the operation.
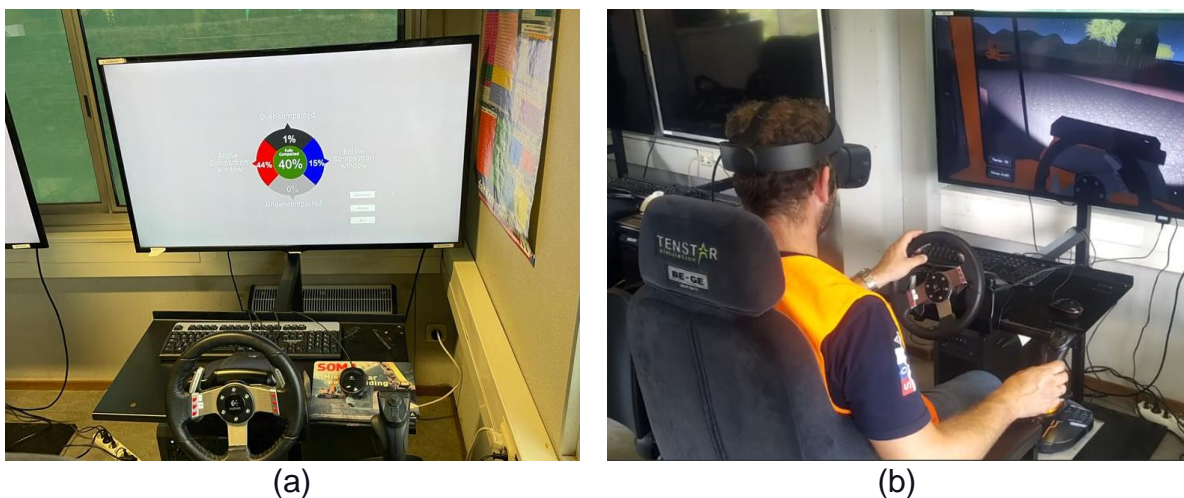

(a)   (b)
Figure 20: (a) multi-screen and (b) VR headset setups for visualization

Finally, the virtual displays in the cabin, as shown in Figure 15, provide the visualization of information elements that were discussed in Section 4.2.4.

As mentioned in Section 4.2.1, the four modules would function in parallel to enable user-simulator interaction. This interaction continues as long as the training session is ongoing. Upon the completion of the user interaction, the simulator proceeds to present trainees/operators with a new set of questions/quizzes, in case it was in use for SA

assessment purposes. In all use cases, the training session is concluded by the presentation of the performance indicators to the users.

The main performance metrics used in this simulator are, the Effective Compaction Rate (ECR), and percentages of cells that were (1) under-compacted, (2) over-compacted, (3) compacted below the compaction window, and (4) compacted above the compaction window. The ECR is calculated using Equation 4, as previously discussed in the work of Makarov et al. (2021a). In a nutshell, it accounts for the number of cells that have been compacted exactly for target compaction passes ± k and at least p% of the compaction passes were within the compaction window.

$$ECR_{p,k} = \frac{n_{p,k}}{N} \qquad \text{Eq. 4}$$

Where:

$n_{p,k}$: the number of cells that have been compacted exactly for target compaction passes ± k and at least p% of the compaction passes were within the compaction window
N: the total number of cells

The above-mentioned metrics allow instructors/researchers to objectively assess and monitor the progress of trainees/operators.

Chapter 6. Implementation

This chapter discusses the implementation of the framework presented in the previous chapter as well as different case studies that were conducted to validate the proposed framework.

6.1. Implementation of the prototype

A prototype of the proposed compaction training simulator. As shown in Figure 21, the prototype has 3 main parts, namely, hardware components, software components, and an information exchange interface. These parts are integrated into Unity3D (2022) as the main development platform. Unity 3D is selected as the main development platform because it is fast and well-integrated with VR headsets. It can also provide many of the most crucial built-in features that a game/simulation requires. Physics, 3D rendering, and collision detection are examples of these features. This means that there is no need to reinvent the wheel from the development standpoint. Rather than starting a new project by designing a new physics engine from the ground up, which would include calculating every movement of each material or the way light should bounce off different surfaces, one could reuse existing assets and libraries. Asset Store is essentially a repository for developers to upload their work and make it available to the public. For example, if we need a fire effect but don't have time to make one from scratch, we might be able to discover one online.

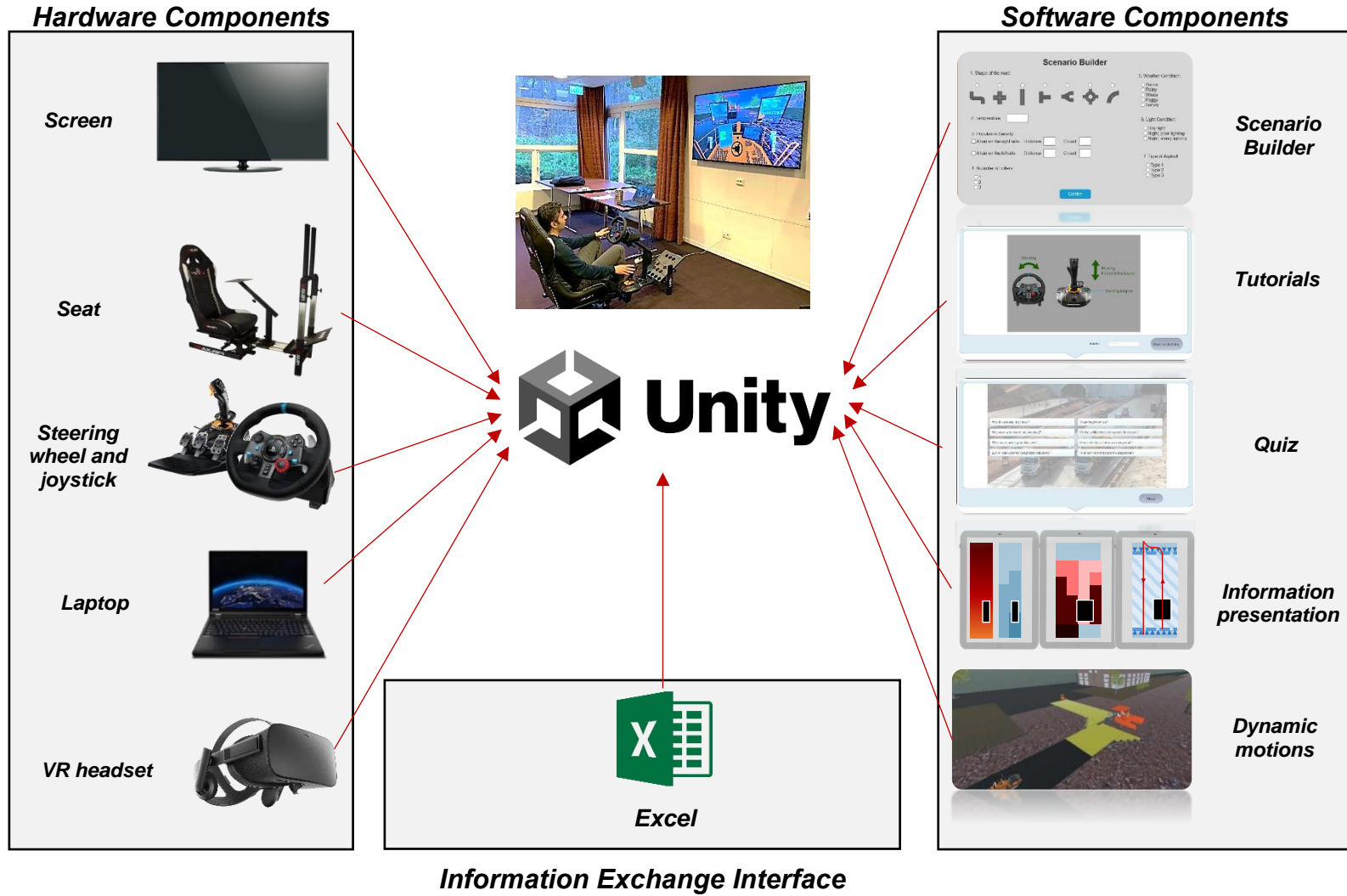The following subsections outline different parts of the system.

51

Figure 21: Structure of the prototype

6.1.1. Hardware Components

In this prototype, the GameSeat Pro+ was used as the main platform of the simulation. A flat panel LED TV (Samsung LED screen, 43 in.) was mounted on the platform as the screen. A Logitech G29 steering wheel and joystick were used as the control elements for user interaction. As the processing unit, a laptop with the following specifications deem to be sufficient: i7 H or K series CPU (H series are designed for gaming and VR purposes, K series are unlocked CPUs and designed for achieving high clock rate), and an at least an Nvidia RTX 2060 (the most affordable VR ready Graphic card in the market).

As for the VR headset, there are two dominant brands in the market, namely, HTC Vive, and Oculus rift. The prototype system is independent of headset type and both of them are adequate. However, Oculus has been selected for development because it is cheaper, and it will reduce the total price of our product (around 400 Euros). Another VR option could be Oculus Quest, which is a standalone headset that runs applications without a PC. It is powered by an Android OS and therefore it can be considered a development experience and user experience pretty similar to Samsung Gear. They are two affordable options, but they are limited in the processing unit and a reduction in quality or accuracy is needed in order to use these devices. PlayStation VR can be used for PC applications but it does not have a built-in processing unit, so it needs the PlayStation 4 as the processing unit when connected to the PC. Accordingly, it is not an affordable option.

6.1.2. Software Components

The first component of the prototype is the scenario builder. As explained in Section 4.2.1, instructors/researchers need to navigate through a number of parameters to set

up a custom training scenario. Figure 22 shows the interface developed for scenario design.

Figure 22: Scenario Builder interface

The following parameters are considered in the implementation.

1. **Type weg:** this parameter allows the designer to choose one of the "Snelweg" (Highway), "Kruising (T-Section)", or "Rotonde" (Roundabout).as the type of road. "Snelweg" is considered the easiest and "Rotonde" is the most difficult one. While the parameters are basically about the geometry of the road, some other elements of the scenario might be changed based on the geometry. If a highway is selected, the paver starts from the edge of cold asphalt. Some barriers will be placed on two sides of the road. And there will be no second roller. If the junction is selected, the second roller starts compacting with the main roller from another side of the junction. The paver starts from the third leg (the first and second legs of the junction are already paved). If the roundabout is selected, the second roller starts compacting as well, and half of the roundabout is paved already.

2. **Duur simulatie:** It determines the duration of the simulator. The user can set it from 30 seconds to 10 minutes. It is not allowed by the system to set the duration to

more than 10 because it is not recommended to work with VR goggles for more than 10 minutes continuously.

3. **Beeldkwaliteit:** The presentation quality can be set to "Weinig detail" or "Veel detail". It refers to the visual details of the asphalt. If high processing power and graphic card are available then high details can be used. If the low details option is chosen, Frame Per Second (FPS) will be reduced. Length of way is also important here, if the scenario has a long paving section, it is recommended to set it to low details. The rain effect also is heavy to process, so if the scenario includes rain, it is better to use low details.

4. **Type asfalt:** this parameter indicates the asphalt type, which can be one of Stone Mastic Asphalt (SMA) set "SMA", Dense Asphalt Concrete (DAB), or Porous Asphalt (ZOAB).

5. **Weer:** Two weather conditions can be normal or rainy. Setting the weather to rainy reduces eyesight and also makes the asphalt cool down faster.

6. **Lengte van de weg (voor snelweg):** This parameters determines the length of the way in meters. This parameter only works if a highway road is selected. The range can vary between 50 to 200 meters.

7. **Lichtstatus:** The scenario can be either in the morning or at night. If this parameter is set to night, the lights of the site and the machines are turned on automatically. In general, having the operation at night is more difficult because of the limitation in eyesight.

8. **Laagdikte:** This parameter is the thickness of the layer of the asphalt, which can be one of 3 cm, 5 cm, or 9 cm.

9. **Omgevingstemperatuur (°C):** With this parameter, the ambient temperature can be set, which is independent of the weather condition.

10. **Soort device:** With this parameter, the visualization of the scenario can be set to either a VR headset or display. The system automatically detects multiple monitors and uses them as mirrors. The orientation and placement of monitors which is used as a mirror can be adjusted outside the simulator environment.

11. **Compaction temperature window (°C):** This parameter would require instructors/researchers to specify the lower and upper temperature threshold for compaction.

12. **Desired number of compaction:** The final parameter is about the target number of compaction passes. This would determine how many passes the trainees/operators need to make to ensure full compaction.

As mentioned in Section 4.2.1, the developed framework supports not only the import of temperature data but also motion data of rollers and pavers. This functionality is especially useful for the use case of project planning. This function was developed as part of the Scenario Builder component. Figure 23 presents the interface developed for the importing of (planning/simulation) data and the replay of these data.
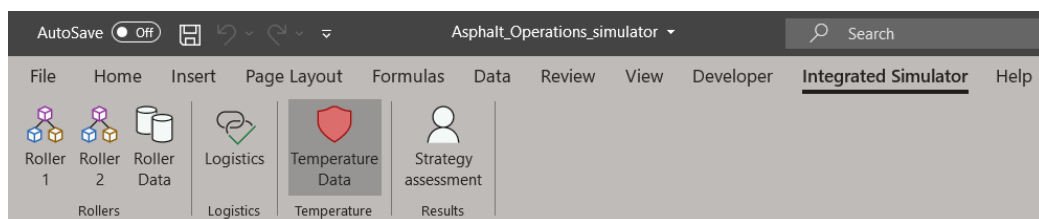

(a)
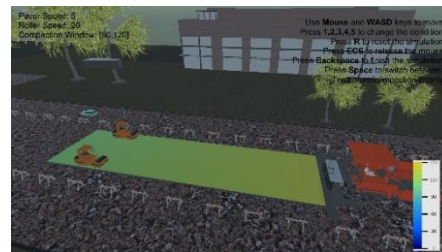
(b)

Figure 23: (a) Interface for the import of context data, and (b) the virtualization of actual sensory data in the training simulator

The tutorial components present instructions on how to operate the simulator. The tutorial is integrated with the log-in page in such a way that while the users are signing into the session, they can review the control mechanism of the simulator, As shown in Figure 24(a). Next to the textual and visual tutorial, it was decided during the implementation that perhaps an audio description of the scenario can also help trainees/operators better understand the purpose of the scenario. Therefore, as shown In Figure 24(b), an audio tutorial is incorporated into the simulator. The audio tutorial is presented to the user immediately after the textual/visual tutorial.
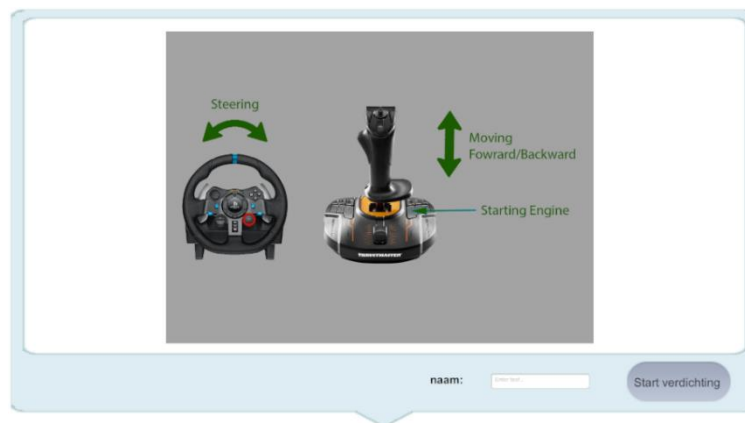
(a)
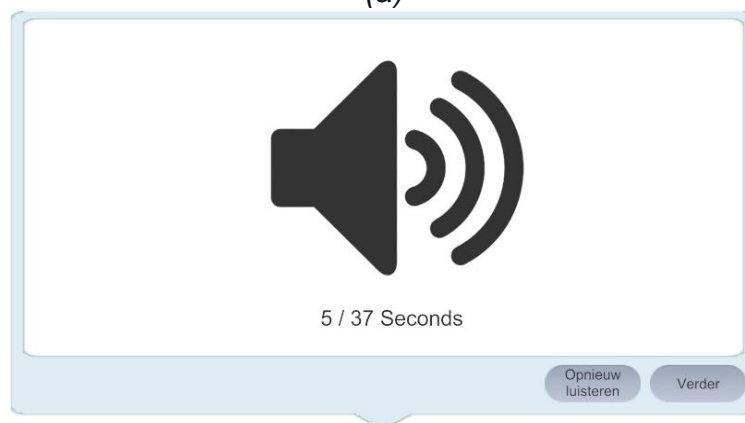
(b)
Figure 24: (a) Visual/textual, and (b) audio tutorial

After, the tutorial windows, the users are presented with a Virtual work meeting, in case the simulator is used for SA assessment purposes. In this step, users can get

information about aspects such as their job, required compaction strategies, and weather conditions, see Figure 25(a). Users get the information that they want to obtain by clicking on questions, after which the answer appears below.
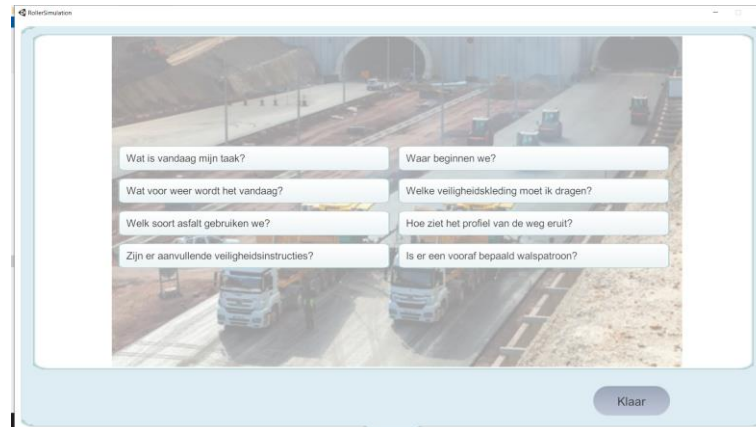
(a)

(b)

(c)

Figure 25: Interface of (a) information for the user presented as a work meeting (b) quizzes embedded into the simulator, and (c) immediate feedback to the user

Then, the user is presented with the pertinent quizzes that assess retention of information presented in the work meeting, in case the simulator is used for SA assessment purposes, as shown in Figure 25(b). If needed, scenario designers can edit the set of questions. Trainees/operators can see the result of the quizzes immediately after their responses, as shown in Figure 25(c).
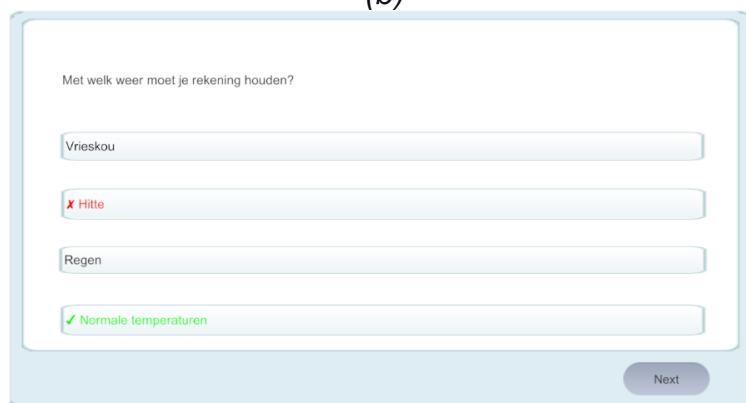
The information presentation component is not only responsible for the presentation of operator support information pieces described in Section 4.2.4, but it also hosts the calculations for asphalt temperature. Two different modes for calculating temperature are implemented: the data-driven method and the equation-based method. In the data-driven method, a set of captured data from an actual operation is used to calculate the temperature of each cell of the asphalt. This method is realistic but might not be suitable for some experiments, because, in many experiments, the operation needs to be speeded up to be able to finish a session in 10 or 20 minutes. In such cases, realistic data has little use. Therefore, the second method of temperature calculating comes in which is based on an exponential equation. The scenario designer can set up a custom cooling curve that matches the scenario.

Additionally, the Information Presentation component is responsible for the presentation of different operator support modes discussed in Section 4.2.4. These three modes are presented to the trainees/operators based on the decision of the instructors/researchers. This choice can be made both before and during the training session. Figure 26 shows how these information pieces are presented to the users.

*Temperature
contour plot*   *Compaction
contour plot*   *Priority Index*   *Guidance
with path*

(a) Descriptive Guidance   *(b) Semi-prescriptive Guidance* *(c) Prescriptive Guidance*
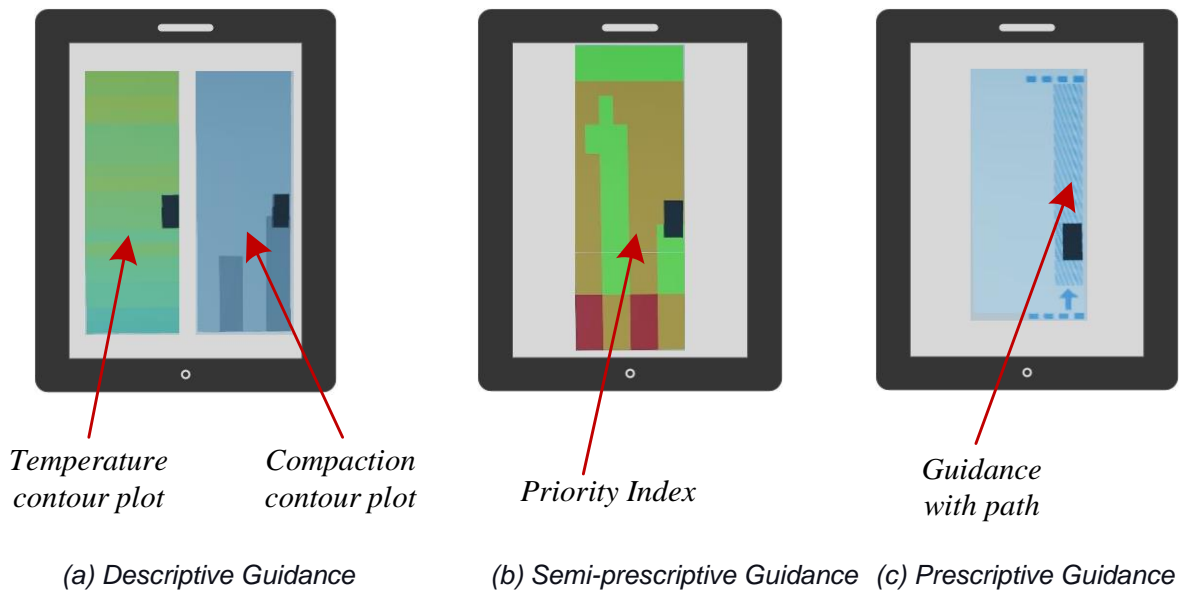
Figure 26. Three levels of support for operator support modes (Makarov et al. 2021b)

Finally, the dynamic component is responsible for the simulation of surrounding traffic and also AI-driven rollers and pavers as explained in Section 4.2.2. Figure 27 shows these dynamic elements in the simulator.

6.1.3. Information Exchange Interface

This component is specially developed for project planning and context import use cases. In other words, this component is responsible for the context and plan importer module presented in Section 4.2. Since the manner in which context and planning data are transferred to the simulator is the same, only one of them is explained for brevity. The process is exactly the same except for the fact the data for one use case comes from tracking devices mounted on actual equipment and from the simulation model in the other use case.

(a)

(b)

Figure 27. Dynamic elements in the simulator (Makarov et al. 2021b)
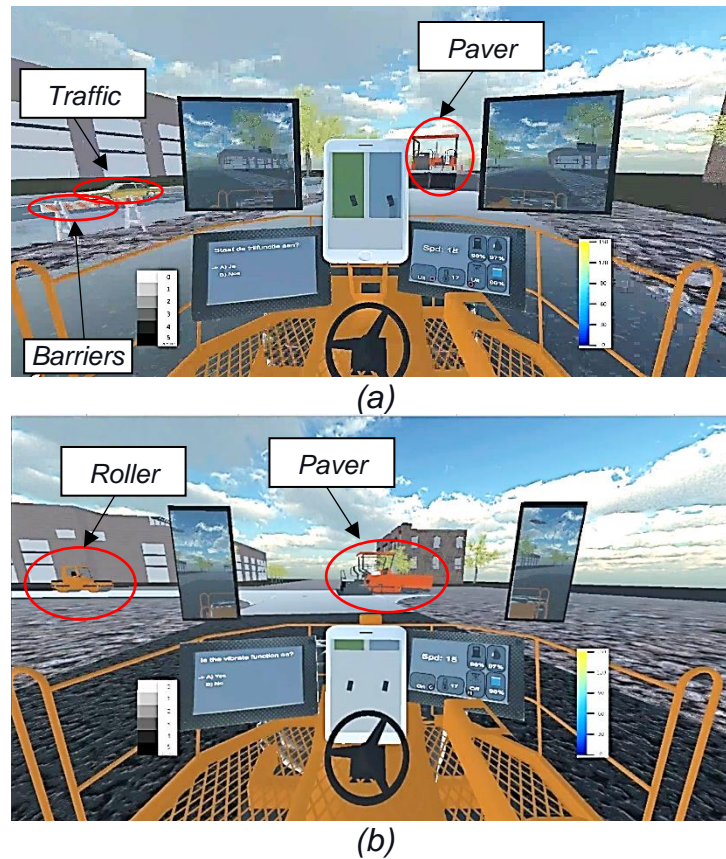
As explained in Section 4.1, one potential use case of the simulator is to use it as a project planning tool. The idea is to connect the outcome of a process simulation model to the simulator so that the results can be visualized and the planners can immediately observe the consequences of their decision-making. The integration between the simulation model and the VR simulation requires a platform for data exchange. To this end, Microsoft Excel was used as an intermediator that is used to read and write information from. Figure 28 shows the integration protocol for this use case. As shown in this figure, Anylogic is used for the development of the ABS model. This model receives a wide range of decision-making variables about the characteristics of the road, transportation, paver, and rollers from planners and generates a detailed plan for roller, paver, and asphalt delivery trucks. Figure 29 shows the interface developed for the collection of planning data. The plan includes the start and end time of all activities to the level of detail (LOD) of a single compaction pass. The agent models presented

in Section 4.2.2 were developed inside this ABS model. The generated detailed plan is transferred to Excel and then the small module in the simulator reads this detailed location data. Finally, the simulator would cease the agent and user-controlled mechanism for equipment motions and just move rollers and the paver based on the location data. When needed, interpolation is used to determine the location of the equipment between the start and end events.
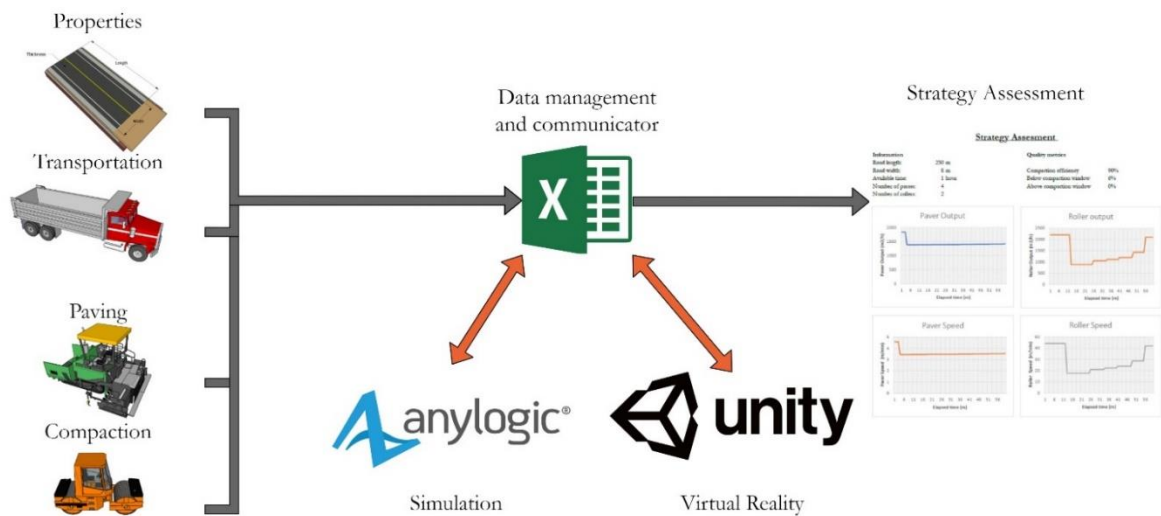

Figure 28. Integration of process simulation with the VR training simulator

Figure 29. The interface for the collection of planning data

Chapter 7. Case studies and Validation

As mentioned in Section 2.3, the developed simulator was evaluated in terms of its contributions to (1) compaction training, (2) technology assessment, (3) situational awareness, and (4) compaction planning.

7.1.1. The simulator as a Compaction Training Tool

As mentioned in Section 2.3, the first validation session was about the main application of the simulator as a training tool. For this purpose, 5 instructors and 34 trainees were asked to use the simulator in a training context. The instructors were asked to use the scenario builder to develop a custom scenario and complete a training session. Trainees were asked to complete one uniform training session. At the end of this session, the questionnaire presented in Table 5 was distributed among the participants.

Table 13 and Figure 30 present the results of this validation session. As shown in Table 13, all categories received higher than neutral scores. In comparison, customizability and usefulness have received the highest and lowest average score, with scores of 3.65 and 3.03 respectively. However, it should be highlighted that the relatively low average score in the usefulness category is due to very low scores in safety training and substitutive-ness criteria. This is quite understandable because safety training was not one of the main focal points of this training simulator, although it is very important for future development. As for the substitutive-ness of the training simulator, again, the score is quite justified and expected as the simulator has never been intended to fully replace the practical training sessions with the actual roller. This is the same for the training simulator of other types of construction equipment. To the best of the author's knowledge, none of the training schools that implement simulator-based training (i.e.,

for any type of construction equipment) has completely removed the physical practical sessions. This is mainly due to the fact that despite tremendous improvement in VR technologies, the physics realism of VR simulators is still not to the level that can fully replace actual experimentation/training with real equipment. That is why simulators have always been incorporated into training curricula in a complementary manner, i.e., to complement the existing practical sessions. The results of this research also indicate the same potential, considering a very high score in the complementarity criterion (i.e., the average score of 4). If the two criteria safety training and substitutive-ness are excluded from the analysis, then the average usefulness score increases to 3.51 which is very much in line with the other categories.

Table 13.The results of the validation of the simulator as a training tool

Category	Criterion	Instructors (5 respondents)		Trainees (34 respondents)	
		Mean	Standard deviation	Mean	Standard deviation
Customizability	Comprehensive	3.8	0.83	N/A	
	Adaptable	3.2	1.09		
	Complete	4	0		
	Fit for assessment	3.6	0.54		
	Average Score	3.65			
Realism	Engaging	3.8	0.44	2.9	0.81
	Auditory realistic	3.4	0.54	3.2	1.12
	Intuitive Control	4.2	1.17	3.9	1.15
	Responsive	3.2	0.83	3.7	1.11
	Visually realistic	3.8	1.3	3.1	0.97
	Average Score	3.52			
Usefulness	Informative	3.8	0.44	3	1.08
	Substitutive	1.6	0.89	2.1	1.06
	Safety training	1.8	0.44	2.8	1.14
	Preparative	3.8	0.2	2.7	0.87
	Skill assessment	3.2	0.83	N/A	
	Detection	3.6	0.54		
	Recommendable	4	0.7		
	Complementary	4	0.7		
	Average Score	3.03			
Usability	Easy to use	4	0	N/A	
	Easy to learn	3.4	0.8		
	Trustable	3.8	0.44		
	Reusable	3.4	0.54	2.6	1.04
	Comprehensible	4.4	0.8	3.6	0.88
	Standalone	3.6	0.49	3.5	1.30
	Reliable	3.8	0.44	3.3	0.66
	Average Score	3.58			

64

The highest-scoring criteria from the instructors' perspective were comprehensibility of visuals (4.4), intuitiveness of the control (4.2), ease of use of scenario builder (4), complementarity (4), recommendability (4), and completeness (4). More or less a similar trend, albeit in a different order, can be observed in the trainees' scores. In general, instructors seem to have given higher scores to almost all criteria, although the differences are small and there seems to be consistency in which aspects of the simulator are more appreciated.
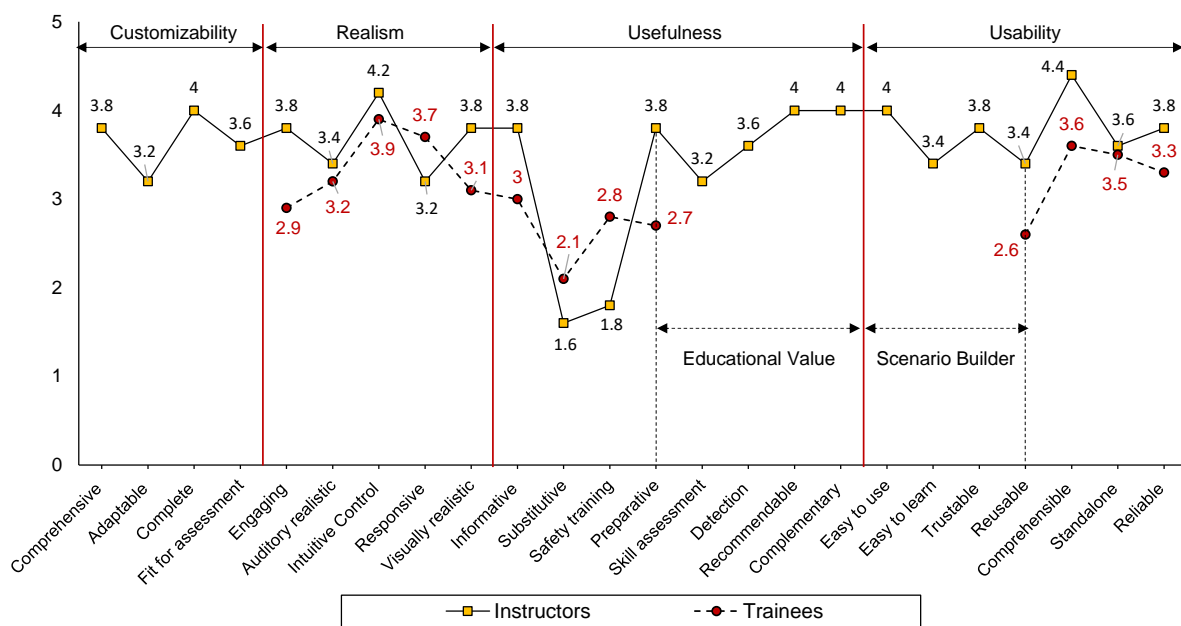

Figure 30. The results of the validation of the simulator as a training tool

It can be observed that instructors appreciated the customizability of the simulator to a good extent. This is quite important as this has been the first high-level requirement specified by the stakeholders, as discussed in Section 3.2. Similarly, the realism of the simulator was appreciated (i.e., the average score of 3.52). Especially, the control mechanism of the virtual roller was found to be highly realistic. This addresses the high-level requirement 4. Also, the simulator's ability as an assessment tool was appreciated (i.e., the average score of 3.6). This highlights the fact that the metrics used for the assessment are found to be informative and useful. This addresses the high-level requirement 5.

Overall, the simulator received acceptable scores in the usability category as well. Both instructors and trainees indicated that the visuals are easy to understand and that they did not feel the need for a technician to walk them through the simulator. Instructors unanimously agreed that the simulator is very user-friendly.

7.1.2. The simulator as a Technology Assessment Platform

To assess the fitness of the simulator as a technology assessment tool, several workshop sessions were held. In total, 50 participants took part in this validation, as explained in Section 2.3. The participants were classified into three groups, (1) novice/inexperienced operators, (2) experienced operators with technology affinity, and (3) experienced operators without technology affinity. Figure 31 shows a few examples of workshops.

Figure 31. Workshop setting for validation of the simulator as a virtual prototyping platform

For the purpose of technology assessment, three different operator support modes (Descriptive, Semi-prescriptive, and Prescriptive guidance) discussed in Section 4.2.4 were developed and incorporated into the simulator. The users of the simulator can easily toggle between these three modes in real time during the operation. This would allow them to compare and contrast different levels of technology-driven support, experiment with them firsthand in a safe environment, and provide feedback to the researchers.

At the beginning of each workshop, participants were familiarized with the simulator through a presentation. Later, a tutorial was provided to the group about how to operate the simulator. This was done to reduce the impact of unfamiliarity with the simulator on the validation results. Then, the participants performed a compaction operation on a highway stretch. In this scenario, there was a second AI-driven roller. The participants were asked to perform two passes on the asphalt layer within the temperature window of [80-120 ºC]. They were given the instruction to use all three support modes to be able to compare and contrast them. At the end of the session, each participant was given the questionnaire presented in Table 6 to assess the usefulness of the simulator for the technology assessment purpose. It should be noted that in the same validation sessions, the participants were asked to systematically compare and contrast the usability of each support mode. But, since it addressed a different set of research questions which is outside the scope of this research, it is kept out of this report. More detail about this can be found in the previous work of ASPARi researchers (Makarov et al. 2021b).

Figure 32 presents the result of this validation session. As indicated in this figure, nearly 21 out of 50 participants scored the adequacy of using the simulator as a VP platform with 4 or 5. This is a strong indication the simulator was found to be useful for

comparing and contrasting different technological solutions in a safe environment. Nevertheless, the respondents thought that the simulator could benefit from more realistic control and audio. This is further substantiated by the relatively low score on the graphical/physics realism of the simulator (2.84).

In addition, the results suggest that participants also see the simulator as a strong platform for investigating different compaction strategies before actual operations, which scored 3.5. Again, similar to the previous validation, a majority of the respondents mentioned that they would recommend the use of the simulator for the evaluation of other technological advancements.
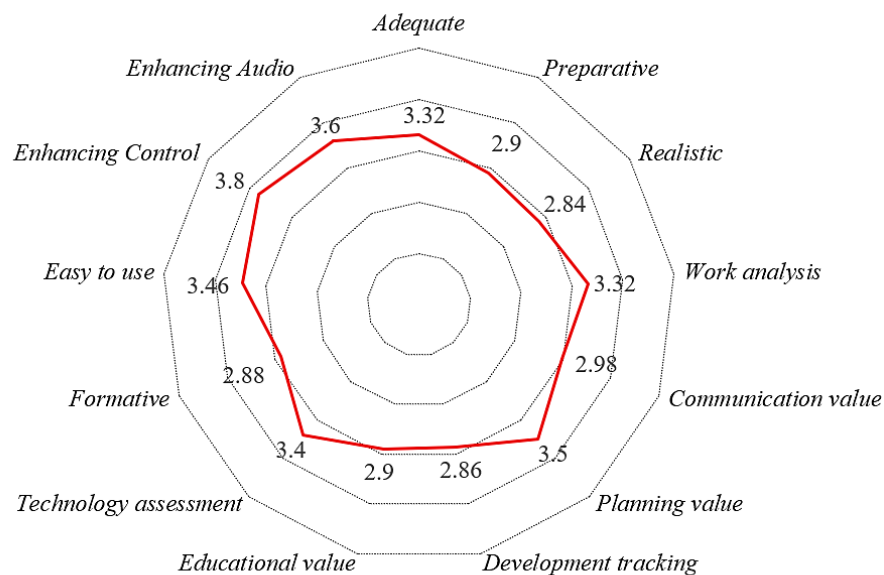

Figure 32. Assessment of the usefulness of the simulator as a virtual prototyping platform (Makarov et al. 2021b)

A disclaimer needs to be here that the version used in this validation session was not the final version used in the previous case study. In this version, the control mechanism and the audio quality of the simulator were still under development. Also, the 3D model of the roller used in the simulator was not very accurate. This has caused many participants to score the realism of the simulator lower than in the previous case study. Many of the suggestions provided by the participants were taken into account to

develop the final version, which was used in the previous case study. The comparison of the scores between the two case studies suggests that the modifications were very successful in improving the realism of the simulator.

By testing the ability of the training simulator to present different technological alternatives and objectively compare and contrast them through clear performance metrics, this case study specifically tried to address high-level requirements 6, 5, and 4. The promising results of the case study suggest that these requirements are well met in the implemented prototype.

7.1.3. The simulator as a Tool for SA Assessment

As mentioned in Section 2.3, three studies were conducted to validate the simulator as a tool for testing and training Situation Awareness: a study for validating the queries, a benchmarking study, and a training study.

In the first study, 40 road construction students took part in two compaction scenarios: a roundabout scenario and a crossing scenario. Complexity of these scenarios was varied by randomly assigning students to versions of the simulations in which one simulation contained rain and the other contained darkness. After the simulation ended, participants answered SA queries designed to assess their SA. Results of this study showed that there was no immediate practice effect; participants did not show growth in number of correctly answered SA queries. However, a significant interaction between training order and road condition suggested that students were better able to gain awareness of relevant aspects of the environment in the roundabout condition than in the crossing condition. Moreover, analyses of performance on the various items demonstrated that the construct SA is complex and multifaceted, and that performance cannot be interpreted as a reflection of a single skill or process. This phenomenon will be analyzed in greater detail in dedicated academic output.

The second study was a benchmarking study in which SA performance was investigated in the light of expertise of the user. To this end, three groups of participants were included: a group of road construction professionals, a group of road construction students, and a group of secondary school students acting as laymen. The scenarios were constructed in the same way as in the first study. Results of this study still need to be analyzed in detail, but preliminary analyses show that students answered more SA queries correctly than laymen, $p = .001$. This finding contributes to validating the design of the simulations by demonstrating the expected role of expertise in gaining SA within the virtual environment.

Finally, in the third study, students ($n = 55$) from vocational education participated in three training conditions: training with debriefing and video playback, training with debriefing and no video playback, and training without debriefing. Participants took part in up to four training sessions, depending on class attendance. In each session, a specific scenario was targeted: 1) a motorway in rainy weather, 2) a motorway in hot and sunny weather, 3) a roundabout in hot and sunny weather, and 4) a roundabout in rainy weather. Results show a sharp incline in SA scores between the first and second session (see Figure 33). This incline is significant, $p < .001$, and no more change can be observed after the initial incline. It should be concluded that the simulator is able to facilitate a relevant amount of performance gain upon first exposure. Differences in performance gains between training groups were non-significant, although this result should be interpreted with caution due to the small sample size.
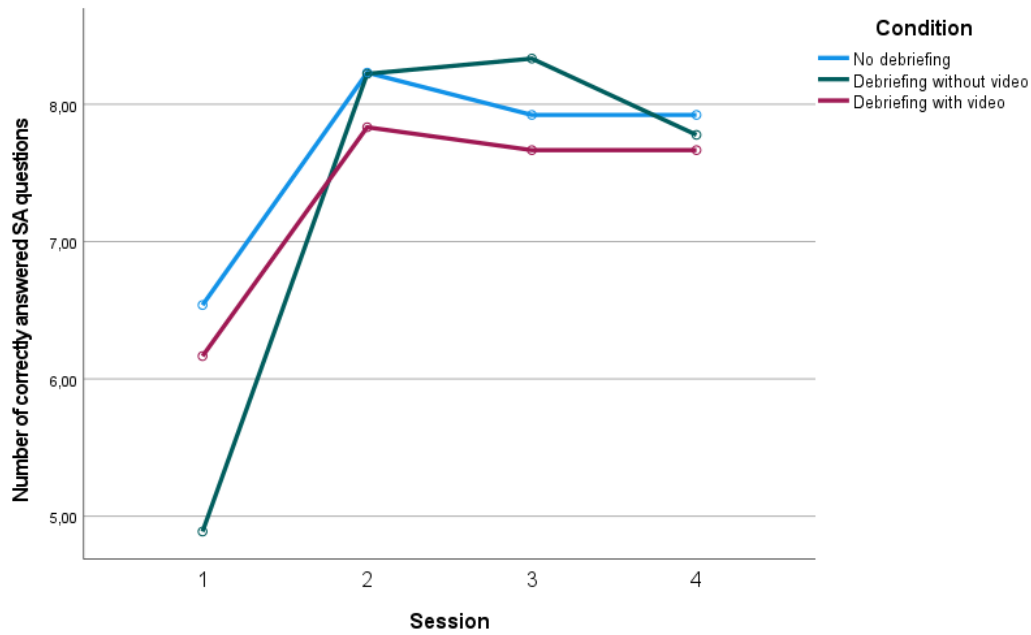
Figure 33. Performance gains in SA for three training conditions including VR sessions

7.1.4. The simulator as a Compaction Planning tool

As mentioned in Section 2.3, a case study was implemented where three planners. The case study began with a presentation of the framework and the prototype. Then, through an open discussion with the planners, the usefulness of the planning tool was investigated. Finally, the experts were asked to fill in the questionnaire presented in Table 7 to reflect on the usability of the tool.

Table 14 presents the results of the case study. In general, the planning tool was very well appreciated. The planners especially underlined the usefulness of the tool in making the decision-makers and planners aware of the consequences of their decision beyond what is currently feasible in conventional planning practices. Also, the tool was found to be very useful for providing quality-related feedback to the planners as well as for comparing and contrasting different compaction strategies. The ability of the planning tool for fostering collaboration between different levels of planning (i.e., tactical and strategic planning) received a lower score than other criteria.

To further elaborate on the impact of using the tool on improving the current planning practices, the planners were asked to fill out the same questionnaire but this time for the conventional paper-based planning methods. Figure 33 presents the result of this comparison. As shown in this figure, the proposed planning tool scored much better in all categories except user-friendliness. The planners especially found the navigation through two different environments (i.e., ABS model and VR simulator) a bit overwhelming.

Although in an indirect manner, this case study tried specifically to address the high-level requirement 2. The results of the case study show the possibility of using real/simulated data in the simulator for project planning and/or review.

Table 14. The results of the validation of the simulator as a planning tool

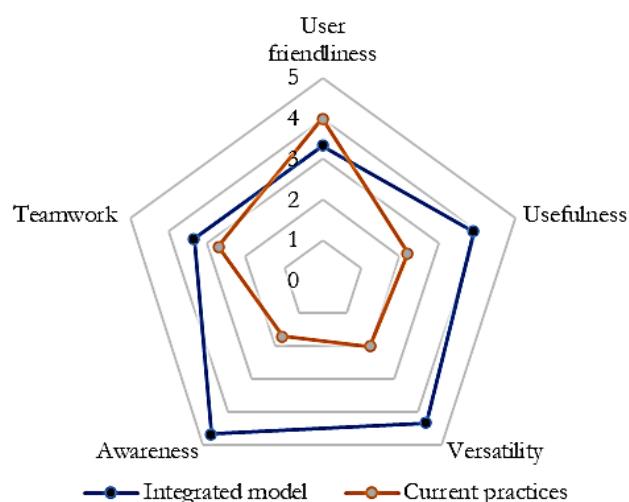| Criterion	Criterion	Score	
		Mean	**Standard deviation**
User-friendliness	Ease of use	3.3	0.94
Usefulness	Comprehensive	4	0
	Visualization	4	0
	Feedback	4.33	0.47
	Standardization	3.33	0.94
Versatility	Versatility	4.33	0.47
Awareness	Awareness	4.67	0.47
Teamwork	Teamwork	3.33	0.47

Figure 34. Comparison of the proposed planning tool with the current practice (Revollo 2021)

Chapter 8. Discussions and Conclusions

8.1. Project Summary

This design research tried to address the gap in the development and implementation of a training simulator for compaction operations. The main problems are the lack of realistic representation of site dynamics, inflexible scenario design, and the sheer absence of any training simulators for compaction operations. To this end, this research pursued the design objective of developing a framework for a parametric and context-realistic compaction training simulator. To achieve this objective, the core stakeholders of the project were identified and their chief requirements were taken into account. Based on these high-level requirements, the training simulator is expected to provide support for (1) customizable scenario development, (2) integration with real project data, (3) SA assessment, (4) realistic physics and visuals, (5) providing clear assessment metrics, and (6) application as a VP platform.

After the identification of the high-level requirements, the project proceeded with the identification of the functional requirements of the simulator. These functional requirements were then used as a guide to develop a set of distinct use cases that would address different requirements. By combining the use cases and functional requirements, a comprehensive framework for the compaction training simulator was developed. Through 5 different distinct modules, this proposed framework offers not only a more realistic representation of compaction operation but also support for various application domains (i.e., training, project review, technology assessment, SA assessment, and planning). The framework was later developed in a prototype

implementation. The prototype included several hardware and software components that were integrated with an information exchange interface.

Finally, the developed simulator was used in four different case studies to investigate its fitness and usefulness for (1) compaction training, (2) technology assessment, (3) situational awareness, and (4) compaction planning. In each of these case studies, a number of participants were exposed to one specific application domain/use case of the simulator and were asked to fill out a questionnaire about their experience and suitability of the simulator for the given use case.

8.2. Discussions

The main contribution of this design project is the generation of insight into the immense power of VR-based simulators beyond their commonly assumed applications. The multi-purpose simulator developed in this study was designed for application in a wide range of applications that comprised different stakeholders across the entire lifecycle of paving operations. Through the case studies, it is shown that not only training schools (i.e., instructors and trainees) can benefit from this simulator but also academics and contractors. The fact that the same platform can be used for training, assessment, job review, and technology assessment indicates the great potential of VR technology in the construction domain. To the best of the author's knowledge, such versatile application of a VR simulator in single research is unprecedented not only in the construction domain but also across the entire engineering discipline. The author would like to invite contractors and educators to appreciate the power of VR simulators and try to invest in this technology more proactively. The author also would like to sensitize the professionals in the domain to the fact that the development of this technology needs to be propelled and lead from within the industry. Experience in other domains has indicated that externally-

developed simulators commonly suffer from a very slow development cycle because the design is commonly not user-centered. The researcher would like to attribute much of the success in this research to the fact that this project was the result of a highly user-centered methodology where the final product is the co-creation of many professionals. It is the firm conviction of the research that the same approach needs to be followed in the future to better guarantee success both in technology development and adoption.

The results of the case studies suggest that the proposed framework and the developed simulator indeed addressed the high-level requirements of the stakeholder. Instructors from SOMA have already indicated their willingness to continue their support for the simulator development. Researchers from OWK and CME have already used the simulator in many different contexts for SA assessment and technology assessment. The ASPARi contractors who have been indirectly involved in this project showed interest in pursuing this research further. At the request of the contractors, CME and ASPARi researchers have already organized several workshop sessions for the experience roller operators to experience the simulator. The results have consistently been positive. One main advantage raised by several contractors and project managers is that the use of a simulator for re-training of expert operators and for familiarizing them with new technological advancements in the domain has contributed to opening a constructive dialogue among operators. This kind of knowledge/experience sharing seldom happens between expert operators. However, this is highly valuable especially considering the significant shortage of labor in recent years and also considering the urgent need for peer training and knowledge transfer between aging and younger operators. Therefore, it can be argued that the indirect

impact of the training simulator on the compaction operation industry, which is mainly achieved through its multi-functionality, can be significantly disruptive and timely.

The application of training simulators in other industries, such as aviation, has aptly demonstrated the long-lasting impact of the technology on reducing cost and improving sustainability. Conventionally, operators need to use actual equipment to become acquainted with the most basic principles of operating complex equipment especially when dexterity and motor skills are required for the job. Given that the acquisition of skills required for this job has different learning curves, depending on the complexity of the equipment kinematics, the use of actual equipment for training has severe cost implications. By partially transferring the learning objectives to training simulators, training schools can more efficiently use their fleet and also offer more learning opportunities to trainees with fewer concerns about the financial ramifications. On the other hand, trainees can benefit from the opportunity to spend more time in the practical training sessions and even use the simulator as a reflection/practice tool after their on-equipment training. In turn, by cutting down on the use of actual equipment, which is usually not very environment-friendly, the training schools can reduce the detrimental impact of having equipment operated by novice operators for a long time. The ease of developing and incorporating various performance metrics in the training simulator can also facilitate the expansion of the training curriculum to otherwise marginalized dimensions, such as sustainability.

8.3. Conclusions and Future Work

By revisiting the objective of the design project, it can be concluded that the developed framework indeed ensured customizability and context-realism. The flexible architecture that was used for the development allowed easy retrofitting of the simulator to prepare it for various applications. In terms of identified functional

requirements, Table 15 presents the desired and achieved requirements. As shown in this table 15 out of 22 requirements were met fully (i.e., 68%). Another 3 requirements (i.e., 14%) were met partially. Partial satisfaction of the requirement means that although some steps have been taken to address these requirements, further improvements are required. Only 4 of the requirements (i.e., 18%) were not addressed in this research due to the limitation of time.

Table 15. Status of different functional requirements at the end of the project

ID	Functional Requirement	Priority	Status
FR.1	Training	Must-have	Met
FR.2	Scenario builder	Must-have	Met
FR.3	Road designer	Good to have	Not met
FR.4	Road slope	Good to have	Not met
FR.5	Cross-section realism	Good to have	Not met
FR.6	Asphalt realism	Good to have	Met
FR.7	Controller realism	Must-have	Met
FR.8	Data collection	Must-have	Met
FR.9	Second roller AI	Must-have	Met
FR.10	On-board screen	Must-have	Met
FR.11	Tutorial	Must-have	Met
FR.12	Mistake notification	Good to have	Not met
FR.13	VR support	Must-have	Met
FR.14	Share screen	Must-have	Met
FR.15	Video playback	Must-have	Met
FR.16	Multiple displays	Good to have	Met
FR.17	Environment realism	Good to have	Partially met
FR.18	Sound realism	Good to have	Partially met
FR.19	Visual realism	Good to have	Partially met
FR.20	Context-realism	Must-have	Met
FR.21	Project planning	Must-have	Met
FR.22	Virtual prototyping	Must-have	Met

Although this research indicated the potential of a compaction training simulator, and a fully functional prototype was developed, still there is much room for improvement and future work. First of all, it is important to include a flexible road designer that allows building complex roads not only for training purposes but mostly to be able to visualize

different kinds of real projects in the simulator. Secondly, the 3D model of the site is predominantly developed within unity and can be considered hard-coded. However, to achieve the true extent of context-realism discussed in Section 3.4, it is important to make the framework compatible with Building Information Modeling (BIM) products. In this way, different designed projects can be easily imported into the simulator. Third, although some rudimentary agents were developed to represent auxiliary rollers and pavers in the simulator, the realistic representation of these pieces of equipment would require more development. Finally, a more realistic physics modeling is required to better represent the behavior of the asphalt inside the simulator. This is quite important because as stated by many operators much of the assessment performed by the operators about the quality of their work depends on their visual and haptic feedback from roller-asphalt interaction.

References

Aboagye-Nimo, E., & Raiden, A. (2016). Introducing site sense: Comparing situated knowledge in construction to coalmining. In P. W. Chan & C. J. Neilson (Eds.), *32nd Annual ARCOM Conference* (pp. 467-476). September 2016, Manchester UK. Association of Researchers in Construction Management.

Arbeider, C. G. (2016). Planning the asphalt paving and compaction process-The alignment between paver output, roller capacity and available tme for compaction (Master's thesis, University of Twente).

Bandura, A. (1997). *Self-efficacy: The exercise of contro*l. Macmillan.

Biggs, J. (1996). Enhancing teaching through constructive alignment. *Higher Education, 32*(3), 347-364. Retrieved from https://doi.org/10.1007/BF00138871. doi:10.1007/BF00138871

Biggs, J. & Tang, C (2011) *Teaching for Quality Learning at University: What the Student Does*. Buckingham: SRHE / Open University Press.

Binkley, M., Erstad, O., Herman, J., Raizen, S., Ripley, M., Miller-Ricci, M., & Rumble, M. (2012). Defining twenty-first century skills. In P. Griffin, B. McGaw, & E. Care (Eds.), *Assessment and Teaching of 21st Century Skills* (pp. 17-66). Dordrecht: Springer Netherlands.

Bolstad, C. A., Endsley, M. R., & Cuevas, H. M. (2014). A theoretically based approach to cognitive readiness and situation awareness assessment. In H. F. O'Neil, R. S. Perez, & E. L. Baker (Eds.), *Teaching and Measuring Cognitive Readiness* (pp. 161-177). Boston, MA: Springer US.

Bruner, JS, (1961) The act of discovery. *Harvard Educational Review. 31*(1): 21–32.

Bruner, J (1987) *Actual minds, possible worlds*. Cambridge, MA: Harvard University Press.

Beuving, E., & Luby, M. (2016). Education and training of roller operators contributing to durable and sustainable asphalt pavements. Proc. of the 6th "Eurasphalt, 1-6.

Calleja, G. (2014). Immersion in virtual worlds. In M. Grimshaw (Ed.), *The Oxford handbook of virtuality* (pp. 222–236). New York, NY: Oxford University Press.

Clifford, R. M. S., Khan, H., Hoermann, S., Billinghurst, M., & Lindeman, R. W. (2018, 18-18 March 2018). *Development of a multi-sensory virtual reality training simulator for airborne firefighters supervising aerial wildfire suppression.* Paper presented at the 2018 IEEE Workshop on Augmented and Virtual Realities for Good (VAR4Good).

Clifford, R. M. S., McKenzie, T., Lukosch, S., Lindeman, R. W., & Hoermann, S. (2020, 22-26 March 2020). *The effects of multi-sensory aerial firefighting training in virtual reality on situational awareness, workload, and presence.* Paper presented at the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW).

Conole, G., Dyke, M., Oliver, M., & Seale, J. (2004). Mapping pedagogy and tools for effective learning design. *Computers & Education, 43*(1), 17-33. doi: 10.1016/j.compedu.2003.12.018

Crawley, E, Malmquist, J, Ostlund S, Brodeur, D, (2007) *Rethinking Engineering Education – The CDIO Approach*. Springer, ISBN 978-0-387-38287-6.

Dalgarno, B., & Lee, M. J. W. (2010). What are the learning affordances of 3-D virtual environments? *British Journal of Educational Technology, 41*(1), 10-32. Retrieved from http://dx.doi.org/10.1111/j.1467-8535.2009.01038.x. doi:10.1111/j.1467-8535.2009.01038.x

Duderstadt, JJ (2008) Engineering for a changing world: A roadmap to the future of engineering practice, research, and education. Ann Arbor, MI: *The Millennium Project*, The University of Michigan.

Dyer, JH, Gregersen, HB, Christensen, CM (2009) The innovator's DNA. *Harvard Business Review 87*(12): 61–67.

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors, 37*(1), 32-64. doi:10.1518/001872095779049543

Endsley, M. R., Selcon, S. J., Hardiman, T. D., & Croft, D. G. (1998). Comparative analysis of SAGAT and SART for evaluations of situation awareness. Proceedings of the Human Factors and Ergonomics Society, 1, 82-86. doi: 10.1177/154193129804200119

Fanning, R. M., & Gaba, D. M. (2007). The role of debriefing in simulation-based learning. *Simulation in Healthcare, 2*(2), 115-125. doi: 10.1097/SIH.0b013e3180315539

Fowler, C. (2015). Virtual reality and learning: Where is the pedagogy? *British Journal of Educational Technology, 46*(2), 412-422. doi: 10.1111/bjet.12135

Gardner, R. (2013). Introduction to debriefing. *Seminars in Perinatology, 37*(3), 166-174. doi: 10.1053/j.semperi.2013.02.008

Gherardi, S., & Nicolini, D. (2002). Learning the trade: A culture of safety in practice. *Organization, 9*(2), 191-223. doi: 10.1177/1350508402009002264

Hart, S. G. (2006). NASA-task load index (NASA-TLX); 20 years later. In Proceedings of the human factors and ergonomics society annual meeting (Vol. 50, No. 9, pp. 904-908). Sage CA: Los Angeles, CA: Sage publications.

Hashim, W., Hainin, M. R., Ismail, N. N., Yusoff, N. I. M., Abdullah, M. E., & Hassan, N. A. (2016). Evaluating the cooling rate of hot mix asphalt in tropical climate. Jurnal Teknologi, 78(4).

Jeffrey, B (2006) Creative teaching and learning: towards a common discourse and practice. *Cambridge Journal of Education 36*(3): 399–414.

Kamoche, K., & Maguire, K. (2011). Pit sense: Appropriation of practice-based knowledge in a UK coalmine. *Human Relations, 64*(5), 725-744. doi: 10.1177/0018726710386512

Lo, J. C., Sehic, E., Brookhuis, K. A., & Meijer, S. A. (2016). Explicit or implicit situation awareness? Measuring the situation awareness of train traffic controllers. Transportation Research Part F: Traffic *Psychology and Behaviour, 43*, 325-338. doi: 10.1016/j.trf.2016.09.006

Makarov, D., Vahdatikhaki, F., Miller, S., Jamshidi, A., & Dorée, A. (2021a). A framework for real-time compaction guidance system based on compaction priority mapping. Automation in construction, 129, 103818.

Makarov, D., Vahdatikhaki, F., Miller, S., Mowlaei, S., & Dorée, A. (2021b). Usability assessment of compaction operator support systems using virtual prototyping. Automation in construction, 129, 103784.

Makarov, D., Vahdatikhaki, F., Miller, S., Mowlaei, S., & Dorée, A. (2022). Towards the Next Generation of Compaction Operator Support Systems; Real-time Compaction Trajectory Planning. Automation in construction (under review).

Mayes, J. T., & Fowler, C. J. (1999). Learning technology and usability: A framework for understanding courseware. *Interacting with Computers, 11*(5), 485-497. doi: 10.1016/S0953-5438(98)00065-4

Mikropoulos, T. A., & Natsis, A. (2011). Educational virtual environments: A ten-year review of empirical research (1999–2009). *Computers & Education, 56*(3), 769-780.

Piaget, J (2001) *The psychology of intelligence* (2nd Ed.). London: Routledge. [Originally published in 1950].

Revollo Dalence, A. (2021). Integrating VR and simulation to deal with complex planning challenges: A case of asphalt compaction (Master's thesis, University of Twente).

Riva, G., & Waterworth, J. A. (2014). Being present in a virtual world. In M. Grimshaw (Ed.), *The Oxford handbook of virtuality* (pp. 205-221). New York, NY: Oxford University Press.

Schön, D. A. (1995). *The reflective practitioner: How professionals think in action.* Aldershot [England]: Arena.

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators & Virtual Environments, 6*(6), 603-616.

SUS: A "Quick and Dirty" Usability Scale. 1996. In: Usability Evaluation In Industry. CRC Press. p. 207–212.

Timm, D. H., Voller, V. R., Lee, E. B., & Harvey, J. (2001). Calcool: a multi-layer asphalt pavement cooling tool for temperature prediction during construction. International Journal of Pavement Engineering, 2(3), 169-185.

Unity Technologies, Unity 3D, (2022).

Vahdatikhaki, F., El Ammari, K., Langroodi, A. K., Miller, S., Hammad, A., & Doree, A. (2019). Beyond data visualization: A context-realistic construction equipment training simulators. Automation in construction, 106, 102853.

Vahdatikhaki, F., Langroodi, A. K., olde Scholtenhuis, L., & Dorée, A. (2022). Feedback support system for training of excavator operators. Automation in Construction, 136, 104188.

van Merriënboer, J.J.G. (1997). *Training Complex Cognitive Skills: A Four-Component Instructional Design Model for Technical Training*. United Kingdom: Educational Technology Publications.

Voogt, J., & Roblin, N. P. (2012). A comparative analysis of international frameworks for 21st century competences: Implications for national curriculum policies. *Journal of Curriculum Studies, 44*(3), 299-321. doi: 10.1080/00220272.2012.668938

Vygotsky, LS (1994) Imagination and creativity of the adolescent. In R. Van Der Veer & J. Valsiner (Eds.), *The Vygotsky reader* (pp. 266–288). Cambridge: Blackwell Publishers. .

Vygotsky, LS (1978) *Mind in society*. Cambridge, MA: Harvard University Press.

Wang, Y. F., Petrina, S., & Feng, F. (2017). VILLAGE—Virtual Immersive Language Learning and Gaming Environment: Immersion and presence. *British Journal of Educational Technology, 48*(2), 431-450. doi: 10.1111/bjet.12388

West, R. E., Tateishi, I., Wright, G., et al. (2012) Innovation 101: Promoting undergraduate innovation through a two-day boot camp. *Creativity Research Journal 24*(2): 243–251. DOI: 10.1080/10400419.2012.677364.

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and Virtual Environments, 7*(3), 225-240. doi: 10.1162/105474698565686

Wright, G. A., Skaggs, P., West, R.E. (2013) Teaching innovation in high school technology classes. *The Technology and Engineering Educator 72*(4): 18–23.

Appendices:

8.4.   Appendix I: Technical manual for setting up the simulator

This document is written for people who want to install the simulator on computers.

The installation process has four steps, checking hardware requirements, installing

drivers and software, checking controllers/goggle, installing simulator. These four

steps will be explored in what following.

Checking hardware requirements:

The simulator can be run on only windows OS, so running the simulator on Mac

machines, Android/Chromium machines or any Linux distribution is not possible.

Running the simulator on PC is recommended, however it can be run on powerful

laptops. Regarding the details of minimum system specification, you can refer to the

below table.

Table 16. Hardware requirements

RAM	The system is not RAM consuming, it approximately uses 2.5 GB of system RAM. 16 GB of RAM is preferred, however, if the system has 8 GB it is doable, but you should close any other applications while running the simulator.
GPU	The simulator has been tested on RTX 2060 and GTX 1080 and it works. To determine the minimum requirement, it should be tested on different GPUs which is not possible for this project. If you are using a not very powerful GPU, do not use rain effect.
CPU	The system is not dependent heavily on CPU and can be run on any CPU. The most recent CPUs allow you to have a smoother experience.
HDD	The software size is under 500 MB. If you want to record videos from the screen, each 10 minutes session need around 300 MB to be stored.
VR requirement	If you want to use VR goggles, make sure the computer is "VR Ready". Most of the PCs with powerful GPUs are VR Ready, but most laptops aren't. Consider that the limitation is not just the power of the GPU, the bandwidth of video port on the device and the ampere of the USB ports also matters. Search for "VR Ready" keyword for the GPU model or laptop model on the internet.

Installing drivers and software:

In order to run the simulator on the computer there are a couple of software and driver

which should be installed. Most of them are depended on the controller and the VR

goggle which you are using, in what follow we discussed all of them.

1) **GPU's driver:** Make sure the graphic card driver is up to date. There are two companies that provide GPU, Nvidia and AMD. Both have software to manage the GPU. You can download and install the latest driver of your graphic card using them.

2) **Controller's Driver:** Depending on the controller, you may need to install the driver of the device. Some of controllers does not need a driver and will be recognized and work perfectly by the OS. Some of controllers may be recognized and work partially without the driver so keep in mind if the device comes with a software always install it. For this project, a racing set controller (a steering wheel without pedals) and a joystick are used. The model of the steering wheel is "Logitech G29", it needs a driver. The driver can be downloaded and installed easily from Logitech website, look for "Logitech G Hub" software. It is a generic driver for all Logitech controllers, you should add your device and configure it after installing the software. The model of the joystick is "Thrustmaster t16000m". This device does not require a drive and will work without problem. You can use any steering wheel and joystick in the market as long as it is recognizable by the OS, however, for key binding, you may need to modify the project in Unity3D and export it again. A technical document for this purpose is prepared.

3) **VR Goggle's Driver:** This project utilized Oculus Rift and Oculus Rift S. Both works with the simulator, but they need driver and other software to work. First you should install Oculus application for either goggle, then you should login with a Facebook account then add your device. You need to pass the safety steps to be able to use the goggle in the simulator. Remember each time you connect the goggle or restart the computer you should pass the safety steps

again. After installing the oculus software, you may need to install "Steam" software. If the goggle does not work after installing Oculus, installing steam may help to resolve the issue because it gives you more flexible interface to setup the goggle. After installing, make an account. Then install "SteamVR" using "Steam". We just installed "Steam" to be able to install "SteamVR", from this moment you have nothing to do with "Steam" software. Before running the simulator, you should launch the "SteamVR" software and make sure the device is recognized by the software.

4) **Screen Capture Software:** For educational purposes, the performance of the people who work with the simulator should be recorded. A screen recorder is embedded into the simulator t make it automatic, but it makes the simulator slow. The best solution is using another application. Any screen recorder can be used. However, using "OBS" software is recommended because it is light and has no impact on performance. After installing the software, do not forget to launch it and start recording before starting the simulator.

Checking Controllers/VR goggle

Before starting the simulator, the status of controllers and VR goggle should be checked. Make sure all the cables are connected and detected by the OS, find "Setup USB game controllers" from the "Start Menu" or "Control Panel" to check controllers. In order to check the VR, first launch the "Oculus" software and make sure the safety steps are passed and you can see the Oculus Home if you look through the goggle. Then launch the "SteamVR" and make sure the headset and controllers are detected by the "SteamVR". Then you are ready to launch the application.

Installing Simulator and Scenario Builder

This part is the easiest one, you just need to copy and paste the directory into any drive on your computer, no installation is required. The simulator and scenario builder are exported as a standalone application to make it as easy as possible to run. After coping the folder, you can run them by clicking on them.

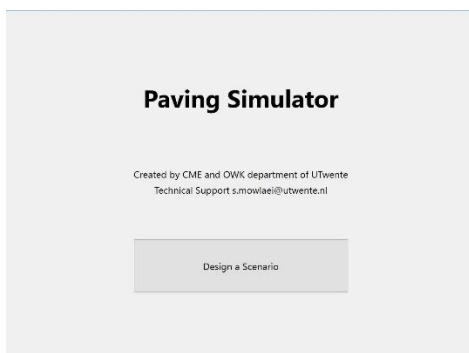## 8.5. Appendix II: User interface manual for teachers

This user manual is written for teachers who want to work with the scenario builder and the simulator. It describes how to run the application and modify scenarios. Scenario Builder and Simulator are two separated applications. In the Provide folder you can find both:
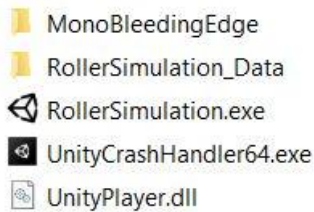
In order to modify or create scenario, first you need to run the "Scenario Builder" application. It is marked in the following picture.
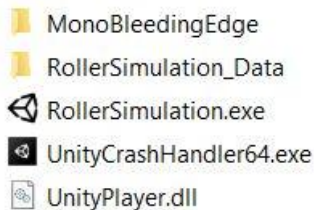
After running the "Scenario Builder" application, the following window will be open.

Click on the "Design a Scenario" button. You will see the main window of the application.

In this page, you should set the parameters to what you want and click on the "Save and Exit" button. In what follow I describe each parameter:

13. **Type weg:** You can set this one to "Snelweg", "Kruising (T-splitsing)", or "Rotonde". It determines the shape of the road to work on. They are sorted from the easy one to the difficult one. "Snelweg" is considered as the easiest and "Rotonde" is the most difficult one.

14. **Duur simulatie:** It determines the duration of the simulator. You can set it from 30 seconds to 10 minutes. It is not allowed by the system to set the duration more than 10 because it is not recommended to work with VR goggles for more than 10 minutes continuously.

15. **Beeldkwaliteit:** you can set it to "Weinig detail" or "Veel detail" .It refers to the visual details of the asphalt. If the computer you use is powerful you can use high details, if not use low details option to avoid drop in FPS. Length of way is also important here, if you want to define a scenario with a long way, it is recommended to set it to low details. Rain effect also is heavy to process, so if you are setting a scenario with rain set it to low details.

16. **Type asfalt:** It indicates the Asphalt type. You can set "SMA", "DAB", or "ZOAB".

17. **Weer:** Two weather condition is implemented, the normal condition and rainy. Setting the weather to rainy, reduces the eyesight also the asphalt cools down faster.

18. **Lengte van de weg (voor snelweg):** it indicates the length of the way in meters. This parameter only works if you select the motorway scenario and, in the case of selecting other parameters, it will be ignored. You can select between 50 to 200 meters.

19. **Lichtstatus:** You can set it to "Dag" or "Nacht". If you set it to night, the lights of the site and the machines will be turned on automatically. In general, having the operation in the night is more difficult because the limitation in eyesight.

20. **Laagdikte:** This parameter is the thickness of the layer of the asphalt. You can set it to 3 cm, 5 cm, or 9 cm.

21. **Omgevingstemperatuur (°C):** You can set the temperature of surrounding by this parameter. It is independent from the weather condition.

22. **Soort device:** It has two options, "VR bril" and "Monitor(s)". If a VR goggle is available and you want to use it as a display, select the "VR bril", or if you want to use regular monitors select "Monitor(s)". The system automatically detects multiple monitors and use them as mirrors. The orientation, and placement of

monitors which is used as mirror is adjusted with Soma simulators. If you use other setups, it may not work properly.

After setting parameters, you should press "Save and Exit". Now if you run the simulator by clicking on "Simulator" in the project folder, the scenario you built will be executed.

MonoBleedingEdge
RollerSimulation_Data
RollerSimulation.exe
UnityCrashHandler64.exe
UnityPlayer.dll