MASTER THESIS

Integrating VR and simulation to deal with complex planning challenges: A case of asphalt compaction

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Integrating VR and Simulation to deal with complex planning challenges: A case of asphalt compaction

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Abstract

The current decision-making practices in construction projects, such as 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. New simulation-based planning techniques try to address this issue by offering a more realistic representation of the construction processes through capturing uncertainties and interdependencies between parameters that impact project execution. However, the current simulation-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 especially 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. The proposed framework provides a stepwise guideline into (a) collection of appropriate data for the simulation, (b) development of agents, physics, and environment for the simulation, (c), integration of the simulation output with VR, (d) generation of a VR environment with data-driven agents and physics, and (e) assessment of the equipment behavior and operational quality feedback. 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. Therefore, this work provides to the body of knowledge a framework for a holistic HMA planning tool able to capture all the temporal and spatial characteristics of a project and translating them into relevant decision variables for planners.

Keywords: Compaction, Simulation, Virtual Reality, Planning, Road construction

1. Introduction

Asphalted road construction is a complex field in the construction industry. In general, actors involved in a construction project must cope with different factors that affect the optimal outcome of the project. For instance, they struggle with uncertainties, different stakeholders, interconnection and interdependence of construction processes, and, most importantly, with time and budget constraints. Usually, to cope with the above, decision-makers rely on heuristic knowledge, gut feeling, and historical data to plan and manage construction projects (Dawood & Castro, 2009).

That being said, regardless of the inherent complexity of construction projects, the construction industry in The Netherlands has endured remarkable changes in the past few decades. Since the collusion scandal, new procurement and tendering strategies have been introduced (Miller & Dorée, 2008). Although these changes protect the interests of clients, taxpayers, and aim at delivering better products; construction firms have experienced additional challenges. For instance, the new contracts are stricter and pursue higher quality, the guarantee and warranty periods are extended, and competition became tougher (Miller S. R., 2010). Additionally, the firms must consider challenging maintenance periods, and they are susceptible to high fines for traffic disturbance (Arbeider, Miller, Dorée, & Oosterveld, 2017). Therefore, in an effort to obtain high-quality products and outweigh their competitors, firms merged efforts with academia to improve the asphalt pavement's performance, the paving process control, and the planning and scheduling of resources and work (Miller & Dorée, 2008).

1.1. Problem definition

The ultimate performance of asphalt pavements is predicated on two factors, i.e., the asphalt-mix and the compaction process. A high-quality pavement depends on both factors' satisfactory performance. Although, it was shown that the final quality of the pavement is more susceptible to compaction than to the asphalt-mix (Beainy, Commuri, & Zaman, 2010; Hughes, 1989). Similarly, Vasenev et al. (2013) argued that the quality, durability, and performance of an asphalted road has a strong dependency on the profiling and compaction of the asphalt.

With that in mind, experts and scholars agreed that the compaction process depends heavily on tacit knowledge and craftsmanship, the monitoring of key parameters is limited, and the planning phase is often based on tradition and custom (Bijleveld F. , 2017; Miller S. R., 2010; Miller & Dorée, 2008; Vasenev, Hartmann, & Dorée, 2013). Moreover, it has been shown that the compaction process is affected by a myriad of factors, i.e., material properties, initial density, equipment, traffic, and environmental (ter Huerne, 2004; Hughes, 1989), which are deeply interconnected and interdependent. Considering all of the above, Miller (2010) argued that there is extensive variability in the compaction process, and modest attempts are being made to monitor and reduce it. Hence, he claimed that it would be feasible to decrease this variability if the following criteria are met, (1) operational behavior is made explicit, (2) work processes are eased through visualization, and (3) construction teams are included in the improvements of the processes.

Accordingly, simulation models and visualization techniques have been developed to meet the above criteria and to assess decision-makers during the planning phase. Specifically, the former exhibited good results in reducing compaction variability and assessing variables from a temporal perspective. For instance, they provide the ability to evaluate the process from different scenarios and improve the use of resources (Nassar, Thabet, & Beliveau, 2003). On the other hand, Virtual Reality (VR) offers a robust 3D visualization of the process, providing enhanced spatial awareness to planners. For example, Vahdatikhaki et al. (2019) developed a framework to generate coherent context-realistic training simulators for compaction operations. These simulators demonstrated to be able to capture the spatial complexities of the process, providing relevant feedback regarding the productivity, safety, and quality of the asphalt pavement.

However, there is a lack of a robust planning tool that can capture all the affecting factors inherent in the process and translate them into relevant decision-making variables. Provided that, the existing simulators focus on the temporal perspective of the process, such as resource improvement but offer minimum spatial awareness to the planners. In that sense, due to the nature of the compaction process, it is highly advisable to account for the spatial perspective. For instance, it has been established that temperature is of utmost importance during the entire process (Miller S. R., 2010). Thus, a planning tool should be able to replicate the thermal behavior of the asphalt, which a simulation model is unable to provide.

Therefore, it could be appropriate to investigate the potential added value that an integrated model of simulation, along with VR, can bring about the improvement, from a planning perspective, of the asphalt-pavement compaction process. In essence, the integrated model would be able to capture all the relevant factors that affect the process and translate them into applicable temporal and spatial decision variables and provide operational quality indicators in a holistic manner. Likewise, this integration could help planners by improving resource allocation, estimating durations more accurately, potentially increasing the final quality of the pavement, and reducing the reliance on experts' experience and empirical knowledge.

1.2. Research objective

With the information stated above, the objective of this research is to develop a framework for integration of simulation of the compaction process and VR, to enhance the efficiency and consistency of the decision-making process, and to provide more accurate data for improved planning of road construction.

The structure of the research is as follows. First, the literature background is presented and reviewed. Then, the research methods, requirements analysis, and proposed framework are thoroughly discussed. Afterward, the implementation of the framework is detailed, leading to a discussion of the results. Finally, the conclusions are presented.

2. Literature review

2.1. Compaction of asphalt pavement

HMA compaction is defined as follows "…the process of reducing the air voids content of asphalt pavement between the solid particles. It involves the packing and orientation of the solid particles into a more dense and effective packing arrangement" (Hughes, 1989). HMA construction process (HMA-CP) starts with the manufacturing of the HMA at a plant; then, it is transported to the pouring site with trucks. Once the trucks arrive on site, the asphalt is poured into a material transfer vehicle (MTV) or directly into the paver. Afterward, the paver spreads the mixture in a uniform layer of desired thickness and shape. Finally, the compaction of the newly paved mat starts with the help of rollers. The final density of the layer is the indicator that evaluates whether the compaction has been performed successfully. To achieve the desired final density, it is vital to consider the influence of its affecting factors, which are divided into four categories, namely, material properties, initial density, traffic, and environmental, as shown in **Figure 1** (Hughes, 1989; ter Huerne, 2004)

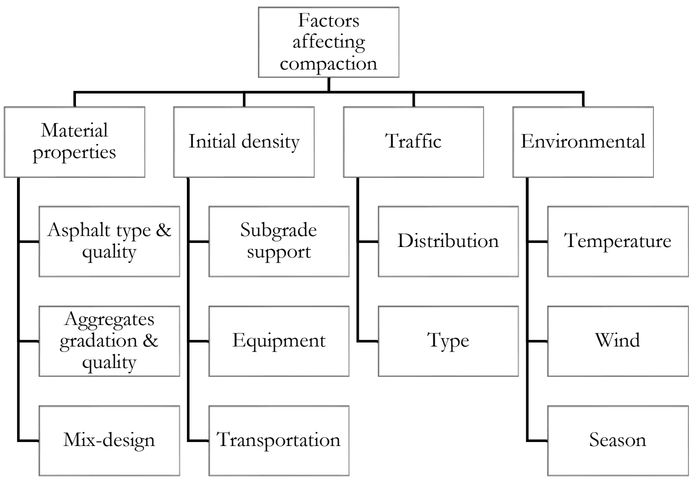


Figure 1. Factors affecting compaction

The material properties category has three main elements, namely asphalt type, and quality, aggregates quality and gradation, and the mix-design. The latter is the most important element within this category. Since the mix characteristics have a large impact on the final pavement quality (Hughes, 1989). However, the other two elements must be carefully considered since satisfactory compaction is also influenced by the asphalt viscosity and the size, shape, grading, texture, and absorption of the aggregates.

The next category concerns the initial density factors. The subgrade support stiffness needs to be high enough to bear, despite the traffic loads, the effect of the compaction process (Hughes, 1989). Also, with respect to paving equipment (i.e., roller and paver), a decision must be made regarding the type, number, speed, frequency, trajectory, and the number of compaction passes to ensure proper compaction. Finally, with respect to the transportation of asphalt to the site, the number, type and speed of the truck, distance, and time of hauling operation need to be strategically selected (Hughes, 1989). Furthermore, it is worth noting that within the logistics, it is essential to preserve the mix-temperature since it has paramount importance in the compaction process. Among other things, a stable mix-temperature enhances the compactability of the mixture, leading to a higher-pavement-quality and easing the compaction related works (ter Huerne, Dorée, & Miller, 2009). Conversely, low mix-temperature or inhomogeneous mixture hampers the compaction process and makes the pavement permeable to air and water, possibly leading to pavement damage (Advanced Asphalt Technologies, et al., 2011).

Although the traffic category seems to not play an important role in compaction, it has been shown that it is possible to reduce air voids in the mixture, up to 3 %, as traffic passes over the road, increasing the final pavement quality (Advanced Asphalt Technologies, et al., 2011). Another important category is the environmental factors which consist of weather conditions, wind, season, and temperature. These factors are essential because they have a direct impact on the cooling rate of the asphalt and available time for compaction (Miller S. R., 2010). Thus, they must be tackled appropriately to enhance overall pavement quality.

From a different perspective, these influential factors can be labeled as either temporal, i.e., a variable whose main evaluation indicator is time (e.g., number of trucks), or spatial, i.e., a variable whose main evaluation indicator is space (e.g., roller trajectory).

Evaluation of the affecting factors

Thorough planning of paving operations requires the evaluation of both spatial and temporal factors. Consideration of these factors in the planning helps achieve the required final density of the asphalt layer, which would then be translated into the desired final quality of the pavement. However, this evaluation is extremely challenging. On one hand, the factors are inherently interconnected and interdependent, e.g., the asphalt-mix depends on the type of aggregates and asphalt. On the other hand, the evaluation of the factors is commonly done by different actors, e.g., the project planner is in charge of the resource allocation, whereas the quality control team defines the number of roller passes. Meanwhile, the asphalt crew makes decisions on how to proceed with the compaction (Vasenev, Hartmann, & Dorée, 2013; Krishnamurthy, et al., 1998). Essentially, it can be stated that the planning of paving projects is commonly done at two levels, namely the organizational and project levels (Miller S. R., 2010; Winch, 2009). In the former, the logic and decision-making process of planners is revealed, and a generic model is developed (Tactical simulation). Whereas, in the latter, the model is refined to be a project-specific model (Operational simulation), which could be more suitable to improve the resource allocation, planning, and scheduling of the construction process. This fragmented structure renders a coherent and aligned decision making difficult.

At the same time, the current approach towards paving projects relies heavily on tacit knowledge and craftsmanship of the operators of the equipment. Also, the monitoring of key parameters is limited, and the planning phase is often based on tradition and custom (Bijleveld F. , 2017; Hassan & Gruber, 2008; Kassem, Scullion , Masad, & Chowdhury, 2012). Hence, it has been argued that there is extensive variability in the process (Miller S. R., 2010; Kassem, Chehab, & Saad, 2015; Guo, Zhou, Sha, & Bai, 2009). However, it would be feasible to decrease variability of the process if the following criteria are met, (1) operational behavior is made explicit, (2) work processes are eased through visualization, and (3) construction teams are included in the improvements of processes (Miller S. R., 2010). To meet these criteria, the use of digital technologies seems inevitable. However, these technologies can be used at two different stages, namely the construction and the planning stage.

2.2. Variability reduction during construction

Table 1 offers a summary of selected relevant investigations aimed at reducing variability in asphalt compaction during the construction phase. Bijleveld & Dorée (2014) adopted a method-based learning framework for asphalt teams. They claimed that this framework led to improved awareness of the quality and value of communications with and within the asphalt teams. Meanwhile, Makarov (2018) proposed a real-time process control system for asphalt paving and compaction, which can make the process more explicit for operators and managers on site. Specifically, the control system could support the asphalt team with essential information, such as the temperature of the asphalt mat and compaction parameters. In another endeavor, an interactive simulation visualization environment, focusing on asphalt compaction, was developed. The environment can represent documented equipment trajectories and experiment with alternative trajectories in context (Vasenev, Hartmann, Miller, & Dorée, 2016). In that line of thought, a novel framework, using VR environments, was developed by Vahdatikhaki et al. (2019), which can generate coherent context-realistic training simulators using data retrieved from construction sites. They showed that the new training simulators could improve various aspects of operator training, especially safety and teamwork. Furthermore, a real-time planning system for compactors was developed within the SmartSite project (Kuenzel, Teizer, Mueller, & Blickle, 2016). Basically, this is an assistance system for roller operators that generate instructions to compact, hence leading to high-quality compaction results. In another research, a system able to perform automatic data collection and provide real-time feedback to the construction site was developed. Claiming that it could enhance the asphalt construction procedure quality control and asphalt pavement construction quality (Zhu, Li, Wang, & Yu, 2018). Likewise, Liu et al. (2019) developed a framework for multi-roller compaction monitoring, wherein the system provides real-time feedback and proposes adjustments to achieve the compaction objectives. Although the above variability reduction tools proved to be very helpful when reducing quality variability in the compaction process, a robust variability reduction strategy needs to start at the planning phase (Arbeider, Miller, Dorée, & Oosterveld, 2017; Runneboom, Dorée, & Miller, 2018).

2.3. Variability reduction during planning

To elaborate on the scope of planning, it should be highlighted that some of the factors shown in **Figure 1**, such as the mix-design, are not part of the planner's decision-making process. Therefore, those types of factors could be perceived as fixed parameters when planning. A holistic planning tool needs to consider all the decision variables (temporal and spatial) at both organizational and project levels to ensure a coherent strategy for the reduction of variability.

Simulation and visualization techniques have the potential to provide the desired holistic overview, each focusing on specific types of decision variables. Simulation models can capture the resources, rules, parameters, decision variables, and stochastic events of the process over time, i.e., the temporal decision variables (Leite, et al., 2016). On the other hand, visualization techniques provide a platform to assess spatial variables (Retik & Shapira, 1999).

Table 1. Selected investigations that aimed at reducing variability in asphalt compaction

Authors	Year	Description
Beainy et al.	2010	A method that provides density measurement of the road underneath the roller drum during compaction.
Mostafavi et al.	2012	A methodology for assessing the impact of qualitative factors, on the productivity of asphalt paving process in night-time operations.
Labban et al.	2013	A DES simulation model of asphalt paving operations. It aims at simplifying simulation models, for inexpert stakeholders.
Vasenev et al.	2013	VR tool to extract tacit knowledge from machine operators.
Kassem et al.	2015	A FEM-predictive tool for simulating the cooling characteristics of freshly paved asphalt.
Kuenzel et al.	2016	Development of SmartSite. A real-time planning system for compactors.
Arbeider et al.	2017	A support tool for decision-making related to equipment allocation and compaction strategies.
Bijleveld et al.	2017	Improve the operational strategies of asphalt teams undertaken at construction sites.
Zhu et al.	2018	A system that performs automatic data collection and transmission for real-time feedback to the construction site for quality control.
Chang et al.	2018	Use of Intelligent compaction and Thermal Profiling Technologies to improve asphalt pavement construction quality.
Liu et al.	2019	Collaborative control of multiple rollers in the construction site to enable them to follow the right path at the right time.

Simulation and temporal variables

According to Leite et al. (2016), simulation models have the potential to be a critical decision-support tool for the quantitative and temporal assessment of operations and processes that are part of a project lifecycle. In the construction industry, simulation is defined as follows "…the science of developing and experimenting with computer-based representations of construction systems to understand their underlying behavior" (AbouRizk, 2010). Nassar, Thabet, & Beliveau (2003) concluded that the use of simulation provides decision-makers and contractors with useful information, which enables planning and scheduling improvement.

Hassan & Gruber (2008) developed a simulation model that yields an adequate accuracy compared to field measurements. They claimed that decision-makers may count on simulations to evaluate different decision variables with a high level of accuracy. Meanwhile, Miller and Dorée (2008) unravel the logic that planners follow when determining truck resources for transporting asphalt from the plant to the construction site. Also, they provided planners with more accurate means to plan truck resources. Meanwhile, an asphalt simulator was built to estimate, plan, and manage asphalt operations. Providing a framework to build simulations quickly and with minimal simulation model building skills (Labban R. , AbouRizk, Haddad, & Elsersy, 2013).

With that stated, it is safe to say that a simulation model could be employed to capture and evaluate the temporal decision variables of the HMA-CP. However, its ability to do the same with the spatial decision variables could be argued. Particularly, it has been established that temperature is of utmost importance during the entire process. Thus, any quality indicator used for the assessment of the paving process needs to consider the temperature gradient during the compaction. For instance, the quality indicators, i.e., compaction efficiency and process consistency, suggested by Vahdatikhaki et al. (2019), are directly related to the spatial decision variables. Although the simulation can capture this relationship and provide feedback from a temporal perspective, the thermal behavior of the asphalt cannot be captured. Hence, simulation alone would not fulfill the purpose of a robust planning tool. Nevertheless, the behavior of the asphalt cooling curve can be replicated in a VR environment as data-driven physics. The environment can capture the complex causal relationships that impact the thermal behavior of the asphalt and provide a 3D temperature contour of the asphalt mat and the cooling curve of the asphalt at the core and surface (Vahdatikhaki, et al., 2019). Therefore, VR can capture and evaluate the required spatial decision variables. However, to the best of the authors' knowledge, the current simulation models ignore (or greatly simplify) the spatial variable.

Virtual reality and spatial variables

VR can provide high-fidelity spatial awareness, and consequently address the relevant spatial decision variables. In that sense, VR is defined as follows "…mosaic of technologies that support the creation of synthetic, highly interactive three-dimensional (3D) spatial environments that represent real or non-real situations" (Micropoulos & Natsis, 2011).

VR has been successfully employed to enhance construction processes from different perspectives. For instance, VR is used to integrate construction site procedures into the planning and scheduling of an entire construction project (Retik & Shapira, 1999). Further, it was argued that the system could aid practitioners in visualizing the construction progress. In other words, it provides comprehensive spatial awareness to planners (Retik & Shapira, 1999). Likewise, Rekapalli & Martinez (2011) used VR to study complex earthmoving operations and argued that DES-based VR could be an effective method to test and validate complex simulation models. Specifically, by providing spatial awareness to identify and rectify possible errors in the simulation. Meanwhile, Sacks, Perlman, & Barak (2013) strongly recommended VR for safety training in construction sites. Vahdatikhaki et al. (2019) also used VR for training operators of asphalt operation equipment, providing relevant feedback from a safety, quality, and productivity perspective.

VR provides users the ability to assess processes from different perspectives and offer high-fidelity spatial awareness. Hence, they could potentially diminish the reliance on craftsmanship and tacit knowledge (Vasenev, Hartmann, & Dorée, 2013; Vasenev, Hartmann, Miller, & Dorée, 2016). However, their capacity to capture all the HMA-CP decision variables is debatable. For example, when evaluating the resource allocation variables, such as quantity and/or speed of equipment, it is more relevant to have temporal feedback and to capture their stochastic behavior than obtain spatial awareness on them. Thus, it seems that integration of simulation and VR could offer a tool that can capture all the relevant decision variables of the HMA-CP. It is worth noting that this integration is not new for other industries. For example, Akpan, Shanker, & Razavi (2019) researched the potential benefits of combining simulation and VR in different projects. Namely, they claimed that stakeholders could use visualization techniques in addition to simulation to guarantee the success of a simulation project. Also, Turner et al. (2016) described the benefits of using simulation (Discrete Event Simulation) and VR in industrial plant decision-making.

The benefits of simulation and VR techniques for the planning of HMA-CP are well documented in the literature. Nevertheless, as discussed in this section simulation and VR techniques, when applied separately, are not able to capture all the relevant decision variables and translate them into useful quality indicators, hence, the integration of both techniques is required. However, to the best of the authors' knowledge, such an integrated model is not studied for holistic modeling of HMA-CP. In an 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, and VR could deal with the spatial decision variables, such as areal output of equipment, rollers' trajectory, asphalt cooling rate, and translate them into relevant quality indicators, i.e., compaction efficiency and process consistency.

3. Methods

3.1. Research methodology

Figure 2 shows the methodology applied in this research. Essentially, it follows a variation of the design research methodology (Blessing & Chakrabarti, 2009). It is divided into four parts, i.e., literature review, requirement analysis, framework development, and synthesis. The first stage focuses 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 HMA-CP. Likewise, an extensive review of simulation and VR, regarding asphalt pavement, is performed. Finally, the first stage identifies a research gap in the current body of knowledge concerning the integration of simulation and VR techniques for asphalt paving operations. Then, the essential requirements for the integrated model are obtained. For that purpose, interviews are completed with asphalt experts in The Netherlands. The interviews have a semi-structured approach, and the experts are chosen using the key informant sample technique (Young, et al., 2018). Furthermore, questionnaires are delivered to substantiate the acquired knowledge. According to Olson & Rueter (1987), questionnaires are a direct, efficient, and fast method of knowledge elicitation. Likewise, they are useful in uncovering relationships, such as the ones inherent in the HMA-CP.

In Phase Three, the framework is developed. The data collection is explained and detailed. Then, the simulation is built. Agent-Based Simulation (ABS) is proved to be one of the most suitable methods to investigate the dynamic interactions of complex systems (Wilensky & Rand, 2015). It is a bottom-up approach wherein actors are programmed as agents and their behavior is captured as rules and routines. Furthermore, the agents interact with other agents or with the environment, to build the target complex system (Wilensky & Rand, 2015). Upon simulation completion, it is integrated with a VR Environment. To this end, the existing VR developed by previous research of the ASPARi group (Vahdatikhaki, Langroodi, Makarov, & Miller, 2019) is used.

Lastly, the framework is implemented, verified, and validated. The former is done with prototype development and scenario analysis, which is based on an existing case study, i.e., the surface rehabilitation of the A-15 highway, in Rotterdam, The Netherlands (Vahdatikhaki, et al., 2019) Then, the prototype is verified by evaluating the output with different flow diagrams to make sure that the model is built correctly. Finally, the model is validated in two different ways. First, its accuracy is compared and contrast with ASPARi case studies. Mainly, data from the surface rehabilitation explained above. And, to complement it, it is further compared with data from monitored road construction projects (Arbeider C. G., 2018). Second, the usefulness of the model is assessed with the input of asphalt experts. For that, a use case is used and, subsequently, a questionnaire, with relevant metrics to evaluate the model's usefulness, is filled.

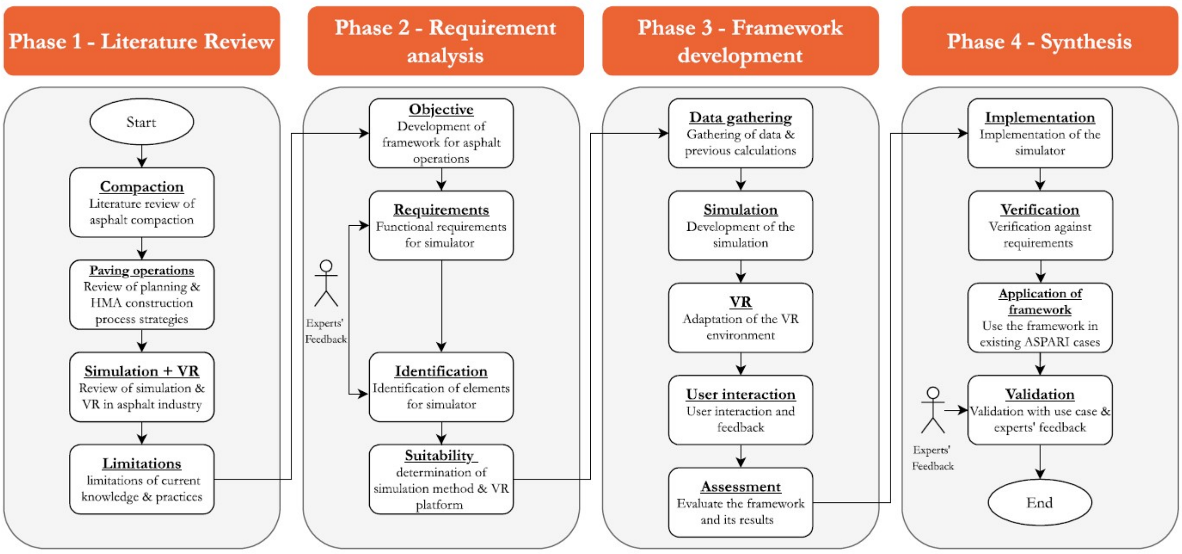


Figure 2. Overview of the Research Methodology

4. Requirements analysis

To identify and analyze the functional requirements that an HMA-CP simulator should have, a set of four interviews are 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.

Moreover, both of them, while being part of academia, conducted research focusing on asphalt pavement. Thus, they both have a theoretical and practical background. On the other hand, the experts from the latter company have been working on asphalt related projects for several years. One of them belongs to the tactical realm and gave a broader overview of the process. Whereas the other expert belongs to the operational realm, providing relevant feedback from an operational point of view. Finally, questionnaires are fulfilled by few asphalt experts in The Netherlands to substantiate the acquired knowledge from the interviews.

4.1. Functional requirements

The starting point for determining the functional requirements of a holistic HMA planning tool is to identify and categorize two crucial characteristics of it. First, who is involved in the process and to what extent. And second, what are the key factors that the decision-makers consider when designing a strategy for the construction process. Therefore, based on the knowledge acquired in the preceding sections and the experts' input, the following characteristics are identified and subsequently translated into functional requirements of the integrated model.

Among the people involved in the construction process, the crucial identified decision-makers are the tactical planner, asphalt foreman, who is the leader of the asphalt team, the paver and roller operators, and the quality & control (QC) team. Each of the experts has different involvement in each of the HMA-CP phases, i.e., transportation, paving, and compaction.

Consequently, to capture the holistic view of the HMA-CP decision variables, the overall requirements of the integrated model have been identified. (1) The model must provide the user with resource allocation alternatives, (2) The model must 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 must provide the user with relevant feedback about the quality of the compaction, which is evaluated with operational quality metrics, i.e., compaction efficiency, and process consistency. Then, due to the entangled nature of the key people and key affecting factors, it is highly recommended to further divide the functional requirements into the respective HMA-CP phases.

Transportation phase requirements

The transportation phase involves the tactical planner and the QC team. The goal of this phase is to preserve the mix-temperature and to have a constant delivery of asphalt. To achieve the latter, the tactical planner must allocate enough hauling trucks and assess the unique project characteristics. For that, the simulator should allow the planner to obtain the minimum number of trucks for a project considering the target production, the truck capacity, the hauling time, and also include the stochastic effects within the phase. In other words, the simulator must capture and evaluate the number of trucks needed for completing the job.

Paving phase requirements

Unanimously, the experts conveyed that alignment of paving and compaction outputs potentially lead to uniformity and continuity in paving operations. That being said, the paving phase includes the tactical planner, the asphalt foreman, the paver operator, and the QC team. The tactical planner, based on the productivity target, sets the resource allocation and provides average values for the speed of the paver. The operational team, namely asphalt foreman and paver operator, evaluates constantly the output of the paver, and sets the speed accordingly, in order to reach the production target in the allocated time. Finally, the QC team is present during the whole process to guarantee that the quality threshold of the pavement is met. Therefore, the model should capture the behavior of the paver and represent the characteristics of its behavior as accurately as possible. That is, on one hand, the model should capture the intermittent movement of the paver, such as the waiting stops for the asphalt trucks, the speed-up or slow-down for achieving the productivity goal, and/or for staying aligned with the rollers. On the other hand, the model needs to account for the impact in the areal output of different road geometry, i.e., curves, intersections, roundabouts.

Compaction phase requirements

Finally, the compaction phase design relies on the tactical planner, the asphalt foreman, the roller operator, and the QC team. As in the previous phases, the tactical planner allocates the rollers, evaluates their output, and provides reference values for its speed. Then, with the allocated resources, the operational team and the QC team develop the compaction strategy, namely length of roller track, number of passes, rolling path, and speed of roller. These choices are made based on the environmental conditions, road geometry, productivity and quality requirements, and asphalt cooling rate. Furthermore, the roller operator must be aware of other rollers' movement and keep up with the paver. Therefore, the simulator should be able to provide the following features of this phase. First, it should capture the impact of the affecting factors, such as the environmental conditions, the cooling characteristics of the asphalt-mix, the geometry of the road. Second, represent the rollers' movement accurately, i.e., speed adjustments, asphalt mat coverage, roller's transitions. Third, provide the user with compaction strategies alternatives to evaluate its repercussions on the final quality of the pavement.

Specific requirements and categorization

Scholars and asphalt also pointed out the importance of considering the temperature issue during the HMA-CP. 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, this must be able to capture as far as possible the behavior of the asphalt cooling curve. **Table 2** summarized the identified functional requirements of the framework.

4.2. Requirement analysis—Conceptual model

The next step in the requirements analysis is to build the conceptual model for the simulation model. For that, the operational factors inherent in each HMA phase are identified. Then, with the experts' insight, the factors are divided into fixed (input) parameters and decision variables. The former refers 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-maker's hands and, consequently, can be modified within the model. To illustrate, **Figure 3** and **Table 3** show a schematic overview and presents the parameters and decision variables, respectively.

Figure 4 shows the conceptual model. To clarify, the process starts at the asphalt factory. Where the mixture is produced based on the mixture design. The factory must provide a delivery rate sufficient to deliver asphalt uninterrupted. Then, the transportation phase begins, which is affected by the distance between the plant and the construction site, as well as the weather conditions. Then, the delivery rate is assessed to guarantee that the allocated equipment is sufficient to provide the required asphalt. Afterward, in the construction site, the paving and compaction phase takes place. It is vital to consider the available time for operations, a value obtained based on the rate of asphalt cooling, which in turn is influenced by the subsurface conditions, the mixture properties, the weather conditions, and the layer thickness. Then, the areal output of the paving and compaction must be aligned to theoretically provide uniformity in the construction process. The output is affected by the type, number, width, speed of the equipment. As well as the number of rollers passes. Finally, the output is evaluated regarding the productivity target. If the requirements are not met, the equipment parameters must be reassessed.

Table 2. Functional requirements summary

Phase	Experts	Requirements
Transportation	TP, QC	Capture and evaluate the minimum number of trucks
Paving	TP, AF, PO, QC	Capture and evaluate the movement of the paver and areal output
Compaction	TP, AF, RO, QC	Capture and evaluate affecting factors, rollers' movement, provide compaction strategies alternatives
General	TP, QC	Capture and account for the asphalt cooling curve

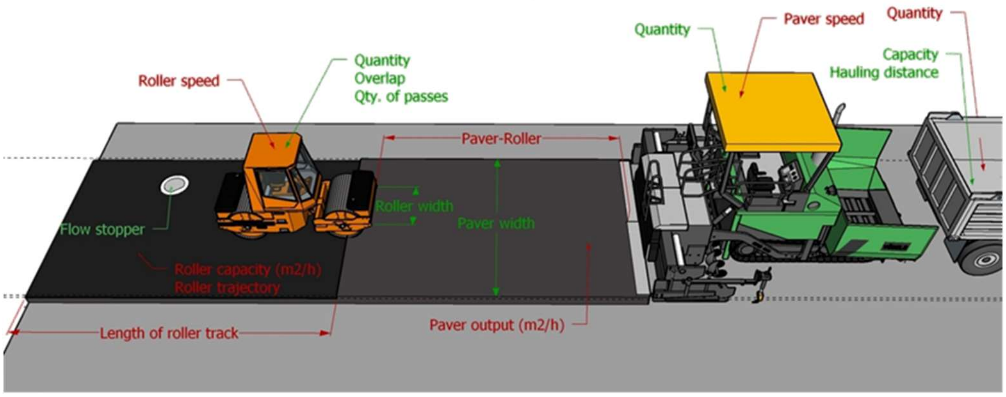


Figure 3. Schematic overview of the HMA-CP parameters (green) and decision variables (red)

Table 3. Relevant factors for the HMA-CP

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

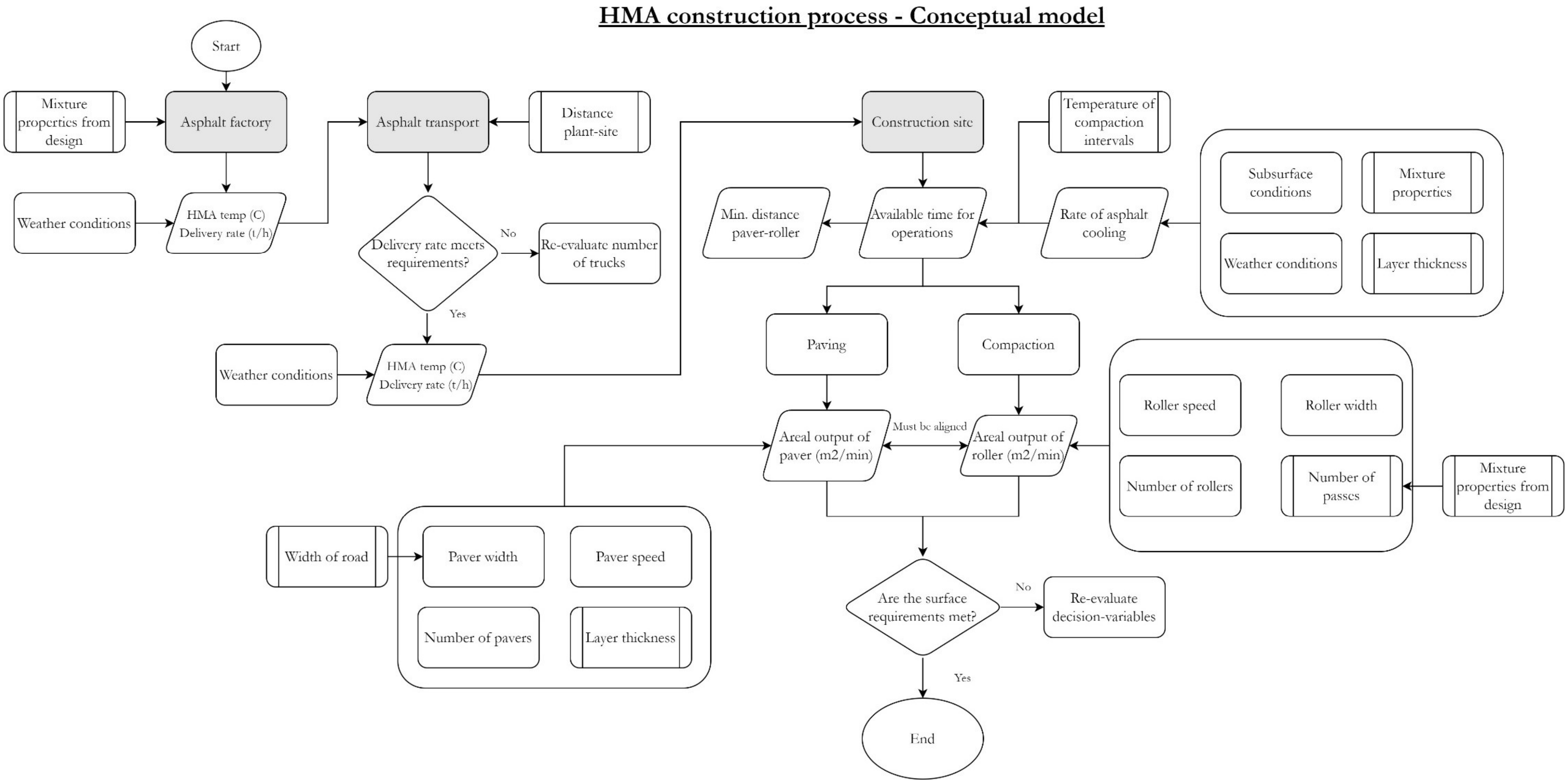


Figure 4. HMA-CP, conceptual model

5. Proposed framework

As shown in **Figure 5**, this research proposes a hybrid, i.e. simulation and VR, planning tool for the HMA-CP. In this platform, simulation is responsible for capturing the parameters described in **Table 3**, and generating temporal decision variables, i.e. quantity of trucks, equipment output, and average speed, for the expert's evaluation. Then, the simulation feeds all the factors to the VR, in which the virtualization of all the planning decisions takes place. Within the environment, the decision-maker is able to evaluate the spatial decision variables, i.e. roller trajectory, length of roller track, and distance Paver-Roller, of their strategy. On top of that, the VR offers operational quality feedback of the work done.

Figure 5. Proposed integrated planning tool

To materialize the above, **Figure 6** 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 3.** 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 feeds 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. Next, the user can evaluate their strategy in the VR environment. That is, the possibility to assess, in virtual real-time and with high spatial awareness (3D), the impact of their choices on the asphalt mat, such as equipment movement, mat cooling, and rolling pattern. 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 effectively compacted and within the temperature range. The remaining of this section describes in detail each phase of the framework.

5.1. Data collection

The data collection begins with the compilation of the parameters shown in **Table 3.** Afterward, the data is organized and initial values for the decision variables are computed, such as the paver and roller speed, length of roller track, minimum distance paver-roller, and the selection of the roller trajectory. To be in line with the previous section, this phase is divided into properties, transportation, paving, and compaction.

Properties

As stated during the requirements phase, the available time to deliver the product and the surface target are the starting point for planning the HMA-CP. Then, the geometry of the road, which will be modeled as parametric, must be stated, i.e., road length, width, and layer thickness. Also, if there are any, the number of curves, intersections and/or roundabouts. Besides, to provide an enhanced representation of the surroundings, the environment can be captured using available CityGML and digital cadastral data. Alternatively, on-site cameras, drones, or LiDAR scanning can be used, as proposed by Vahdatikhaki et al. (2019).

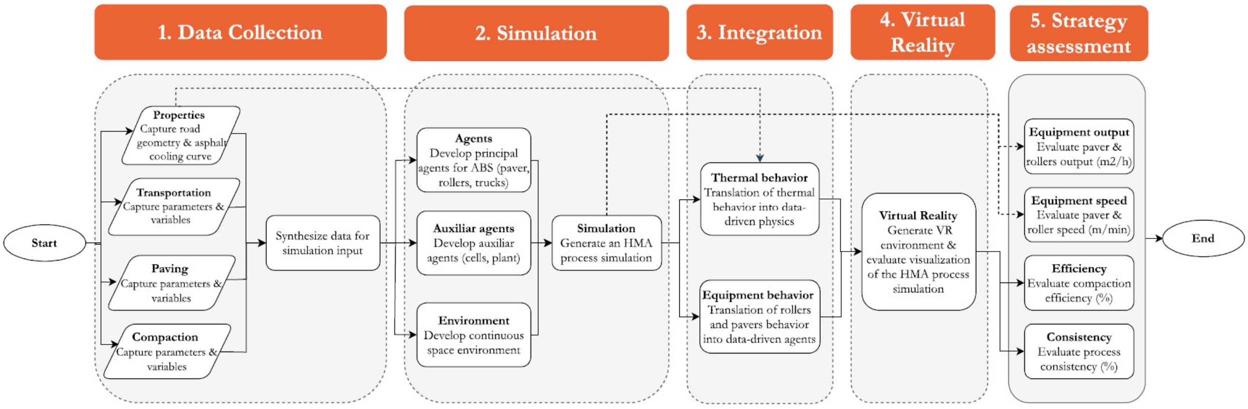


Figure 6. Overview of the proposed framework

The temperature of the asphalt mix is of utmost importance in the HMA-CP. On one hand, if the mixture is too hot while being compacted, it can be overstressed, hence the mat would spread laterally rather than being compacted. On the other hand, 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 (Miller S. R., 2010). 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. For that, the temperature of the laid asphalt mixture can be collected using thermocouples, placed at the core and surface of the mat, and an infrared camera that constantly measures the temperature at the location of the thermocouples, as shown in **Figure 7** (Vahdatikhaki, et al., 2019). Alternatively, if the above collection is not feasible, the software PaveCool can be employed, which is a fairly intuitive application that provides the asphalt cooling curve based on input parameters, i.e., layer type, layer thickness, environmental forecast.

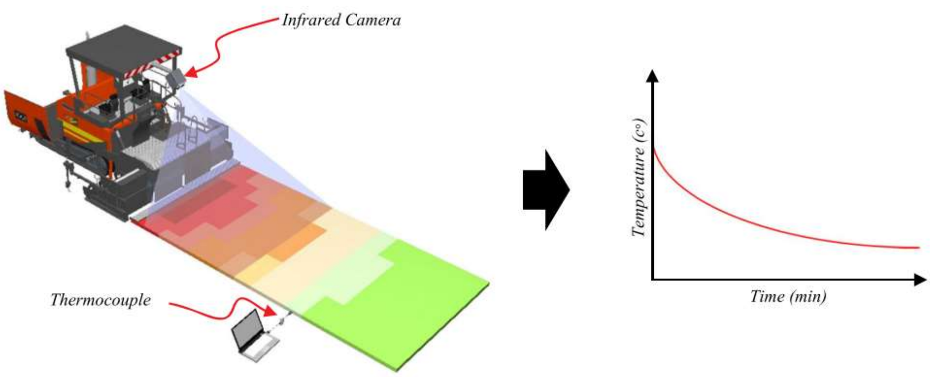


Figure 7. Determining the asphalt cooling curve based on embedded thermocouples and infrared camera (Vahdatikhaki, et al., 2019)

Transportation

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 simulator can represent the behavior of the trucks, and also capture the stochastic effect inherent in construction, as suggested by Miller & Dorée (2008).

The user needs to state the distance from the asphalt plant to the construction site, the estimated time for hauling operations, for loading and unloading of the truck, as well as the truck capacity. 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 to pave 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.

Paving

Theoretically, if the paver areal output and the roller capacity are aligned, continuity and uniformity can be achieved in the paving operations (Arbeider, Miller, Dorée, & Oosterveld, 2017). To theoretically achieve the alignment and perform the computations thereof, a choice must be made regarding the leading equipment. In other words, deciding whether the paver output is the starting point or the roller capacity. Usually, the paver is regarded as the leading equipment. Hence, the initial calculations are performed with that premise.

First, the paver features, such as type, number, and desired screed width, must be stated. With that information retrieved, the model offers two ways to choose the paver speed. For the first one, the initial average speed is computed based on the productivity goal. Alternatively, 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 (Runneboom, Dorée, & Miller, 2018). Therefore, these so-called flow stoppers, e.g., roundabouts, crossing points, curves; must be considered when representing the behavior of the paver. Fortunately, based on the number and type of the flow stoppers, their occurrence on the paving behavior can be represented with the model. This is possible by employing the assumptions proposed by Runneboom (2018). Based on these assumptions, the impact of different flow stoppers is identified, categorized, and translated to output rate parameters. Thus, the simulator quantifies the flow stoppers and, using the above rates, translates them into the paver behavior by reducing its speed.

Compaction

Following the logic on the preceding phases of the data gathering the user must provide the roller characteristics, width, number, type, and the number of passes. Then, since the overlap, length of roller track, and distance paver-roller are dependent parameters, they are automatically calculated using Equations 1 to 4, which are based on the formulas proposed by BOMAG (Kloubert, 2009). To illustrate, **Figure 8** depicts the above factors.

$$Ov = \frac{B - N \cdot b}{b(N-1)} \qquad \text{Eq. 1}$$

$$L = \frac{T \cdot v_R}{N \cdot n} \qquad \text{Eq. 2}$$

$$X = f(cooling\ rate) \qquad \text{Eq. 3}$$

$$v_R = \frac{N \cdot n \cdot v_p}{\sum Rollers} \qquad \text{Eq. 4}$$

where:

Ov: Overlap
B: Paver width
b: Roller width
L: Path length
N: Parallel roller tracks
n: Roller passes
v_R: Roller avg. speed
T: Available compaction time
x: Minimum distance paver-roller

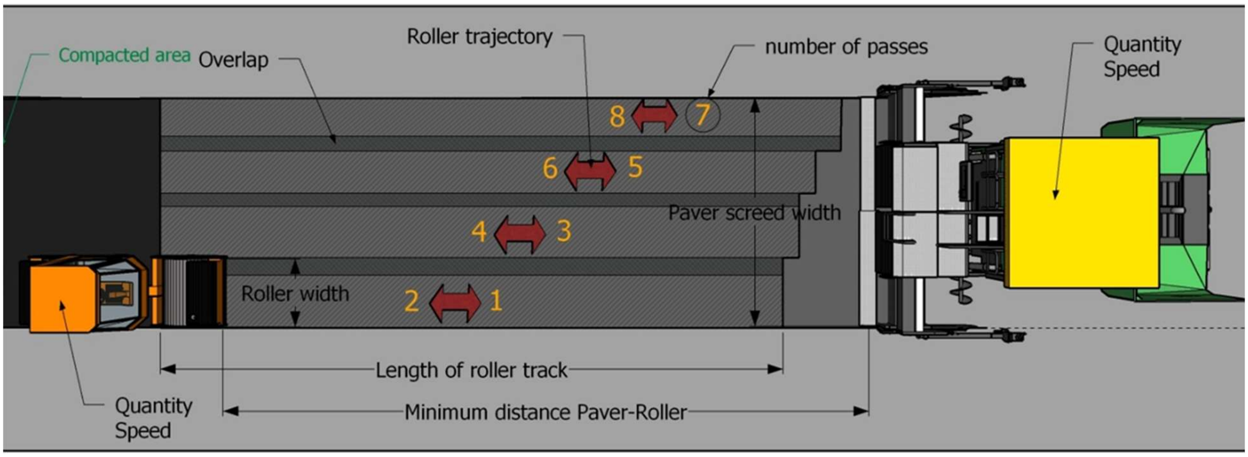


Figure 8. Data gathering parameters and variables

Once the above values are determined, it is time to choose the roller's speed. This can be done in two ways. Either the user states an initial average speed, or the model suggests a value based on the premise that the paver output and the roller capacity are aligned, using Equation 4.

Finally, the compaction strategy must be chosen. That is, the trajectory that the roller will follow to cover the mat completely and with the desired number of passes. The simulator offers path alternatives based on the number of strips, which is the width coverage of the roller, number of passes, and number of rollers. The suggested paths are based on the standard compaction strategies available within the body of knowledge (Kloubert, 2009; Krishnamurthy, et al., 1998).

5.2. Simulation

5.2.1. Input & agents

The data collected and organized in the previous phase of the model serves as an input for the simulation. Two elements that must be defined within an ABS is the environment and the agents. For this study, the former is constructed as a continuous space, provided that the simulation is a simplification of the overall model and the spatial features will be part of the VR environment. Regarding the agents in the ABS model, five agents have been modeled. Three of them belong to the HMA actors, i.e., truck, roller, paver, and the remaining two correspond to the asphalt plant and the discretized paved surface as cells. To illustrate, **Figure 9** shows the agent's flowcharts.

The truck behavior is characterized by its interaction with the plant, paver, and the environment. First, 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. The parameters that define the agent are its capacity, speed, transition time, and unloading rate.

The paver, on the other hand, is characterized by its interaction with the truck, the roller, and the cells. When the truck is pouring the asphalt-mix into the paver-hopper, the machine starts paving at the initial speed. Each paved unit is represented in the model with a cell. Furthermore, 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. The parameters that define the agent are its initial speed, width, and the flow-stoppers.

The cell behavior is fairly simple. When the equipment paves the cells appear discretized in strips. Wherein, the width corresponds to the width of the road and it is further divided into ten cells. As for the length, each strip has a unitary length, in this case, it is one meter. Afterward, the cell "cools down". i.e., it changes progressively its color from red (freshly paved) to green (cold).

Due to the sensitivity of the compaction process, the roller's behavior is more elaborated. To start compacting, two conditions must be met. Firstly, there should be a minimum distance between the 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 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. Furthermore, after rolling each section, i.e., complete coverage of the road width and path length (Eq. 2), the roller evaluates whether its capacity is aligned with the paver output, and its distance with the paver is within the allowable limits. Then, the roller modifies its speed accordingly. Lastly, the parameters that define the agent behavior are its initial speed, the number of stripes, the target number of passes, the length of the rolling path, the asphalt cooling curve, and the compaction strategy.

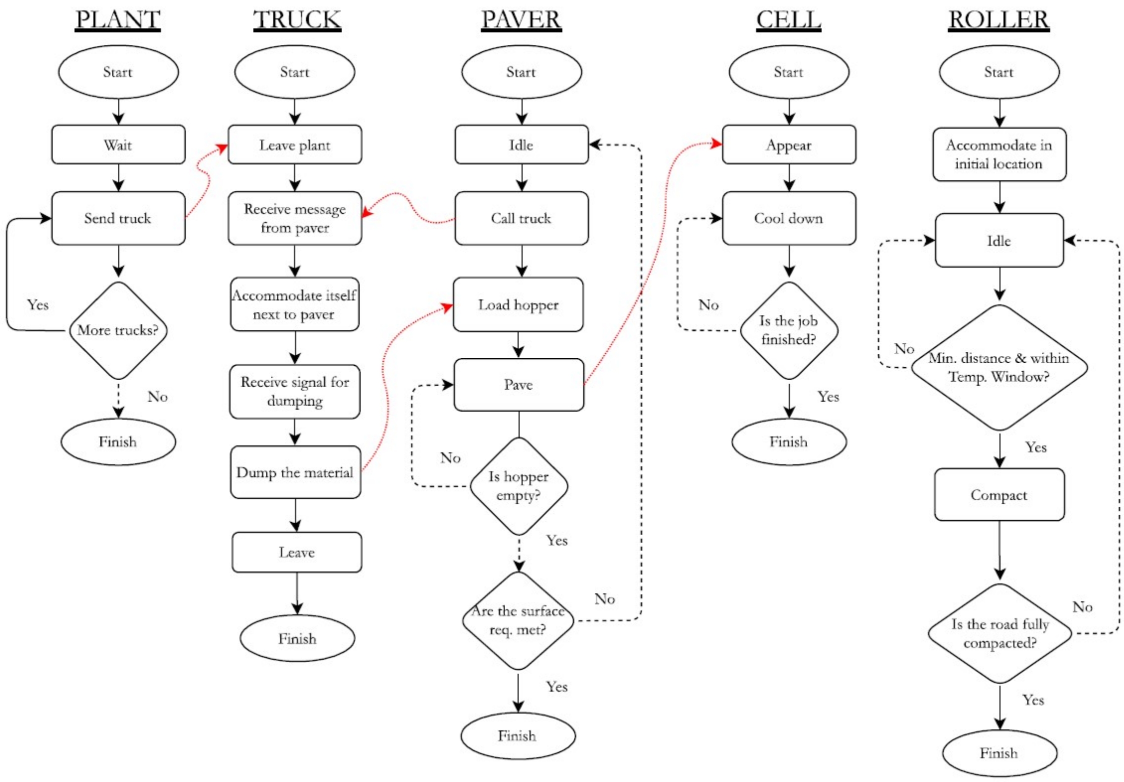


Figure 9. Overview of agents' flowcharts

5.2.2. Output

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 to successfully complete 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.

5.3. 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 refers to the equipment behavior. First, the converter captures the movement of the paver and roller in terms of cyclic timestamp location. Then, the values are translated into local VR environment coordinates, allowing it to replicate the movement as data-driven agents. Afterward, the physics conversion relates to the asphalt cooling. For that, the converter captures the cooling curve obtained in the previous phase as timestamped values. Then, the VR environment uses that data for representing the temperature, as data-driven physics, of each cell after it has been paved. Finally, the logistics features, such as equipment quantity, and available time, is converted into data that the VR environment can use.

5.4. Virtual reality

The VR environment allows the user to evaluate their strategy in virtual real-time and with high spatial awareness (3D). Besides the realistic equipment movement, they can 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 60 % of the cells have had at least one compaction outside the compaction temperature window (Vahdatikhaki, Langroodi, Makarov, & Miller, 2019). Equation 5 demonstrates how the index can be obtained. On the other hand, process consistency refers to the compaction homogeneity of the cells. This index is used to determine whether a cell remains in the compaction temperature window or is too cold for proper compaction. Also, it can show how much time left a cell has to have successful compaction (Vahdatikhaki, et al., 2019).

$$CE = \frac{\sum_{i,j=1}^{n}(FP_{i,j} \times LP_{i,j})}{N_c} \qquad \text{Eq. (5)}$$

$$P_{i,j} = 1 \rightarrow FP_{i,j} = \begin{cases} 1 & l \leq CT_{i,j} \leq u \\ 0 & otherwise \end{cases} \qquad \text{Eq. (6)}$$

$$P_{i,j} = PD \rightarrow LP_{i,j} = \begin{cases} 1 & l \leq CT_{i,j} \leq u \\ 0 & otherwise \end{cases} \qquad \text{Eq. (7)}$$

where:

CE	=	*Compaction efficiency*	$P_{i,j}$	=	*Compaction achieved at cell i and j*
$FP_{i,j}$	=	*successful first compaction at cell i and j*	$CT_{i,j}$	=	*Current temperature of the cell i*
$LT_{i,j}$	=	*Successful last compaction at cell i and j*	l	=	*Lower bound temperature*
N_c	=	*Total number of cells*	u	=	*Upper bound temperature*

5.5. 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.

6. Implementation

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 (Abar, Theodoropoulos, Lemarinier, & O'Hare, 2017), and the VR environment is built with Unity (Yang & Jie, 2011). To clarify, **Figure 10** depicts the architecture of the built prototype. In short, the parameters shown in **Table 3** 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.

The prototype has been validated in two different ways. First, the accuracy of the model was compared with results from actual projects. Mainly, data from a surface rehabilitation of a highway was used (Vahdatikhaki, et al., 2019). To complement, it was further compared with data from road construction projects (Arbeider C. G., 2018). Second, the usefulness of the framework was assessed with the input of asphalt experts. For that, a use case is employed, and subsequently, a questionnaire, with relevant metrics to evaluate the model's usefulness, is filled.

6.1. Scenario analysis

For this study, the main case to be evaluated is a 250 m surface rehabilitation of the A-15 highway, in Rotterdam, The Netherlands (Vahdatikhaki, et al., 2019). The total allocated time to execute the job is one hour. Also, four different compaction strategies are evaluated, two with one roller and two with two rollers.

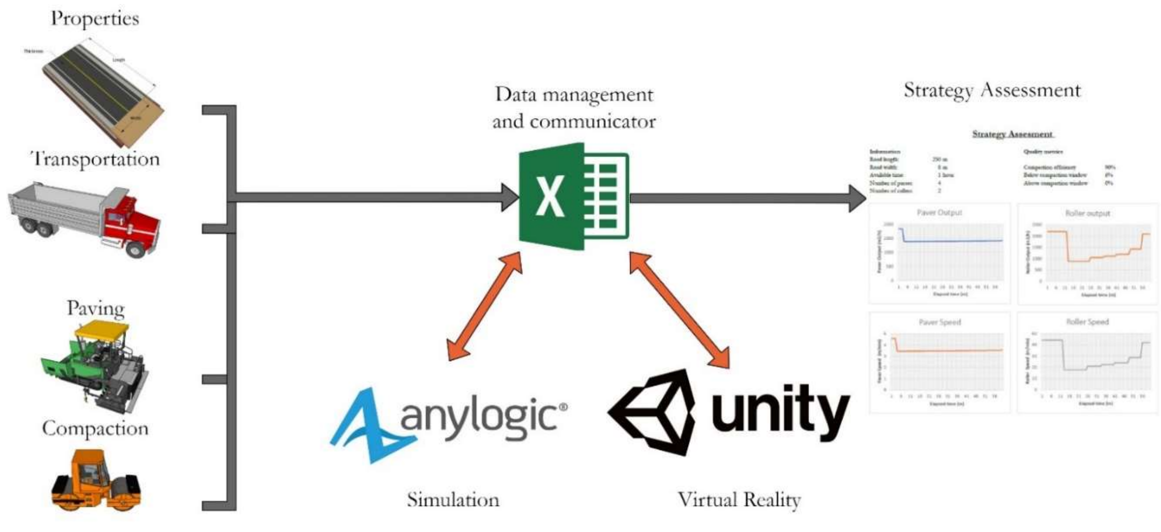


Figure 10. Proposed architecture of the prototype

Data collection

The asphalt cooling curve is depicted in **Figure 11**. According to the experts, for this particular case, the best thermal interval for compaction is within 120 °C and °80 C. Moreover, after the asphalt is paved, there is a minimum waiting time of ten minutes prior to compaction. **Figure 12** shows the interface developed in this research for the collection of the parameters. Furthermore, a summary of the collected and analyzed input data is presented in **Table 4**.

It is worth noting that for this case the user selects an automatic calculation of the initial values for the speed of the equipment, as suggested in section 5.1.

Table 4. Data collection summary

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

Furthermore, two simplifications are made during this phase. The first one, considering the nature of the project, the trucks are already at the construction site. Hence, the model only considers their capacity and the transition time, which is the interval of empty truck departure and full truck maneuvering. The second simplification is about the compaction strategies. For this project, four alternatives are considered.

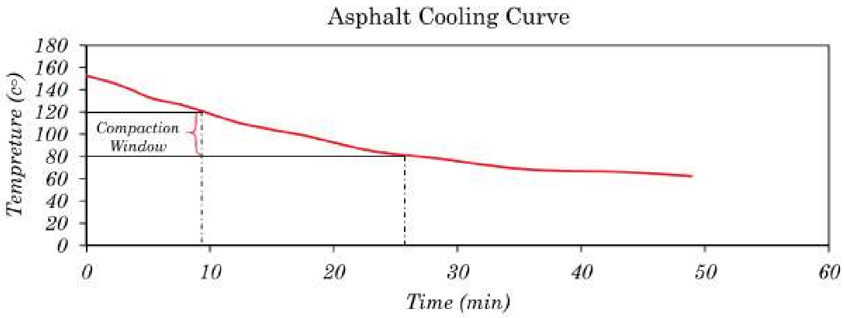


Figure 11. Asphalt cooling curve (Vahdatikhaki, et al., 2019)

To illustrate, **Figure 13** depicts the above alternatives. In short, option (a) starts at one edge of the road and progressively and uniformly compacts the stripes towards the opposite edge. The transitions must be made in the already compacted pavement, to prevent irregularities in the newly paved asphalt. Alternatively, the roller can compact the inside stripes first (b) and leave the outer stripes to be compacted last, allowing stabilization by cooling, and, in that way, preventing pressing out the mixture (Kloubert, 2009). In the case of two rollers, option (c) completes the job with two consecutive rollers. The first roller, or master roller, is the one that defines the compaction pattern and path. Whereas the second roller, or slave roller, simply follows the leading roller. This scenario could be used when one of the operators needs to obtain more experience performing the job. Alternatively, option (d) places the two rollers side by side. This could be beneficial in the case that the mat needs to be compacted at the hottest temperature possible. Finally, it is worth mentioning that the framework proposed in this study is flexible enough to accommodate different customized compaction strategies. But, at the same time, by clearly capturing the compaction strategy and explicitly indicating its impact on the operational quality, which is usually ignored in the simulation models, this framework helps decision-makers to become aware of the significance of developing more standardized compaction patterns/strategies.

Simulation

The simulation model is constructed in AnyLogic and follows the guidelines proposed in section 5.1. That being said, the model reads the input parameters, for the agents, from the excel-based GUI. Considering the requirements, the simulation stops when the target time is achieved. While the simulation is running in virtual real-time, the user is able to evaluate the equipment's movement. Besides, five interactive graphs are part of the interface. These graphs depict the areal output, the equipment speed, and the total surface paved. Depending on the input parameters, such as manually selecting the equipment speed, it can be the case that the job is not completed in the allotted time. For that, the user must evaluate whether the speed of the equipment is realistic in regards to the productivity target. As an illustration, **Figure 14** depicts a sample of the simulation environment, wherein on the upper part the user can see the output graphics, in the middle the 2D visualization of the process, and in the bottom the equipment speed and the paved length.

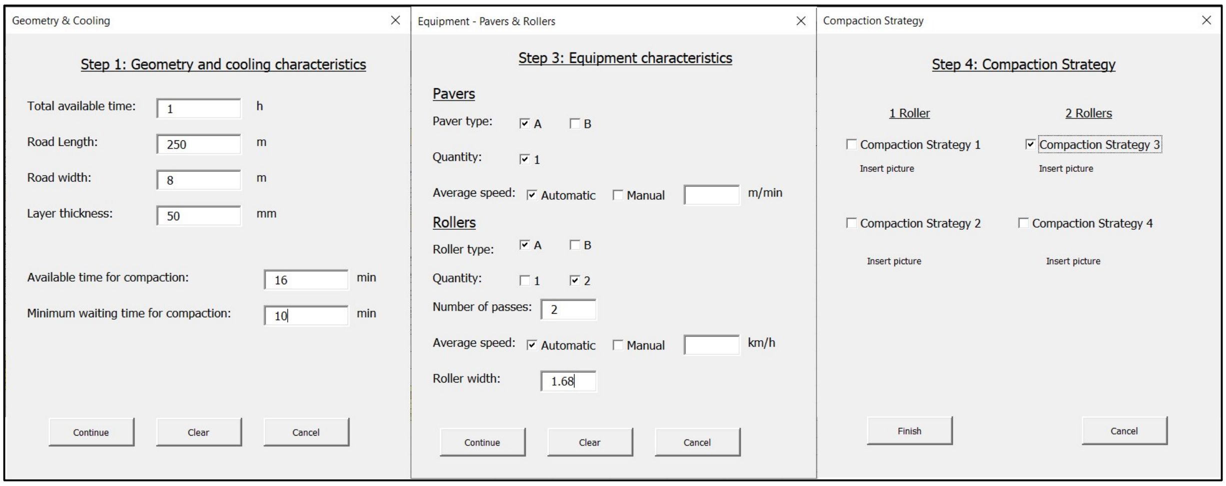
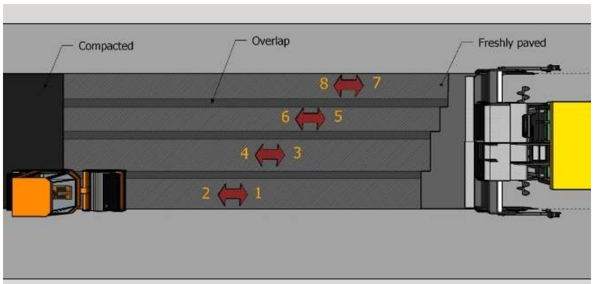
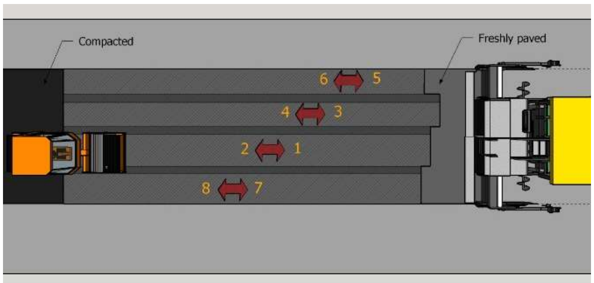


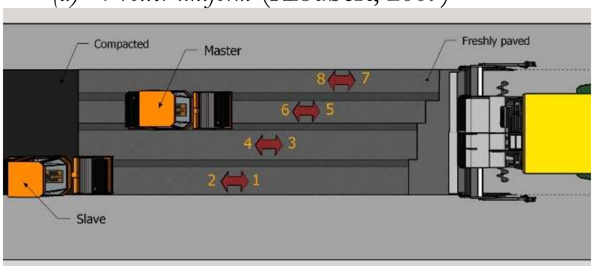
Figure 12. Sample of data collection with GUI



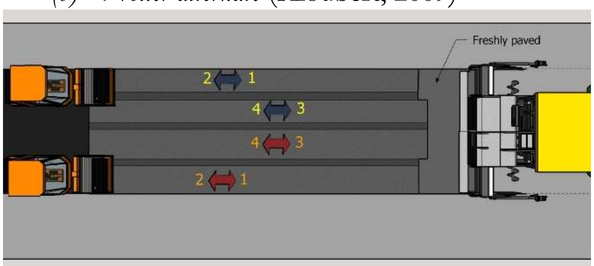
(a) 1 roller uniform (Kloubert, 2009)



(b) 1 roller alternate (Kloubert, 2009)



(c) 2 rollers in series (Lender, 2019)



(d) 2 rollers in parallel (For Construction Pros, 2019)

Figure 13. Prototype rolling sequence alternatives

Integration

Once the simulation is completed, the integration part takes place with the help of the GUI. For that, a series of macros are developed and customized into a ribbon in the Excel interface, as can be seen in **Figure 15**. Basically, the integration part does the following job. First, AnyLogic writes the equipment coordinates at a fixed interval, for this case, it writes every second. Then, the user selects the integration ribbon and clicks to integrate the data, i.e., rollers movement, rollers data, general logistics, and thermal behavior. This integration automatically generates output files that the VR environment can read and utilize. Finally, the user closes the GUI and executes the VR environment.

Virtual Reality

The VR environment is developed in such a way as to accommodate agent-driven equipment from the simulation model. The integration phase automatically feeds the agents' behavior, the physics behavior, and the logistics data to the VR environment as input data. Afterward, the user needs to run the Unity executable file. Within the environment, it is possible to assess, in virtual real-time, the compaction completeness, and the cooling of the asphalt mat. **Figure 16** depicts an overview of the two mentioned features. To finish this phase, the expert generates the strategy result, by clicking the strategy assessment button in the integrated ribbon and can continue with the next phase.

Strategy assessment

Following the guidelines provided in section 5.1, the expert can evaluate their strategy with the following output. In a graphical fashion, they assess the paver and roller output (m2/h), and their respective speed (m/min). Meanwhile, the quality metrics are stated, such as compaction efficiency (%), cells compacted below and above the compaction window (%). To illustrate, **Figure 17** depicts an example of the output for the strategy assessment.

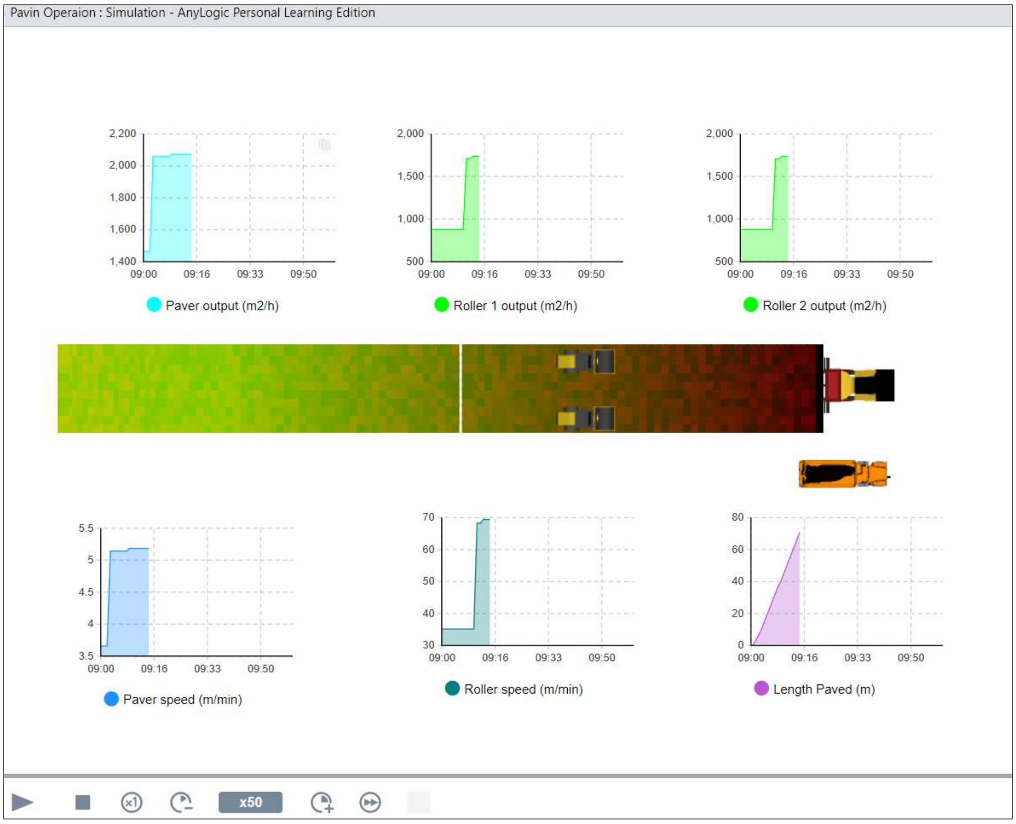


Figure 14. Simulation environment in AnyLogic

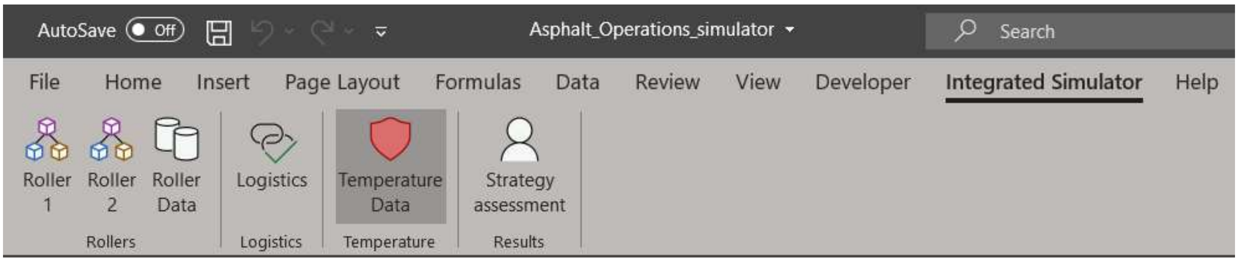
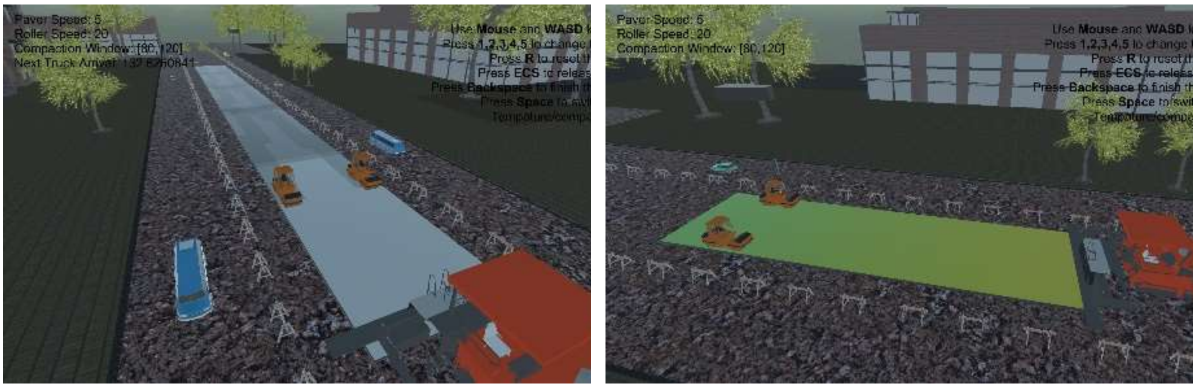


Figure 15. Integrated model customized ribbon



(a) Compaction completeness *(b) Asphalt cooling map*

Figure 16. Virtual Reality Environment

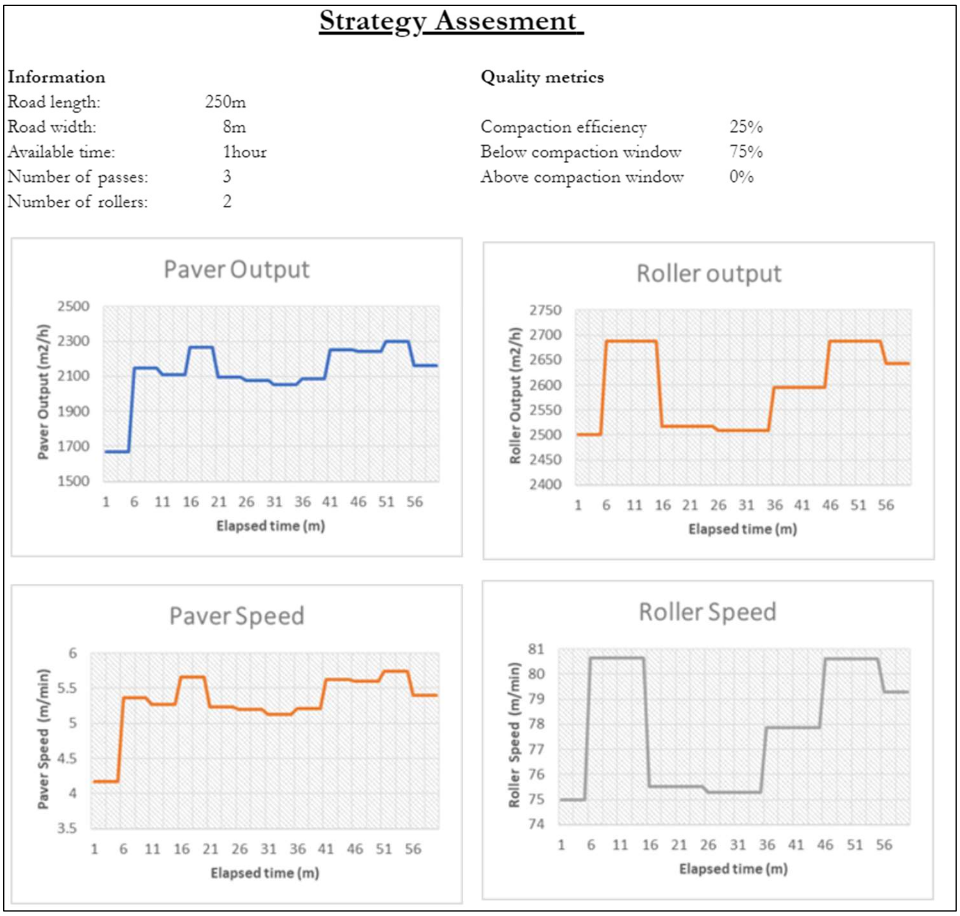


Figure 17. Strategy assessment output sample

6.2. Validation

The proposed method and implementation have been validated in two different ways, i.e., accuracy and usefulness. Within the former, the prototype was tested against two real projects. In the first case, the surface rehabilitation of the A-15 highway was considered (Vahdatikhaki, et al., 2019). this case study focused on the output validity, i.e., equipment output, equipment speed, and compaction efficiency. In the second case study, the model was compared with data from a monitored inner-city road (Arbeider C. G., 2018). In this case study, the emphasis was on the process validity, that is equipment output and speed along the entire process. On the other hand, the usefulness validity was achieved through interviews with three experts from Heijmans, BAM, and ASPARi. Specifically, the interviews began with a presentation of the framework and the prototype. Then, a thorough discussion took place, where the experts provided vital insight regarding the usefulness of the prototype in the industry. Finally, the experts were asked to fill in a questionnaire about the proposed framework.

Case study 1

A portion of the A-15 highway was considered for this case study. **Table 5** presents the output, in terms of productivity and operational quality, of the case study and the simulation with the integrated model. In general, the accuracy of the model was around 90%. However, some remarks are worth mentioning. The discrepancy can be explained along two lines. First, from the specifications, the target number of roller passes was three. In the integrated model, this is a fixed parameter, thus, every cell would receive three roller-passes. However, for the real case, the average number of passes per cell was 2.5. Moreover, the compaction trajectory is rather unsystematic in the real project. Whereas the model had a fixed length of the rolling path, which was set to be the average of the real case. Due to the above reasons, an increase in the deviation can be observed regarding the number of passes, i.e., compaction index (20%), and compaction efficiency (15%). The productivity values are very close (7%). Regarding the paving, the average paver speed was inferred using the time available and the length of the road, reaching a deviation of 9%. Meanwhile, the error in the estimation of rollers speed and output is small, i.e., 5%. **Figure 18** shows the comparison of roller speed.

Case study 2

In this case study, a portion of monitored inner-city road construction was considered (Arbeider C. G., 2018). In this case, the accuracy of the model is around 95%. The difference with the previous case is mainly about the data availability. For this case, the equipment output along the process was captured and compared. In that sense, **Figure 19** and **Figure 20** depicts the mentioned output of the monitored project as well as the simulation with the proposed framework. As can be seen, the average and overall behavior are fairly close. On the other hand, as in the previous case, there is a difference in the average number of passes and the length of the rolling path. Finally, the case offered a compaction efficiency of 63%. Although there is no quantitative comparison with the monitored case, Arbeider (2018) claimed that the monitored cases were compacted below the compaction window. This can be reflected and to a certain extend represented by the mediocre operational quality feedback provided by the model. Finally, **Table 6** offers a summary of the obtained values.

Usefulness validation

Table 7 shows the questionnaire given to the experts and **Figure 21** shows the results. The assessment was based on five indicators, namely, user-friendliness, usefulness, versatility, awareness, and teamwork. Also, the experts were asked to score their current practices along with the same criteria. As shown in the table, the experts conveyed that the awareness (4.67) and versatility (4.33) of the framework is very useful. Specifically, this means that the prototype fulfills its purpose of allowing the user to evaluate different planning strategies, and more importantly, it raises awareness to the planners regarding the operational quality. Meanwhile, usefulness (3.92) and teamwork (3.33) were shown to be somehow useful. Although the experts confirmed the usefulness of simulating the entire HMA-CP (4.0) with a high visualization power (4.0), they scored the usefulness of the proposed framework for standardizing current practices (3.33) and to enhance coordination and collaborative work (3.33). This can be partially because the prototype is limited to proof of concept. However, it was shown and explained that the model is flexible enough to adapt itself to different rolling patterns and, in that way, improve the standardization of current practices. The experts score the user-friendliness of the framework fairly average (3.33). This is mainly because of the GUI design. As mentioned by the interviewees, since the user needs to interact with three different software, the use of the prototype is not very user friendly. However, this could easily be enhanced in future work by providing a better GUI.

Table 5. Comparison of A-15 highway and Framework

Index	A-15 highway	Proposed framework	Error rate
Length (m)	250	250	0%
Number of passes	2.50	3.00	20%
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%
Below compaction window	-	77%	

Table 6. Comparison of inner-city road and Framework

Index	AC 16 surf	Proposed framework	Error rate
Length (m)	250.00	250.00	0%
Number of passes	5.25	5.00	5%
Roller output (m2/h)	1150	1180	3%
Paver output (m2/h)	1150	1138.73	1%
Roller speed (km/h)	5.00	5.15	3%
Paver speed (m/min)	4.60	4.14	10%
Compaction efficiency	-	63%	
Below compaction window	-	37%	

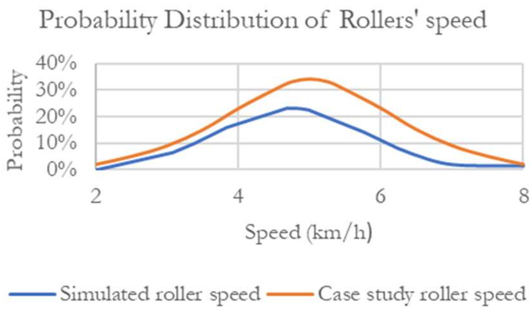


Figure 18. Probability distribution of Rollers' speed

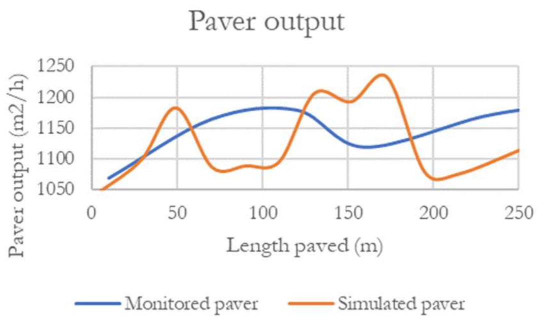


Figure 19. Monitored and Simulated paver output

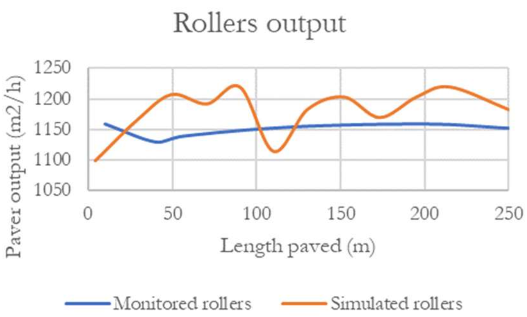


Figure 20. Monitored and simulated rollers output

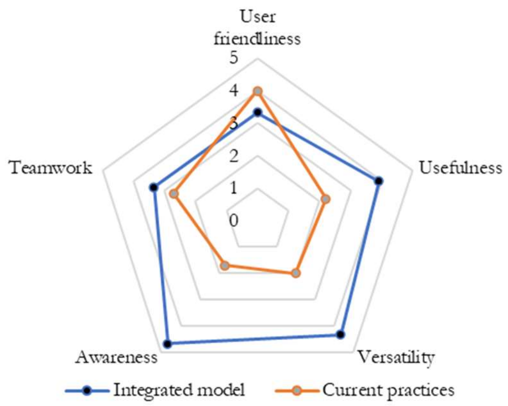


Figure 21. Comparison of Integrated model and current planning practices

Table 7. Usefulness validity (3 respondents)

		Absolutely useless (score 1)	Not useful (score 2)	Neutral (score 3)	Somehow useful (score 4)	Very useful (score 5)	Average
		User-friendliness					
Q1.	How easy is it to use the integrated model?		1		2		3.33
		Usefulness					
Q2.	How useful is it to simulate the whole process (Transportation, Paving, Compaction)?				3		4
Q3.	How useful is it to visualize the strategy in a virtual reality environment?				3		4
Q4.	How useful is it to receive operational quality feedback?				2	1	4.33
Q5.	How useful is the integrated model to standardized current planning practices?		1		2		3.33
		Versatility					
Q6.	How useful is the integrated model to assess different planning strategies?				2	1	4.33
		Awareness					
Q7.	How useful is the integrated model for better showing the consequences of compaction strategies in operational quality?				1	2	4.67
		Teamwork					
Q8.	How useful is the integrated model to enhance coordination and collaborative work?			2	1		3.33

7. Discussion

Planning the HMA-CP is a complex task. During this study, it was highlighted that, on one hand, it relies heavily on tacit knowledge, tradition, and custom. On the other hand, the process has complex relationships between its affecting factors and within the experts involved in the planning phase. On top of it, contractors are pushed even more to deliver better quality products and competition became tougher. This has created momentum for the contractors to join their efforts with academia to understand and tackle the complex relationships within the process. It is shown that digital technologies enhance the understanding of the process, hence assisting planners to cope with the complex challenges of planning the HMA-CP. However, from the planning perspective, it was shown that, although the available planning tools proved to be very helpful with assisting planners, a tool that is able to capture all the relevant affecting factors of the process in a holistic manner and translate them into appropriate decision variables is missing.

With that purpose, this study offers the following contributions to the body of knowledge: (1) the functional requirements for a holistic HMA-CP model are identified and categorized. (2) A framework that details the required steps to build the above model is developed. It was argued though, that to capture all the relevant affecting factors of the process, the use of hybrid technologies, i.e., simulation and VR, is necessary. (3) An approach for capturing the behavior of the equipment, the physics, and the environment is presented. It was shown that the development of realistic agents is feasible and thus ensure the model accuracy. (4) An approach for translating physics and equipment behavior as data-driven physics and data-driven agents for the VR environment is presented. It was shown then that an integration of the above technologies is possible to construct the model.

Particularly, this framework improves awareness among decision-makers concerning the development of more standardized compaction patterns/strategies. This is achieved by clearly capturing the compaction strategy and explicitly indicating its impact on the operational quality of the process, which is usually ignored in existing simulation models. Also, the proposed framework provides a platform that allows all the involved experts, especially the tactical planners, to enhance their knowledge and participation in all the phases of the construction process. This is claimed by explicitly capturing and visualizing in a holistic manner the affecting factors of the process and translating them into relevant decision-variables.

Finally, the proposed framework paves the way for the development of integrated virtual models of quality sensitive products. Integrating the power of simulation models with the high spatial (3D) awareness that a VR environment can provide.

8. Conclusions and future work

This research offered a framework for the integration of simulation of asphalt-pavement compaction and VR. Which focuses on capturing the influential factors of the process in a holistic manner, as opposed to specific-phase simulation. A comprehensive review of the HMA-CP and a detailed description of the framework for capturing the relevant factors and provide productivity and operational quality feedback was presented. A prototype was developed, and previous ASPARi case studies were analyzed 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 the HMA-CP.

It can be concluded that: (1) it is vital to capture all the relevant affecting factors and include every expert input to enhance the planning phase of the HMA-CP. (2) It is shown that historical data and collected data from 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. (3) It is shown the value of using more standardized practices in quality sensitive products—such as asphalt-pavement compaction. (4) Through expert's insight, it is shown the advantages of using an integrated model for the HMA-CP. Especially, in allowing users to evaluate different compaction strategies and providing relevant operational quality feedback.

There are some limitations in the current research. The prototype should be further tested with case studies, and its validity could be further enhanced by using the framework in actual construction works. Also, the rolling trajectories are limited due to a gap in the current body of knowledge. Therefore, it is highly advised to collect real data from rolling sequences. Only then, the actual impact of the compaction strategies can be assessed.

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10. APPENDIX

10.1. Appendix A—Interview layout

PLANNING AND SCHEDULING ASPHALT COMPACTION

Information

- Date: …………………………………………………………………………………
- Interviewee: …………………………………………………………………………
- Company: …………………………………………………………………………….
- Role: ………………………………………………………………………………….

Disclaimer

To be in line with the ethical considerations of interviewing, the purpose of the project is to provide an integrated model of simulation and virtual reality of asphalt pavement compaction, to enhance the process from a quality perspective, and, in that way, provide planners with more accurate data for planning and scheduling. The data retrieve from this interview will be used for academic purposes. It is the interviewee's choice whether he wants to remain anonymous or his name could be mentioned in the final document. Finally, the interviewer will ask permission for recording the session, the recording will be stored until the end of the investigation, and then it will be eliminated. The interviewee will be asked if he wants a copy of the transcript to assess if it goes according to what has been said.

Part I

Description: The first part consists of 10 main questions. Since it is a semi-structured interview, a discussion will take place after each question. Further, main questions have support questions that aim at helping the interviewer in extracting the required knowledge.

As of this part, the recording starts.

Questions:

1. Could you give a glimpse of your company's work?
2. Could you tell me what is your role in the company?
3. Could you tell me more about the last or current project you are working at?
   3.1. What is the size of the project?
   3.2. Do you work in different projects simultaneously?
4. Could you explain to me in detail how do you perform your task?
   4.1. Are you the only person who plans and schedules in your company?
   4.2. How does it work when you are not on the company? i.e. holidays
5. Could you tell me what are the essential parameters that you consider when planning and scheduling the compaction strategy?
   5.1. What are the resources that you consider?
   5.2. How many people are involved in the process?
   5.3. Could you highlight the key actors in the compaction process?
   5.4. Could you explain me why do you consider them essential?

5.5. What is the logic you follow when allocating resources?

5.6. Which perspective requires more attention? i.e. quality, productivity, time, cost.

6. What do you consider is the most challenging part in designing a compaction strategy?

    6.1. In your perception, what are recurrent issues that arise when designing a compaction strategy?

    6.2. What are the key factors for success in asphalt compaction?

7. Could you explain to me how does your communication works with the asphalt teams?

    7.1. How does the asphalt teams prepare for the job?

    7.2. How many asphalt teams do you manage?

8. Does your company employ technological devices in the equipment?

    8.1. What type of equipment does your company have?

    8.2. Who oversees the technological devices?

    8.3. Who gathers and translates the data?

9. What is a key piece of advice that you would give to a compaction planner and scheduler?

    9.1. What advice could you give on doing scheduling?

    9.2. What advice could you give on planning compaction?

10. In your opinion, what do you think is lacking in the improvement of asphalt compaction process?

Break.

Part II

Description: The interviewee will receive a brief introduction and description of the existing virtual reality environment. Also, some selected snapshots of the model and the feedback that delivers will be explained. Afterward, in a more open conversation, a discussion will take place of which requirements the integrated model could have. For that purpose, two open questions will be asked.

1. What do you think of the model?
2. What are the essential requirements that the model must have to facilitate your decision-making?

Closing

The recording will stop, and the interviewee will be asked if he wants to be part of the follow-up to validate the model once is concluded. It goes without saying, that the gratitude towards his help will be offered.

10.2. Appendix B—Questionnaire layout

HET PLANNEN VAN HET ASFALT-BOUWPROCES

Disclaimer

De gegevens die uit dit interview worden opgehaald, worden gebruikt voor academische doeleinden. Het is de keuze van de geïnterviewde of hij anoniem wil blijven of dat zijn naam in het definitieve document kan worden vermeld. Als de geïnterviewde anoniem wil blijven, vul dan alleen de datum en rol in.

Informatie

- Datum: ....
- Geïnterviewde: ....
- Bedrijf: ....
- Rol: ....

Deel I – Algemene vragen

U kunt meer dan één optie selecteren voor elke vraag

1. Welke categorie beschrijft uw werk:
   a. Asfalt-productie
   b. Asfalt-transport
   c. Asfalt-aanleggen
   d. Asfalt-verdichting
   e. Overige (opgeven)____________
2. In het algemeen, wat zijn de communicatiekanalen binnen actoren die betrokken zijn bij het proces?
   a. Vergaderingen
   b. Online vergaderingen
   c. E-mail
   d. Telefoon/bellen
   e. Overig (opgeven) _________________
3. Wat is de frequentie van de communicatie?
   a. Dagelijks
   b. Wekelijks
   c. Maandelijks
   d. Overig (opgeven) ___________________

Voor de volgende vragen, geef zoveel mogelijk kenmerken als u kunt bedenken

4. Welk merk en model spreidmachines gebruikt uw bedrijf?
5. Welk merk en model wals gebruikt uw bedrijf?
6. Gebruikt uw bedrijf technologische apparatuur om het proces te volgen (zoals Linescanner, GPS, enz.) Op walsen en/of spreidmachine?

Deel II – Hypothetisch scenario

In deze sectie wordt een hypothetisch scenario geconstrueerd. Het doel is om de logica van het asfalt-bouwproces te begrijpen.

Beantwoord de volgende vragen vanuit het oogpunt van de Asfaltcoördinator. Houd in gedachten dat de waarden uitgedrukt in deze vragenlijst slechts indicatief zijn, het algemene doel is om de logica te begrijpen in plaats van het hebben van nauwkeurige waarden.

Hypothetisch scenario: Een rechte weg moet worden geasfalteerd met asfalt, de maximale beschikbare tijd om de klus te klaren is 5 uur.

Kenmerken:

- ❖ Weglengte: 1500 m
- ❖ Afstand tussen asfaltfabrieksterrein: 45 km.
- ❖ Wegbreedte: 6 m
- ❖ Gemiddelde reistijd van vrachtwagens: 45 min.
- ❖ Beschikbare tijd voor verdichting na bestrating: 15 min (verdichtingsvenster voor afbraak- en afwerkingsfasen)
- ❖ U mag de kenmerken van de apparatuur van uw bedrijf aannemen.
- ❖ Mix: AC 11, laagtype: oppervlak, laagdikte: 50 mm
- ❖ Verdichtingsfase: afwerking

Resourcetoewijzing:

1. Hoeveel vrachtwagens (gem. Capaciteit 30 ton) zou u toewijzen voor deze klus?
   a. 5
   b. 10
   c. 15
   d. Overig (Opgeven) ___________________
2. Hoeveel spreidmachines zou u toewijzen voor deze klus?
   a. 1
   b. 2
   c. 3
   d. Overig (Opgeven) _______________

3. Wat zou de gemiddelde spreidmachinesnelheid zijn?
   a. 5 m/min
   b. 8 m/min
   c. 10 m/min
   d. 20 m/min
   e. Overig (Opgeven) ____________________________

4. Hoeveel walsen zou u toewijzen voor deze klus?
   a. 1
   b. 2
   c. 3
   d. Overig (Opgeven) _____________________________________
5. Wat zou een gemiddelde walsnelheid zijn?
   a. 25 m/min
   b. 35 m/min
   c. 45 m/min
   d. 55 m/min
   e. Overige (opgave)____________

6. Wat zou een gemiddeld aantal walsgangen zijn?
    a. 3
    b. 4
    c. 5
    d. Overige (opgave)____________
7. Wat zou een goede lengte van walspatroon zijn?
    a. Ongeveer 10 m
    b. Ongeveer 20 m
    c. Ongeveer 30 m
    d. Ongeveer 40 m
    e. Ongeveer 50 m
    f. Overig (opgave)____________
8. Als U bekend bent met walspatroon, kunt U een rollend patroon schetsen?
9. Kunt U kort uitleggen welke logica u hebt gevolgd om alle bovenstaande waarden te bepalen?
10. Naast de gepresenteerde variabelen, overweegt u een andere variabele? Zo ja, welke?
11. Kunt U in een project in uw bedrijf aanwijzen wie verantwoordelijk is voor de selectie van de volgende variabelen? (Het is mogelijk om meer dan één verantwoordelijke te selecteren).

Variabele	**Verantwoordelijk**						
	Projectleider	Werkvoorbereider	Balkman	Walsmachinist	Asfaltcoordinator	Asfaltuitveorder	Andere (opgeven)
Aantal vrachtwagens							
Aantal walsen							
Aantal spreidmachines							
Snelheid van walsen							
Snelheid van spreidmachine							
Aantal walsgangen							
Walspatroon							

12. Vanuit het perspectief van de planner, kunt u het belang van elke indicator hieronder geven bij de planning van het asfalt-bouwproces voor een gemiddeld project?

(1) vertegenwoordigt een minimumaan belang en (5) is maximaal van belang.

Indicator	**Belang**				
	1	2	3	4	5
De totale kosten van het asfalt-bouwproces					
De uiteindelijke kwaliteit van het asfalt					
De productiviteit van het bouwproces					
Tijd beschikbaar					
Overig (opgeven): ___________					

Bedankt voor Uw tijd!