SmartSite: Intelligent and Autonomous Environments, Machinery, and Processes to Realize Smart Road Construction Projects

R. Kuenzel[a], M. Mueller[a], J. Teizer[b], A. Blickle[b]

[a]Information Systems 2, University of Hohenheim, Germany
[b]Ed. Züblin AG, Germany
E-mail: marcus.mueller@uni-hohenheim.de, robin_kuenzel@uni-hohenheim.de, jochen.teizer@zueblin.de, alexander.blickle@zueblin.de

ABSTRACT

This article presents an overview of the SmartSite research project that adopts machine learning, decision theory and distributed artificial intelligence to design and test a multi-agent system (MAS) for asphalt road construction. SmartSite puts major emphasis on sensing and communication technologies that integrate real-time automated information exchange in the supply chain of road construction. As part of the larger SmartSite project, this article introduces a novel real-time path planning system for compactors. It operates based on BDI software agents and real-time sensory inputs. The newly developed integrated and information rich process benefits asphalt compactor operators, as they are now capable to control their machinery and react to changing environmental, material-related and process-related disturbances or changes. This improves the quality of the delivery and laying of asphalt material, prevents compactors from over-compacting certain road segments, increases the road's pavement longevity during the operational life cycle phase; refocuses the work tasks of the site managers, and reduces the construction budget and schedule.

Keywords - Automation, Equipment, Lean organization and management, Logistics management, Multi-agent systems, Road infrastructure construction, Sensors, Supply chain.

1 Introduction

The European construction industry contributes nearly 10% to the EU-27-GDP but close to 90% of its projects suffer from budget overruns or delays. A main cause seems to be inadequate planning and management, in particular of capital-intensive infrastructure construction projects.

Modern road construction operations are in unique and dynamic work environments. They require highly complex logistics systems and tight coordination among the multiple participating stakeholders, including companies with vastly different economic objectives, inter- as well as intra-procedural dependencies. Current manual project coordination methods fail in addressing these issues adequately. As a result, project budget overruns and delays are quite common.

Recently, several techniques emerged to support project site management with in-time information about the construction processes and performance of machines and staff. Multi-agent systems (MAS) tend to be a promising technology for automated site management that reduces the centralistic, strictly hierarchical work portfolio of a traditional site manager.

In the last phase of black-top assembly, asphalt compaction is one of the most important steps in road construction. Faults during this phase are almost always irreversible without incurring high costs for milling-off and re-building [1]. Construction experts estimate, that 5% of the construction sum is spent on fixing quality defects – in Germany, 2.2 B€ are spent annually to mitigate quality defects on public roads [2]. An adequate compaction of asphalt is crucial in high quality road construction and for the longevity of the roads.

Key determining factors for the compaction process are: environmental preconditions, like ambient air temperature, wind speed, or the amount of rainfall, and material properties of the surface, like thermal conductivity or core temperature of the asphalt [3]. These influencing factors are not under the control of the compactor operators.

Asphalt density – and therefore quality – is essentially dependent on machine handling and driving behaviour of the compactor operators. Operators have to judge about the machine velocity, number and uniformity of passes of certain areas, overlapping areas and vibration parameters. Thus, operators need to be very sensitive towards the uniformity of compacting alongside the whole pavement mat. The latter is determined according to numerous environmental, material-related and process-related pre-conditions.

Errors in judgments of human operators during compaction are inevitable, since they are not supported by adequate assistance systems. These must work in real time to gather, process, and communicate sensor information about all relevant factors instantly [3].

Researchers and practitioners have developed several technical and non-technical approaches to this problem and introduced them into the current field of practice. Today's predominant method is to hand over pre-planned and fixed rolling patterns to the operators to aim at operational efficiency and optimal asphalt density after compaction. The main deficit of this solution is its rigidness and inflexibility regarding any environmental and process-related changes.

Furthermore, today's operators have to judge material-related characteristics like actual asphalt temperature and its compressibility on their own. Up until recently, it has been difficult for human operators to determine the remaining number of passes – and sometimes even to remember how often their machines have already compacted a certain area.

Original equipment manufacturers (OEM) as well as special machinery equipment vendors provide a variety of, mostly proprietary, technical solutions to support machine operators in their work, e.g., by mounting a Global Positioning Systems (GPS)-based counter to visualize the number of passes. The main focus of market-available solutions, however, is to provide data about temperature and compaction for documentation purposes subsequent to the construction process rather than to support the operators during compaction.

Moreover, current systems are mostly isolated solutions with a special purpose. They are not integrated with other environmental, material-related and process-related information. These systems are partially suitable for use in applications subjected to operators' assistance. Hence, there is a need for developing a real-time integrated control system to support human machine drivers at an operational level during the compaction phase of a road construction project.

A solution to the problem is to sense, exchange, store, and analyse data about physical and process-related conditions for every machine in use. Today, this is possible with already market available solutions. We use such a system based on standard, service based interfaces and a set of pre-planned rolling patterns to develop an intelligent assistance system for compactor operators that is capable of adjusting itself to changing conditions – no matter if these changes are caused by the environment or by any steps in upstream processes.

The developed system is capable of controlling a compactor. As such it is also capable of assisting human operators where to steer the machine next according to their current position. Recent and most relevant work history as well as compliance to projected work plans, trajectories of other compactors, actual work progress of the paver itself, and environmental and material-related parameters are also included in the decision making.

This article adopts techniques from the field of distributed artificial intelligence – namely multi-agent systems – to contribute a method that automatically generates driving instructions for human compactor operators. The method is capable to react to variable and changing field-realistic conditions. We conducted a simulated experiment to evaluate the method and to show the feasibility of our artefact. The SmartSite research project (http://smartsite-project.de) aims at the optimization of the entire logistical chain of black-top assembly. It is envisioned to integrate our proposed software agent as an assistance system into a broader construction site logistics management and operations system once the simulated experiments have tested successful.

The remainder of the article is structured as follows. In Section 2 we provide a brief overview of the current state-of-the-art in the construction of hot-mix asphalt, assistance systems for compactor operators, and multi-agent systems. While Section 3 describes our artefact in detail, Section 4 introduces the evaluation scenario. Results to the simulation are analysed in Section 5. Section 6 concludes the paper.

2 State-of-the-Art

2.1 The Black-Top Assembly Phase

A road construction site during the black-top assembly phase is a highly complex logistical system influenced by a large amount of environmental, technical, social, and managerial factors. To get the right amount of asphalt on time in the right quality (i.e., the right temperature) to the paver and "on the road" at minimum costs is a quite challenging task. The logistics chain incorporates asphalt batch plants, transportation facilities, pavers and compactors (see Figure 1).

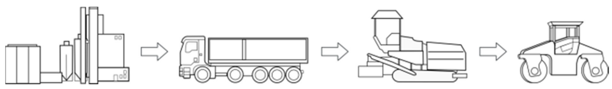


Figure 1. Logistics chain of a road construction site during black-top assembly

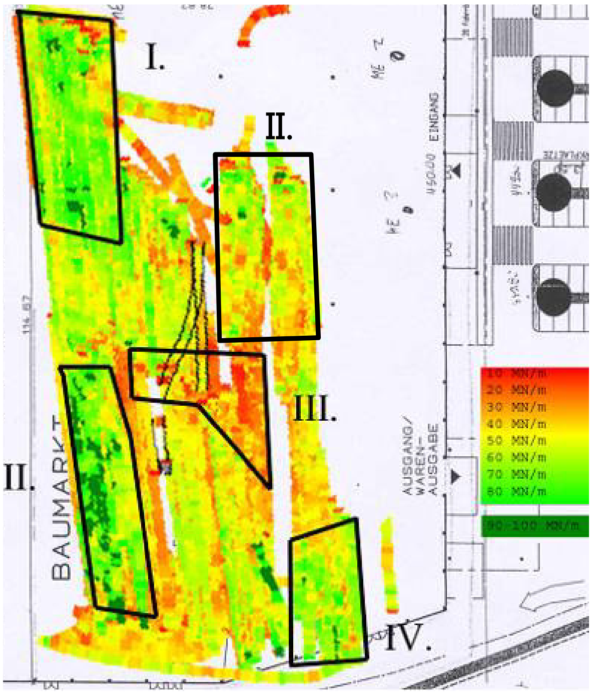
Each step is susceptible to numerous disruptions and the paving crew on site as the focal point of the whole system often lacks information about disruptions at upstream logistical steps. Research and practice concerning this problem are based on proprietary, isolated, and in parts heterogeneous data structures [4]. Furthermore, current solutions are focused on performance monitoring and on documentation subsequent to the construction phase rather than on supporting machine operators during construction and on an operational level. These shortcomings have a notably effect especially on the compaction of asphalt.

As the last step in the logistics chain, compaction is of particular importance for the quality of the final road. An inappropriate number of passes leads either to over- or under-compaction of the asphalt. For the human compactor operators it is often difficult to impossible to estimate the right number of passes remaining. Even if all areas are passed an appropriate number of times, too low core temperatures of the asphalt during the pass can lead to an under-compaction or damage to the asphalt surface. If compactors pass too hot areas, liquid components of the bitumen are pressed out and there is an additional risk of subsidence. The right number of passes within the right temperature range (influenced by environmental and material-related conditions) is the crucial factor for quality. Today, operators are not adequately supported by appropriate methods and systems and the desired density after compaction is often not reached (see Figure 2).

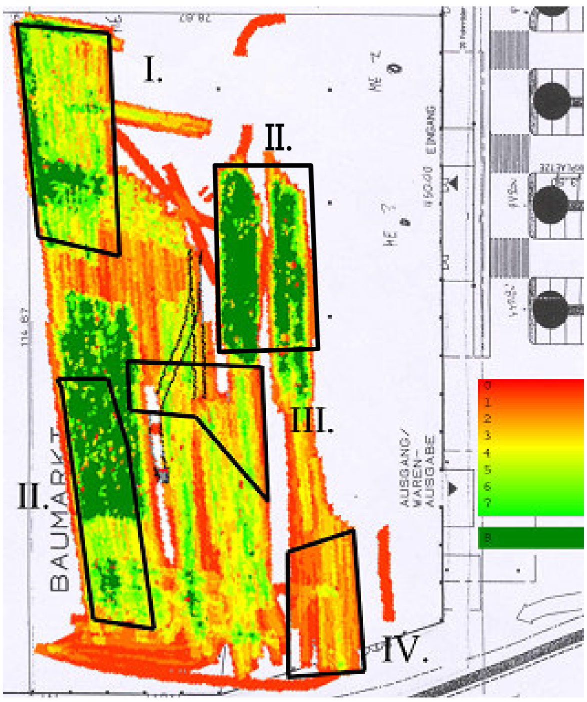
The SmartSite approach addresses all steps of the logistics chain starting from the asphalt batch plant to the very end of compaction. During the last step, human compactor operators are supported by an assistance system generating driving instructions based on real-time sensory inputs and computational intelligence.

Table 1. Related work in the field of assistance systems for compactor operators

Authors	Year	Evaluation method	Quantitative Results	Difference to our approach
Utsuka et al.	1992	Field Test	Not reported	Predefined working area instead of a dynamically changing area; environmental conditions (e.g. temperature) not considered.
Froumentin & Peyret	1996	Field Test	Not reported	Environmental conditions (e.g. temperature) are not considered.
Fujikawa et al. [11]	1996	Field Test	Avg. & stdv. of reached density	Environmental conditions (e.g. temperature) are not considered.
Tserng et al.	1996	Simulation	Not reported	Environmental dynamics and temporal restrictions were not considered.
Tserng et al.	1996	Informed argument	Not reported	Fixed rolling patterns and paths. No real time sensory inputs; no real time decisions about paths.
Lee et al. [12]	1998	Simulation	Math. function for density acc. to temp. & no. passes	No automation of path planning; method of data gathering unclear
Lee et al.	1998	Informed argument	Not reported	Fixed rolling patterns and paths. No real time sensory inputs; no real time decisions about paths.
Peyret	2000	Field Test	Not reported	Environmental conditions (e.g. temperature) are not considered.
Furuya & Fujiyama [13]	2011	Field Test	Distribution function for stiffness	Sensory input is limited to stiffness.
Vasenev et al. [14]	2014	Field Test	Not reported	No automation of path planning.



(a) Stiffness



(b) Passes

Area I: Inhomogeneous compaction
Area II: Partially insufficient compaction
Aera III: Insufficient compaction
Aera IV: Insufficient compaction

Figure 2. Example of condensed compaction report with undesired densities after compaction

2.2 Related Work in the Field of Assistance Systems for Compactor Operators

The literature provides several approaches for equipment operator assistance systems and automated compactors. These approaches mainly rely on pre-planned path calculations and lack flexible decision and reaction on changing conditions [3, 5, 6]. Real time sensory inputs are often not considered [5, 7] and information about environmental conditions are not incorporated in the path calculations [8-10]. Table 1 shows some of the recent approaches within the literature and reports about evaluations results as well as differences to our approach.

2.3 Technical Background

This paper adopts techniques from the field of multi-agent systems to automatically generate driving instructions for human compactor operators based on commercially available solutions for acquiring, communicating, and storing real time sensory inputs. A software agent "is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives" [15]. Intelligent agents hold a model of their environment (as their "mental state") continuously updated by sensory perceptions. Intelligent agents are realized as intentional artefacts [16] described by a knowledge base (e.g. rules for generating rolling patterns, physical cause-effect-models) and intentions to reach a certain goal state like a desired asphalt density after compaction. Agents are able to communicate with each other in order to coordinate and cooperate; an agent is also able to perform action via its actuators. An action can be a manipulation of the physical world (e.g. open and close a valve) or it can be a virtual/digital action like sending a calculated driving instruction to the display of the compactor operator. Figure 3 shows a graphical overview of an intentional software agent.

Each compactor on the construction site is represented as a software agent within the system. We used Petri nets and algebra of sets to model the internal state of an agent. Each agent holds a set of rolling patterns and is able to choose a pattern that is appropriate to the current situation. The software agent knows about the kinematic characteristics of the compactor that it represents. The agent also holds a representation of the material characteristics subject to physical conditions of the environment notated as a function for estimating the core temperature of the asphalt regarding to the surface temperature, ambient temperature, wind speed, and incident solar radiation. This function is well-founded on empirical measurements [17]. The agent transforms perceived sensory inputs into driving instructions for human compactor operators considering its knowledge about rolling patterns as well as physical causes and effects. In the subsequent section we introduce our artefact by presenting the internal architecture of our agents using Unified Modeling Language (UML) diagrams.

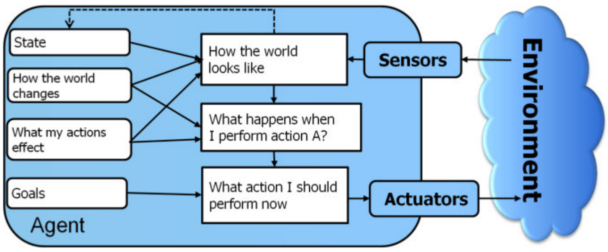


Figure 3. Model of a software agent

3 Intelligent Assistance for Compactor Operators

A compactor agent denotes a software agent representing a physical compactor within the assistance system. The behaviour of a compactor agent is determined by rolling patterns. In practice today, rolling patterns are a well-established means to guide human compactor operators during compaction. The behaviour of a compactor agent thus seeks to emulate the behaviour of an immaculate human operator while utilizing the available sensor data and derived data in real time for additional accuracy beyond human capabilities. The compactor agent is implemented as a BDI agent. The BDI-Agent-Architecture is inspired by concepts of the psychological Belief–Desire–Intention (BDI) model of human practical reasoning [18]. All information an agent holds about the current state of its environment and its internal state or knowledge (e.g. the dimensions of the compactor), are part of its beliefs. Desired future goal states of the agent's environment are represented by its desires. An agent's intention denotes the concept of creating a concrete plan respectively an ordered set of actions to reach a desired goal state based on an agent's current beliefs. The procedure of deriving a plan from an agent's beliefs and desires is denominated as practical reasoning. This procedure is subdivided into parts: Deliberation and means-ends reasoning. The first is the procedure of deciding, which goal should be achieved within a set of different goals, the latter refers to the decision about how the goal should be achieved [19].

In order to enable a compactor agent to assist a human operator as best as possible, the agent needs to be able to control the compactor – at least during normal operation – better than a human operator could. Consequently, the proposed system is designed to control a compactor in real time. The agent's decisions, as well as additional sensory information, eventually are displayed human operator and thus provide optimal assistance to a human operator.

On an architectural level, a compactor agent is realized by three hierarchic architectural layers. The first (lowest) architectural layer describes all possible mechanical actions based on an agent's internal kinematic model to fulfil a part of a plan, e.g. following a path or continuously accelerating. The middle layer performs advanced actions such as changing the compaction path. The output of a software module on the lower level or mid-level is a combination of a desired change in linear speed and a desired change in steering angle – both bounded to the internal kinematic model. Software modules on the top layer execute the dynamically parameterized rolling pattern and check to compatibility of the lower layers results against the beliefs about the real world state. This also includes the avoidance of collision with other machines, if present, as well as avoidance of leaving the compactable surface. Each layer can draw results from underlying modules before execution. The communication between the three layers of an agent as well as the communication with the sources of sensory perceived data is modelled as an UML sequence diagram in Figure 4.

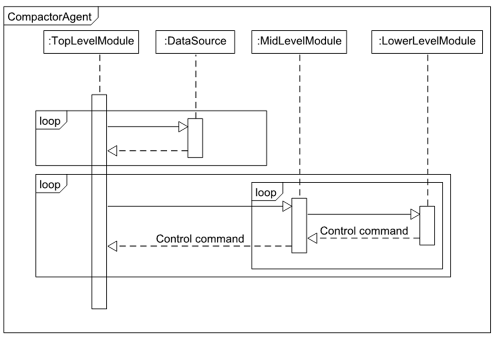


Figure 4. Sequence diagram

Since rolling patterns prescribe the sequence of compactor paths, the remaining major challenge for the compactor agent is to determine the correct moments for the turns at the ends of the compaction area. In order to allow the agent to determine turns, the agent holds a computer model of the compactor, which is initialized with the kinematic and physical (e.g. acceleration) attributes of the compactor. The agent also holds an analogous kinematic and physical model of the paver operating in front of the compactor and models of other compactors in its environment. All machines are equipped with high-precision GPS sensors. Positional information about the laid asphalt is derived from the movement of the paver, allowing the compactor agent to accurately calculate the compactors position relative to the asphalt surface at any time. While the system uses a raster approach to track the compactor's movements, the outlines of the asphalt surface are tracked by a ribbon line as described in [5].

The system further incorporates an asphalt core temperature estimation model as described by [17]. The paver's screed is expected to measure the thickness of the laid asphalt to allow for an accurate estimation of the asphalts temperature. In lieu of the compaction sensors available in modern compactors, the compaction is estimated by a user-provided function when no compaction sensor is available. Figure 5 shows the UML component diagram of the system.

The compactor agent's steering is calculated by comparing the Euler spiral projected by the current position, direction, speed and steering angle to the target path. For complex steering, a series of Euler spirals (e.g. a vertex clothoid) is used instead. For security reasons the calculation is slightly modified to favour oversteering over understeering due to the difficulty of recovering from understeering while being restricted to the compactor's steering rate. If a human operator is present, the calculated distance to the target path is displayed through a heads-up display (HUD). The human operator is also notified when the optimal turning spot is reached.

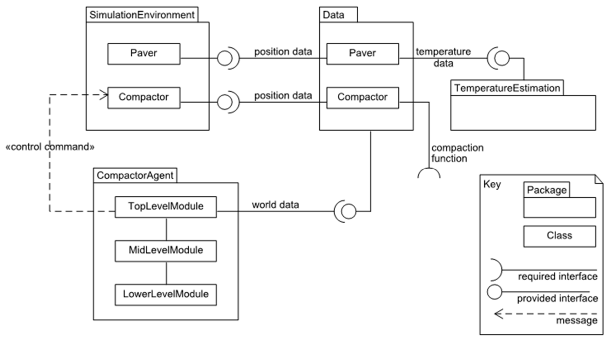


Figure 5. Component diagram

4 Evaluation

We conducted a simulation experiment to show the feasibility of our artefact. The designed agent's steering recommendations are fed back into the system using the same interface a human operator would use to steer a compactor. To conduct the simulation we used a pre-designed scenario. The parameters of the simulation are specified in Table 2.

Once the compactor agent reaches asphalt with a surface layer core temperature below temperature threshold 2, it is no longer allowed to use vibration and must turn back towards the paver. When steering on asphalt with a surface layer core temperature below temperature threshold 1, the compactor agent may steer at a rate of 5° per second opposed to the usual steering constraint of 2.5° per second. This relaxation of the constraint is possible due to the reduced ductility of colder asphalt.

Table 2. Simulation Parameters

Paver speed	6 m/min
Screed width	4.5 m
Asphalt core temperature	130 °C
Temperature threshold 1	120 °C
Threshold 1 reached	360s (340s)
Temperature threshold 2	100 °C
Threshold 2 reached	1400s (1330s)
Target compaction speed	5 km/h
Drum width	1680 mm
Raster size	10 cm
Test field length	50 m
Distance between initial positon and start of the test field	30 m

The weather parameters are chosen in such a way that the temperature thresholds are reached after 360 and 1400 seconds, respectively, if the asphalt had time to cool without treatment. Since the cooling of the surface layer is accelerated by its compaction, these temperature thresholds are reached during the simulation after approximately 340 seconds and 1330 seconds, respectively.

All kinematic and physical characteristics of the compactor are similar to an Ammann ARP 95 vibration compactor.

A test field of 50 m in length, beginning 30 meters beyond the starting position of the paver, with a raster width of 10 cm is used.

Target parameters were the count of individual drum passes, the standard deviation of individual drum passes, compaction equivalent, and the standard deviation of compaction equivalent.

An additional parameter was the percentage of the test field where a compaction equivalent of 10 or more was reached.

The aforementioned compaction equivalent is calculated as shown in Equation (1).

The compaction is further weighed by a factor of (temperature/100) to account for the asphalt's steadily decreasing ductility as its temperature falls.

$$C_e = \sqrt{\frac{1}{8} * \left|v - \frac{5}{3}\right|} * sgn\left(v - \frac{5}{3}\right) * \left(1 + sgn(b)\right) \qquad (1)$$

with:

C_e: Compaction equivalent
v: Speed in m/s
b: Vibration with $\begin{cases} b = 0 \rightarrow vibration\ off \\ b > 0 \rightarrow vibration\ on \end{cases}$

The control variables used were variations of the turn condition on the far side of the paver. Different compaction path lengths in combination with additional turn conditions based on the compaction reached were simulated. The compactor agent reverses direction back towards the paver whenever at least one turn condition is met. It should be noted, that the compactor agent was always forced to turn back to the paver if the asphalt surface layer core temperature directly underneath the compactor fell below temperature threshold 2 (or if the end of the compactable surface was reached). The strategies used to determine the turning points are depicted in Figure 6:

1) The turning point is solely determined by the length of the compaction path specified in the roller pattern. Consequently, roller paths always have the same length (see the compactor 1 in Figure 6; it always turns when reaching the projected turning distance).
2) The compactor turns early if the desired compaction requirement is fulfilled along the entire path from its current position to the projected turning point (see the checkered area in front of compactor 2 in Figure 6).
3) The compactor turns early if the desired compaction requirement is fulfilled along the path from a position 10 meters ahead of the roller to the projected turning point (see the checkered area in front of compactor 3 in Figure 6).

In order to provide a visual feedback of our simulation, we implemented a graphical user interface showing the drums of each compactor on the site (see Figure 7).

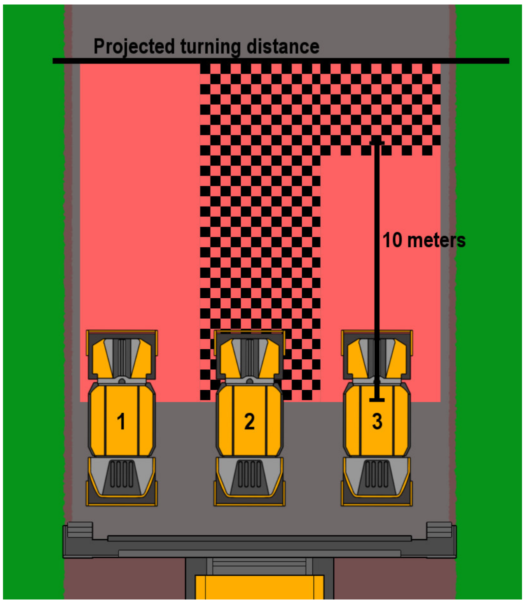


Figure 6. Compaction measurement strategies

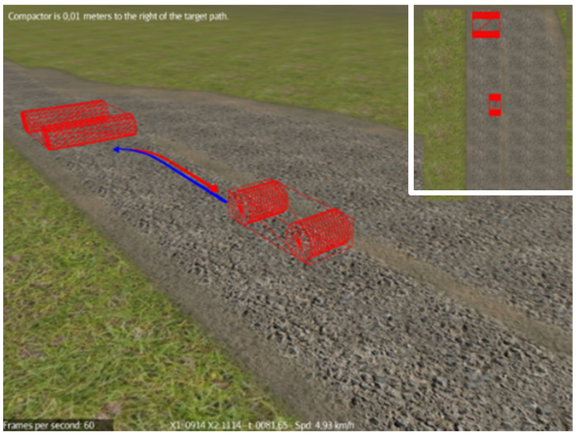


Figure 7. Graphical user interface

5 Results and Discussion

The results of the simulation, as shown in Table 3, favour medium length compaction paths. The columns "10 or more comp. equiv." (see Equation 1 for the definition of "compaction equivalent") and "8 or more comp. equiv." should ideally reach 100%.

Maximum compaction path lengths of 20 m always result in poor values below 85%. On the other hand, very long (maximum) compaction paths of more than 50 m not only produce an unnecessarily high pass count (column "Passes (avg.)") but also increase the variance in pass count (column "Passes (std dev.)"). Furthermore, using long compaction paths introduces further problems into the construction process because the asphalt is colder after the compactor ultimately leaves an area. This complicates subsequent compaction work. Longer compaction paths also enlarge the construction site in general and reduce the work speed of the compactor due to unnecessary passes. Compaction path lengths of 30 or 50 m achieved sufficient compaction while limiting variance.

Figure 8 exemplarily shows the results achieved by using a fixed rolling path length of 30 m. The maps show the achieved compaction equivalent and passes, respectively. On a greyscale ranging from 0 to 255 a value of 255 means no passes were registered on the corresponding measuring point while each additional pass – or compaction equivalent, on the compaction map – reduces the brightness by a value of 4. The histograms shown in Figure 8 depict the distribution of grey values, and therefore passes or compaction equivalent. The parameters of the simulation and statistical analysis are shown in the boxes. The field "Success" states the percentage of the test area in which at least 10 or at least 8 compaction equivalent where achieved, respectively, and are thus equivalent to the last two columns in Table 3.

Table 3. Results

Maximum compaction path length	Compaction measurement	Compaction equivalent (avg.)	Compaction equivalent (std. dev.)	Passes (avg.)	Passes (std. dev.)	10 or more comp. equiv. (% of area)	8 or more comp. equiv. (% of area)
20m		14.26	5.41	8.16	2.76	80.2	88.6
30m		15.33	5.16	8.98	2.78	92.0	97.9
50m		16.58	5.19	10.32	2.94	98.9	100.0
70m		17.61	6.0	11.23	3.44	100.0	100.0
∞		17.68	5.94	11.66	3.55	99.0	99.0
20m	At Position	14.73	5.42	8.44	2.79	82.9	91.8
30m	At Position	15.05	5.41	8.73	2.81	82.0	94.6
50m	At Position	15.64	5.49	9.02	2.83	85.7	97.5
70m	At Position	18.77	6.38	11.20	3.51	92.3	100.0
∞	At Position	18.31	6.56	11.01	3.62	89.3	100.0
20m	10m ahead	13.53	5.66	7.66	2.88	70.7	84.8
30m	10m ahead	14.79	5.17	8.57	2.72	84.1	99.5
50m	10m ahead	15.46	5.98	9.10	3.16	83.6	96.4
70m	10m ahead	15.45	5.83	9.21	3.07	85.0	98.9
∞	10m ahead	15.67	6.01	9.34	3.20	80.7	98.1

As passes and compaction equivalent are based on individual drum passes, the achieved numbers are quite satisfactory. Especially noteworthy is the even distribution of the passes over the width of the road, except for the unavoidable overlap between compaction paths. Areas of higher than average pass counts and compaction are caused by the turns of the compactor and thus are not entirely avoidable. Their negative influence on the distribution of the compaction can, however, be partially mitigated by avoiding repeated turns in the same area of the road. This influence further decreases when employing more efficient dynamic compaction since dynamic compaction is typically disabled while performing turning manoeuvres.

The influence of the compaction based turn conditions (lines 6-15 in Table 3) are in general detrimental to the quality of the compaction. The measurement of compaction 10 m into driving direction (lines 11-15 in Table 3) lowers the pass count, which is to be expected when adding an additional termination condition to a compaction path. However, the variance is higher and the achieved compaction is worse than without this condition. The measurement of achieved compaction at the current position (lines 6-10 in Table 3) of the compactor turned out to be worse than no compaction measurement with regard to all target parameters.

Apparently, the self-organization effect of uniform compaction path lengths outweighs the benefits of being able to terminate compaction paths early. The risk of turning in the same area multiple times is greatly increased when using longer compaction paths due to the resulting overlay of consecutive compaction paths. Turning earlier also causes the turn to be on warmer, more ductile asphalt, increasing the impact of the turn on the compaction result. Due to the defensively chosen compaction function for active vibration and the decreasing compaction effect of further passes, which was not included into the simulation in order to avoid another compactor-specific variable, the negative effect of turns and compaction path changes is especially noticeable in this study.

Maximum path length:	30m
Minimum temperature:	100 (360s)
Maximum temperature:	120 (1400s)
Paver speed:	6m/min
Target passes:	-
Target compaction equivalent:	-
Screed width:	4.5m
Compaction measurement:	-

Passes Ø:	8.98 passes
Variance σ^2:	7.70 passes^2
Std. dev. σ:	2.78 passes
Compaction equiv. Ø:	15.33 comp.eq.
Variance σ^2:	26.62 comp.eq.^{2}
Std. dev. σ:	5.16 comp.eq
Success (Area in %):	92.0|97.9 (no.)

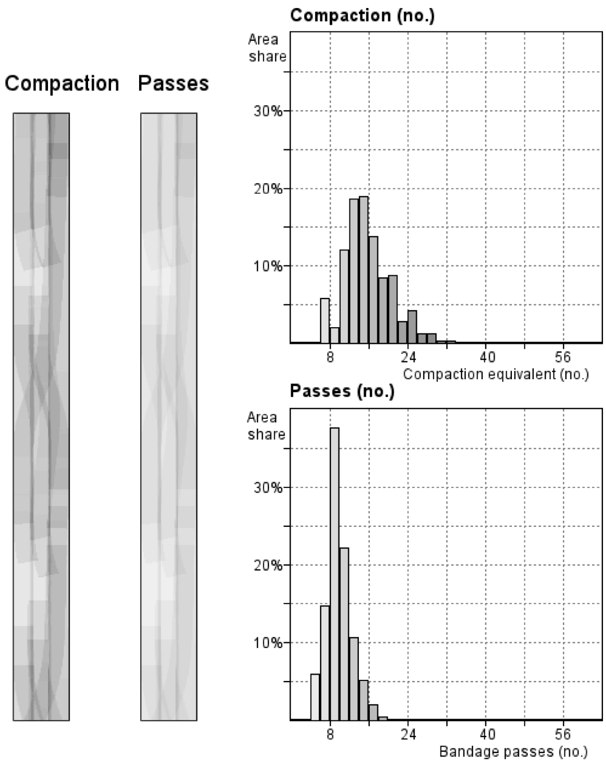


Figure 8. Result sheet

6 Conclusions and Future Work

The last phase of paving asphalt, the compaction process, is crucial for quality and longevity for the remainder of the life cycle phase. Errors in human judgment during asphalt compaction lead to high costs of reversing procedural faults. Assistance systems are promising in reducing quality related faults and help to prevent construction companies from high costs of rectification of defects.

We proposed a novel real-time path planning system for compactors based on BDI software agents and real-time sensory inputs.

The system is capable of reacting to changing environmental, material-related and process-related disturbances or changes. In our evaluation we demonstrate the feasibility of our approach and we show evidence that the proposed system generates instructions which, when followed by human compactor operators lead to high quality compaction results. Since all data are gathered by a simulation study, further research will be conducted by using real equipment under realistic construction site environments. Examples [20-26] have shown outdoor experimental procedures that can be followed.

7 Acknowledgment

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