Developing a real-time process control system for asphalt paving and compaction

Denis Makarov
2017
Developing a real-time process control system for asphalt paving and compaction

PDEng Candidate

Author
Denis S. Makarov

Organization

University
University of Twente

Faculty
Engineering Technology (ET)

Department
Construction Management & Engineering (CME)

Trajectory
Professional Doctorate in Engineering (PDEng), Civil Engineering

Case study organization
ASPARi network

Examination committee

Director PDEng program
Dr. J.T. (Hans) Voordijk

Professor responsible chair
Prof.dr.ir. A.G. (André) Dorée

Supervisor at University of Twente
Dr.ir. S. (Seirgei) Miller

Supervisors at ASPARi
ir. B. (Berwich) Sluer
ir. M. (Marco) Oosterveld
ir. L.A.M. (Laurens) Smal

Expert from the other research chair
Dr. ir. F. (Farid) Vahdatikhaki

Report

Status
Final

Date
August, 2017
Preface

This research was an exciting journey. I would like to thank my supervisors at the University of Twente Prof.dr.ir André G. Dorée, Dr.ir. Seirgei R. Miller and Dr.ir. Farid Vahdatikhaki as well as at ASPARi ir. Berwich Sluer, ir. Marco Oosterveld and ir. Laurens Smal for their recommendations and thoughtful advices during the project.
I am grateful to all my colleagues and friends from the Construction Management & Engineering department.
Also, I am indebted to my family who always supports me.
Management summary

Asphalt construction is a complex process where many variables can carry significant implications on the asphalt quality. Variables such as the temperature of the asphalt mat and compaction consistency need to be measured and observed using high accuracy sensors. The analysis of the sensor-driven Temperature Contour Plots (TCPs) and Compaction Contour Plots (CCPs) over the last decade shows that the asphalt quality is directly linked to the behaviour of the operators. In the current practice, the operator decision-making is mainly based on tacit knowledge and implicit experiences.

To assist operators develop more methodology based approaches, an appropriate system is needed to provide operators with essential real-time data. This report describes the results of the PDEng development project. A real-time process control system for asphalt paving and compaction has been designed for the ASPARi (Asphalt Paving Research and innovation) network. There are four main modules of the system namely a Paver Module (PM), a Roller Module (RM), a Cooling Curve Station Module (CCSM) and a Communication Module (CM). The system is developed together with the required verification and validation procedures.

The report is structured in six chapters, as shown in Table 1.

Table 1. Management summary (project’s flow)

<table>
<thead>
<tr>
<th>Problem definition</th>
<th>Problem analysis and system requirements</th>
<th>Design, verification, validation and implementation</th>
<th>Conclusions and recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Project description and problem statement</td>
<td>- Problem analysis</td>
<td>- Design and development of a real-time process control system</td>
<td>- Matching requirements</td>
</tr>
<tr>
<td>- Project objectives</td>
<td>- Analysis of the stakeholder needs</td>
<td>- Implementation</td>
<td>- Lessons which have been learnt</td>
</tr>
<tr>
<td>- Methodological approach</td>
<td>- System requirements</td>
<td>- Verification and validation</td>
<td>- Further development trajectory</td>
</tr>
</tbody>
</table>

The developed system aims to support asphalt team during paving and compaction activities, making operators’ behaviour more reasonable, based on explicit real-time data. In addition, the system itself is a vivid example of an off-the-shelf solution that might help construction companies to develop their own hi-tech approaches and not to be lost among the market’s offers. Moreover the suggested solution could inspire developers from industry to improve currently available systems and to provide better adjusted feedback to the needs of paving and compacting operations.
Product summary

This chapter provides brief answers to key questions related to real-time process control system development before going into further details:

- What solution is provided to which problem?
- What are the requirements of possible solution?
- How is the development process managed?

What is the problem?
The problem-solving dimension of the design process provides a technical solution to the problem. As the first step towards problem-solving, a problem investigation phase is organized. Previous monitoring, observation and analysis of asphalt construction projects indicate that asphalt teams mostly rely on their tacit knowledge and gut-feeling. On the other hand, the analyses suggest that there are numerous parameters that play a role in the final quality of the asphalt. Among these parameters are: the temperature of the asphalt layer, the number of roller passes, the truck availability with asphalt mix, and the delivery time of the asphalt mix. A slight variation in any of these parameters introduces a great degree of variability in the quality of the asphalt. Currently, paving teams tend not to take into account these influential parameters, at least in a holistic manner, in their decision-making and as a result the quality of the asphalt is rather uncertain. These variables are implicit for the construction teams due to the fact that they could not be observed without special tools and sensors. The paving assistance system should provide the asphalt crews with real-time data so that the correct paving and compaction strategies can be applied during construction. Thus, the solution should contribute to improved process control during asphalt construction.

What are the requirements of possible solution?
The system should be designed with a high level of flexibility, where the number of active elements depend on the amount of machines involved in a construction project. The main sub-systems are the Paver Module (PM), the Roller Module (RM), the Cooling Curve Station Module (CCSM) and the Communication Module (CM). Each sub-system contains its own elements, such as sensors and other equipment.

How is the development process managed?
The design process of the system development is supported by the ASPARi (the network of organizations working collaboratively to improve the asphalt construction process). In particular, the asphalt construction companies, who are members of the network, provide the researchers with an opportunity to participate in real construction projects during the asphalt paving season. These projects are aimed at process quality improvements, where developers can gather the input to design and think about possible solutions.
# Table of Contents

Chapter 1. Goals of the project development ............................................................................. 3  
1.1 ASPARi network ............................................................................................................. 3  
1.2 Project description and problem statement ..................................................................... 4  
1.3 Project objectives ........................................................................................................... 5  
1.4 Asphalt life cycle description .......................................................................................... 5  
1.5 Site observations and Process Quality Improvement (PQI) projects .................................. 6  
1.6 Methodological approach ............................................................................................... 7  
   1.6.1 Problem analysis .................................................................................................... 7  
   1.6.2 Solution investigation ............................................................................................. 8  
   1.6.3 Implementation and evaluation ................................................................................ 8  
1.7 Report Overview .............................................................................................................. 9  

Chapter 2. Problem analysis .................................................................................................... 11  
2.1 Introduction ...................................................................................................................... 11  
2.2 Definition of stakeholders with analysis of the stakeholders’ needs ............................... 12  
2.3 Analysis of existing solutions ......................................................................................... 13  
2.4 Discussion and conclusions ............................................................................................ 18  

Chapter 3. System requirements ............................................................................................ 19  
3.1 Requirements engineering .............................................................................................. 19  
   3.1.1 Scenario development ......................................................................................... 19  
   3.1.2 Solution requirements ......................................................................................... 21  

Chapter 4. Proposed system ................................................................................................... 23  
4.1 Overview of the developed system .................................................................................. 23  
4.2 Design of a real-time process control system for asphalt paving and compaction .......... 23  

Chapter 5. Implementation, Verification and Validation .......................................................... 31  
5.1 Prototype development .................................................................................................... 31  
5.2 Implementation .............................................................................................................. 33  
5.3 Algorithm design ........................................................................................................... 34  
5.4 Data representation ........................................................................................................ 35  
5.5 Verification .................................................................................................................... 38  
5.6 Validation meetings and workshops ................................................................................ 40  
5.7 Testing on construction sites .......................................................................................... 42
5.8 Discussion and conclusions ..........................................................................................................................47

Chapter 6. Recommendations ..........................................................................................................................48
  6.1 Matching requirements ...............................................................................................................................49
  6.2 Lessons from the prototype development .................................................................................................49
  6.3 Future development ..................................................................................................................................50
  6.4 In closing ....................................................................................................................................................50

References ..........................................................................................................................................................53

Appendices .......................................................................................................................................................55
Chapter 1. Goals of the project development

The Netherlands is a world leader in asphalt process control initiatives that have been tested or implemented in the construction processes. This is due to the fact that the Dutch road construction industry has faced changing roles for agencies and contractors, where important risks shifted from road agencies to road companies [1], resulting in more focus on process control of the asphalt during construction.

One of the important aspects during the implementation of new solutions, which might help identify core quality parameters, is to understand the whole paving and compaction process with mutual interdependencies of different factors. Often, the systems presented by machine manufacturers and other developers concentrate on one particular part of the process (e.g. compaction) and do not take into account the rest. Although such solutions help the construction companies by making the construction process less and less dependent on the implicit experiences of their employees, they still disregard some critical data (e.g., temperature of the asphalt mat and locations of the construction machines) that can help further enhance the process. This research specially focuses on a design that can incorporate such decisive data into paving and compaction decision making procedures.

The goal of this PDEng project is to make the process of paving and compaction more explicit for machines’ operators and managers on site. Thus, essential data during construction, such as temperature of the asphalt mat and locations of the construction machines, has to be collected and analysed for determining appropriate solutions. Based on the problem analysis, it is concluded that this objective can be best achieved by developing a real-time process control system for asphalt paving and compaction. Through this system, operators and managers involved in construction can more efficiently monitor their own behaviour and adjust their own work procedures based on information provided in real-time.

1.1 ASPARi network

This PDEng project is supported by the ASPARi (Asphalt Paving Research and innovation) network, a collaboration between researchers of the University of Twente and several road construction companies. Since 2006 ASPARi has evolved and became the largest asphalt construction collaboration society in the Netherlands, including such companies as: Boskalis, Ballast Nedam Asfalt, BAM Infra, Dura Vermeer Infrastructuur, Heijmans Infra, KWS, Roelofs, Strabag, Strukton (REEF Infra & Ooms Nederland), and Twentse Weg - en Waterbouw. Since the very beginning, the network worked towards mutual goals of improving process control by sharing knowledge and experience among the participants.

All companies of the network are involved in Process Quality improvement (PQi) monitoring exercises. Where project data related to paving and compaction activities are collected. Researches from the University of Twente together with companies’ representatives conduct data analysis for all projects. Mutual discussions about gathered data and projects’ outcomes make the construction process more explicit and contribute to improving asphalt teams’ behaviour. Despite improving understanding of the
processes involved in asphalt construction, one of the hot topics, which stand in front of the network, is how to make the process of data collection and analysis more efficient and effective.

The main drawback of the PQi monitoring process is that results are given to companies postmortem, i.e., after the construction project. In such applications of the PQi, all the mistakes that took place are either irreversible or very difficult/costly to resolve. Thus, the need to have reliable data in real-time. Even though there are several solutions on the market, they do not fully meet the requirements defined by ASPARi network construction companies (Section 2.4).

1.2 Project description and problem statement

Roads play essential role in the modern society, providing economic growth, facilitating communication and transportation between cities, regions and countries. There is evidence that the quality control of road pavements has been considered since ancient times [2, 3]. Although road networks have grown tremendously in terms of their size and complexity over the centuries, the nature of challenges faced by engineers remained largely the same. Limited project budgets, logistics issues, and the need for skilled personnel still play essential roles in road construction. At the same time the speed of construction and sheer size of the modern construction fleet make it almost impossible to check every single particle of the surface layer. To replace intensive manual labour as well as manual quality control measures, several high-tech solutions have been developed over the last 20 years.

In the middle of the 1980’s GEODYN presented its compaction documentation system [4]. This system mainly focused on the compaction and had manual inputs of the deriver’s operations on site. Although the system lacked automation, it marked the first real effort to explicate the operators’ experience because of the algorithms that could store and analyse operators’ actions. GEODYN was among the pioneers in the area of road automation systems, which emphasized the important role of compaction and initiated a long-awaited trend in research and development. Throughout the last decade of the 20th century and the early 21st century, developers were concentrating on sensors and devices that can be used and implemented in support systems [5-8], shifting from operators’ input to the data provided by sensors, thus making the systems more reliable and user-friendly. Although, for the time, the outcome of the systems was impressive, it did not change the development trend much and still considered compaction as a separate process and as a starting point for systems development. Lately, the efforts to further enhance automation in asphalt construction formed a trend, both in academia and industry, coined Intelligent Compaction [9-16]. Previous and current systems present data showing what has been done in terms of compaction. In the future, the systems should move towards predicting what needs to be done and how to achieve that based on current asphalt mixture parameters (e.g. mixture temperature).

Recently, the accuracy of the asphalt construction support systems is increasing through reconsidering the design procedures and taking into account factors from the previous stages of the asphalt construction supply chain. These novel approaches could improve outcomes of mixture’s temperature and density prediction algorithms, which seem to be quite mature, providing them with a bigger set of sufficient input data gathered from the entire supply chain.

From previous research [12], it is known that it is necessary to control the process of compaction to decrease over- and under-compacted zones on a construction site. The questions that naturally follow are: how is it possible to organize such control?, what are the parameters or groups of parameters that need to be controlled?, and which level of accuracy will be satisfactory? At the same time, the variables
from the different stages of the asphalt construction supply chain, such as the asphalt mixture development, mixture production and delivery to the construction site could influence paving and compaction procedures as well.

Clearly, to improve the operators’ behaviour during paving and compaction activities, the asphalt team must be provided with a proper support system that gives accurate information about relevant process parameters. In this project, the architecture of a real-time process control system for asphalt paving and compaction is proposed.

1.3 Project objectives

The sub-objective of this project that carries the main goal (page 3) is to develop an architecture of the support system for the asphalt paving and compaction phase of road construction. The developed solution should be able to track locations of the paver and rollers on a construction site, measure the surface temperature of the asphalt mat, analyse the cooling process of the asphalt, calculate number of roller passes across the mat in real-time, provide essential information for the operators of the construction machines and store the ‘raw’-data gathered on site, for post processing purposes.

The developed system should be tested in a laboratory and during several real construction projects to test the system’s applicability for the purposes of asphalt construction and to obtain relevant feedback from the end-users of the system. The proposed methods for data collection and analysis, such as calculating number of roller passes during field tests, should be verified.

To summarize, sub-objectives of the project are defined as follows:

a. To identify parameters which significantly influence asphalt quality during asphalt paving and compaction activities;
b. To propose an appropriate solution;
c. To develop and design an architecture for the solution;
d. To implement the proposed solution in real construction projects;
e. To evaluate the implementation of the design project.

1.4 Asphalt life cycle description

To better understand the role of support systems in paving and compaction and during the asphalt life cycle, the holistic picture of the cycle needs to be explained. In addition, it might be helpful to conduct a problem analysis and solution investigation when the challenges in the system development are clearly defined. The typical asphalt life cycle is presented in Figure 1. The main phases of the cycle are asphalt mixture design, asphalt mixture production, road construction, road maintenance, and road rehabilitation. Clearly road construction is an essential link between all preparation activities, such as mixture development and production, and further road maintenance and rehabilitation. The phases that precede road construction might influence the activities during the construction itself. At the same time, the final product of the construction, i.e., the asphalt mat, is the basis for the following activities (e.g. the application of Pavement Management Systems (PMS)). Thus, during the development of a new solution which will be implemented in road construction, possible impacts of previous phases have to be
taken into account. Also, a new solution should support data interoperability so that its output can be easily used in any systems that support the operation and maintenance of the road network.

![Diagram of asphalt life cycle]

Figure 1. Typical asphalt life cycle

1.5 Site observations and Process Quality Improvement (PQi) projects

The main aim of the PQi projects is to improve the quality of the process during the asphalt construction. Researchers from the University of Twente provide the asphalt construction companies (ASPARi network) with a thorough analysis of data that is collected during the road construction in the Netherlands. The analysis supports managers and the site operators of the construction machines to better understand the relations between different factors affecting the quality of the asphalt.

During this project, I visited 12 construction projects in the Netherlands and Belgium to (1) understand the road construction process (particularly paving and compaction activities), (2) the way the asphalt team works and communicates, and (3) the on-site factors that influence the asphalt quality. Observations made during process monitoring helped to build a holistic image of the process and to understand the most important factors needed for the development of a new support system for paving and compaction.

In a nutshell, the process of paving and compaction can be described by the following steps:

1. In the beginning of each project, an asphalt team meeting is organized in order to review the road profile, the type of the mixture, and the compaction and paving fleet;
2. Next, the preparation phase follows. The machines are prepared and the paving and compaction strategies are defined based on the available set of the machines, amount of asphalt mixture on
site, and weather conditions. Also, all the auxiliary support systems are mounted to monitor the construction process during the PQi exercise.

3. After the preparation phase, the active phase of paving and compaction pursues. This is the most crucial phase due to the fact that the work done by paver and roller operators will directly lead to the final quality of the asphalt mat. The factors that might influence asphalt quality have to be identified and presented to the asphalt team in a comprehensive way. For instance, the lack of mixture on site can be a cause for the pavers to stop during the operation. Each stop induces asphalt temperature drop at the stopping place. When the paver continues its work, new hot mixture joints the colder laid mix. This joint is a vulnerable spot on a road during the road life cycle. Another example is a temperature of the asphalt mat after the paver’s pre-compaction. In most cases, the roller operator defines the temperature of the asphalt mat based on his/her own experience. This is a vulnerable approach which only works with high experienced and well-educated roller operators [45]. During this phase the corresponding measurements such as asphalt temperature and density can be collected (optionally).

4. When the last amount of mixture is paved and rollers have reached the predefined number of passes (compaction strategy), the active phase of paving and compaction ends.

5. At the end of construction, all devices and auxiliary systems are dismounted, and construction machines are prepared for transport to the parking and storage place.

For this design project, data collected during PQi monitoring exercises forms the basis for the development of support system for asphalt teams.

1.6 Methodological approach

To develop a technical solution for this specific problem, the design process can be applied [17]. For this project the design process was defined as follows:

1. Problem analysis;
   - Which solution is provided to which problem?

2. Solution investigation;
   - Design of one or more prototypes that solve the defined problem.
     o Do the proposed designs meet the specification requirements?
     o Do these designs solve the problem and meet clients’ expectations?

3. Implementation and evaluation.
   - Implementation of the designed prototype to real problem environment.
     o Was the implemented prototype successful?
     o What problems have been solved? What problems are still to be solved?

The next sections briefly describe the design activities during the project.

1.6.1 Problem analysis

Before thinking actively over possible solutions, the problem itself has to be clearly understood. To do so, several questions are addressed through the problem investigation process including:

1. What is the problem that has to be solved by developed solution?
2. What are the roots of the problem?
To be able to answer these questions, it is necessary to (1) identify stakeholders of the developed solution, to (2) determine why they are not satisfied with current solutions, and finally (3) clearly describe what they need. Answering these questions might help during the design, staying focused on solving the predefined problem and choosing a better solution in case of several trade-offs.

The problem analysis was done through two consequent phases. The first phase involved the studying stakeholders interested in a new solution for paving and compaction. Stakeholders’ needs were therefore clearly identified. The second phase was aimed at determining the shortcomings of current solutions, which have been used by stakeholders or currently available on the market.

**Data collection and analysis**

Both phases of problem analysis are based on the literature reviews. For the first phase, this is the information about parties directly and indirectly involved in the paving and compaction process during road construction. A description of this phase is thoroughly presented in Chapter 2. As for the second phase, the available open source information about current paving and compaction support systems is collected and analysed. This analysis is also presented in Chapter 2.

1.6.2 Solution investigation

After problem analysis and determination of the main problem, a solution for this problem was designed. The factors that influenced the design process can be described as internal and external. External factors define the relations between the road construction phase of the asphalt life cycle (Figure 1) and phases which follow or precede this phase. For instance, the data about mixture parameters before road construction is needed as an input for the support system during the paving and compaction. Thus, a solution needs to provide open interfaces for integration with other systems. Internal factors cover aspects during the paving and compaction activities. Due to the fact that these activities are performed by different machines, historically control and management procedure over these activities are separated. In this way, the solution should cover both activities, providing mutual analysis for paving and compaction parameters. This part is described in Chapter 4.

**Simulation and evaluation**

Every design cycle ends with the validation of the proposed solution. The goal of this validation is to check that the solution satisfies the expectations of stakeholders. To demonstrate that the proposed solution can solve the defined problem and work properly in a real world, it is necessary, first, to perform laboratory tests. Laboratory tests have to be as close as possible to real situations on a construction site. Thus, historical data collected through actual road construction projects has to be used for simulation and evaluation purposes.

1.6.3 Implementation and evaluation

During the implementation phase, the construction machines (pavers and rollers) should be equipped with the proposed solution for the purpose of testing in real conditions. Once the data about the performance of the proposed solution has been obtained (through the log files, visuals, etc.), it will be analysed. The implementation phase will be followed by the evaluation, where the fitness of the proposed solution will be evaluated. The outcomes of the evaluation will be transformed into the revisions to the system design. Implementation and validation procedures are described in Chapter 5.
1.7 Report Overview

The development process for the proposed solution is presented in Figure 2.

![Figure 2. Development process for the proposed solution](image)

The description of the design phases and corresponding activities is shown in Table 2.

<table>
<thead>
<tr>
<th>Design phase</th>
<th>Related activities</th>
<th>Project objectives (page 5), solved by the corresponding design phase</th>
</tr>
</thead>
</table>
| 1. Problem definition is described in *Chapter 1* | - Project description  
- Project objectives  
- Problem statement | |
| 2. Problem analysis is described in *Chapter 2* | - Introduction  
- Literature study, analysis of the stakeholders needs  
- Literature study, analysis of existing systems | a |
| 3. System requirements is described in *Chapter 3* | - Requirement engineering  
- Solution requirements | b |
| 4. Design of a real-time process control system for asphalt paving and compaction is described in *Chapter 4* | - Overview of the proposed solution  
- Design of a real-time process control system | c |
Table 2. Design phases (cont.)

<table>
<thead>
<tr>
<th>Design phase</th>
<th>Related activities</th>
<th>Project objectives, solved by the corresponding design phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Design verification and validation, as well as implementation procedures are described in <em>Chapter 5</em></td>
<td>- Verification and validation procedures during design cycles</td>
<td>d, e</td>
</tr>
<tr>
<td></td>
<td>- Implementation of a real-time process control system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Validation of the implementation</td>
<td></td>
</tr>
<tr>
<td>6. Conclusions are described in <em>Chapter 6</em></td>
<td>- Conclusions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Recommendations</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 2. Problem analysis

2.1 Introduction

The first step before proposing and developing a solution is the investigation of the problem and an analysis of the problem roots. This part of the report presents the problem analysis in road construction, particularly in paving and compaction. After the problem analysis, the solution’s requirements are determined.

The problem analysis starts with the consideration of the road construction phase in an asphalt life cycle (Figure 1). The asphalt life cycle begins with asphalt mixture design and ends with rehabilitation activities. When it is no longer possible to maintain the road on a level sufficient for the main road user the asphalt life cycle begins again. The road construction phase is a link between asphalt mixture design and production, and road maintenance and rehabilitation. The construction phase depends on the previous stages of the asphalt life cycle and provides essential results (asphalt mat with final quality) for the following stages. There are two main activities during road construction. The first is paving, when the asphalt mixture delivered on site is paved by the paver/finisher with the predefined pre-compaction parameters, width, thickness and slope of the asphalt mat. The second is compaction, during which the asphalt mat is compacted by rollers to achieve a predefined density.

To better understand the problem, it is necessary to define and analyse the stakeholders. The result of such an analysis is presented in the following paragraph.
2.2 Definition of stakeholders with analysis of the stakeholders’ needs

The key stakeholders and relevant activities are identified as shown in Table 3.

Table 3. Stakeholders of the proposed solution (prototype)

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>End-user of the proposed solution (prototype):</strong> Construction machine operators and managers from asphalt construction companies.</td>
<td>- Getting clear information about process variables during construction; - Using a non-intrusive system that will not interfere with the main paving and compaction responsibilities of an asphalt team.</td>
</tr>
<tr>
<td><strong>End-user of the road:</strong> Drivers, residents of nearby neighborhoods.</td>
<td>- Using roads with an increased quality and life-cycle.</td>
</tr>
<tr>
<td><strong>Maintenance workers:</strong> Representatives of asphalt construction companies who will be responsible for the system during its life-cycle.</td>
<td>- Supporting the prototype during its usage on the construction site and during its storage.</td>
</tr>
<tr>
<td>Representatives of developers who will be responsible for the system during its life-cycle.</td>
<td>- Providing the client with planned maintenance and updates for the prototype.</td>
</tr>
<tr>
<td><strong>Developers:</strong> PDEng trainee.</td>
<td>- Developing the prototype which meets the client’s requirements and expectations.</td>
</tr>
<tr>
<td><strong>Clients:</strong> Asphalt construction companies.</td>
<td>- Decreasing the variability within the asphalt construction process; - Improving the final quality of the asphalt mat; - Integrating the proposed solution in their construction processes.</td>
</tr>
<tr>
<td><strong>Suppliers:</strong> Asphalt mixture manufacturers.</td>
<td>- Revising and adapting asphalt mix designs based on construction data collected on sites.</td>
</tr>
<tr>
<td>Construction machine manufacturers.</td>
<td>- Providing the machine users with abilities to integrate new on-board systems.</td>
</tr>
<tr>
<td><strong>Road agencies:</strong> Different authorities on behalf of the government.</td>
<td>- The prototype should be able to satisfy the existing rules, regulations and laws.</td>
</tr>
</tbody>
</table>

From Table 3, it can be concluded that the main stakeholders who will use the proposed solution on a construction site are asphalt companies and machine (paver/roller) operators. Previous monitoring, observation and analysis of asphalt construction projects indicate that asphalt teams mostly rely on their tacit knowledge and gut-feeling. On the other hand, the analyses suggest that there are numerous parameters that play a role in the final quality of the asphalt. Among these parameters are: the temperature of the asphalt layer, the number of roller passes, and the delivery time of the asphalt mix.
A slight variation in any of these parameters introduces a great degree of variability in the quality of the asphalt. These variables are implicit for teams due to the fact that they could not be observed without special tools and sensors. The design should therefore provide the asphalt crews with real-time data, so that the correct paving and compaction strategies can be applied during construction. All in all, the solution should contribute to improving quality of the asphalt construction process.

2.3 Analysis of existing solutions

The next step of problem analysis is the consideration of what has been done in academia and industry to provide asphalt companies with appropriate solutions to support them during paving and compaction. Among research initiatives in the area of system development for asphalt paving and compaction, several main periods can be recognized. As shown in Figure 3, the first step towards automation in an area of compaction procedures was done by GEODYN in 1985 [4]. At that time, researchers and developers started to collect data about the operator’s actions on a construction site and tried to analyze the data using various algorithms. As the first step, making the operator’s actions more transparent and traceable was a concrete basis for future systems development. Over the next decade, developers were investigating the suitable sensors and devices that could be integrated into cabins of the construction machines.

Figure 3. Development of the systems for asphalt paving and compaction

With significant improvements in technologies, the first prototype of the automotive system for the compactor was developed and tested in 1994, during one of the construction projects of the French road builder Cochery Bourdin Chaussé [5]. The main focus of the system was to provide the roller operator with the number of passes actually performed on each point of the asphalt mat. This was done by analyzing the positioning of the machine on a construction site via the CAPSY localization system. In spite of the noticeable advantages that the system provided to the operator, i.e., making the compaction process visually understandable, the implementation of such a solution revealed a layer of concomitant problems. Hardly dependent on a positioning system, the solution had a few drawbacks. The CAPSY was a laser-based system, which made it hard to implement on a construction site and very sensitive to rain and vibration. In addition, due to the size of the screen, it was difficult to mount the system inside the compactor’s cabin. Furthermore, the legibility of the screen to sunlight made the system inconvenient to use. The visualization of the compaction process through three colours was quite poor. Nevertheless, the development process was open for further improvements. In 1996 the group of the researcher from the Penn State University, the USA, presented ‘A GIS-based system for tracking pavement compaction’ [6]. Similar to the previous system, the system focused on the improvement of the compaction process through automation. Having made progress in machine’s localization on site through the application of Differential GPS (DGPS), the authors paid more attention...
to improve algorithms for determining and counting number of roller passes. As a culmination of the development of the support systems for compaction, ‘The Computer Integrated Road Construction project’ (CIRC), was presented by Peyret et al. [7]. The system covered both types of machines: paver and roller. Among the objectives for the roller were the exact number of roller passes with the appropriate speed and record of the actual work. As for the paver, the system suggested an accurate trajectory and the appropriate speed. In addition, the system assisted the screed-operator of a paver and recorded the actual work. It was the first system where radio modems and WaveLANs with Peer-to-Peer architecture were implemented for the communication purposes between the machines. Finally, the set of requirements for the system development was defined. Some of the requirements from this set are valid today, such as robustness in terms of hardware, a high level of integration and a high quality of ergonomics.

The new era of the development was marked by the ‘Intelligent Compaction’ (IC) trend. Since 2000, researchers mainly focused on types of information that is possible to get from the roller by adding different sensors, and on prediction algorithms for mixture density and number of roller passes. For instance, Compaction Tracking System (CTS-III), proposed by Oloufa [8], made an assumption that roller frequency, wheel load and roller speed are constant parameters. The major factors that the system analysed were the number of roller passes and the surface temperature of the asphalt mat. Thinking differently, Briaud [13] introduced a system which controled different compaction parameters for the roller such as: drum vibration, amplitude, frequency and working roller speed (impact distance). The main advantage of the proposed solution was the instantaneous and complete evaluation of the compaction zone. Nevertheless, the high cost of the used equipment made the system more expensive than ordinary rollers. Examples of the practical implementation of intelligent compaction were shown by Gallivan et al. [14]. More extensive intelligent compaction field validations put as a base for Quality Control (QC) and Quality Assurance (QA) specifications [15], where the authors study IC equipment, specifying GPS equipment and requirements, validating IC systems and GPS operations on site and other aspects. The Onboard Density Measuring System (ODMS) was proposed in [18, 19]. This measuring system focused on the density measurements in real-time. The system showed a higher accuracy in comparison to the nuclear density gauge, providing the contractor with the ability to recognize and correct compaction problems immediately during the construction process. A similar solution, the Compaction Monitoring System (CMS) was presented by E. Kassem et al.[10]. Concentrating more on the path planning of the construction machines, H.P. Tserng et al. developed algorithms for efficient traffic routing [20].

A thorough analysis of intelligent compaction was presented by Q. Xu et al. [9]. The authors proved that IC systems could help improve the roller patterns and identify the weak or soft areas in the pavement layers. Although developers considered the compaction in a broader level by implementing the density prediction, this work has not made a significant step towards a new generation of asphalt team support systems. The Compaction Monitoring System (CMS) that was proposed E. Kassem et al. [10], mainly focused on the compaction process as well. In this system a set of sensors such as DGPS, temperature sensor, and accelerometer were used to identify the vibration during compaction. A rugged computer was applied to present the compaction process to operators in distances and global coordinates. The possible integration with the methods to obtain density distribution was verified in [21]. In parallel, R. Kuenzel et al. [11] presented the SmartSite project where agent models were developed for the paver and all rollers on a construction site. One of the advantages of the proposed solution was the determination of the core temperature of the asphalt layer. Although the authors stated that to determine core temperatures of the asphalt layer they used asphalt thickness measurements from the paver in relation with the surface temperature of the asphalt mat obtained from the compactor, it is
unclear what methods and models were used. Based on the positions of the machines and the known temperature of the asphalt layer, the SmartSite agent defined where the vibration should be turned on/off as well as the position to change the direction for the compactor. Besides that, the SmartSite developers identified strong relations between the paver’s speed and compaction patterns. Q. Xu et al. [12] identified the following critical problems with intelligent compaction in relation to Quality Control and Quality Acceptance (QC/QA): (1) the on-board computer on a compactor does not supply sufficient post-data analysis; and (2) the IC compactor is unable to directly measure the mixture density. Consequently, the prediction algorithms for the asphalt density have to be developed and proposed.

Based on the analysis of the latest development efforts, the main drawback of the available system is that they all focus on compaction, and, therefore, sometimes what was developed previously is not taken into account in the following one, e.g. speed of the compactor.

Figure 4. Spiral development in area of systems for asphalt road construction

All in all, the whole process of the development in an area of support systems for asphalt construction projects can be presented as a spiral process (Figure 4). At the base of the spiral, we can identify all activities which took place to make the asphalt construction process more explicit via representing the operators’ behaviour. The first turn along the spiral presents systems and solutions which give the team on a construction site as much related information as possible and allowing the team members to adjust their behaviour. The next turn of the spiral is represented by the systems whose focuses shifted to the automation of data analysis. During this era, the attempts were made to implement density predictions algorithms and provide the drivers with the operational steps that can be followed.

With the help of new technologies, devices and sensors, the current turn of the spiral is similar to the first one, in the sense that current solutions aim to provide the operators on site with essential data in real-time. That could be done in combination with the parameters from paving and compaction procedures. In addition, the factors from each phase of the asphalt construction supply chain that might
influence paving and compaction have to be fully considered and analysed. Further, once new solutions are thoroughly tested and validated, the implementation of prediction algorithm, e.g. for mixture density, speed of the machine, or its trajectory, could follow, opening a new generation of the IC systems.

Academia is not alone in the development of asphalt support systems. The industry, i.e. manufacturers of the construction machines and other companies that produce solutions applicable for the construction processes, has shown serious commitment to this cause. Table 4 presents participants that continuously introduce their solutions (Paving Control Systems (PCSs) or Compaction Control Systems (CCSs)) for the market.

### Table 4. Industrial solutions for road construction projects

<table>
<thead>
<tr>
<th>Company</th>
<th>Solution Name</th>
<th>Solution Domain</th>
<th>Solution Features</th>
</tr>
</thead>
</table>
| **Ammann**    | GPS-based compaction (ACE<sup>PRO</sup> and ACE<sup>FORCE</sup>) [22] | Compaction      | - Documenting compaction results;  
- Measures and evaluates material stiffness;  
- Adjusts frequency and amplitude depending on compaction measurements, sending optimal force into the ground;  
- Eliminates drum jumping;  
- Provides mapping with help of GPS. |
| **Atlas Copco-Dynapac** | Continuous Compaction Control (CCC) [23] | Compaction      | - Documenting compaction results;  
- Determines soil stiffness;  
- Counts number of passes made. |
|               | Compaction meter (Dynalyzer) [24]                |                 | - Determines stiffness of the compacted material.                                                                                                                                                                |
| **Bomag**     | Bomag compaction management BCM 05 and BCM 05 positioning [25] | Compaction      | - Documenting compaction results;  
- Representation of the compaction results in relation to the specified target;  
- Real-time display of the compaction and load capacity status in the form of diagrams and numbers;  
- Representation of variations in quality with interval observation;  
- Comparison of the current measurement curve with the measured values of the previous pass;  
- Visual and graphic warning when the measured values deteriorate. |
| **Caterpillar** | Compaction Control Technologies [26]            | Paving and Compaction | - Integrated guidance and automatic grade control. |
| **HAMM**      | HAMM Compaction Quality (HCQ) [27]               | Compaction      | - Measures the stiffness of the soil or asphalt pavement during the dynamic compaction process.  
- Keeps the operator informed of the current asphalt temperature.  
- Creates a real-time “compaction map” of the area to be compacted. |
### Table 4. Industrial solutions for road construction projects (cont.)

<table>
<thead>
<tr>
<th>Company</th>
<th>Solution Name</th>
<th>Solution Domain</th>
<th>Solution Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leica</td>
<td>Leica PaveSmart 3D system [28]</td>
<td>Paving</td>
<td>-Constructs precise as-designed 3D surfaces, 3D data can be imported from practically any CAD system;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Supports controllers from different machine manufacturers;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Compatible with the widest range of GNSS base stations.</td>
</tr>
<tr>
<td>Moba</td>
<td>PAVE-IR [29]</td>
<td>Paving</td>
<td>-Measures of the material temperature to detect thermal segregation;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Creates a real-time, detailed thermal profile of the asphalt layer;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Open interfaces for suppliers of logistics and optimization solutions.</td>
</tr>
<tr>
<td>Sakai</td>
<td>Compaction Information System 2 (CIS2) [30]</td>
<td>Compaction</td>
<td>-Counts number of roller passes;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Controls roller speed;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Controls and adjusts vibration frequency and amplitude, sending optimal force into the ground;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Determines paving surface temperature.</td>
</tr>
<tr>
<td>Topcon</td>
<td>Sitelink3D C-63 intelligent compaction [31]</td>
<td>Compaction</td>
<td>-Documenting compaction results;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Measures paving surface temperature;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Provides accurate pass counts, geographic locations of each run, as well as georeferenced task assignments and completion.</td>
</tr>
<tr>
<td>Trimble</td>
<td>Trimble Compaction Control System (CCS900) [32]</td>
<td>Compaction</td>
<td>-Provides display and mapping of compaction measurements in real-time, and on-machine documentation of compaction results.</td>
</tr>
<tr>
<td>Volvo</td>
<td>Compact Assist for Asphalt with Density Direct [33]</td>
<td>Compaction</td>
<td>-Documenting compaction results;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Pass mapping;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Temperature mapping;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Real-time density calculation over the full mat surface.</td>
</tr>
<tr>
<td>VÖGELE</td>
<td>RoadScan [34]</td>
<td>Paving</td>
<td>-Documenting paving results;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Captures the base temperature before paving;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Records precise positional data;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Documents the wind strength and direction, ambient temperature, air pressure and humidity.</td>
</tr>
<tr>
<td>Völkel</td>
<td>Vökel Compaction Control (VCC) [35]</td>
<td>Compaction</td>
<td>-Documenting compaction results;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Controls and adjusts vibration frequency and amplitude, sending optimal force into the ground;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Controls roller speed.</td>
</tr>
<tr>
<td>BPO Voltz logistics</td>
<td>BPO ASPHALT [36]</td>
<td></td>
<td>-Controls amount of trucks at the asphalt plant, no a way to the construction site and on site;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Controls amount of mixture delivered on a construction site.</td>
</tr>
<tr>
<td>Thunderbuild</td>
<td>APEX / ALIS</td>
<td></td>
<td>-Controls amount of trucks at the asphalt plant, no a way to the construction site and on site;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Controls amount of mixture delivered on a construction site.</td>
</tr>
<tr>
<td><strong>Logistics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AsphaltOpen</td>
<td>An Interactive Visualization Tool for Asphalt Concrete Paving Operations [37]</td>
<td>Paving and Compaction</td>
<td>-Visualizes the temperatures of the asphalt mat after paving in a way of temperature contour plots (TCP);</td>
</tr>
<tr>
<td>SIMPAVE</td>
<td>Interactive Simulations for Planning Pavement Construction [38]</td>
<td>Simulations for paving and compaction</td>
<td>-Provides path planning for hauling, roller motion paths, paver motion;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Provides hot-mix cooling models, in-truck temperature, compaction models;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Simulates wind, temperature rush hour, accidents;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Provides plant output, truck capacity, paver capacity, roller sizes.</td>
</tr>
<tr>
<td>VETA</td>
<td>VETA - Intelligent Compaction [39]</td>
<td>Compaction</td>
<td>-Monitors real-time asphalt or soil compaction progress;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Collects thermal profilers of the asphalt surface temperatures;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Analyses paver-mounted thermal profile;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Defines multiple subplots and filters groups;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Aligns file enhancements.</td>
</tr>
</tbody>
</table>
Based on an analysis of the industrial solutions which are currently presented on a market, it is possible to conclude that the industrial solutions have the same drawbacks as solutions from academia. The main focus of the systems is either paving or compaction and not both. The other disadvantage is that the solutions are ‘black’-boxes for the end user, where the customer (asphalt construction company) has no chance to improve the system or change it, to be able to use it from their own perspective. The systems are closed for system integration and the customer has to use several solutions to control data from all phases of the asphalt life cycle. For instance, one of the most well-known systems is HAMM Compaction Quality (HCQ) system. This system can be assumed as a pinnacle of the development for compaction control since the CIRC project was presented in 1996 [6]. Because of the improvements to determine the machine locations on a construction site, e.g., DGPS, current systems are highly accurate. The main problem is that the approach, which is applied by the systems, has not changed much from the 90s in terms of data collection, storage and visualization. Yet, manufacturers have of late developed systems that enable several roller compactors data to be visualized individually and mutually in order to obtain and overview of all compaction activities. Also several sensors have been added to recent models. However, although roller compactors are equipped with temperature sensors, the surface temperature of the mat could be inaccurate due to the water used by drums of the roller. In addition, the internal temperature of the mat is not under consideration.

2.4 Discussion and conclusions

From the investigation of stakeholders and their needs, it is possible to conclude that the solution/prototype should lead to a better quality of the asphalt construction process. To sum up the analysis of the existing solutions: Better process control and consequently a better quality of asphalt mat can be achieved if the proposed solution can combine and analyse paving and compaction data in relation to each other. Thus, the answers for the questions which were stated in Section 1.6.1 can be defined.

1. What is the problem that has to be solved by developed solution?
   Essential parameters about paving and compaction activities during road construction should be mutually analysed and explicitly presented to the asphalt team (e.g. temperature of asphalt mat, number of roller passes, etc.).

2. What are the roots of the problem?
   Current solutions do not consider paving operations in relation with compaction operations. They mainly focus only on compaction.

Therefore, the developed solution should provide the asphalt team with essential data over both paving and compaction activities in real-time.
Chapter 3. System requirements

Requirements form a concrete base for the development process. Through requirements, clients might express their expectations and needs about the developed solution. As for the developers, they try to match these expectations by focusing on what is required. The lack of requirements could make the development process problematic, leaving both of the involved parties (developers and clients) in uncertainty. Additionally, requirements help decision-making when a trade-off occurs or when essential changes need to be applied to a design.

3.1 Requirements engineering

The simplest way to define requirements is to divide the problem into manageable parts. There are several approaches that might help to define requirements. In this project the scenario exploration and problem investigation from existing solutions were used.

3.1.1 Scenario development

There are diverse scenarios for requirements determination, such as Operational, Storytelling or Use Scenario. One of the most powerful approaches to discuss and define capability requirements is the Use Scenario [40]. It gives the designers the ability to create a structure that is organized hierarchically by time. The scenario encourages the stakeholders (developers and clients) to think about the job they are doing and the way they are doing it. In effect, they are rehearsing the way they would like to do their job. Once the scenario is agreed, individual requirements can be generated to define precisely what stakeholders would like to be able to do at each point of the scenario [40]. Having the scenario, the stakeholders can extract requirements. Also, this is helpful to identify the missing requirements. Figure 5 contains the Use Scenario that has been developed for the proposed solution (Appendix A).
Figure 5. Use scenario for a real-time process control system
3.1.2 Solution requirements

As a starting point to define solution requirements, the investigation of existing solutions and the Use Scenario have been done. To be able to match the expectations of the asphalt construction companies and the end users in particular (operators of the asphalt construction machines), the developed system should satisfy the following requirements:

1. **Non-intrusiveness**: This means that the process of mounting/dismounting of the system and the use of the system during road construction should not interfere with the main paving and compaction responsibilities of the asphalt team. In other words, the developed system should be easily placed on current construction machines, without any additional disturbance to the construction team.

   This requirement is necessary because the road construction process is limited in time. Before paving and compaction starts, everything is planned very tightly. Thus, any setup activities for auxiliary systems, if not planned in advance, should be easily manageable in parallel with regular activities.

2. **Usability**: The solution should be simple to use, this means that the process of mounting/dismounting the system should be simple, without any significant time and cost implications. At the same time, the system should be stand-alone, which means that the system itself and its components should be able to work continuously up to 12 working hours. Thus, the battery capacity of each element should meet this requirement.

   Although pavers can supply the power for the auxiliary system, rollers are not able to accommodate this. The usability requirement is essential and needs to be taken into account.

3. **Real-time data representation**: Due to the speed of work, i.e., approximately 5 m/min and 80 m/min for a paver and roller respectively, it is necessary to provide the operators with data with minimal latencies, otherwise the mismatch between the operator’s behaviour and the real situation on site will occur.

   Real-timeliness plays a crucial role in road construction. Providing asphalt team with outdated information can lead to inappropriate paving and rolling strategies, which in turn, can result in a lower quality of the asphalt mat.

4. **User-friendliness**: For the first system prototype it was planned to develop 2D top views of the construction process. Although 2D is associated with a lower realism than 3D, it is simpler and can be easily comprehended by machines’ operators. Data representation for end users of the system can significantly affect the system’s adoption. If information is provided in a complex and incomprehensible form, the operators of the machines are likely to ignore, or even switch off, the system.

5. **Extensibility**: The developed solution should be able to integrate with other systems by predefined interfaces. The interfaces for the data communication make the solution more flexible to receive additional information and to pass the result to other external systems. At the same time, the ability to integrate the system makes the solution suitable for application on different construction machines. Thus, the client (construction company) stays independent from the type of paver and roller.

6. **Rugged**: The solution should be rugged because of the aggressive asphalt construction environment (high temperature, vibration, weather conditions, etc.). The appropriate level of protection for the system and its components has to be considered.

7. **Robustness**: The solution should provide redundancy. This means that the system should be able to work in case of failures of sensors, controllers, data storages, etc. It is important to consider redundant blocks and elements of the system. Without a sufficient level of redundancy, there is
a risk of losing important data. Hence the proposed solution should be able to obtain data from auxiliary sources or to analyse the current set with an appropriate prediction level. The system should be robust enough to provide a constant flow of essential data to machine operators.
Chapter 4. Proposed system

4.1 Overview of the developed system

To tackle the problem defined in Chapter 2, a real-time process control system for asphalt paving and compaction has been developed. The proposed system takes into account both paving and compaction activities during road construction. Thus, the essential parameters of the construction process (e.g. temperature of the asphalt mat) are considered and analysed in relation to paving and compaction. This provides the asphalt team with a more reliable analysis. The schematic architecture of the developed system is presented in Figure 6.

This chapter presents an overview of the design of the proposed system. The details about system structure, modules and components are described in following subchapters.

4.2 Design of a real-time process control system for asphalt paving and compaction

To be able to provide the clients with the system that can effectively help the operators improve the quality of their work, the developed solution should cover both paving and compaction activities during road construction.

Paver Module

The Paver Module of the system needs to collect the surface temperature of the asphalt mat behind the screed of the paver. This temperature is needed to be presented to the paver operator, thus he or she can identify the asphalt mixture conditions and in consequence adjust the paving strategy (speed and pre-compaction parameters). At the same time this temperature is the first source of information for the Cooling Curve Station Module for analysis and determination of the asphalt cooling process on site in real-time. The other source of information for the Paver Module is the GPS sensor. Firstly, the GPS coordinates of the paver are stored in the predefined database and filtered in real-time. Then, the...
filtered paver’s locations are combined with the temperatures gathered by the corresponding temperature sensor. As a result, the surface temperature of the asphalt mat is presented to the paver operator in relation with the length and the width of the paved sections (Figure 7).

**Figure 7. Concept visualization for the paver operator**

The Paver Module collects data from the positioning system and temperature sensors to construct the temperature map of the asphalt mat. The prototype development issues which are related to this module are the following:
- Selecting suitable devices (positioning system, temperature sensors, on-board computer);
- Creating a software model with the appropriate algorithms for the data collection, filtering/processing, visualization, transmission and storage;
- Selecting the data format and upload rates;
- Identifying the ideal layout for mounting on a construction machine.

**Roller Module**

The Roller Module consists of GPS sensor that sends the machine’s coordinates to the predefined database. Assuming that the GPS sensor is mounted on the middle of the roller’s roof (Figure 8) and considering the dimensions of typical rollers, the visuals for the roller operator can be generated.
The coordinates from the GPS sensor which are stored in a database can be analysed either in global coordinate system (WGS 84) or in the East North Up (ENU) local coordinates. Figure 9 shows the plotted roller paths in two different coordinate systems.

The temperature contour plot (TCP) shows the asphalt surface temperature which cools down in real-time. It is used as a base to build 2D top view visualizations for the roller operator. This TCP is a combination of data from the Paver Module and the Cooling Curve Station Module. The plot represents the width and length (in meters) of a paved asphalt mat. Thus, to build corresponding visualizations for the roller operator, a set of transformations from the global coordinate system to the local coordinate system is done. Figure 10 shows the transition between two coordinate systems. The ENU coordinate system is represented by \( X \) and \( Y \) axes, where all roller’s locations, e.g. points \( P_1, P_2 \), have the corresponding coordinates, e.g., \( (X_{P_1}, Y_{P_1}), (X_{P_2}, Y_{P_2}) \). The new coordinate system or the coordinate system for the roller operator visuals is represented by \( X' \) and \( Y' \) axes. Assume that the \( P_1 \) is the start point of the roller’s movements on a construction site that is placed in the middle of the paved road. The \( O' \) is the base point of the coordinate system for the roller operator visuals. In the \( XY \) coordinate...
Due to the fact that the coordinates of \( P_1 \) is known in \( XY \) coordinate system, then the relation between \( O' \) and \( P_1 \) can be described by following equations (1):

\[
\begin{align*}
  x_{O'} &= x_{P_1} - w \cdot \cos \Theta; \\
  y_{O'} &= y_{P_1} + w \cdot \sin \Theta;
\end{align*}
\]

where \( w \) is:

\[
w = \frac{\text{Width of Road}}{2};
\]

![Figure 10. Transformation of roller's coordinates to the coordinate system of visuals](image)

The angle \( \Theta \) that is needed to solve equations (1) is the angle between two coordinate systems \( XY \) and \( X'Y' \), or in other words rotation angle. This angle can be found by the following formula (2):

\[
(90 - \Theta) = \tan^{-1}\left( \frac{y_{P_2} - y_{P_1}}{x_{P_2} - x_{P_1}} \right);
\]

To be able to find out coordinates of the point \( P_2 \) in the new coordinate system \( X'Y' \), the rotation matrix can be used (3).
\[
\begin{bmatrix}
\cos \theta & -\sin \theta & x'_{O'} \\
\sin \theta & \cos \theta & y'_{O'} \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x_{P2} \\
y_{P2} \\
1
\end{bmatrix}
= \begin{bmatrix} x'_{P2} \\ y'_{P2} \\ 1 \end{bmatrix}
\]  

(3)

where \((x'_{O'}, y'_{O'})\), \((x_{P2}, y_{P2})\), and \((x'_{P2}, y'_{P2})\) are:

- \((x'_{O'}, y'_{O'})\) - the centre of a \(X'Y'\) coordinate system;
- \((x_{P2}, y_{P2})\) - the coordinates of the point P2 in a \(XY\) coordinate system;
- \((x'_{P2}, y'_{P2})\) - the coordinates of the point P2 in a \(X'Y'\) coordinate system.

Using the rotation matrix the values for \(X'_{P2}\) and \(Y'_{P2}\) can be calculated by equations (4).

\[
\begin{align*}
X'_{P2} &= X_{P2} \times \cos \theta - Y_{P2} \times \sin \theta + X_{P1} - w \times \cos \theta; \\
Y'_{P2} &= X_{P2} \times \sin \theta + Y_{P2} \times \cos \theta + Y_{P1} + w \times \sin \theta;
\end{align*}
\]  

(4)

With help of equations (4) all coordinates of a roller from the spatial ENU system can be transformed into the coordinate system for the roller operator visuals. As a result, the typical transition of the roller will be shown to the operator as presented in the Figure 11.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure11.png}
\caption{Typical transition of a roller on a construction site (the coordinate system of visuals)}
\end{figure}

Figure 12 presents conceptual visualization for the roller operator.
Presenting the location of the roller on a construction site is valuable for the operator only in its relation to other essential information. In the proposed system the focus is on providing the roller operator with the real-time data about the temperatures of asphalt mat. Knowing the current temperature of each spot of the mat the roller operator can adjust his/her compaction patterns, thereby avoiding crossing over the places which are too hot or too cold. At the same time, the possibilities of under- or over-compaction of zones of the asphalt mat which are appropriate for the compaction are reduced. This is done by calculating of number of roller passes over the asphalt mat. The whole mat is divided into quadrangles (Figure 13), where the coverage of roller form over each of quadrangles is calculated.

Figure 12. Conceptual visualization for the roller operator
The Roller Module collects data from the positioning system and the combination of data from both Paver and Cooling Curve Station Modules. The prototype development issues for this module are the same as for the Paver Module.

Cooling Curve Station Module

As mentioned in Chapter 2, the majority of solutions available on the market consider “spot” temperatures of the asphalt mat in relation to the number of roller passes. The main drawback of this approach is that the temperature data collected from the mat is unreliable because the sensors are usually mounted on the roller/compactor and as a result the temperature of the asphalt is measured after the interaction of the asphalt with the roller’s drum. In the proposed solution, an alternative approach is adopted for collecting and processing the asphalt mat temperature. To analyse the asphalt mat temperature, the Cooling Curve Station (CCS) Module is designed. The module combines two sources of the temperature data. One set of data comes from the temperature sensor on a paver and represents the surface temperature of the asphalt mat. The second one represents the temperature inside the paved asphalt layer. The results of processing both of these sources will be used for creating the cooling curve of the asphalt mat on a construction site in real-time. The development issues for this module are:

Figure 13. Conceptual visualization for the roller operator, compaction mesh
- Selecting suitable devices (temperature sensors that can be used on several locations along the paved section);
- Developing an algorithm for the temperature prediction.

Truck Module
The Truck Module of the system is designed to collect data about the truck logistics. The estimated time of arrival (ETA) on a construction site is calculated based on the current location of a truck. This ETA can be beneficial for the paver operator to adjust the paver speed during the paving process. Thus, the number of paver stopping places during construction, caused by lack of trucks, can be reduced.

Communication Module
A Communication Module is designed for the purpose of wireless connecting the modules and transmitting data between modules. It receives data about the temperature of the asphalt mat behind the paver. This data is then re-sent to the Cooling Curve Station Module, where it is combined with the inside temperatures of the asphalt, thus cooling rate of the asphalt mat can be predicted. The result of this combination goes through the Communication Module to the Roller Module (Figure 14). The prototype development issues related to this module include:
- Applying wireless Machine-to-Machine (M2M) communication;
- Integrating the cooling curve data.

![Figure 14. Concept of data transferring between system modules](image-url)
Chapter 5. Implementation, Verification and Validation

This chapter explains the implementation, verification, and validation of the proposed method. The main goal of these activities is to identify whether or not the proposed system matches a set of the predefined requirements and meets client’s expectations. In the first step, a prototype of the proposed system is developed. In the verification phase, the prototype is tested and glitches and errors are identified and removed. This phase is followed by the presentation of the design to the client. Thus, the client can provide feedback about the design and point to the parts of the system that can be changed or improved. The more time is spent on the verification, the better design can be achieved. It leads to a higher quality and reduces the implementation cost [42]. After the client’s feedback and fine-tuning of the system, the prototype is tested in a real project. The validation of the implemented system ends the design cycle. The results gathered about the system in the real environment are used as a basis for the next design cycle.

5.1 Prototype development

During the system development, a strategic decision was made to only utilize off-the-shelf and commercially available sensors and devices in the system. This would make the system more readily adoptable and available for the construction companies. The subsections below describe choices that were made in relation to each module of the system.

Paver Module

From numerous PQI projects conducted by ASPARi it is known that the asphalt mat temperature behind the paver can be gathered by a temperature linescanner. This is a reliable and efficient device. For the Paver Module the MP150 Raytek linescanner is used as a temperature sensor on a paver. A high-accuracy RTK GPS system (Trimble SPS 851) is used to localize and track the paver (Figure 15). To provide the paver operator with the relevant information via appropriate visualization a Samsung Galaxy Tab Active tablet was mounted in the cabin of the operator.

Figure 15. Paver Module equipment
**Roller Module**

The Roller Module consists of the GPS-tracker device – Trimble SPS 851 and a tablet – Samsung Galaxy Tab Active. The tablet is mounted in the roller’s cabin and presents the relevant data to the machine’s operator (Figure 16).

![Figure 16. Roller Module equipment](image)

**Communication Module**

For communication purposes, Machine-to-Machine (M2M) communication solutions which are provided by the internet providers around the world (Vodafone, KPN, T-mobile and others) were considered. These companies offer communication solutions where the connections between the specific equipment are set. The Vodafone M2M solution has been assessed and implemented in the developed system prototype. Every module of the system prototype (Paver Module, Roller Module, Cooling Curve Station Module) is equipped with Vodafone MachineLink 4G router and power supply battery (CP1290 12 V 9 Ah).

**Cooling Curve Station Module**

The Cooling Curve Station Module is represented by a set of thermocouples that are spread over the construction area. To be more precise, thermocouples are put inside the asphalt layer when a new section of road is paved. To collect the data from the thermocouples, the thermologger is used (Extech HD200). During the paving and compaction phase, the thermologger is connected to the thermocouple and provide a continuous flow of real-time data (Figure 17).

![Figure 17. Cooling Curve Station Module equipment](image)
5.2 Implementation

Based on the set of sensors and devices that have been described above, the architecture of system prototype has been developed (Figure 18). All data gathered on a construction site goes through the communication server of Vodafone to the processing centre, which is placed at the University of Twente. The processing centre analyses the data and provides the corresponding modules of the system with the relevant information. To enhance the robustness of the system, an additional processing centre is used as a backup (Laptop, Researcher 1).

![Figure 18. Architecture of the real-time process control system for asphalt paving and compaction]
Due to the fact that the system relies on the Machine-to-Machine communication network of Vodafone, the possibility to lose the connection between the machines because of the network itself is low (Figure 19).

Figure 19. Vodafone network coverage in the Netherlands

The Vodafone communication net is a huge decentralized network, where data traffic is sent via different servers. Thus, problems related to communication between machines, might occur due to the functional errors of the devices on site or at the processing centre. To avoid the possible loss of data from the construction site because of communication problems, all the information is stored into the local memories of each module.

It is necessary to point out that the system’s architecture includes an additional module for the truck arrivals on a construction site, but this is out of the scope of the present prototype development.

5.3 Algorithm design

During system development phase, the need arose for several algorithms to be coded in Matlab (R2015a)* and Java (Android Studio). These include:

- Client_Paver (processing of paver GPS and temperature data, forming relevant visuals for the paver operator);
- Client_Roller (processing of roller GPS data and temperature data from the Cooling Curve Station Module, forming relevant visuals for the roller operator);
- CCS_processing (analysis of the asphalt cooling process);
- Paver/Roller Visuals Apps (receiving of the visualizations for the paver/roller operators).

The coding will not be shown in this report because of Intellectual Property issues.

(*) Note that some algorithms are new and some were adopted from the work of Miller (2015) [43] and Vasenev (2015) [44].

5.4 Data representation

Paver Module
Data is visualized in 2D because it is the simplest format to show the operator his/her position on the construction site (Figure 20). With the help of such data representation, the paver operator can more efficiently identify his/her strategy during paving process. The colder or hotter spots of the asphalt mixture are easily detected. Thus, the paver operator can adjust the speed of the machine as well as give advice for the pre-compaction procedure.

![Figure 20. Data representation for paver operator (prototype for the paver tablet screen)](image)

Roller Module
In order to provide the roller operator with the relevant temperatures of the asphalt mat, two sources of data are combined and analysed. These are: the temperature of the asphalt mat behind the paver (the Paver Module of the system) and core temperatures of the asphalt layer (the Cooling Curve Station Module).
Module of the system). The process of the temperature analysis will be described later in the ‘Cooling Curve Station Module’ section. Figure 21 shows the common visualization for the roller operator. In addition to the current temperatures of the asphalt mat, the number of roller passes can benefit the operator by making the compaction process more explicit. Based on the discussions with the roller operators and the representatives of the asphalt construction companies, the idea of representing the compaction process was defined. Figure 22 shows the typical compaction plot that is presented to the roller operator. The core idea is that three colors represent the number of passes performed on an asphalt mat. Among them: black which equals target number of passes, grey equals the target number of passes minus 1, and light grey equals the target number of passes minus 2. The algorithm for the roller passes counting is based on the determination of points of the paved section which were covered by the roller. The roller is represented by a rectangle. The coordinates for the corners of the rectangular are calculated based on the location of the GPS sensor on the equipment and the known dimensions of the roller.

![Diagram of asphalt mat temperatures data representation](image)

**Figure 21.** Asphalt mat temperatures data representation (prototype for the roller tablet screen)
Cooling Curve Station Module

For the purposes of providing the roller operator with the real-time temperatures of the paved asphalt, the core temperatures of the asphalt layer are collected by the CCS Module. The module consists of a set of thermocouples which are set up on a construction site, the thermologger that reads thermocouples measurements, and the corresponding software. The program of CCS Module combines data from the linescanner mounted on a paver with the thermologger’s data according to the algorithm which is thoroughly described in the patent [41].

The graphical user interface (GUI) of the CCS program is shown in Figure 23. The GUI provides the site manager with an overview about the asphalt mixture temperatures and the prediction of the cooling process (cooling curve – a graph that shows expected temperature in certain time after beginning of measurements). All the results of the temperature analysis are sent to the processing centre where they are stored in the database. Consequently, these results are requested by the Roller Module, and the corresponding visuals for the roller operator are created.
5.5 Verification

Lab tests
Laboratory tests of the solution design are a crucial part of the design cycle. To simplify test activities during the development process, every module of the proposed system architecture was tested separately in the beginning. These tests helped to reveal internal errors for the corresponding modules. After all modules were checked separately, the data flows between modules or connections between modules were identified. Figure 24 presents the systems’ modules and their interconnections with each other. The tests of the whole system, where every system’s module was involved, were done using historical data collected previously on construction sites. For instance, to simulate coordinates of the construction machines (paver/rollers) the corresponding GPS data files were used from one of the previous PQi projects.
Check of the solution’s requirements

The requirements of the system were checked simultaneously during the laboratory tests.

1. Non-intrusiveness. Due to the nature of the selected devices and sensors for each module of the system, the system itself can be defined as non-intrusive with straightforward mounting/dismounting procedures.

2. Usability. The batteries of the devices as well as chosen batteries, for power supply of elements for the corresponding system’s modules, provide the system with an ability to work from the beginning till the end of the construction project (approximately 8 hours).

3. Real-time data representation. The latencies between time when the data is received from the system’s modules, and time when the results of data processing are obtained by corresponding modules, were assessed and found satisfactory (up to 1 second) for the real construction projects.

4. User-friendliness. The simpler way of data presenting (2D top views of the construction site with the asphalt paving and compaction) was found to be easy to comprehend by the paver/roller operator.

5. Extensibility. The developed solution has an open interface for integration with other system or other devices.

6. Rugged. Due to the aggressive environment, where the system is planned to be used, all elements of the corresponding system’s modules have a sufficient degree of protection provided by enclosures (Ingress Protection Marking Code). The elements of the modules can withstand temperature of the asphalt mixture at the delivery (up to 180°C), as well as a vibration that is produced by the machines (vibration frequency up to 60 Hz).

7. Redundancy. Because of the possible failures of modules’ elements, the various ways of keeping the system to work properly were addressed. For instance, in case of failure of the processing centre (Figure 2.3...
all data will be analysed by an additional computer, which is placed at the University of Twente. No breakdowns were experienced.

5.6 Validation meetings and workshops

To be able to meet the client’s expectation, the meetings with representatives of asphalt construction companies were arranged. During these meetings the architecture of the system, system’s modules, communication procedures, data analysis and project progress were discussed. The vital feedback from participants over possible improvements was obtained. Thus, validation of the system development was performed, and all participants agreed on possible improvements. The participants of the meetings are listed below:

- ir. B. (Berwich) Sluer (Boskalis Nederland), project supervisor
- ir. M. (Marco) Oosterveld (BAM Infra Nederland BV), project supervisor
- ir. L.A.M. (Laurens) Smal (Dura Vermeer Divisie Infra BV), project supervisor

In addition to meetings with representatives from asphalt construction companies, where more general questions were concerned (e.g. system’s architecture), feedback workshops were planned with end-users of the system i.e. operators of the construction machines. The system and the way of data representation for the paver and roller operator were presented during three workshops at Roelofs, Boskalis Nederland and Twentse Weg- en Waterbouw BV. Then, in order to gather feedback on the proposed solution and on usage of support systems on board of current construction machines, a questionnaire was given to all machines operators (Appendix B). The main goals of the questionnaire were to understand operators’ attitude towards new technologies, their opinion about what information might be useful for them, which current systems are known among operators and which way of data representation suits them best. The results of the questionnaire are presented in Table 5.

Table 5. Questionnaire with the paver/roller operators

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work experience</td>
<td><img src="chart.png" alt="Work experience chart" /></td>
</tr>
<tr>
<td>Attitude towards assistive tech.</td>
<td><img src="chart.png" alt="Attitude chart" /></td>
</tr>
</tbody>
</table>
Table 5. Questionnaire with the paver/roller operators (cont.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Useful information</strong></td>
<td>- Temperature of the asphalt behind the paver</td>
</tr>
<tr>
<td></td>
<td>- Type of asphalt mixture</td>
</tr>
<tr>
<td></td>
<td>- Time of asphalt mix delivery</td>
</tr>
<tr>
<td></td>
<td>- Speed of the paver</td>
</tr>
<tr>
<td></td>
<td>- Temperature of the asphalt mixture in the hopper</td>
</tr>
<tr>
<td><strong>Readiness to a new generation of machines</strong></td>
<td><strong>Known Paving Control Systems (PCS),</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Compaction Control Systems (CCS)</strong> and logistic systems</td>
</tr>
<tr>
<td></td>
<td>Very few systems were mentioned, e.g. VÖGELE RoadScan,</td>
</tr>
<tr>
<td></td>
<td>HAMM Compaction Quality (HCQ), BPO Voltz logistics</td>
</tr>
<tr>
<td><strong>Possible distraction by additional support</strong></td>
<td><strong>Way of data presentation</strong></td>
</tr>
<tr>
<td>system on board</td>
<td><strong>Visualization type</strong></td>
</tr>
<tr>
<td><strong>Visualization type</strong></td>
<td>2D</td>
</tr>
<tr>
<td></td>
<td>3D</td>
</tr>
<tr>
<td></td>
<td>Colored visuals</td>
</tr>
<tr>
<td></td>
<td>Black and white visuals</td>
</tr>
<tr>
<td></td>
<td>Additional sound alerts</td>
</tr>
<tr>
<td></td>
<td>Without sound alerts</td>
</tr>
</tbody>
</table>

![Graph showing the results of the readiness to a new generation of machines with additional support system on board.](image1.png)

![Graph showing the results of the visualization type.](image2.png)
Based on the obtained questionnaire results it can be concluded that in general operators are ready for a new generation of the machines, where more sophisticated systems will be present on board. The attitude towards new systems and auxiliary displays is more positive, rather than negative. It is interesting to note that only few current systems were known among participants. Nevertheless, several parameters were mentioned as valuable for paving and compaction procedures. Among them are – temperature of the asphalt behind the paver, type of asphalt mixture, time of asphalt mix delivery, speed of the paver, temperature of the asphalt mixture in the paver’s hopper. Despite a lack of work experience with Paving Control Systems (PCS) or Compaction Control Systems (CCS) operators mentioned the risk of possible distractions by such systems, mainly because of the necessity to focus on data which is represented by these systems. Regarding data representation and the type of visualizations, visuals with numbers in 3D colored format appear to be more preferable. Also, there is no consensus over the usage of sound alerts.

Some of the operator’s comments have been already implemented into the developed solution, e.g. coloured visuals of temperature of the asphalt mat. Others require further study and analysis.

5.7 Testing on construction sites

First phase, communication tests (checking specification’s requirements)

After the first system’s design was developed and verified the phase of tests on a construction side followed. These tests were carried out in collaboration with the Netherlands asphalt construction company – Boskalis Nederland, on the N207 road (Nieuw-Vennep, the Netherlands). The tests were mainly focused on an assessment of GPS accuracy on a construction site, where the difference between the tablet’s GPS sensor was compared with the Trimble DGPS sensor. Data from the construction site was transferred through the Vodafone network to the processing centre at the University of Twente, where it was successfully stored into predefined database. The estimation of an amount of data (approximately ~1 Mb of GPS data for each roller; ~3 Mb of GPS and temperature data for the paver) with the latencies of data transferring (approximately ~1 sec) was done. In addition these tests proved the following:

- Vodafone routers can be easily set up on the construction machines;
- Battery capacity of 12 V 9Ah to supply Vodafone routers is enough for the whole construction day (~8-9 hours);
- Due to the low strength of the wifi-signal of the Vodafone routers, each module of the system (Paver, Roller, Cooling Curve Station) has to be equipped with a separate router;
- Each tablet was equipped with the Vodafone sim-card and had a direct wifi-connection to the predefined router. This architecture provides a redundant connection to Vodafone network. In the case of losing a connection with the router, the tablet switches to the sim-card within a second and continues data receiving and transferring;
- Tablets can be easily mounted inside the machine’s cabins by suitable holders;
- The battery capacity of the tablet is enough for a typical construction day (~8-9 hours).

After the first series of tests the structure of system’s data flows were checked and improved (Figure 17).
Second phase, system implementation

After the first phase of testing was finished and algorithm corrections took place, the second phase was planned. This phase was carried out in collaboration with Roelofs on the N228 road (Montfoort, the Netherlands).

The tests were mainly focused on system implementation into the real environment. Figures 25, 26 and 27 present the Paver Module, the Roller Module and the Cooling Curve Station Module, deployed on a construction site.

Figure 25. Paver Module, mounted on a machine
Figure 26. Roller Module, mounted on a machine

Figure 27. Cooling Curve Station Module on a construction site
During construction project the paver and the compactor paths were collected (Figure 28, 29). Although, Trimble GPS Base station was used for gathering GPS corrections in real-time, the signal disturbance can be observed because of high dense of trees and houses near the construction site.

Figure 28. Paver path, asphalt construction project
Figure 29. Compactor path, asphalt construction project

Similar to the first testing phase, data from the construction site was transferred through the Vodafone network to the processing centre at the University of Twente and stored into database. Based on GPS coordinates of the paver and temperature from the paver linescanner the visualizations for the paver operator were created (Figure 30, left). These visualizations represent surface temperature of the asphalt mat in relation to length and width of the paved area.

Based on the temperature data from the paver linescanner and from the cooling curve station thermologger, the cooling analysis of asphalt temperatures was done. This analysis combines surface temperature of asphalt with the temperature inside the asphalt layer and forms prediction of cooling process during construction project. The visualizations for the compactor operator (Figure 30, right) were built based on GPS coordinates of the compactor and cooling data of the asphalt mat.
5.8 Discussion and conclusions

During the development of the prototype, implementation, verification and validation activities took place. First of all the specification requirements were verified, to confirm that the system performs as it was determined. These verification activities were done through the laboratory tests that helped to diagnose mistakes in the solution’s architecture, communication between modules and the developed algorithms. Also the specification requirements were checked via tests on a construction site which followed after the laboratory tests. These tests help checking system behaviour during real construction activities.

To check the clients’ expectations as well as end-users of the proposed solution, the meetings with asphalt construction companies representatives and workshops with machines’ operators were organized.

Validation of system implementation was performed through the system’s tests during field work. The results showed that the system can be easily mounted on a set of the construction machines, regardless of the model, type and machine manufacturer. Further, the proposed solution can withstand the harsh environment of a real road construction project, supporting the asphalt team with essential information about current paving (temperature of the asphalt mat) and compaction parameters (number of roller passes).
Chapter 6. Recommendations

This PDEng project aimed to develop a real-time process control system for asphalt paving and compaction. During prototype development, the initial focus was to study paving and compaction activities for detailed analysis and the appropriate presentation of results to the operators of asphalt machines. In this study the history of the support systems for paving and compaction was reviewed and current solutions presently in the market have been investigated. In order to propose a new solution the main activities during road construction (paving and compaction) were analysed. The architecture of a new system has been developed, which consists of four interconnected modules, namely: Paver Module, Roller Module, Cooling Curve Station Module and a Truck Module.

The architecture design for the proposed system revealed the necessity for communication between the system’s modules. Thus, the communication module for data transferring was developed. This included the definition of the type and the amount of data needed to be transferred among modules. In order to satisfy the real-time requirement, possible latencies in data transmission between modules were assessed.

Importantly, the proposed solution was tested on construction sites. The results show that the system can be used during road construction projects and will benefit asphalt teams by making their work procedures more explicit in real-time and hence reduce the variability in quality of the constructed asphalt layers.

The next section provides an overview showing whether system requirements have been met and is followed by the lessons learnt during prototype development.
6.1 Matching requirements

Table 6 presents an overview of the system’s requirements with a corresponding conclusion: ‘Yes’ in the case of the system satisfying the requirement or ‘No’ if the system does not meet the requirement.

Table 6. Matching requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Matches system requirement?</th>
<th>Proof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-intrusiveness</td>
<td>Yes: System’s modules easily mounted/dismounted on corresponding machines and do not interrupt main asphalt team activities.</td>
<td>Tested on a construction site.</td>
</tr>
<tr>
<td>Usability</td>
<td>Yes: System able to work from the beginning till the end of the common construction project.</td>
<td>Tested on a construction site.</td>
</tr>
<tr>
<td>Real-time data representation</td>
<td>Yes: Latencies in data transmission do not exceed 1 second.</td>
<td>Tested in a laboratory and on a construction site.</td>
</tr>
<tr>
<td>User-friendliness</td>
<td>Yes: 2D visualizations for the paver and the roller operators are comprehensible to start work and support operators during their work.</td>
<td>Tested on a construction site and during workshops with operators.</td>
</tr>
<tr>
<td>Extensibility</td>
<td>Yes: The proposed system’s architecture has an open interface for integration with other systems and devices.</td>
<td>Tested in a laboratory.</td>
</tr>
<tr>
<td>Rugged</td>
<td>Yes: Devices which are used in the system have a sufficient degree of protection.</td>
<td>Tested on a construction site.</td>
</tr>
<tr>
<td>Redundancy</td>
<td>Yes: Additional ways of data storage and processing were designed in the system’s architecture.</td>
<td>Tested in a laboratory.</td>
</tr>
</tbody>
</table>

6.2 Lessons from the prototype development

Asphalt construction companies

The main lesson for asphalt construction companies is that the support system for paving and compaction procedures can be built using off-the-shelf components. Thus, the companies themselves are free to choose different construction machines for their fleets.
Also the proposed system shows that it is possible to link paving and compaction during road construction and therefore steer the compaction process in terms of actual temperature data. A combination of paver temperature data, actual cooling curve data and the actual GPS location of the roller compactor enables operator to undertake compaction activities within an ideal or predetermined temperature ‘window of opportunity’. This is the main difference between this developed solution and other existing solutions on the market.

**Machine manufacturers**
Currently, machine manufacturers and developers of support systems for asphalt paving and compaction develop closed systems that do not integrate with others. This design project shows that it is possible to develop open interfaces and mutual data communication protocols that combine logistics, paving and compaction.

**System developers**
In general, lessons for the developers of auxiliary systems for asphalt paving and compaction can be described as follows:
- system’s modules (devices and sensors) should be smaller in size;
- communication between system’s modules, also between components of modules and between sensors should be wireless;
- the system should be easily implemented on a corresponding machine’s board through open interfaces;
- the mounting/dismounting procedures should be simple.

### 6.3 Future development

Based on the results of the system development and implementation the following is recommended:

1. The development of a Truck Logistics Module for the system (Figure 6). This would link an important part of the process to ensure continuity i.e. no stappages;
2. To seek improvements to devices which are used for each module of the system (e.g. replacement of temperature linescanner in the Paver Module by a suitable infrared (IR) camera);
3. To seek improvements for the localization system. Any GPS or similar solutions should be easy to use in the systems’ modules;
4. To consider the devices’ capacities for data analysis on a construction site;
5. To collect additional data about the construction process, e.g. the thickness of the asphalt layer, thus, improving of cooling analysis;
6. To improve visualizations – the resolution, more accurate models for rollers with more solid definition of footprints and the compacted area of asphalt mat.

### 6.4 In closing

This prototype is just the starting point of the current turn of the development spiral shown in Figure 4 (page 15), which can give a new impulse to the design initiatives in the area of support systems for the
road construction industry. Some possible improvements for the Paver Module includes: the generation of a recommended trajectory for the paver considering the paver speed and the number of trucks and a recommended trajectory for the paver’s screed considering the pre-compaction parameters and the current mixture parameters. The Roller Module could be improved through a more accurate calculation of the roller’s footprints and accommodating different types of rollers. The prediction of the density of the asphalt mat, retrieved from the amount of roller passes with a determination of static or dynamic compaction, can definitely benefit the roller operator as well.

To reduce the installation time for the sensors on the construction machines, alternative sensors should be investigated. For instance, the most promising device to substitute the linescanner is an infrared (IR) camera. Currently, there are several series of IR-cameras available with the characteristics and features suitable for collecting data in a harsh construction environment. In addition, the algorithms for the analysis of work for several asphalt teams can be defined and added to the system.

![Compaction plot](image)

**Figure 31. Conceptual visualizations for the roller operator**

With respect to the visualization for the roller operator, the cooling process of the asphalt mat can be divided into zones, namely Red, Green and Blue, where the Red zone represents a part of the asphalt mat with the temperatures higher than a predefined ‘compaction window’ for the particular mixture, the Green zone shows a part of the asphalt mat which can be compacted right now and, finally, the Blue zone shows a part of the asphalt mat where no more compaction should be applied. The conceptual visualization mentioned above is presented in Figure 31. Presenting data to the roller operator in such a
way might decrease the reaction time needed for the operator to analyse the provided information and thus, improve his/her work strategies.

Overall, this design project shows that it is possible to develop systems using of-the-shelf components, with open interfaces and mutual data communication protocols.
References

[37] https://sourceforge.net/projects/asphaltopen
[38] https://ntl.bts.gov/lib/26000/26800/26839/TNW2007-03.pdf

(*) Valid for May 27, 2017
<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>What machine do you work with?</td>
<td>□ Roller □ Asphalt Paver □ Bar/Compaction machine</td>
</tr>
<tr>
<td>How many years of experience do you have?</td>
<td>□ 0 ÷ 5 years □ 5 ÷ 10 years □ &gt;10 years</td>
</tr>
<tr>
<td>What is your attitude towards assistive technology in general?</td>
<td>□ Very positive □ Positive □ Neutral □ Negative □ Very negative</td>
</tr>
<tr>
<td>What kind of information might be useful for you from the assistive technologies?</td>
<td></td>
</tr>
<tr>
<td>What do you find useless in assistive technologies?</td>
<td></td>
</tr>
<tr>
<td>Are you familiar with Compaction Control Systems (CCS)?</td>
<td>□ Yes (model______________________) □ No</td>
</tr>
<tr>
<td>Are you familiar with Paving Control Systems (PCS)?</td>
<td>□ Yes (model______________________) □ No</td>
</tr>
<tr>
<td>Are you ready to the situation when new generations of the machines will be equipped with CCS/PCS systems?</td>
<td>□ Yes □ No Why?:</td>
</tr>
<tr>
<td>Do you think that additional equipment/system could distract your work abilities?</td>
<td>□ Yes □ No Why?:</td>
</tr>
<tr>
<td>In case of usage an additional system on-board of your construction machine, which way of information providing do you prefer?</td>
<td>□ Numbers □ Visuals □ Graphs □ Other Why?:</td>
</tr>
<tr>
<td>What kind of visualization and voice alerts do you think could be useful for your work process?</td>
<td>□ 2D □ 3D □ Colored view □ Monochromatic view □ Additional sound alerts □ System without sounds Why?:</td>
</tr>
<tr>
<td>Company naam:</td>
<td>Datum:</td>
</tr>
<tr>
<td>--------------</td>
<td>--------</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Op welk materieelstuk bent u machinist?</th>
<th>Datum:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wals</td>
<td>□</td>
</tr>
<tr>
<td>Hoeveel jaar ervaring heeft u?</td>
<td>Datum:</td>
</tr>
<tr>
<td>□ 0 ÷ 5 jaar</td>
<td>□ 5 ÷ 10 jaar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wat is uw mening over ondersteunende technologie in het algemeen?</th>
<th>Datum:</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Erg positief</td>
<td>□ Positief</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wat zijn, volgens u, de voordelen van ondersteunde technologie?</th>
<th>Datum:</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Wat zijn, volgens u, de nadelen van ondersteunde technologie?</th>
<th>Datum:</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Bent u bekend met Compaction Control Systems (CCS) ofwel verdichtingsmonitoring?</th>
<th>Datum:</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Ja (model____________________)</td>
<td>□ Nee</td>
</tr>
<tr>
<td>Bent u bekend met Paving Control Systems (PCS) ofwel asfaltverwerkingsmonitoring?</td>
<td>Datum:</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>□ Ja (model____________________)</td>
<td>□ Nee</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vindt u dat de nieuwe generatie machines standaard uitgerust moeten worden met monitoringssystemen als CCS/PCS?</th>
<th>Datum:</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Ja □ Nee</td>
<td>Waarom?:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Denkt u dat de aanvullende systemen met bijbehorend materieel u afleiden tijdens uw werkzaamheden?</th>
<th>Datum:</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Ja □ Nee</td>
<td>Waarom?:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stelt u zich voor dat uw machine wordt uitgerust met ondersteunende technologie. Op wat voor manier wilt u liever geïnformeerd worden?</th>
<th>Datum:</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Getalwaarden</td>
<td>□ Visueel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Kuntest u omschrijven wat voor soort visuele en auditieve communicatievormen waardevol zijn voor u tijdens uw werkproces?</th>
<th>Datum:</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ 2D □ 3D</td>
<td>□ In kleur</td>
</tr>
</tbody>
</table>