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A framework for real-time compaction guidance system based on compaction priority mapping

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ABSTRACT

The quality of hot mixed asphalt (HMA) is heavily dependent on the quality of the compaction. However, this operation is very complex, where a large number of parameters (e.g., logistics, weather condition, the skill level of operators, paver speed, etc.) play a role in the operation. To ensure high-quality compaction, operators and site managers need to process a large volume of data in real-time. The high dependency of compaction quality on the largely tacit knowledge of the operators introduces a considerable variability to the quality of compaction operations. In recent years, several compaction support systems are developed to provide operators and site managers with real-time temperature and compaction information. However, these support systems mostly provide the support data in a descriptive manner, i.e., just indicating the current status of the asphalt layer in terms of temperature and compaction maps. In this sense, the operators and managers still need to analyze and interpret the provided data and develop compaction strategies. As a result, it is argued that these systems not only do not reduce the dependency on the tacit knowledge but also can increase the cognitive load on the decision-makers and thus affect the compaction adversely. This research argues that for any compaction support systems to be more effective, it is necessary to provide more prescriptive feedback, i.e., translate the sensory data into actionable guidance that requires less interpretation from the operators and decision-makers. Therefore, the main objective of this research is to develop a framework for compaction guidance systems that can translate the temperature and compaction count (i.e., descriptive) data into clear suggestions for compaction strategies (i.e., prescriptive). A novel priority mapping method is developed to translate the data of (1) the temperature and compaction status of the asphalt mat, and (2) the location of compactors into an index representing the compaction priorities of different parts of the asphalt at any given time. Also, a novel effective compaction rate (ECR) index is proposed in this research to enable an objective and quantitative assessment of compaction operation quality. A prototype is developed and implemented in a case study to investigate the feasibility of the proposed framework. The effectiveness of the proposed guidance system is then assessed through a case study where the proposed method was tested in terms of the extent to which it improves the efficiency of the compaction. It is shown that the transition from the descriptive compaction support system to a more prescriptive guidance system can improve the efficiency of compaction up to 115%. Nevertheless, it is discovered that such a transition may not resonate well with the operators who tend to perceive a loss of control over the compaction strategy as a drawback of the guidance systems. This suggests that the technological transition to compaction guidance systems should coincide with a change of operators' mindset towards new ways of interaction with the collected sensory data

1. Introduction

Hot Mix Asphalt (HMA) is being widely used as the dominant material for roads in many countries. However, the quality of HMA roads depends heavily on the extent to which density is (1) compliant with the design and (2) homogenous. This highlights the criticality of proper compaction for the HMA asphalt layer [1]. Nonetheless, compaction is an intricate operation that is influenced by a myriad of design (e.g., the type of asphalt mix and mat thickness), execution (e.g., uniformity of compaction), logistic (e.g., the temperature of the asphalt at the delivery

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time), and environmental (e.g., weather condition) factors [2]. Of particular importance to the quality of HMA layers is to ensure that compaction force is applied at the right temperature, to avoid over- and under-compacted asphalt layer [3]. It should be highlighted that essentially it is the responsibility of the site superintendent or project quality manager to set the overall compaction strategy at the beginning of the compaction operation. However, once the project commences, in practice, operators rely on their interpretation and experience to cope with the dynamic aspects of the project. Given the time-sensitive nature of the compaction operation, it is difficult for site managers to actively intervene and re-adjust the compaction strategy as the uncertainties unfold. That leaves a lot to largely implicit, experience-driven, and unstructured knowledge of the operators [2–5]. An inextricable outcome of this dependency on operators' tacit knowledge and skill is the high variability in the quality of compaction operation, and thus the asphalt layer [3].

In recent years, similar to other equipment-intensive construction operations, the advent of sensing and information technologies, has propelled the development and application of onboard support systems for compaction [4–9]. These support systems deploy, collect, and integrate both design (e.g., pavement design) and real-time (e.g., asphalt temperature and roller pass count) data to help operators better plan (or re-plan) and execute compaction operations based on the specific context of each operation. In particular, these systems intend to keep operators abreast of the number of passes and the current temperature of different parts of the asphalt mat. To this end, as shown in Fig. 1, these systems commonly generate compaction and temperature maps, i.e., a color-coded grid.

While proven effective in providing more insight into the operators [10], these systems have a major limitation. These systems present only minimally processed compaction pass and temperature data to the operators, usually in separate dashboards, in a descriptive manner, i.e., only indicating the current status of the asphalt mat in terms of temperature and compaction. The operators need to monitor and track these data and translate them into an action plan in real time. Since the compaction (re-) planning is very case-dependent, the operators need to mentally augment these data with other types of mix design and weather data, to determine the best compaction strategies. This can impose an additional cognitive load on the operators, which in times can become overwhelming. Based on the field observation of the authors, this additional cognitive load precipitates the operators to become perceptually disengaged from the system after a period of time. This takes a toll on the efficiency of the operator support systems.

Accordingly, it appears to be essential to reduce the cognitive load imposed by operator support systems by transferring the task of data interpretation and integration to the system as much as possible. In other words, operator support systems need to transition from descriptive systems, i.e., systems that only provide information pieces needed for planning a compaction operation, into prescriptive systems, i.e., systems that suggest actionable compaction strategies based on the collected data. Since the role of these systems changes from supporting operators to guiding operators, they will be referred to as operator guidance systems from now on. Literature indicates that the transition to guidance systems has been very successful for other pieces of construction equipment, such as cranes [11–14] and excavators [15–18]. Nevertheless, to the best of the authors' knowledge, although some autonomous rollers exist, such a guidance system is not widely available for compaction equipment.

The transition to operator guidance systems for compaction operations requires another major change to the way the current compaction support systems function. Currently, although there are a few exceptions (e.g., Hamm [19] and BOMAG [20] IC rollers) that support machine to

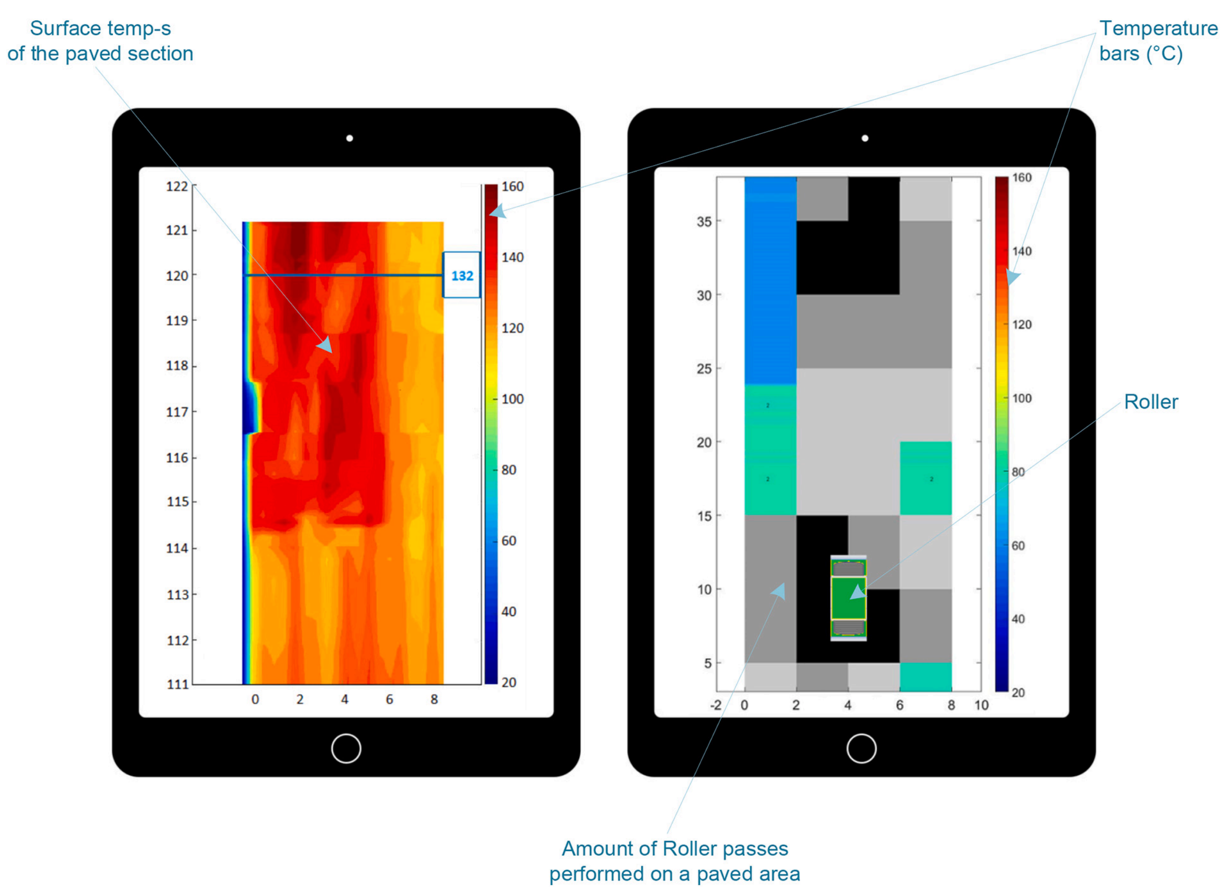

Fig. 1. Common Temperature and Compaction Contour Plots.

machine communications, the majority of compaction support systems adopt an isolated view of the operation, meaning that each system is dedicated to one compactor and only provides data that can be collected from the sensors attached to the same equipment. However, for the compaction guidance systems to work, especially in large projects where several rollers work in tandem, it is crucial that these systems maintain a global view of the entire operation so that the provided guidance takes into account the status of the entire fleet. It is only by doing so that the compaction guidance system can ensure the provided guidance can be translated into safe and efficient actions. The importance of such a fleet-level approach has been already indicated for other types of equipment [21].

By hypothesizing that the transition from compaction support to compaction guidance can improve the efficiency and user-friendliness of these systems, this paper aims to develop and assess a framework for providing roller operators with prescriptive, actionable, and easy-to-follow guidance that adopts a holistic view of the compaction operation. This will be done by deploying the Internet of Things (IoT) technologies and methods to integrate various sources of design (i.e., pre-existing) and real-time sensory data collected from the entire compaction fleet. More precisely, the proposed framework intends to (1) collect and analyze data about temperature and compaction of the asphalt mat in real time, (2) translate these data to actionable guidance for operators by considering the priority of compaction on different parts of the asphalt mat. In other words, this research proposes to provide guidance to the operators in terms of indices that indicates the compaction priority of different parts of the asphalt mat. By doing so, this research intends to provide an insight into (a) how to transit from descriptive compaction operator support systems to prescriptive operator guidance systems, and (b) how this transition can contribute to improving the efficiency of compaction operations.

The remainder of the paper is structured as follows: First, the literature review is presented. Next, the proposed framework is described in detail. Subsequently, the prototype implementation and case study are presented. Then, the analysis of the results of the case study is presented. Finally, the discussions and conclusions are presented.

2. Literature review

2.1. Important factors in compaction monitoring

HMA is produced by mixing aggregates with a heated binder [22]. During the construction of roads, HMA is delivered to the site, dumped onto the paver, and then laid on the base layer. The HMA layer is then compacted using rollers to the desired density. Density is normally used as a reference for the quality of the HMA layer [23,24]. However, to achieve the desired density two factors are overriding, namely sufficient compaction effort and the compaction at the appropriate temperature.

Compaction effort is directly correlated with the number of passes made by rollers [25,26]. It has been shown that tracking of rollers, e.g., by GPS, provides an essential awareness about whether or not the asphalt mixture has been properly and sufficiently compacted [26]. However, due to the different types of the rollers (e.g. tandem roller, three drum roller, rubber-tired roller), the rolling phase (e.g. break-down, intermediate or finish rolling), and the type of compaction (e.g. static or vibratory), the force that is applied to the asphalt layer differs. The number of roller passes is a cumulative parameter that has to include other relevant variables for compaction, e.g., the number of rollers and their mutual work, rollers' speed, the width of the compacted area, overlaps between compacted lines, distance between paver and rollers, rollers' areal output and uncompacted areas [27].

Compacting the HMA layer when it is too hot or too cold results in over- or under-compacted layers, respectively [3,28]. The appropriate temperature range for compaction is normally referred to as the compaction window and is indicated on the cooling curve of the asphalt [28,29], as shown in Fig. 2. It is the responsibility of the roller operators to ensure that the compaction effort is made within the compaction window. Nevertheless, asphalt's cooling behavior depends on many different factors such as production, delivery, ambient temperature, wind speed, the temperature of subsurface, etc.

However, the conventional and intuitive monitoring of compaction passes and temperature in real time is very challenging for operators, especially for large projects, and proven to be inefficient [3]. This is mainly because the number, interdependency, and unpredictability of factors that need to be considered during a compaction operation are simply too overwhelming and complex to be left to the intuition, experience, and skill of operators. This highlights the significance and exigency of onboard support systems that can help roller operators better interpret and comprehend the task at hand.

2.2. Construction equipment operator support systems

Many construction operations are equipment-intensive and complex, e.g., earthwork operation [21,30,31]. The complexity of these operations renders the upkeep of safety and productivity in construction sites challenging. Therefore, researchers have tried to develop various types of operator support systems for construction equipment to collect and provide contextualized data to the operators [15,17,18,32,33]. Various types of equipment have been investigated, such as cranes [12,34–41] and excavators [42–57].

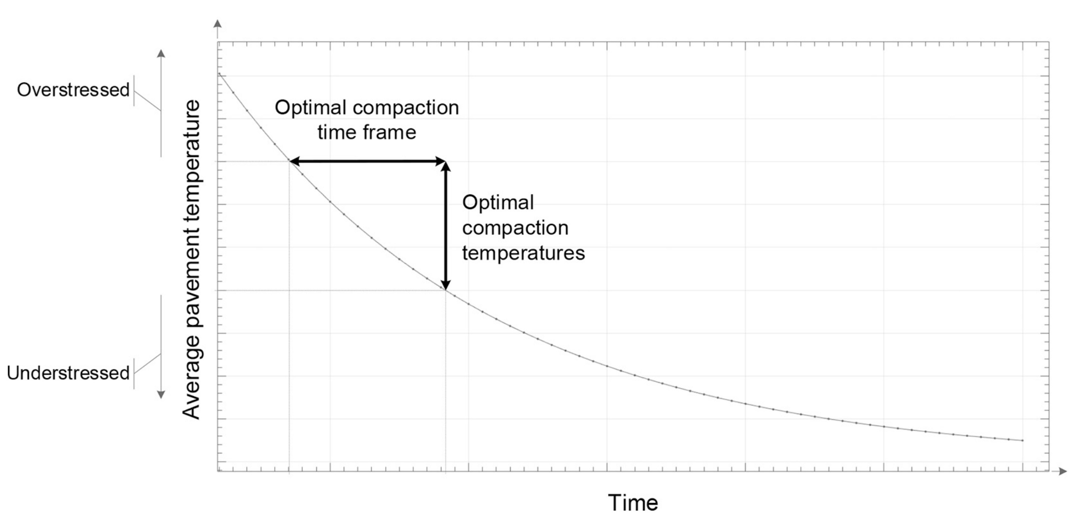

Fig. 2. Cooling curve of an asphalt mixture with optimal compaction window (adapted from Timm et al. 2001).

Overall, it is evident in the recent scholarly work that the application of guidance systems can have a positive impact on the safety and productivity of equipment-intensive operations [41]. However, the main limitation of the majority of the existing research is that the developed guidance systems are developed as standalone systems that adopt an isolated (i.e., restricted to single equipment) view of operations. The authors [21] have indicated this limitation and argued that to further enhance the performance of the machine guidance systems, fleet-level support is a must.

2.3. Roller operator support systems

As discussed in Section 2.1, compaction operations are complex and therefore can benefit from descriptive operator support systems. Intelligent Compaction (IC) technologies have tried to address this need [9,58]. This technology has matured significantly over the past 20 years, to the point that the American Association of State and Highway Transportation Officials (AASHTO) has started to regulate the use of IC systems [59].

In the conventional form [26,60], IC systems were standalone units that were installed on a single roller and integrated GPS with temperature sensors to determine the compaction count and initial compaction temperature of different parts of the asphalt mat. Further research was carried out to add a real-time density estimation feature to IC systems [7,61,62]. Chang et al. [63] proposed to use an Infrared camera for the purpose of monitoring the thermal profile of the mat behind the paver and to control potential temperature segregation. Addressing these gaps, researchers have started to consider more comprehensive IC systems

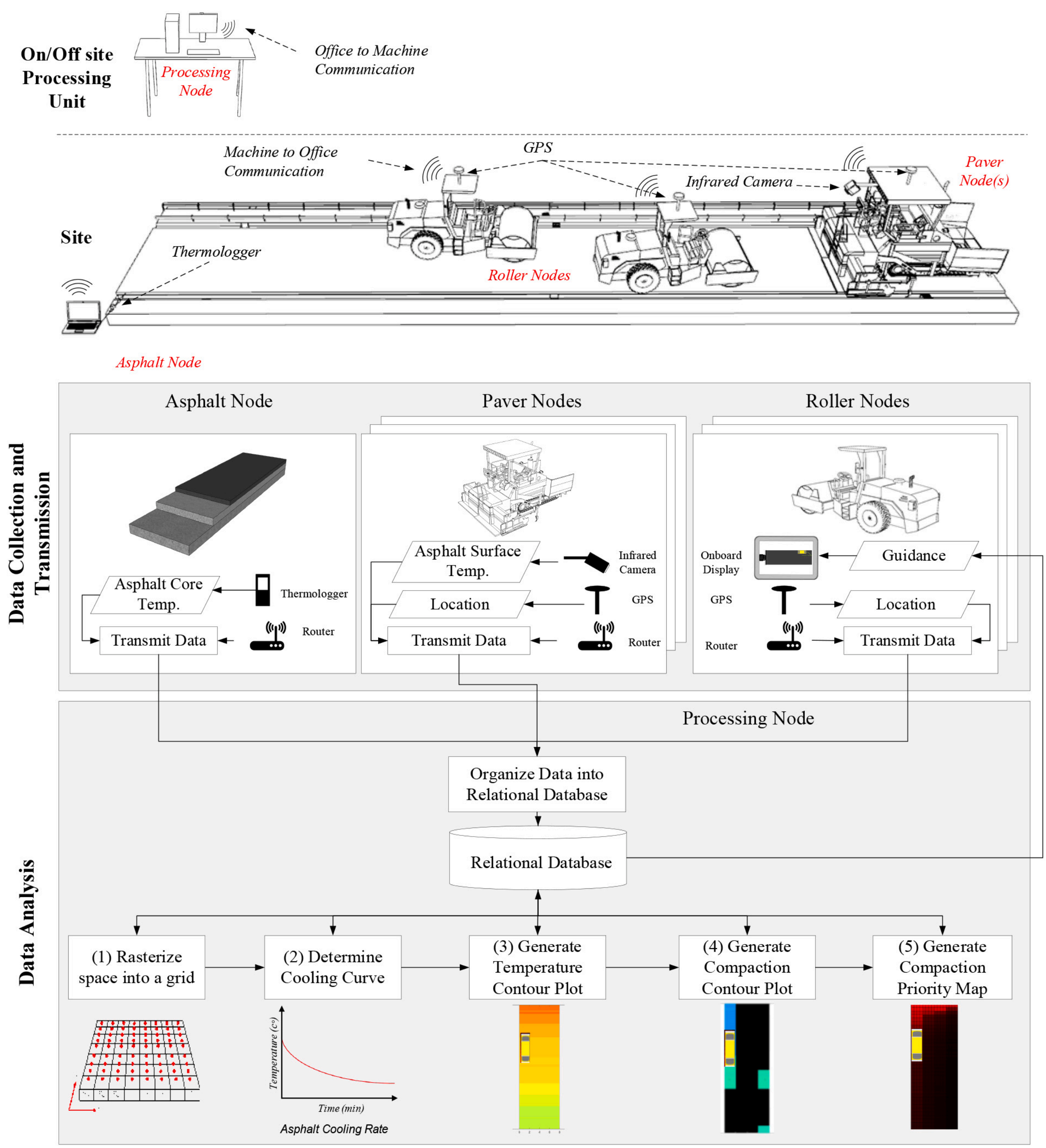

Fig. 3. Overview of the Proposed Framework.

based on sensor network architecture and machine-to-machine communication [10,64]. In these systems, a sensor network is used to collect data from all the pavers and rollers involved in a project and transmit them to the central processing unit that integrates and analyses the data in a global manner. The processed data are then tailored for the need of different operators and transmitted back to the onboard unit on each equipment. This structure is proven to be more efficient in providing more extended insight to operators in terms of the global quality of the compaction operation [10]. Although the presented fleet-level support system in the work of Liu et al. [64] is shown to be effective, this system mainly position itself as a warning system that can warn operators about deviations from the planned strategy. In doing so, the proposed system does not concern itself with the provision of prescriptive guidance that operators can use to (1) assess the operational quality in terms of compaction at the right temperature, and (2) develop new strategies in real time.

While the state-of-the-art compaction operator support systems are successful in collecting and presenting a wide range of data to the operators, there is a major limitation in how these data are presented. The plethora of data presented to the operators for decision making makes it difficult for machine operators to (1) find the relevant information to their tasks. For instance, while the operators are more interested in knowing where to compact next and how long should the compaction length be, the current systems only provide them with temperature and compaction count data.; and (2) analyze, process, and translate this information into actions in real time. This makes operators experience cognitive overload and lose attention to operator support systems, as a result of which they may inadvertently revert to the sub-optimal intuitive decision making. Therefore, it is essential for compaction operator support systems to follow the footprint of the operator support systems of other types of construction equipment and try to transit from descriptive support systems to prescriptive guidance systems that can translate the temperature and compaction data into actionable and easy-to-follow guidance.

3. Proposed framework

Fig. 3 presents an overview of the proposed framework. It is noteworthy that the process shown in Fig. 3 represents the data collection and analysis for 1 frame of the data collected from the site. This process is recursively applied until the project is finished in real time. In this framework, the required data for the operator guidance system are collected using the IoT concept. According to this concept, the important players in the compaction process are categorized into four types of nodes, namely Asphalt, Paver, Roller, and Processing nodes. Asphalt, Roller, and Paver nodes are equipped with appropriate sensing and data transmitting hardware to collect, transmit, and receive data to and from the Processing node. At the Processing node, the collected data is organized in a database and then processed to generate (1) the cooling curve, (2) temperature contour plot, and (3) compaction contour plot. The geo-referenced and time-stamped temperature and compaction data are then integrated to determine the compaction priority of different parts of the asphalt mat. The remainder of this section describes each part of the proposed framework in detail.

3.1. Data collection and transmission

As mentioned earlier, the IoT concept is proposed to collect and transmit data to and from the main players in the compaction process. In the proposed framework, as shown in Fig. 3, a centralized architecture is used where all the data are collected and processed in a central Processing node, which can be located on the site or in a remote location. The centralized architecture is chosen because the compaction guidance would require data from all the nodes, as will be explained in Section 3.2.7. In this situation, a decentralized architecture would require all-to-all data transmission between every node in the network. Besides, given that the generation of roller guidance requires similar computation, a decentralized architecture would require redundant computations. Finally, maintaining a global repository of all the data, which can be later used for Quality Control of asphalt operation, is more complicated in a decentralized network. Therefore, to reduce the communication load on the network, eliminate redundant computation, and also to maintain a global database for post-processing of the data, a centralized architecture is chosen. Fig. 4 presents an overview of the communication in the proposed centralized architecture. The communication scheme will be explained in the subsequent sections.

3.1.1. Asphalt node

The Asphalt node consists of a set of thermocouples that are placed in the asphalt layer. Fig. 5 shows how the Asphalt node can be set up on the site. As shown in Figs. 5 (a) and (b), the thermocouples are placed inside a stand that can be placed on the base layer before the paving. The stand helps keep the thermocouples at the desired location in the asphalt profile. Once the paving starts, the stand and the thermocouples, which are connected to it, are buried compacted the hot asphalt, allowing thermocouples to measure the core temperature at different depths of the asphalt profile. A thermologger collects the temperature data and transmits them to the Processing node, using a router connected to the thermologger.

3.1.2. Paver nodes

The Paver node is responsible for collecting the surface temperature of the freshly laid asphalt. For this purpose, an infrared camera is installed at the back of the paver, as shown in Fig. 6(a). Also, to geo-reference the temperature data, a GPS rover is installed on the paver.

The infrared camera registers temperature data in a grid pattern as shown in Fig. 6(b). The width of the data capturing field is determined based on the width of the lane. This can be determined manually by the operator at the beginning of the project. The resolution of data collection depends on (1) the resolution of the camera, (2) the camera's field of view, and (3) the installation height of the camera. The captured temperature data is registered in terms of the pixel coordinates in the images taken by the camera. These data will be transmitted to the Processing node using the router that is mounted on the paver.

3.1.3. Roller nodes

These nodes are dedicated to the tracking of rollers' activities and also displaying the guidance to the operators. Therefore, these nodes consist of GPS rovers, which are mounted on each roller, routers, which transmit the data between Rollers and Processing node, and onboard displays, which present the operator guidance. The GPS data is used to measure the amount of compaction effort made on different parts of the asphalt layer.

3.1.4. Processing node

The Processing node, which can be on the site or a remote location, receives all the data from other nodes, performs the necessary analysis to generate the guidance for the roller operators, and transmit the guidance back to the Roller nodes for visualization. Section 3.2 elaborates on the data analysis performed by the Processing node.

3.2. Data analysis

Once all the data are transmitted to the Processing node, the data analysis begins. The data analysis consists of several steps, including structuring of the data into a relational database, generation of a cooling curve for newly laid asphalt, generation of compaction/temperature contour plots, and the generation of the operator guidance, i.e., the priority map of compaction.

3.2.1. Structuring data into a relational database

The data received by the Processing node is heterogeneous and

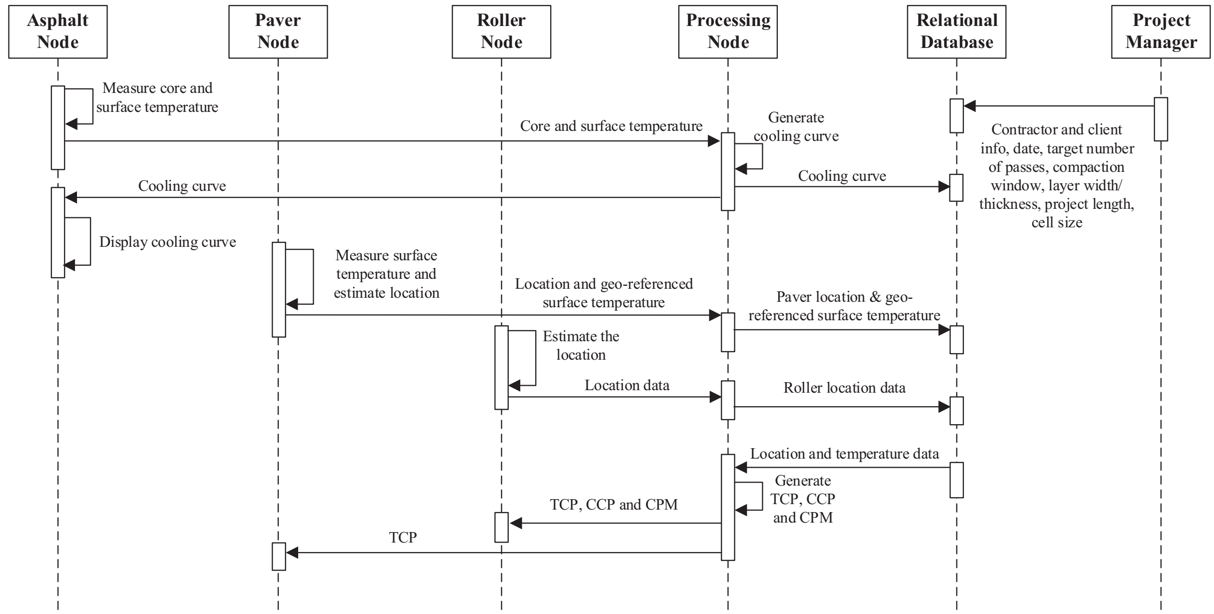

Fig. 4. Sequence diagram of the proposed architecture.

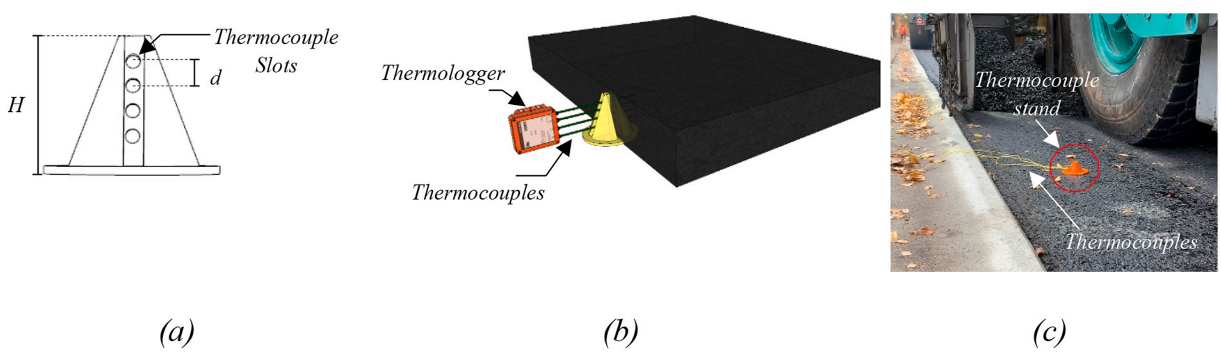

Fig. 5. Configuration of Asphalt Node.

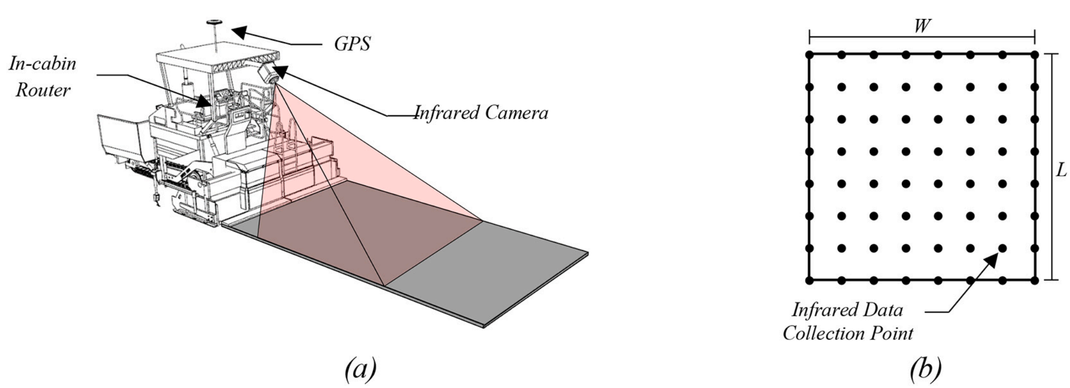

Fig. 6. Configuration of Paver Node.

asynchronous. Therefore, it is important to organize the data into a relational database. This database would serve the following purposes: (1) as an integral part of the centralized architecture, it helps reduce redundant peer-to-peer communication between nodes, (2) provides easy access to the data to multiple clients both in real-time and for post-processing, and (3) helps modularize the architecture of the guidance system so that the future development can be done without the need to drastically change the structure of the data.

The database holds 3 different types of data, namely design, sensory and analytic data. Design data are those that are known from the design of the asphalt or process. This includes data such as the geometric specifications of the pavement layer, number of equipment, date, project location, client, etc. Sensory data are the raw data collected and transmitted by different nodes of the system. Examples are the location of equipment, equipment heading, the core temperature of asphalt, etc. The final type of data includes analytic data, which are the result of processing and integrating sensory and design data into a new type of data that can help generate relevant guidance. Rasterized temperate data, compaction count, time left for compaction of different parts of the asphalt layer are examples of analytic data. It is important to note that, as shown in Figs. 3 and 4, the database is completed incrementally. In other words, at each step of the framework, the result of the relevant data analytics is stored in the database and used in the subsequent steps.

Fig. 7 shows an overview of the relational database used in the proposed framework. A one-to-one relationship is represented by (1–1) and means that each record in a table relates to one, and only one, record in another table, and the other way around. For instance, the operator is responsible and drives one machine during the project. In a one-to-many relationship, that is represented by (1-*) one record in a table can be associated with one or more records in another table. For example, each project can have many pieces of equipment. In the database, data are categorized into 10 classes. At the top layer of the database, the pavement project is defined. The project layer consists of a variety of design data about the nature, location, geometry, and data of the project. The weather layer hosts the collected/retrieved data about the weather condition at the site location. This includes such data as high and low temperature, humidity, wind direction/speed, and barometric pressure. The data about the client and contractor of the project are stored in separate classes, each including the name and ID of the relevant party. The details of the asphalt layer, which is a mix of design, real-time, and analytic data, is stored in a separate class. In this class, in addition to the type and geometry of the asphalt layer, the operational requirements of the compaction work are specified. The Effective Compaction Rate (ECR) indicates the quality of the compaction process in terms of the proportion of the asphalt layer that has been compacted enough within the appropriate temperature window, as will be discussed in Section 3.2.7. The cooling rate indicates the rate at which the core and surface of the asphalt layer cool down and is determined as will be explained in Section 3.2.3. To facilitate data registration, analysis, and visualization, the asphalt layer is rasterized into a cell grid. Each cell contains a suite of analytic data including the temperature, compaction pass, priority index, etc. The description of each attribute within this cell will be elaborated in Section 3.2.2.

Finally, the sensory and analytic data about the paver and roller are stored in respective classes. The data about the operator of each equipment is also stored in a separate class. Paver class holds data about the type/model of the equipment, the size of the hopper, the arrival time of the last truck, asphalt left in the hopper (approximated based on the paved asphalt and the capacity of each truck), the current location of the equipment, current speed, and current heading of the paver. The roller class hosts a wider range of information that includes the equipment type, compaction mode (vibratory or static), current location/speed/heading, the current destination of the roller (this will be used to guide the operators to the optimized path), efficiency, productivity and different types of plots that will be presented to the operators as a form of possible guidance. These analytical data will be explained in Section 3.2.4 to 3.2.7.

3.2.2. *Rasterization of space*

The size of the cell determines the resolution of data analysis and depends on the resolution/update rate of the infrared camera, the available processing power, the size of rollers, and the accuracy of GPS rovers used for tracking equipment. As suggested by Eq. 1, the cell width cannot be smaller than the resolution of the infrared camera installed at the back of the paver. For instance, if the infrared camera captures 20 points across the specified width, the cell size must be at least greater than 1/20 of the width. Also, to provide operators with sufficiently accurate and actionable information, the cell size should not be bigger than half of the width of the rollers' drum. Having the necessary information, the system's operator would determine the cell sizes at the beginning of the operation.

$$\frac{W}{R} \leq w \leq \frac{W_r}{2} \tag{1}$$

where:

W: Width of the road

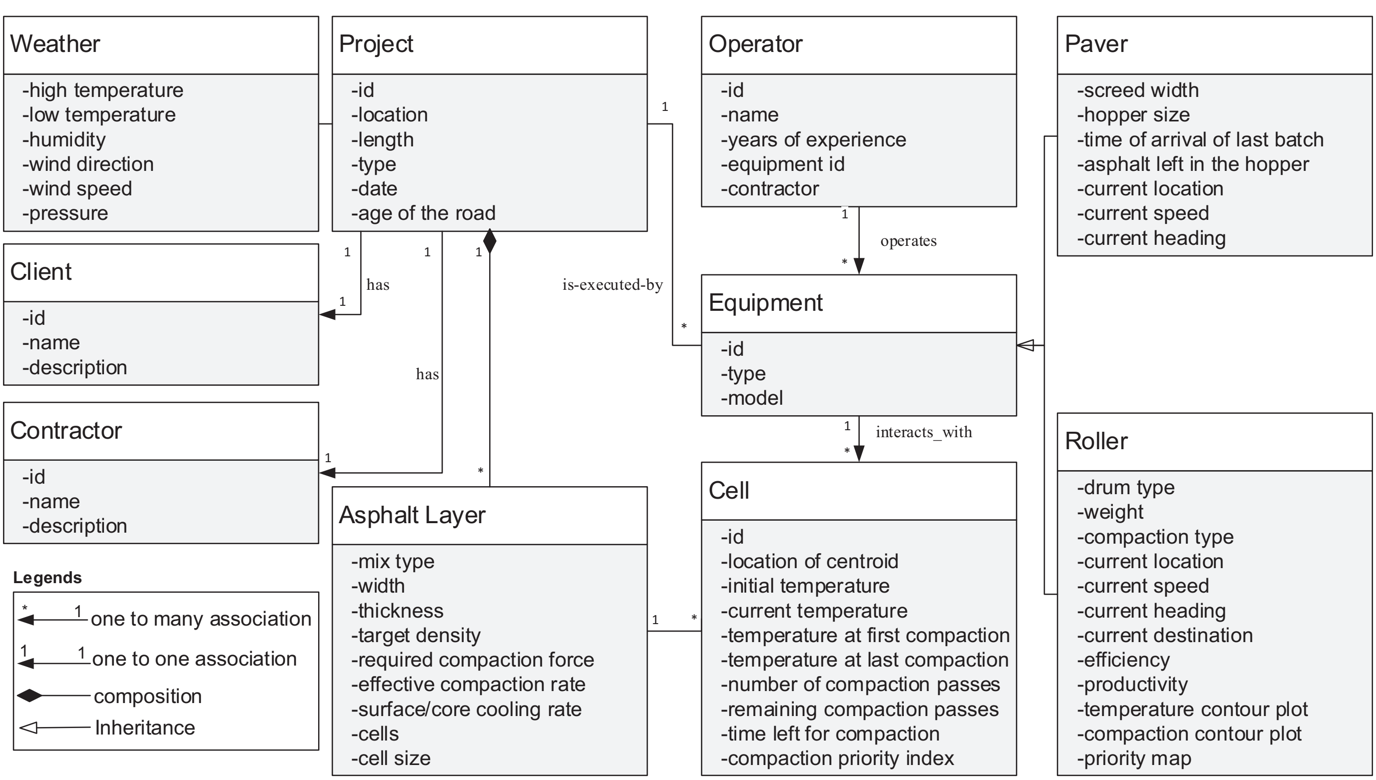

Fig. 7. Overview of the relational database used in this framework.

R: Resolution of the infrared camera
w: Width of the cell
W_r: Width of the roller's drum

With the size of the cells known, the grid is built from the first location where the paver starts paving. Each cell ($C_{i,j}$) hosts various types of data, as shown in Fig. 8, including the initial temperature ($IT_{i,j}$), current temperature ($CT_{i,j}$), the temperature at the first pass ($TFP_{i,j}$), the temperature at the last compaction pass ($TLP_{i,j}$), number of compaction passes ($P_{i,j}$), remaining compaction passes ($RP_{i,j}$), time left for compaction ($TL_{i,j}$), and compaction priority of cell ($R_{i,j}$).

To structure the collected data into a cell-based structure, first, the surface temperature registered by the infrared camera need to be geo-referenced. This is done by (1) determining the fixed translation vector between the physical location of the camera and GPS rover on the paver, and (2) determining the transformation matrix for the camera images based on the translation vector, installation configuration of the camera (height and tilt angle) and camera's intrinsic matrix. At the end of this process, the projection matrix that maps temperature pixel data into the world coordinate is determined. This projection matrix can be continuously applied to all the streamed data as long as the installation configuration of the camera is the same.

After the geo-referencing of the infrared data, they need to be mapped into the grid. Therefore, the coordinates of the geo-referenced temperature data ($IT_{x,y}$) need to be intersected with the grid to map the temperature data into the cell coordinates ($IT_{i,j}$). Interpolation is applied to calculate the temperature at the centroid of each cell.

3.2.3. Generation of cooling curve

As it was mentioned in section 3.2.1, the asphalt cooling rate can provide an insight into the thermal behavior of the asphalt layer during construction procedures (e.g. paving, compaction). This information is essential to estimate the time at which rollers should start the compaction and how much time is left before the asphalt layer is too cold to compact. To be able to accurately grasp asphalt layer temperatures, the methodology that has been developed in previous authors' work is used [10]. Fig. 9 depicts the setup of an Asphalt node on site and represents the main data sources to generate the asphalt cooling curve. Among these sources:

1. *Surface Temperatures (T_{surf}):* asphalt surface temperatures that are gathered by Asphalt node;
2. *Core Temperatures (T_{core}):* asphalt core temperatures that are gathered by Asphalt node.

As discussed in Section 3.1.1, depending on the thickness of the asphalt layer, several thermocouples can be placed within the newly paved asphalt layer. These thermocouples are distributed evenly along the asphalt mat thickness to capture the temperature gradient profile of the layer. Fig. 10 represents an example of raw field data that are collected by the Asphalt node and the cooling curve that is generated in real-time based on the obtained dataset.

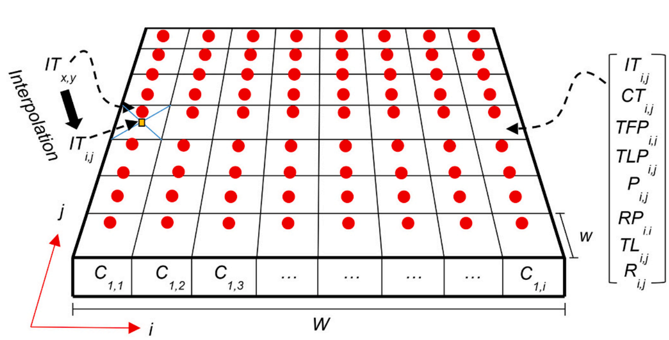

Fig. 8. Cell formation on the asphalt layer.

The Surface temperature curve shows data points that are collected by IR thermometer. The curve that represents core temperatures of the asphalt layer is based on thermocouples' readings and is determined by taking the average of readings from all thermocouples at any given time. After every interval (e.g. every minute), the Processing node predicts the asphalt cooling rate based on the collected temperature data. In particular, T_{core} and T_{surf} are used to find a fitting function to predict temperature changes during construction. As shown in the previous research [65], the equation used for the determination of the cooling rate takes into account the thickness of the layer, thermal conduction, and thermal transition coefficients. As a result, the Processing node generates the cooling curve (Fig. 10). Based on a compaction temperature range that is predefined for the particular asphalt mixture (e.g. [T0, T1] (°C) in Fig. 10), the cooling curve provides a basis to determine the compaction window or time left to finish compaction operations on site, as shown in Eq. 2. This helps to mitigate possible damages of the asphalt layer with compaction above or below the compaction window [66].

$$\Delta t = (t_1 - t_0) \tag{2}$$

where:
Δt: Compaction window
t_0: Start time of a compaction window
t_1: End time of a compaction window

3.2.4. Generation of temperature contour plot

Temperature Contour Plots (TCPs) are 2D visuals from the top view that are generated by the Processing node based on the data collected by the Paver node. As it is explained in Section 3.1.2, the required data for generating TCP plots include surface temperatures of the asphalt mat behind the screed of the paver and paver coordinates during the paving operation. After paver operator manually determines the width and length of the field that is captured by IR camera, the collected surface temperatures of the paved asphalt layer are synchronized with paver coordinates. Geo-referenced infrared data are then intersected with the cell grid ($IT_{x,y}$ □ $IT_{i,j}$, in Section 3.2.2) and saved as initial temperatures.

Fig. 11 shows a typical TCP that is generated by the Processing node based on collected temperatures and coordinates from the paver. This plot presents surface temperature conditions of a newly paved asphalt stretch within the predefined distance that can provide an insight into the homogeneity of the asphalt mixture laid by the paver.

3.2.5. Generation of compaction contour plot

For generating Compaction Contour Plots (CCPs) of a particular roller, its locations on the construction site are collected with the use of GPS sensors. These locations are further sent to the Processing node, where they are filtered to remove the outliers. Processed data are then analyzed in terms of the compaction achieved on different parts of the asphalt mat. During the analysis, the cell grid that is prepared for rasterization (Section 3.2.2) is used. Thereby, in addition to the already saved information such as initial temperature ($IT_{i,j}$) and current temperature ($CT_{i,j}$), each cell of a grid stores temperature at the first roller pass ($TFP_{i,j}$), when the roller starts the compaction. Moreover, the cell saves temperature at the last roller pass ($TLP_{i,j}$), when the roller finishes the compaction procedure on a certain part of the asphalt mat. For the further analysis of the compaction process, the number of compaction passes ($P_{i,j}$) and the number of remaining compaction passes ($RP_{i,j}$) for each cell of a grid are calculated as shown in Eq. 3.

$$RP_{i,j} = (TRP - P_{i,j}) \tag{3}$$

where:
$RP_{i,j}$: Number of remain compaction passes for a certain cell of a grid
TRP: Target number of roller passes, defined by project (site) manager
$P_{i,j}$: Number of compaction passes calculated for a certain cell of a grid

Based on the calculated numbers of achieved and left compaction passes ($P_{i,j}$, $RP_{i,j}$), the compaction map is created (Fig. 12). This map

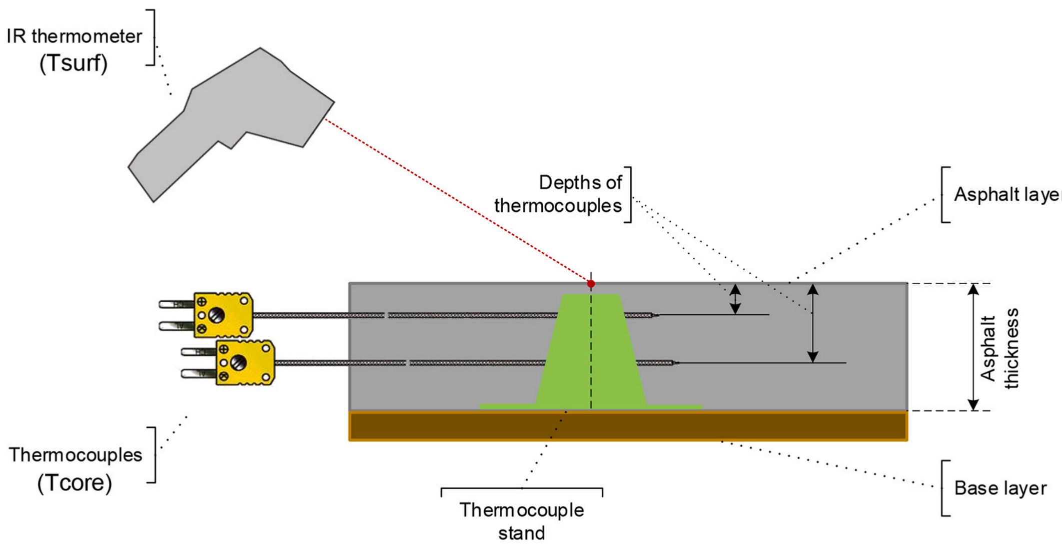

Fig. 9. Setup of an asphalt node on site.

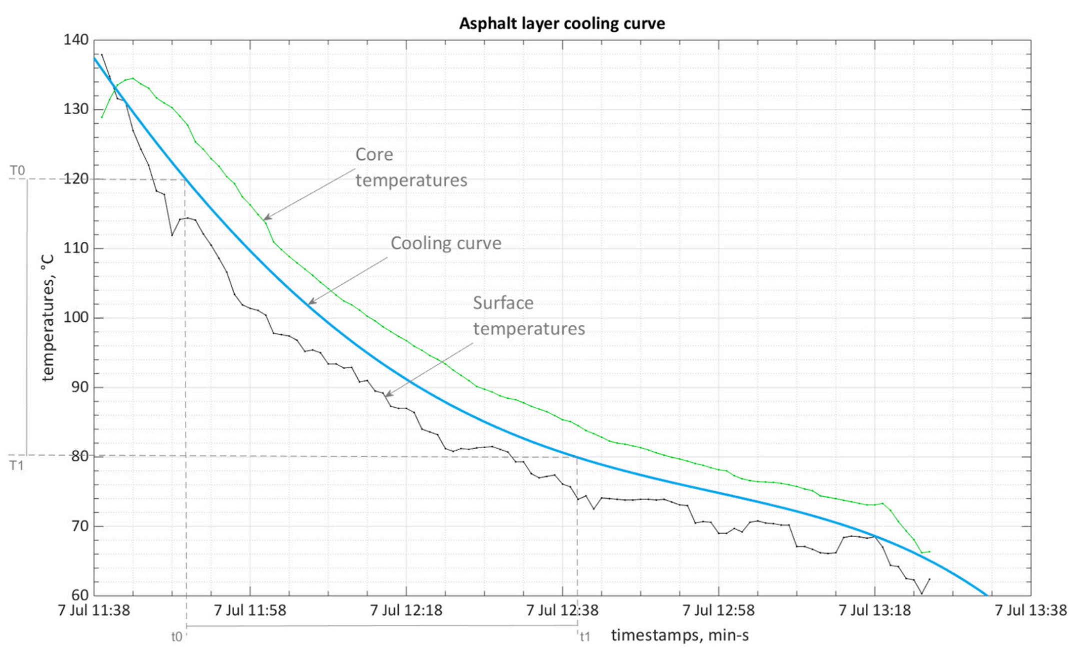

Fig. 10. Generation of the cooling curve.

represents accomplished compaction with the predefined color scheme.

Ideally, the roller operator needs to start the compaction procedure after the upper limit of a compaction window and end it before the lower limit of a compaction window (i.e., temperatures T0°C, T1°C at times t0 and t1, respectively, in Fig. 10) to avoid over- and under-compacted asphalt layer. The time left for the compaction of each cell ($TL_{i,j}$) is determined by considering the cooling curve and the current temperature of each cell ($CT_{i,j}$), which can be derived from *TCP*. With the combination of $TL_{i,j}$, $CT_{i,j}$, and $RP_{i,j}$, the roller operator can decide whether or not a change of compaction strategy is needed (i.e. speed up or slow down the process, or focus on particular parts of the mat).

3.2.6. *Generation of compaction priority map*

While the previous two types of data (i.e., TCP and CCP) merely indicate the state of the asphalt layer in terms of asphalt temperatures and compaction, the priority map tries to combine the two conditions data into guidance about how compaction of different parts of the asphalt needs to be prioritized. In order to generate the priority map, two parameters are considered. The first parameter is the time left for the compaction of a cell. As shown in Fig. 13, this is determined by calculating the $TL_{i,j}$ for each cell at every frame. The second parameter is the number of compaction achieved so far for each cell ($P_{i,j}$). These two parameters are translated to a priority index using Eqs. 4 to 6.

$$R_{i,j} = CP_{i,j} \times TP_{i,j} \tag{4}$$

$$CP_{i,j} = \begin{cases} \dfrac{PD - P_{i,j}}{PD} & PD \geq P_{i,j} \\ 0 & PD < P_{i,j} \end{cases} \tag{5}$$

$$TP_{i,j} = \begin{cases} 0 & TL_{i,j} > t_c \\ \dfrac{t_c - TL_{i,j}}{t_c} & 0 < TL_{i,j} \leq t_c \\ 0 & TL_{i,j} = 0 \end{cases} \tag{6}$$

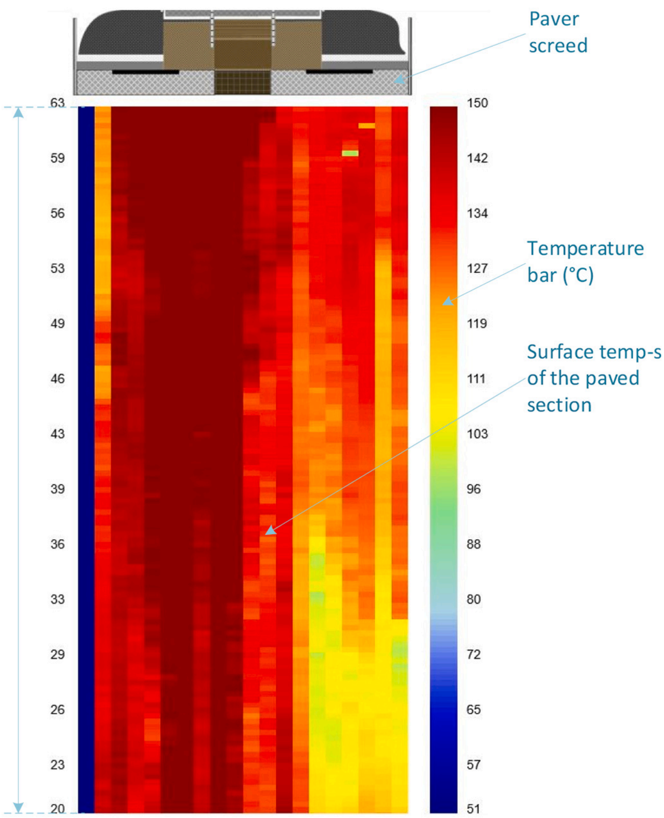

Fig. 11. Temperature contour plot.

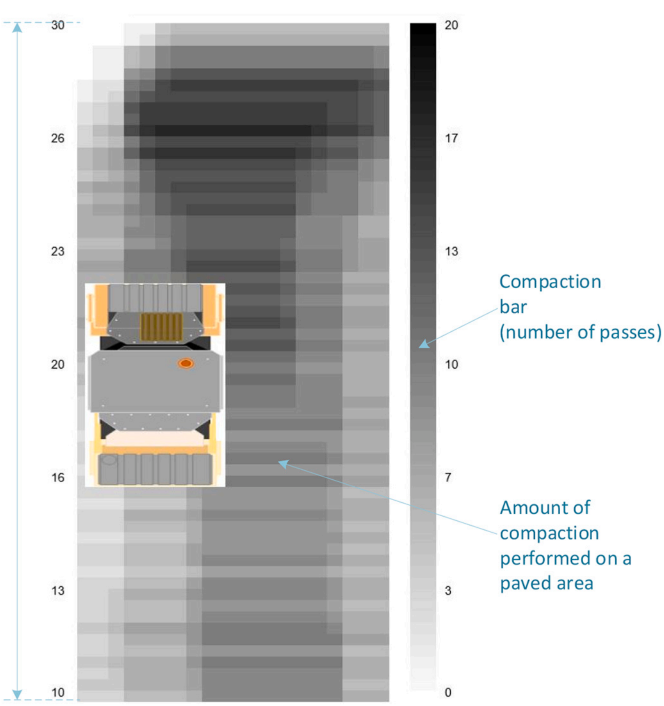

Fig. 12. Compaction contour plots (Roller node).

where:

$R_{i,j}$: *Priority of cell i and j*
$CP_{i,j}$: *Compaction priority of cell i and j*
$TP_{i,j}$: *Temperature priority of cell i and j*
PD: Desired number of compaction (number of roller passes)

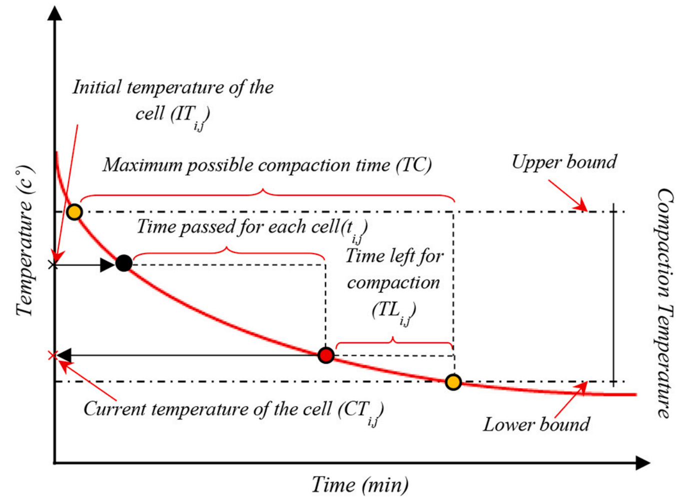

Fig. 13. Basic parameters for the determination of compaction priority (adapted from [68]).

$P_{i,j}$: *Compaction achieved at cell i and j (number of roller passes)*
TC: Maximum possible compaction time
$TL_{i,j}$: *Time left for compaction of cell i and j*

Fig. 14 represents an example of the Compaction Priority Map (CPM) that is generated based on the TCP and CCP. In this particular example, the map indicates parts of the asphalt mat that have already been properly compacted or too cold to compact (i.e., cells highlighted in black). CPM helps the roller operator detect the parts that are in a higher demand for compaction based on current conditions. For instance in Fig. 14, cells with priorities higher than 0.75 are highlighted with light red. It should be noted that due to the roller moving patterns, the overlapping between compaction passes could occur. In Fig. 14 discrete black cells inside the continuous red area represent such situation, and basically indicate that these cells have already reached the necessary compaction level (have already been properly compacted). This is explained in the following lines.

3.2.7. Effective compaction rate

In order to be able to measure the quality of the compaction opera-

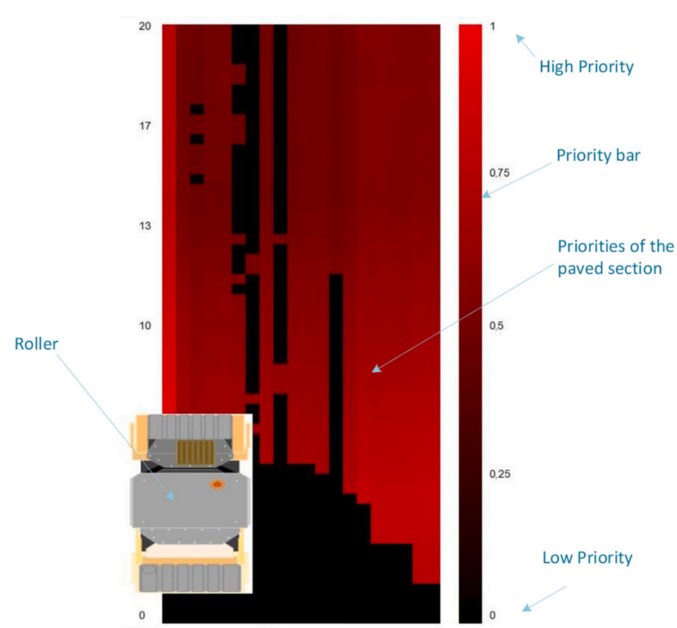

Fig. 14. Compaction priority map.

tion, this research proposes ECR index, as mentioned in Section 3.2.1. This index indicates the ratio of cells that have received at least a pre-defined proportion (e.g., 80%) of their compaction passes within the compaction window. The sufficient compaction is defined in terms of the target compaction pass, which is determined based on the mix characteristics during the design phase, and tolerance (i.e., ± 1 pass). This tolerance is used to account for a set of parameters that can result in an inaccurate measurement of compaction passes, including localization error, over- and under-estimated compaction pass count due to partial point in polygons assessment, etc. The closer the ECR to 1, the more cells have been compacted sufficiently within the compaction window. Lower ECR indicates an improper compaction strategy, where many cells have been over/under compacted and/or compacted considerably outside the compaction window.

Table 1
Prototype hardware.

Asphalt Node	***Paver Node***	***Roller Node***
		
IR-camera	Wide range IR-camera	GPS rover
		
Thermologger	GPS rover	Compact Mini-PC
		
Thermocouple	WiFi router	LCD screen
		
Compact Mini-PC	Compact Mini-PC	Battery
		
LCD screen	LCD screen	
		
Battery	Battery	

$$ECR_{p,k} = \frac{n_{p,k}}{N} \quad (7)$$

where:

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

N: the total number of cells

4. Implementation and case study

4.1. Prototype development

A prototype is developed to test and validate the proposed framework. In this prototype, the Paver, Roller, Asphalt, and Processing nodes were designed and developed as presented in Section 3.

Table 1 presents the hardware sets that were used in the development of the prototype. The Asphalt node consists of (a) Voltcraft IR-1600 CAM infrared thermometer, for measuring surface temperatures of the asphalt mat; (b) Extech HD200 thermologger for collecting the data from thermocouples; (c) thermocouples, that were placed inside the asphalt mat; (d) Ultra HD Compact Mini-PC for collecting, storing and pre-processing data of the Asphalt node; (e) 10.1 in. HDMI LCD screen for displaying the user interface of the Asphalt node software; and (f) CSB Battery 12 V 30 Ah, for power supplying Asphalt node within asphalt construction procedures.

Paver and Roller nodes included high-accuracy RTK GPS rovers (Trimble SPS 852) that were utilized for the localization of heavy construction equipment. Every machine node of the developed prototype was equipped with a Compact Mini-PC for data collection and its pre-processing, and a power supply battery (CSB Battery 12 V 30 Ah). Additionally, 10.1 in. HDMI LCD screens were used for providing machine operators with real-time asphalt construction process-related data (i.e., TCP, CCP, and CPM). Also, the Paver node was equipped with a wide range FLIR IR camera that was installed on a paver's roof for gathering surface temperatures of the paved asphalt behind the paver's screed. To geo-reference infrared data, first, the time stamp of infrared imagery data is used to find the corresponding GPS coordinates. Next, the following data are used to derive the projection matrix as explained by Mostafa and Schwarz [67]: (1) the calibration measurement at the beginning of the test (i.e., camera orientation, the Euclidean distance between the camera and GPS, the height of camera), (2) intrinsic matrix of the camera, and (3) the heading of the equipment. In this process, an assumption is made that the longitudinal and traversal gradients of the road are negligible.

All data from deployed prototype nodes on the site were sent to a relational database that was prepared and run on the Processing node through an open-source relational database management system (MySQL). For communication purposes among the nodes, a local Wi-Fi network was set up. A mobile Netgear broadband wireless router was installed on a paver, to be able to provide essential network range and facilitate communication activities between all the nodes. This router offers an effective range of up to 250 m To increase the robustness of a prototype, for example, in case of losing the connection between nodes and thus secure gathering of a data flow in a database, all collected information from different sensors were also stored in memories of mini-PCs of each corresponding node.

To design and develop software packages for the prototype's nodes, C sharp and Visual Studio were used as main programming tools and platforms. Necessary source codes were written for Asphalt, Paver, and Roller nodes to be able to connect to the corresponding sensors, gather the sensors' data, pre-process and store it in nodes' local memories. Further, pre-processed data were sent and saved into the database. This database was used for querying necessary information for processing and visualizing TCP, CCP, and CPM for the operators of paver and roller.

4.2. Case study

To test the developed prototype, a case study was conducted at SOMA college in the Netherlands, which is the largest training school for construction equipment in the country. At SOMA, as shown in Fig. 15, a stretch of 70 m was paved and then compacted. During this case study, a compaction operation was simulated using an actual paver and roller. The only difference between this simulated case study and an actual HMA compaction project was the use of cold asphalt mixture instead of HMA. This was necessary because the experiment needed to be repeated several times in order to investigate and compare/contrast the impact of different levels of guidance provided to the operator on the quality of the operation. The experiment on an actual construction site would not allow such an investigation because of (a) the cost associated with the repetition of the experiments, (2) interruption caused by the installation and readjustment of the prototype system, and (3) liability issues pertaining to conducting an experiment on an actual paving project for the quality of which contractors are contractually responsible. To compensate for the use of cold asphalt instead of HMA, operators are asked to consider the mix as HMA and compact accordingly. Then, the temperature data collected from the sensors (i.e., IR camera and thermocouples) are calibrated in such a way to mimic the readings of sensors from an actual project that was monitored before this case study. Table 2 presents the parameters that were communicated with the operators to help them better mimic the compaction of the HMA layer. Some of these parameters are based on the actual situation and some of them are simulated.

Before the experiment, operators of paver and roller were informed about the experiment, functionalities of the prototype, the information it provides during different support modes, asphalt mixture test conditions, and compaction that was needed to be performed.

In this experiment, the paver operator had to pave the mixture with a constant speed of 4 m/min. Then, three different scenarios were simulated: (a) *No guidance*: compaction of the layer without the use of an operator support system, i.e., the roller operator worked based on his expertise and intuition; (b) *Descriptive Operator Support*: compaction of the layer with the use of descriptive support (i.e., TCP/CCPs); and (c) *Prescriptive Operator Guidance:* compaction of the layer with the use of prescriptive guidance (i.e., CMP). The results of the performed tests are discussed in the following section. Fig. 16 shows the setup of the prototype system on the site.

Fig. 17 shows the different types of guidance provided to the roller operator in three different scenarios.

5. Results and analysis

The performance of the operator was analyzed in terms of $ECR_{80\%,1}$. This means that any cells which received at least 80% of 7–9 compaction passes within a range of 120–150 °C is considered as properly compacted. The value of 80% was chosen by the recommendation of the mix designer who had analyzed the mix in the lab. On top of ECR, a distinction is made between under-compacted (i.e., <7 passes), over-compacted (i.e., >9 passes), and improperly compacted (i.e., <80% of 7–9 passes were in the compaction window). Using Eq. 1 and also through a grid search of various options to determine the optimum cell size from the computation cost and resolution of data, the best cell size was determined to be 20 × 7 cm.

Fig. 18 and Table 3 presents the results of the comparison of the three scenarios in terms of $ECR_{80\%,1,}$ and other indicators.

As shown in Fig. 18 and Table 3, in the first scenario. i.e., no guidance, 13.3% of the cells were compacted properly with 7 to 9 roller passes majorly performed within the compaction window. Percentages of under- and over-compacted cells were 26.7% and 33% with an average number of under- and over-passes 1.8 and 3.5, respectively. In the second scenario (i.e., descriptive operator support with TCP and CCP), the effective compaction ratio rose to 22.3% of cells. Additionally,

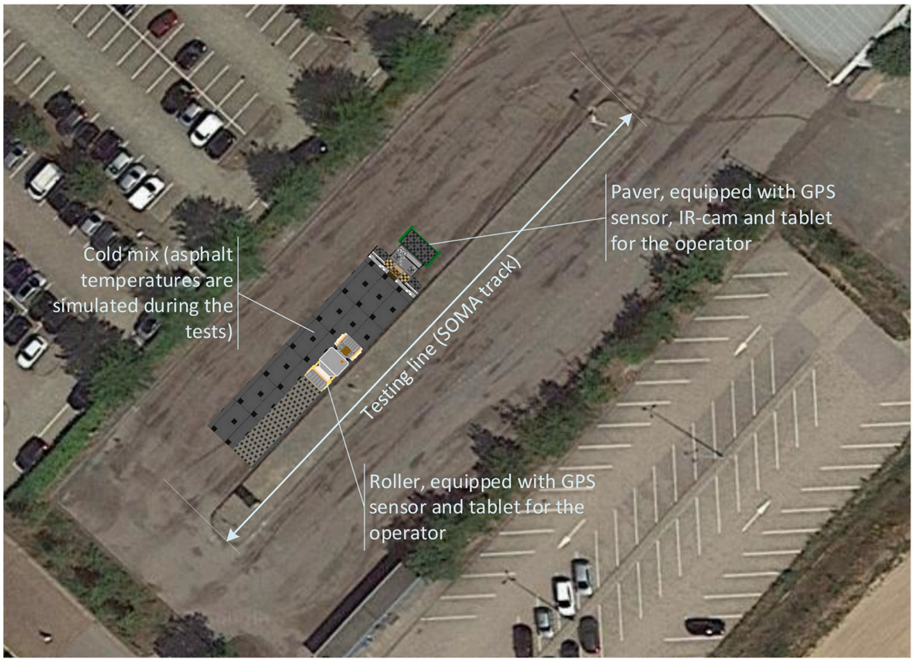

Fig. 15. Testing site.

Table 2
Testing assumptions.

Parameter		Value
Simulated parameters	mixture type	AC22
	temperature of the mixture at the delivery	~160 °C
	compaction breakdown phase	[120–150 °C]
	number of roller passes	8
Actual parameters	layer thickness	50 mm
	layer width	4 m
	ambient temperature	+15 °C
	wind speed	5 km/h
	paver speed	4 m/min

the ratio of under- and over-compacted cells decreased to 23.3% and 32% with an average number of under- and over-passes 1.9 and 3.4, respectively. In the last scenario (i.e., prescriptive operator guidance system with CPM), the effective compaction ratio increased to 28.7%. In this scenario, the over-compacted cells decreased to 19.2% while the under-compacted cells increased to 39.5%. The average number of under- and over-passes were 1.9 and 2.1, respectively.

Fig. 19, plots the relative improvement margins when moving from no guidance to (1) Descriptive Operator Support (i.e., TCP and CCP), and (2) Prescriptive Operator Guidance (i.e., CPM) in terms of (a) increase in the effective compaction ratio, (b) decrease in ineffective compaction ratio, (c) decrease in under-compaction ratio, and (d) decrease in over-compaction ratio. As shown in this figure, the use of descriptive operator support improved all aspects of the compaction operation. Most significantly, this level of support has resulted in 67.67% improvement in $ECR_{80\%,1}$. However, the improvement in other aspects is not as significant. Consistent with the hypothesis of this research, the transition to a more prescriptive guidance system has even further improved the compaction efficiency, with over 115% improvement in $ECR_{80\%,1}$. In addition, a 53.3% reduction of ineffectively-compacted areas and 41.8% reduction of over-compacted areas are significant. However, the use of prescriptive guidance resulted in a tendency to under-compact the layer.

To further investigate the impact of the transition from operator support systems to the operator guidance system, the distribution of compaction efficiency indicators across the paved layer is plotted in Fig. 20. As shown in this figure, with the transition from no guidance to descriptive support and then to prescriptive guidance, the over-compaction of the centerline of the layer has decreased. However, the cells closer to the edges of the road tend to be less compacted. This supports the pattern seen in Fig. 19. This can be attributed to the fact that without the CPM, operators tend to pay more attention to CCP (i.e., compaction passes) and try to make sure they always meet the requirement for the minimum number of compaction passes. In doing so, operators tend to over-compact the centerline of the road (which will be overlapping in the two adjacent passes). This pattern is prevented in the case of the operation guidance system with CPM because the attention of the operators is steered towards compaction priority indices rather than only the compaction passes. As a result, when operators see the compaction priority indices of the cells in one row of cells is decreasing in general, they tend to under-compact the edges. This results in an overall significant improvement in terms of efficiency but at the cost of an increased rate of under-compaction. It can be argued that this tendency can be corrected through more training and exposure to the system.

6. Discussion

The main contribution of the research is the development of a novel framework for providing more actionable and easy-to-follow guidance to the operators of compaction equipment in terms of a newly developed Compaction Priority Map (CPM) concept. To this end, a novel IoT-based method was proposed to integrate various sources of real-time and offline information to generate the compaction priority map to the operators. This method facilitates the transition from descriptive to prescriptive operator support systems, which were proven to be effective for other construction equipment but, to the best of authors' knowledge, has never been proposed for compaction equipment before. Also, a novel index (i.e., $ECR_{p,k}$) was introduced to measure the efficiency of the compaction operation in a quantitative manner. This index, for the first time, enabled a quantitative assessment of compaction operations and can be used by practitioners and researchers to objectively analyze their strategies for improving the quality of compaction operations. This index is considered a novel contribution because, to the best of authors' knowledge, currently there are no standards or conventions about the assessment of paving operational quality. Most existing researchers use

Fig. 16. Prototype's nodes set up on the construction set.

separate statistical analyses for the number of compaction passes or temperature homogeneity. This can be misleading because separate indicators give the wrong impression that the two parameters are mutually independent. However, this is not the case and the compaction operational quality should be assessed in terms of the combined effect of compaction and temperature homogeneity [3]. To this end, the present research, for the first time, propose the ECR index as a way to capture the intricate co-dependence between compaction and temperature homogeneity. Potentially, ERC can become the standard index for the assessment of paving operator support system.

The results of the conducted case study substantiate the hypothesis of this research that the transition to more prescriptive guidance can significantly improve the efficiency of compaction operation (i.e., 115% improvement compared to traditional compaction strategies). However, despite the significant improvement achieved in terms of construction efficiency, there is still the question of how much the operator would appreciate the new way of presenting the compaction data (i.e., the usability of the system). To gauge this at a small scale, the operator who participated in the case study was asked to compare and contrast different scenarios in terms of usability and usefulness.

The operator highlighted that with him being responsible for the ultimate quality of the pavement, he would rather develop his strategy himself rather than being "told" (i.e., guided) what to do. He emphasized that he acknowledges the fact that CPM guidance is actually easier to use but he would rather know what is the state of the pavement in terms of raw measurements so that he can decide for himself how to strategize the remainder of the work. Given the noticeable difference in the efficiency of the compaction performed with the guidance system, this anecdote points out the issue of mistrust of the technology-based guidance and the matter of work liability. At the same time, roller operator maintained that CPM-based guidance was superior in terms of clarity and prevention of infobesity or cognitive overload.

The above testimony indicates that operators still feel more comfortable with following the traditional intuition-based methods of

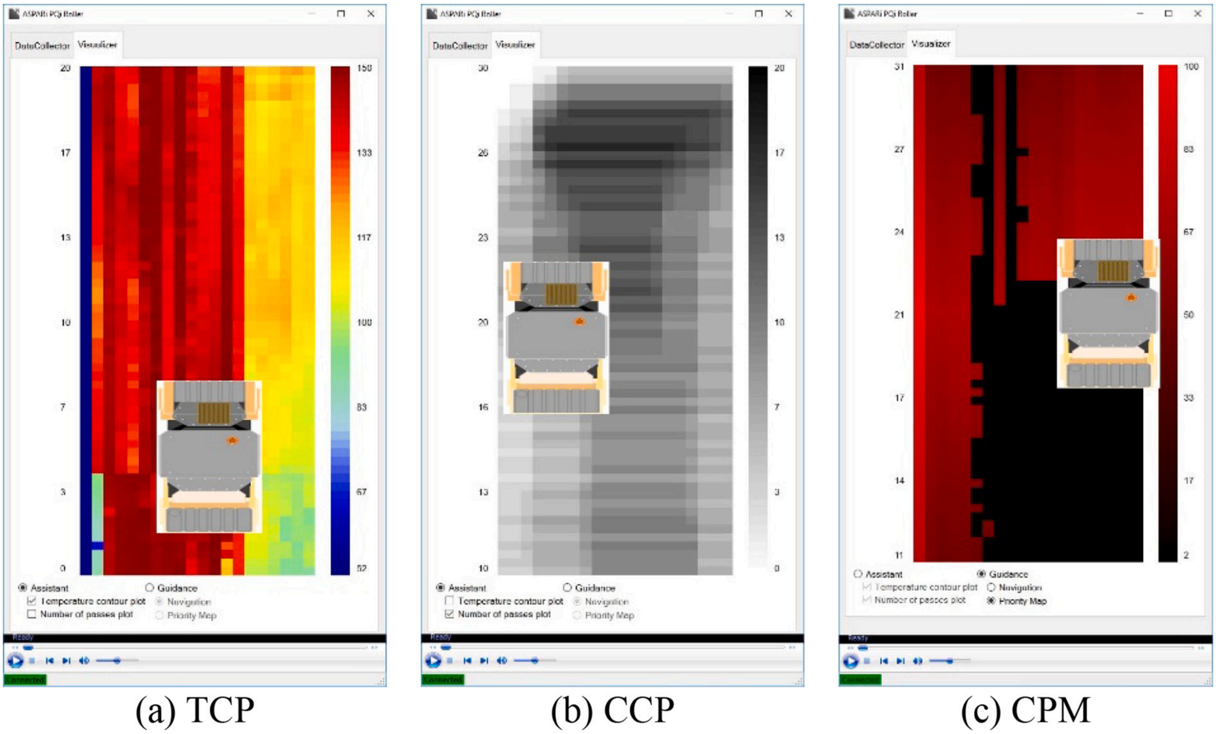

Fig. 17. SOMA site results of prototype deployment.

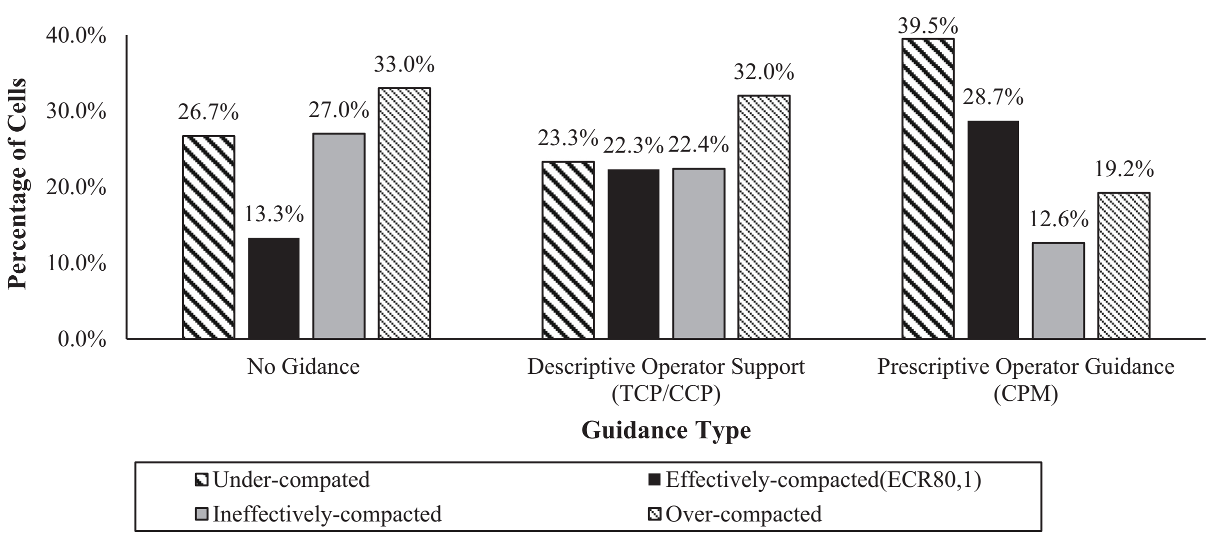

Fig. 18. Comparison of the three scenarios in terms of effective compaction rate ($ECR_{80,1}$).

Table 3
Comparison of the three scenarios.

Scenario	Compaction quality indicators			
	Under-compacted	Effectively-compacted ($ECR_{80,1}$)	Ineffectively-compacted	Over-compacted
No Guidance	26.70%	13.30%	27%	33%
Operator Support	23.30%	22.30%	22.40%	32%
Operator Guidance	39.50%	28.70%	12.60%	19.20%

operation. This means that a successful transition to the next level of compaction operator support systems requires a mindset adjustment and adaptation period. This is mainly because the dominant mindset of operators is still based on intuition and experience. In this mindset, operators have a strong sense of control over their compaction strategy. The transition to more prescriptive guidance systems disturbs this mindset by requiring the operators to transfer part of the decision-making to the support system. Considering the human factor associated with the use of operator support systems, this cannot be achieved without (1) a shift in the training strategies of new generations of operators, and (2) trust-building in the system through providing more opportunities for exposure to and experimentation with the guidance system. Additionally, with responsibility for the quality of the work placed primarily on the site superintendents/quality managers and operators, the tendency and

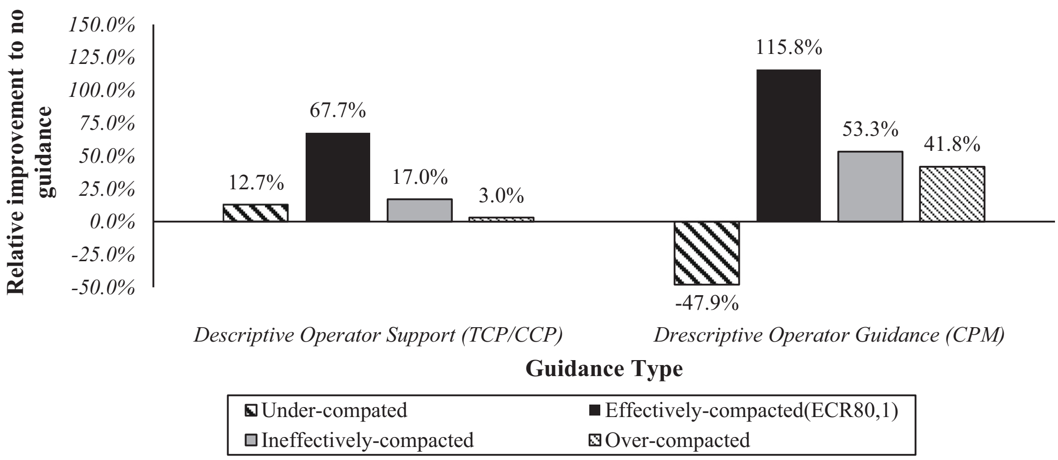

Fig. 19. Relative improvement margin for operator support (TCP/CCP) and guidance (CPM).

willingness to transfer part of strategic decision-making to a semi-automated system is marginal. This brings to fore the intricate issues of project liability vis-à-vis the adoption of operator support system. For these systems to have potentials for adoption, it is important that operators and site managers are able to trust the system and for this trust to translate to proper liability consideration. However, for this transition to take place, both in terms of policy and culture/mindset, it is imperative that the proposed system is applied in more pilot projects to build a substantial evidential base for industry-wide debate and discussion. Having said that, it should be highlighted that this paper positions itself as the developer and initiator of the proposed concept mainly from the technical standpoint to showcase the potential of the transition.

The presented research was tested on a small scale. To further substantiate the results observed in this research, the experiment must be tested on a larger scale. However, this is very difficult in the context of HMA compaction operations for the reasons mentioned earlier in Section 4.2. This justifies the use of an alternative method for testing and validation of new support and guidance systems. One possible strategy is to use Virtual Reality (VR). Currently, VR technologies are becoming more popular in different domains due to their high-fidelity, physics-based environment, and high-resolution computer graphics. In the construction area, VR offers possibilities to reconstruct a digital replica of actual construction sites to provide an opportunity for safe experimentations. Several scenarios can be developed in controllable VR environments to test different modes of the compaction support system, i.e. Descriptive Operator Support (TCP/CCPs), Prescriptive Operator Guidance (CPM). Also, VR environment facilitates a faster and easier collection of end-users' feedback, providing the opportunity to rapidly improve the designed system prototype.

In the current setup, the thermocouples are set up near the edge of the road. Although this temperature reading is used to find the relative cooling of the surface and core temperatures (by comparing the surface temperature of the exact same location as the thermocouple), the heat transfer boundary condition may have an impact on this repetitive pattern. Therefore in future, the authors will try to use an array of thermocouples inside the asphalt at different distances from the edge of the road to investigate this issue.

Finally, the prescriptive guidance can be pushed even further by transiting from CPM to compaction paths. At this level, the operator will be provided with a clear compaction path based on the analysis of the real-time data. This would be a necessary step in moving towards the concept of autonomous compaction in the future.

7. Conclusions and future work

This paper presents an IoT-based framework for compaction guidance systems that translates a combination of the performed number of roller compaction passes and the actual temperature at which compaction took place (i.e., descriptive support information) into suggestions for compaction strategies (i.e., prescriptive guidance). A novel method for the generation of a compaction priority map was developed and implemented. Additionally, to enable a quantitative analysis of the operator support system, a novel Effective Compaction Rate (ECR) index is developed. This index helps measure the area of the asphalt layer that has been compacted for the right number of times at an appropriate temperature. A prototype of the proposed framework was developed and tested in a case study.

Based on the results presented in this research, the following conclusions can be made. The transition from a descriptive support system to a prescriptive CPM-based guidance system offers a significant improvement in the efficiency of the compaction in terms of the ratio of pavement that has been compacted sufficiently at the right temperature window. In the presented case study, this improvement was about 115% in terms of compaction efficiency. Although this is a very promising initial result, it should be highlighted that these findings should be perceived with caution. This is mainly because the system was tested under a controlled environment and on a small-scale case study. It is important to further investigate the proposed CPM-based method in more case studies.

From the operators' perspective, while the proposed guidance system was testified to be effective and useful, the fact that the guidance system would reduce the operators' sense of control and freedom to follow an own, implicit compaction strategy, is a limitation. Given that the guidance system is shown to improve the efficiency of compaction operation in a considerable manner, there is a need to develop a trust-building agenda within the industry to educate the existing and new operators about ways in which they need to interact with the new system and how this transition would reflect positively on their work.

In the future, the two main research directions can be envisioned. In the first direction, a VR-based technology assessment platform can be developed to establish an easy-to-use and safe medium for testing operators' user experience with different levels of guidance. This platform would allow us to target a much larger group of operators, from different levels of expertise and technological affinity, to have a better understanding of the usability aspect of compaction guidance systems. Another possible research trajectory can be about the further development of operator guidance systems so that the compaction priority map can be translated into a navigable path. This would require the development of a path planning method based on the objective to maximize Effective Compaction Rate. This is an important next step because the proposed CPM does not take into account the physics and kinematics constraints of the rollers for the execution of the compaction path. The

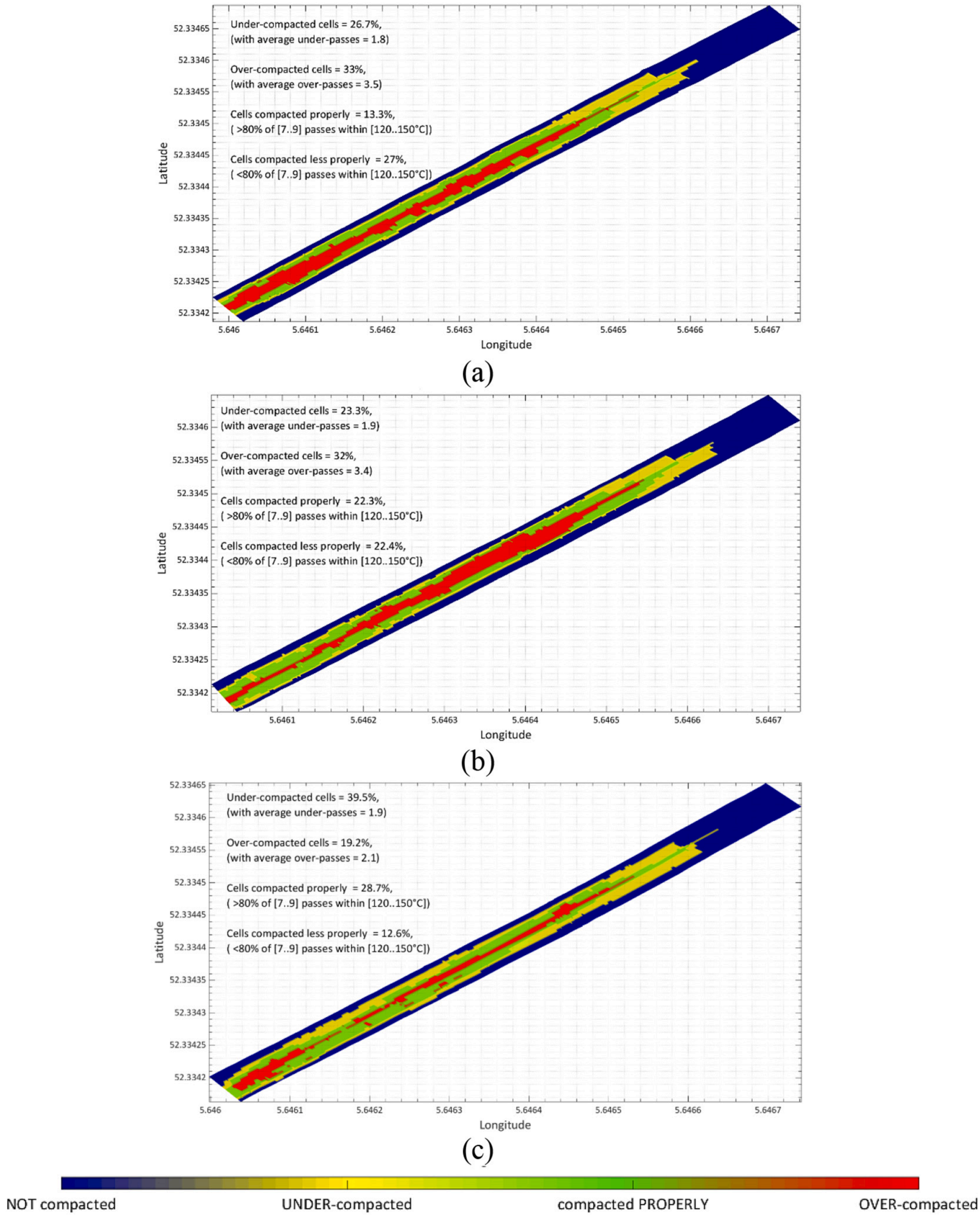

Fig. 20. Compaction quality plot.

feasibility of compaction trajectory needs to be taken into account and develop an actionable and executable path for the operators. In this trajectory, the issue of improved localization accuracy through the use of multi-sensor solutions can be addressed. This is important because the accuracy of localization impact the assessment of the compaction priority and the compaction path thereof. Finally, as mentioned in Section 5, the acceptance and adoption of this method vis-à-vis the liability issues need to be further investigated.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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