Integrating VR and Simulation for Enhanced Planning of Asphalt Compaction

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Abstract

The current decision-making practices in road construction, are largely based on tacit knowledge, craftsmanship, tradition, and custom. This results in considerable variability in the execution of projects and deviation between as-planned and as-executed practices. The current simulation-based planning techniques are limited because they tend to present spatial and temporal characteristics of projects separately. This segregated approach ignores the interdependencies between spatial and temporal aspects of projects specially with respect to safety and process quality assessment. This is more palpable in the asphalt compaction projects because the quality of the compaction depends on a myriad of temporal (e.g., compaction speed) and spatial (e.g., homogenous compaction of the mat) parameters. Therefore, this research aims to develop a novel framework to capture the factors affecting the compaction process in a holistic manner and translate them into relevant decision variables. This framework achieves this objective by integrating simulation and virtual reality technologies. In this framework, simulation is responsible for capturing the affecting factors and generating temporal decision variables, whereas VR virtualizes them and provides high (3D) spatial assessment and awareness. A prototype is developed and tested with ASPARi case studies to demonstrate the feasibility of the framework. It is shown that compared to current planning practices, the integrated model can significantly improve various aspects of planning the construction process, especially by improving awareness among decision-makers concerning the development of more standardized compaction patterns.

Keywords –
Simulation; Virtual Reality; Compaction; Planning

1 Introduction

The ultimate performance of asphalt pavements is predicated on the asphalt mix (i.e., design) and the compaction process (i.e., construction). While a good design is crucial for high-quality pavement, it is shown that the compaction process plays a more important role in explaining variability in asphalt quality [1,2,3]. This is mainly due to the fact that while the production of asphalt mix benefits from the highly controlled industrial environment of asphalt plants, the compaction process on the site is largely unstructured, experience-driven, uncertainty-laden, and more difficult to control [3,4,5,6]. Besides, compaction is a highly complex process that depends on and is sensitive to a myriad of factors, e.g., material properties, initial density, equipment, traffic, and environment [1,7]. This renders the control of the compaction process very difficult and strongly ties the success of compaction to meticulous and detailed planning.

Miller [5] suggested that proper planning of the compaction process needs to (1) make the operational behavior explicit, (2) visualize the compaction process, and (3) engage all construction crew in the decision making. In recent years, construction simulation methods have been deployed for the planning of different types of operations. These methods are shown to be able to meet the above-mentioned requirements [8]. However, the current simulation-based planning techniques have a major shortcoming for application in compaction operations. It is mainly because the current methods tend to present spatial and temporal characteristics of projects separately. This segregated approach ignores the interdependencies between spatial and temporal aspects of compaction operations. This is especially important because proper planning of compaction requires concurrent consideration of temporal (e.g., compaction speed and delivery schedule) and spatial (e.g., homogenous compaction of the mat) parameters. In other words, while spatial modeling concerns itself mainly with planning at the strategic level of operation, tactical planning requires decision-making at the spatial level (i.e., precise compaction route planning). The fragmented modeling approach keeps strategic and tactical planning separate and forces planners to take a sequential planning approach, where first strategic decisions are made and then the tactical decisions are made. This separation ignores the intricate interplay between strategic and tactical planning in compaction operations. Therefore, it seems to be more optimal to have an integrated platform that supports comprehensive and concurrent planning. Nevertheless, the existing compaction simulation models primarily focus on the temporal perspective (i.e., strategic planning) of the process and offer limited support for tactical planning.

Virtual Reality (VR) has been successfully employed to increase the spatial awareness of construction processes [9]. Rekapalli [10] used VR to study complex earthmoving operations and argued that simulation-based VR could be an effective method to test and validate complex simulation models (i.e., identify and rectify possible errors in the simulation). Turner [11] and Akpan [12] demonstrated the potential benefits of integrating simulation and VR in different projects. However, to the best of the authors' knowledge, the integration of VR representation of the asphalt process with the temporal simulation models has been seldom investigated.

Therefore, the objective of this research is to develop a framework for the integration of temporal simulation of the compaction process and 3D spatial representation (i.e., through VR) to enhance the efficiency and consistency of the decision-making process and to support concurrent strategic and tactical planning. It is argued that this approach would open dialogue between compaction planners and operators and help them better sensitize themselves to the intricacies involved at different levels of compaction planning. In this integrated approach, the simulation could deal with the temporal decision variables, such as quantity and speed of equipment, roller passes, and translate them into relevant assessment indicators, i.e., time and cost. VR, on the other hand, could deal with the spatial decision variables, such as the areal output of equipment, rollers' trajectory, asphalt cooling rate, and translate them into relevant quality indicators, i.e., compaction efficiency and process consistency.

The remainder of the paper is structured as follows. First, the research methodology applied in this research is presented. Next, the requirements of the new framework are discussed. Subsequently, the proposed framework is explained in detail. This is followed by the presentation of the implementation and case study. Finally, the conclusions are discussed.

2 Research Methodology

This research applied a variation of the design research methodology [13]. Accordingly, the research is divided into four phases, i.e., literature review, requirement analysis, framework development, and synthesis. The first phase focused on acquiring relevant knowledge regarding the asphalt pavement industry, simulation methods, and VR platforms. Particularly, the interconnections, interdependencies, current decision-making practices, and characteristics of the hot mix asphalt. This phase resulted in the identification of research gaps in the current body of knowledge concerning the integration of simulation and VR techniques for asphalt paving operations. In Phase Two, the essential requirements for the integrated model were obtained through interviews with asphalt experts in The Netherlands at both tactical and strategic levels. In Phase Three, the framework was developed. In this framework, Agent-Based Simulation (ABS) is integrated with a VR representation of the asphalt compaction process. To this end, the existing VR developed by previous research of the ASPARi group [14] was used. In Phase Four, the framework was implemented, verified, and validated. This was done by developing a prototype and then using it in a case study. The model was then validated in two different ways. First, its accuracy was assessed based on data from an actual compaction operation. Second, the usefulness of the model was assessed with the input of asphalt experts.

3 Requirement Analysis for the New Framework

To identify and analyze the requirements of the new framework, a set of four interviews were conducted with experts from BAM and Heijmans, i.e., two of the largest construction companies in The Netherlands. The interviewees from the former company belong to the tactical realm of project planning and their focus lies on asphalt construction projects. Both of them, while being part of academia, conducted research focusing on asphalt pavement. On the other hand, the experts from the latter company have been working on asphalt-related projects for several years. One interviewee had a more tactical background and gave a broader overview of the process, whereas the other was more experienced in the operational realm, providing relevant feedback from an operational point of view.

Based on these interviews, the overall requirements of the integrated model have been identified as follows: (1) The model should provide the user with resource allocation alternatives, (2) The model should allow the user to evaluate different strategies with different fixed parameters, e.g., provide different strategies for two allocated (fixed) rollers, or provide different strategies for (fixed) paver speed, (3) The model should provide the user with relevant feedback about the quality of the compaction. The interviewees also pointed out the importance of considering the temperature issue during the compaction process. Every single phase of the process is affected by the asphalt-mix temperature. That being said, to properly represent the process in a simulation model, the asphalt cooling behavior needs to be captured in the model.

To be able to translate these high-level requirements to specific parameters that need to be molded in the integrated simulation, the experts were asked to identify the operational factors involved in asphalt compaction processes. Then, these factors are divided into fixed input parameters and decision variables. The fixed parameters refer to the factors that cannot be altered in the planning phase, such as layer thickness, mixture design, road geometry. In contrast, the decision variables, i.e., equipment speed, equipment output, compaction strategy,

are the factors that fall into the decision-makers' hands and, consequently, can be modified within the model. To illustrate, Figure 1 and Table 1 present the parameters and decision variables, respectively. In essence, the integrated model needs to capture all these parameters and allow the planners to capture them in their decision-making.

4 Proposed framework

This research proposes a hybrid, i.e., simulation and VR, planning model for the simulation of asphalt compaction operations.

In this platform, simulation is responsible for capturing the parameters described in Table 1, and generating temporal decision variables, i.e., the quantity of trucks, equipment output, and average speed. Then, the simulation feeds all the factors to the VR, in which virtualization of all the planning decisions takes place. Within this environment, the decision-maker is able to evaluate the spatial decision variables, i.e., roller trajectory, length of roller track, and distance Paver-Roller. On top of that, the VR offers operational quality feedback for the work done.

Figure 2 depicts an overview of the proposed framework, which is divided into five phases, i.e., Data Collection, Simulation, Integration, VR, and Strategy Assessment. The first phase begins with the collection of the parameters shown in Table 1. Afterward, the data is organized and initial values for the decision variables are computed. Specifically, the paver and roller speed, length of roller track, and roller trajectory.

Then, the data is fed to the ABS simulation, and the user can assess, in virtual real-time and 2D, the equipment movement, paved surface, and the asphalt mat cooling. Once the simulation is finished, it is possible to evaluate the paver and roller output (m2/h) along the entire process. Subsequently, the integration phase translates the thermal and equipment behavior into data-driven physics and data-driven agents for the VR, respectively [15].

Table 1. Relevant factors for the asphalt compaction modeling

Factor	Unit	Type of factor	Category
Available time for operations		Parameter	-
Mixture properties	-	Parameter	Mat. properties
Road geometry	m	Parameter	Mat. properties
Pavement dimensions	m	Parameter	Mat. properties
Delivery temperature	°C	Parameter	Mat. Properties
Asphalt cooling rate		Parameter	Environmental
Distance asphalt plant-site	km	Parameter	Equipment
Truck capacity	m3	Parameter	Equipment
Truck cycles	-	Parameter	Equipment
Waiting periods	-	Parameter	Equipment
Number of trucks	#	Variable	Equipment
Quantity of pavers	#	Parameter	Equipment
Width/screed width	m	Parameter	Equipment
Flow stoppers	-	Parameter	Equipment
Areal output	m2/h	Variable	Equipment
Average paver speed	m/min	Variable	Equipment
Quantity of rollers	#	Parameter	Equipment
Number of passes	#	Parameter	Equipment
Roller's width	m	Parameter	Equipment
Overlap	m	Parameter	Equipment
Average roller speed	m/min	Variable	Equipment
Length of roller track	m	Variable	Equipment
Distance paver-roller	m	Variable	Equipment
Roller trajectory	-	Variable	Equipment
Areal output (capacity)	m^2/h	Variable	Equipment

Next, the user can evaluate the impact of their choices on the asphalt mat, such as equipment movement, mat cooling, and rolling pattern with high spatial resolution in the VR environment. Finally, the strategy assessment phase takes place. The user receives resource output feedback and operational quality feedback. The resource output feedback concerns the equipment output (m2/h), and their speed (m/min). The operational quality feedback concerns compaction efficiency (%) and process consistency (%), i.e., whether the mat has been

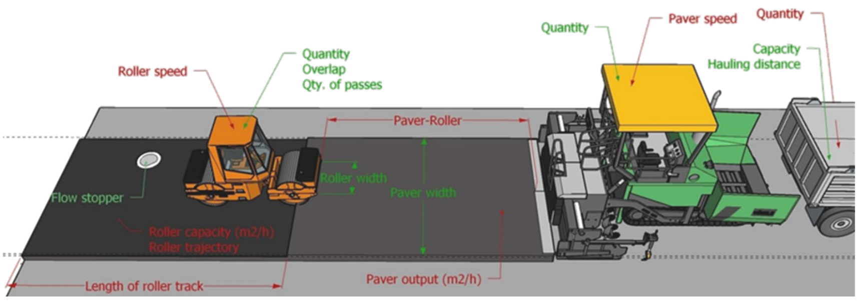


Figure 1. Schematic overview of the HMA-CP parameters (green) and decision variables (red)

effectively compacted and within an appropriate the temperature range. A detailed description of how compaction efficiency and process consistency are calculated is presented in the previous work of the authors [14].

4.1 Data Collection

The available time to deliver the hot asphalt to the site is the starting point for compaction planning. Then, the geometry of the road, i.e., road length, width, and layer thickness must be stated using a parametric model.

The temperature of the asphalt mix is of utmost importance in asphalt compaction. If the mixture is too hot, it can be overstressed, hence the mat would spread laterally rather than being compacted. If the mixture is cold while being compacted, it can be under-stressed, hence the roller cannot create sufficient shear force to increase the density of the mat [5]. Therefore, the compaction of the mat must be achieved within a certain temperature range, which can be obtained from the asphalt cooling curve.

This cooling behavior of asphalt can be determined either through the use of data from actual construction sites or cooling curve prediction tools such as PaveCool [16].

To guarantee uniformity in the paving operations and to have a constant delivery rate of asphalt mix, the planner needs to evaluate the number of trucks that are going to be employed in the operations. The user needs to state the distance from the asphalt plant to the construction site, truck capacity, the estimated time for hauling operations, loading and unloading time. The above information is employed to simulate the hauling operations and to provide the minimum number of trucks required to guarantee a constant delivery of asphalt mix. Moreover, depending on the particular characteristics of the road, there is a transition period between trucks. That is, when a truck is ready to pour the asphalt mix into the paver, there is an interruption in the paver flow between the empty-truck departure and the full-truck steering for unloading. This transition is captured and represented in the simulation model. The user needs to state an average time for this shift.

The paver features, such as type, number, and desired screed width need to be specified. With that information retrieved, the model offers two ways to choose the paver speed: (1) the initial average speed is computed based on the productivity goal, (2) the user can state the initial average speed based on their expertise. Furthermore, some specific road sections have a certain degree of complexity, which impacts the productivity of the paver, and consequently, the uniformity and continuity of operations are affected [20]. Therefore, these so-called flow stoppers, e.g., roundabouts, intersections, curves, must be considered when representing the behavior of the paver. Runneboom [20] proposed an approach for the consideration of the number and type of flow stoppers in a simulation model. Based on this approach, the impact of different flow stoppers is identified, categorized, and translated to output rate parameters. Thus, the simulation model quantifies the flow stoppers and translates them into the paver behavior, i.e., reduction in the average speed.

The user also needs to provide information about the roller characteristics, e.g., width, number, and type of rollers as well as the number of required passes. Then, the overlap, length of roller track, and distance of paver-roller can be calculated using equations proposed by BOMAG [17]. The roller speed can be specified in two different ways. Either the user specifies an initial average speed, or the model suggests a value based on the premise that the paver output and the roller capacity should be aligned, again using equations proposed by BOMAG. Finally, the compaction strategy must be chosen. Compaction strategy refers to the trajectory that the roller will follow to cover the mat completely and with the desired number of passes. The simulation model offers different compaction strategies based on the number of lanes, the width coverage of rollers, the number of passes, and the number of rollers. The suggested paths are based on the standard compaction strategies available within the body of knowledge [17].

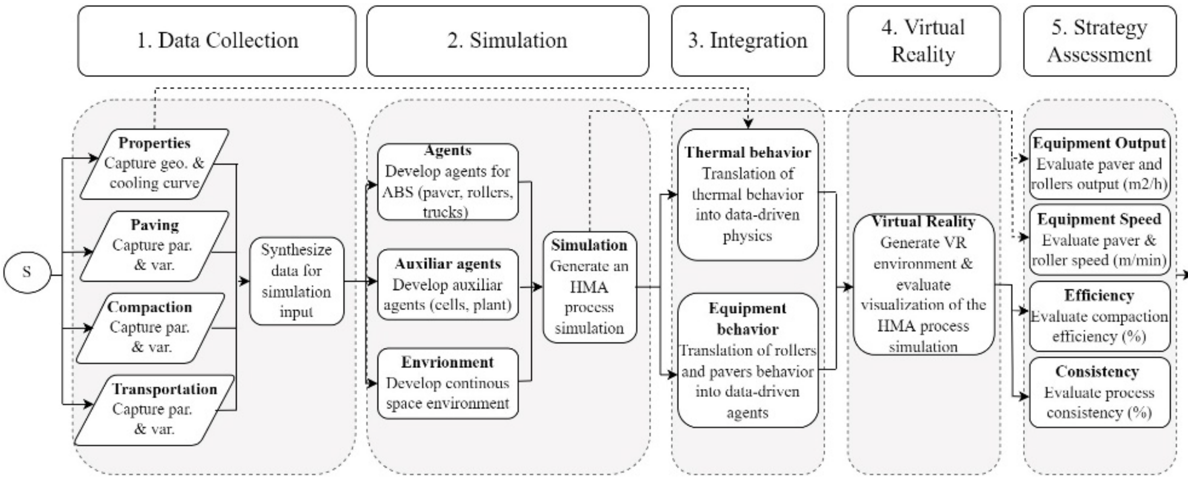


Figure 2. Overview of the proposed framework

4.2 Simulation

Regarding the agents in the ABS model, five agents have been modeled, namely truck, roller, paver, asphalt plant, and cells, which represent the discretized paved surface. Figure 3 shows the overview of the agent's flowcharts.

The truck is dispatched from the plant at a given rate. Then, the truck awaits a signal from the paver to accommodate itself next to the paver-hopper and later dump the material while moving along with the paver. Once the job is completed, the truck leaves the construction site. When the truck is pouring the asphalt mix into the paver-hopper, the paver starts paving at the initial speed. Each paved unit is represented in the model with a cell. The paver evaluates regularly whether the current speed is sufficient to finish the job, if not, the paver modifies its speed, based on the target productivity.

When the paver moves, cells appear in form of discretized lanes. The width of the lane corresponds to the width of the road and it is divided into ten cells. As for the length, each lane has a unitary length, in this case, it is one meter. Afterward, the cell cools down according to the cooling curve.

To start compacting, two conditions need to be met. Firstly, there should be a minimum distance between paver and roller before the roller can start the compaction. Secondly, the cell temperature is equal to or less than the upper limit of the compaction temperature window. To assess the latter, the model considers the time passed from freshly paved asphalt to the upper threshold, which is obtained from the asphalt cooling curve. After rolling each section, the roller evaluates whether its capacity is aligned with the paver output, and its distance with the paver is within the limits. Then, the roller modifies its speed accordingly.

The simulation allows the user to partially evaluate their strategy, i.e., assess it from a temporal point of view. On one hand, the user can visualize in virtual time and 2D environment, the equipment movement, the paved surface, and the asphalt cooling. Besides, they can evaluate whether the resource allocation is capable of successfully completing the job with the allocated time. On the other hand, once the simulation is completed, the user receives graphical feedback in terms of paver and roller output (m2/h) and their speed along the entire process. If the user is happy with the partial results, they can move forward to the next phase.

4.3 Integration

In general, the integration phase is responsible for the conversion of the simulation output data into input data that feeds the VR. That being said, three main conversions are needed, i.e., agent conversion, physics conversion, and logistics conversion. The agent conversion is about translating the movement of the paver and roller to the timestamp location series. Then, the values are translated into local VR environment coordinates. The physics conversion translates the cooling curve obtained in the previous phase to timestamped values. Then, the VR environment uses this data to represent the temperature of each cell. Finally, the logistics features, such as equipment quantity, and available time, are converted into data that the VR environment can use.

4.4 Virtual Reality

The VR environment allows the user to evaluate their

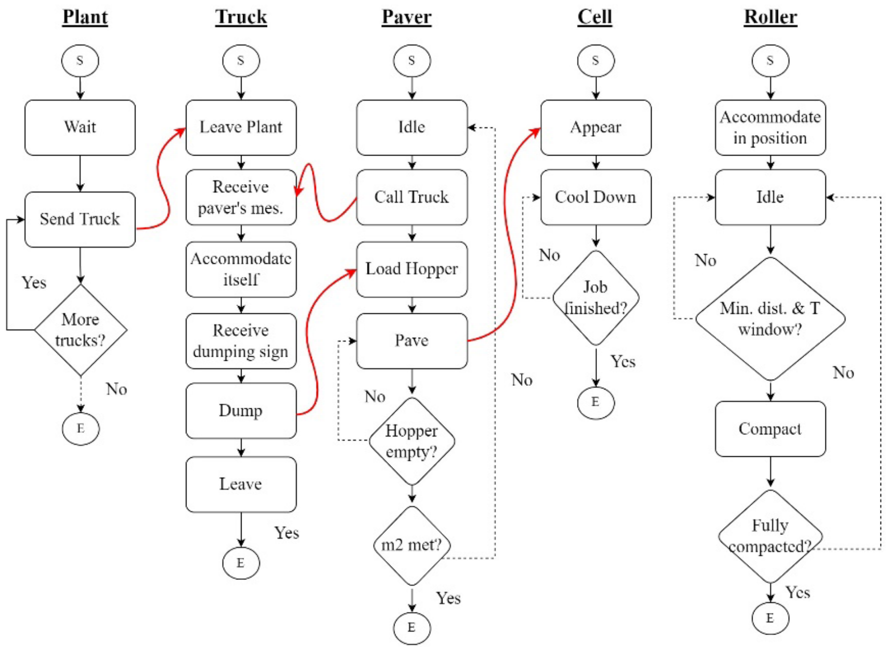


Figure 3. Overview of agents' behavior

strategy in virtual real-time and with high spatial resolution in 3D. VR allows planners to assess the asphalt mat cooling, and the compaction completeness interactively. The quality metrics used for this phase are compaction efficiency and process consistency. The former refers to how many cells have been compacted within the allowable temperature window. To clarify, if the compaction efficiency is 40 %, it means that 40 % of the cells have had all compaction passes within the temperature window [14]. The remaining 60% had at least one pass outside this window. Process consistency show how much time is left for a cell to have successful compaction [15].

4.5 Strategy Assessment

Once the user evaluated the simulation and the VR environment, they can assess their overall strategy. In general, the expert can evaluate the performance of their choices with four metrics, i.e., equipment areal output (m2/h), equipment speed (m/min), compaction efficiency (%), and process consistency (%). Further, for the last metric, the model provides the percentage of cells that have been compacted below and/or above the compaction window.

5 Implementation and Case Study

A prototype is built to test and validate the proposed framework. In this prototype, the data collection, integration, and strategy assessment phases are performed with Excel. Whereas the simulation phase is developed with AnyLogic [18], and the VR environment is built with 3D Unity [19].

In short, the parameters shown in Table 1 are collected and the initial values of the decision variables are computed, both with an excel-based Graphical User Interface (GUI). Then, AnyLogic reads the data from excel and performs the ABS simulation. Once the simulation is finished, AnyLogic provides to Excel the cyclic timestamped location of the equipment. Next, Excel integrates the data and generates the input for the VR environment. Then, Unity creates the VR environment and allows the user to evaluate their strategy. Finally, excel generates an output PDF file with the strategy assessment values.

To evaluate the performance of this model, the case study was performed for a 250 m surface rehabilitation of the A-15 highway in Rotterdam, The Netherlands. The total allocated time to execute the job is one hour. In this project, the temperature window of 120~80 °C was specified. The other input values are shown in Table 2. It is assumed that at the start of the project the trucks are already on the construction site.

Table 2. Data collection summary

Parameter	Value
Available time	1h
Road length	250m
Road width	8m
Layer thickness	50mm
Available time for compaction	16min
Minimum time for start compaction	9min
Truck capacity	27t
Transition time	3min
Paver quantity	1
Width	8m
Initial speed	4m/min
Roller quantity	1-2
Roller width	2m
Number of passes	2
Number of lanes	4
Initial speed	18m/min
Length of roller track	73m

Four different compaction strategies can be evaluated, as shown in Figure 4. In scenario a, the compaction is performed from one edge of the road to the other. In Scenario b, the roller compacts the inside landes first and leaves the outer lanes to be compacted last. This would allow the edges to be slightly cool down before the compaction and thus have a smoother edge [17]. In Scenario c, the first roller, or master roller, is the one that leads and the second roller, or slave roller, follows. Finally, in Scenario d, two rollers compact in parallel each from one edge inward. For this case study, given the

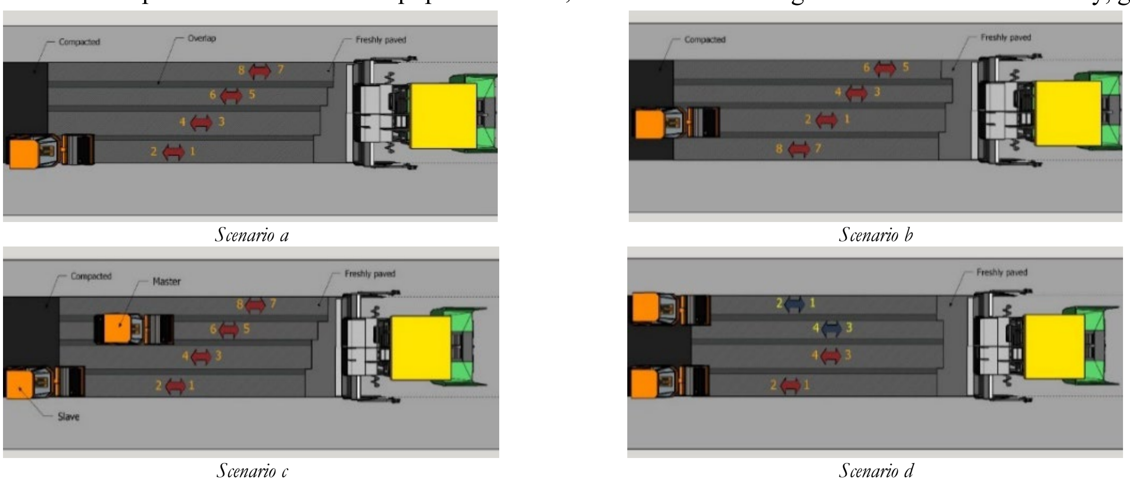
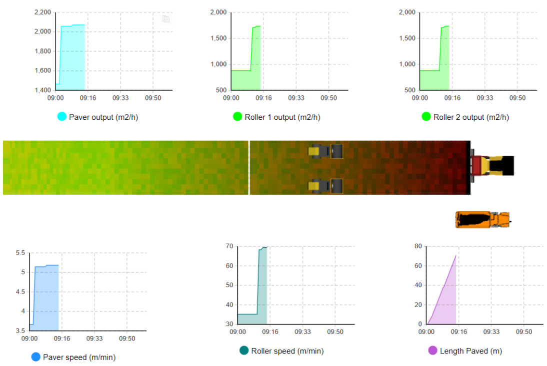


Figure 4. Different compaction strategies

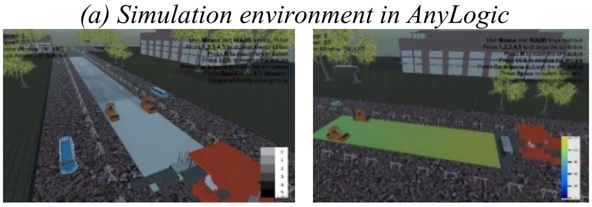
characteristics of the actual project, Scenario d was selected.The simulation model is constructed in AnyLogic and includes all the agents presented in Figure 3. The model reads the input parameters from the excel-based GUI. The simulation stops at the specified target time. Different interactive graphs present the areal output, the equipment speed, and the total surface paved, as shown in Figure 5(a).

Once the simulation is completed, the integration part takes place with the help of the GUI in Excel. During this process, the data generated by Anylogic are imported into Excel, where they are translated to the format readable by Unity. Afterward, the user runs the Unity executable file. Within this environment, it is possible to assess the compaction completeness and the cooling of the asphalt mat. Figure 5(b) presents the snapshots of the VR model.

The user can navigate through the VR model and slow and speed up the process to find the potential bottlenecks. In the end, the analysis of the entire operation, which incorporates the results of both spatial and temporal analysis is presented to the user, as shown in Figure 6.



(a) Simulation environment in AnyLogic



(b) VR representation

Figure 5. System Interface

In terms of accuracy, the simulated results are compared to the actual project statistics. Table 3 presents the result of this comparison. As shown in this table, the average estimation error is about 9%, i.e., considering rollers and pavers together. This would represent high estimation accuracy.

Also, the usability of the proposed method was assessed through a workshop with expert planners. The experts were asked to assess the current and proposed planning method in terms of user-friendliness, usefulness, versatility, teamwork between tactical and strategic planners, and helping planners become more aware of the compaction process. Figure 7 presents the result of the user assessment. In this figure, orange line represents the current situation and the blue line represents the proposed method.

6 Conclusions and future work

This research offered a framework for the integration of simulation of asphalt-pavement compaction and VR. A review of the asphalt compaction practices and a detailed description of the framework for capturing the relevant factors and providing productivity and operational quality feedback was presented. A prototype was developed, and a previous actual case study was used to demonstrate the feasibility of the proposed framework. The prototype was presented to asphalt experts and it was shown that the integrated model has a great potential to improve the operational quality and planning of compaction operations. The model was also found to have high estimation accuracy.

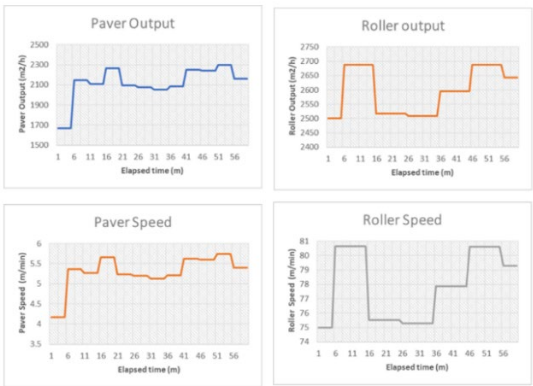


Figure 6. Report of the strategy assessment

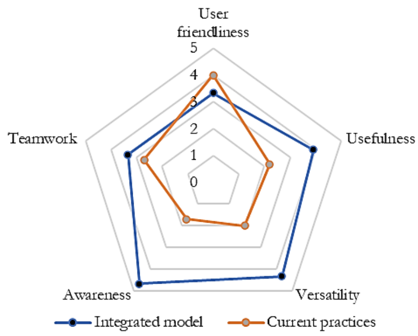


Figure 7. Usability assessment of the framework

It is shown that historical data and collected data from the site can be synthesized in an integrated model. It is demonstrated that this data can be converted into computer agents able to replicate the thermal behavior of the asphalt mat as well as the equipment operator's behavior. However, there are some limitations in the current research. The prototype should be further tested in more case studies, and its validity needs to be further assessed. Also, the number of compaction strategies supported in the model is limited at the moment. It is highly advised to collect real data from more compaction operations to build a comprehensive library of compaction strategies.

Table 3. Simulation results Vs. the actual data

Index	Actual	Simulated	Error rate
Roller output (m2/h)	2790	2629	6%
Paver output (m2/h)	2000	2180	9%
Roller speed (km/h)	5.00	4.74	5%
Paver speed (m/min)	5.00	5.45	9%
Compaction efficiency	20%	23%	15%

Moreover, bearing in mind the quickness of Artificial Intelligence (AI) evolution, the prototype could eventually use AI methods for automatic reasoning and, more interestingly, the development of AI-based compaction strategies.

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