The quest for quality: avenues to monitor layer thickness during paving operations – a technology scan and assessment

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ABSTRACT: This paper is a state-of-the art review of non-destructive technologies that show potential for monitoring the asphalt layer thickness during paving operations. The monitoring of layer thickness fits the recent trend of changes towards a more controlled asphalt paving process based on the monitoring of several key parameters. Layer thickness is such a key parameter with a high impact on the quality of the product and the process. This research argues that the monitoring of layer thickness needs to be standardised in order to be able to control the asphalt layer thickness and to meet the desired thickness. In this paper two incentives are discussed for standardising the monitoring of layer thickness during paving operations, which are: a) the negative consequences of the current practice of measuring the layer thickness, and b) the potential of various technologies for measuring the layer thickness during paving operations. The potential of various technologies is reviewed in the context of technological functionalities through a literature review and by validating the results through expert interviews. The results show that the ground penetrating radar (GPR), the laser scanner (LIDAR) and the magnetic imaging topography (MIT) scanner have a high potential for the adoption in practice for measuring the layer thickness during paving operations. Nevertheless, these technologies still have some challenges that need to be resolved in order to be ready for the adoption in practice. To overcome these challenges developments are needed, which have been presented in a roadmap. By following the developments in the roadmap the challenges of each technology can be overcome, which opens up the road for the sector-wide standardisation of monitoring the layer thickness during paving operations.

KEYWORDS: Non-Destructive, Monitoring, Layer thickness, Quality Control, Asphalt Pavement, Quality Improvement, Paving Process, Technology Assessment.

1. Introduction

In the last decade a trend in the road construction sector can be identified in which operational behaviour of the asphalt paving process is made explicit by monitoring key process parameters. This gives insights in the quality of the asphalt paving process. These insights are intended to assist the construction crew in eventually improving the quality of the asphalt pavement [1]. For this quest for quality a methodology is developed in which key Process Quality improvements (PQi's) are sought [2]. In this methodology parameters, such as the asphalt surface temperature and the number of roller passes, are monitored to give insights in the parameters that ensure the right amount of compaction at the right temperature. Monitoring these parameters results in new insights about the paving process. Contractors are increasingly interested in these new insights regarding the pavement process and its key parameters, since this could lead to a more efficient construction process and eventually a better asphalt quality. Besides this market pull, the monitoring of key asphalt parameters is also stimulated by asset owners who challenge contractors to monitor the paving process with data [3]. Asset owners benefit from this data regarding their assets, since it can help improve their prediction models for efficient maintenance strategies. A more efficient maintenance strategy will decrease the maintenance costs, the negative effects of maintenance on the environment (e.g., nature, traffic disruptions) and reduces the use of materials.

The quality of asphalt is depended on many factors. One of the factors, which is important for the quality control of an asphalt pavement, is layer thickness [4]. Although the layer thickness has to meet certain quality standards, and directly affects other quality parameters (e.g., density), contractors are not able to constantly monitor the layer thickness during the process of paving. This does not suit the trend of the increase in monitoring of the asphalt paving process. Moreover, contractors often encounter a deviating layer thickness, which affects the quality of the process and the end product. This paper therefore focusses on discussing these consequences and on scanning for potential technologies and assessing these for their potential of measuring the layer thickness during paving operations. The technologies have to be able to deliver real-time thickness measurements of an asphalt pavement during the paving process. This data can serve as feedback for the process operator (e.g., screed operator) for optimising the layer thickness.

2. Current practice

In this research the state-of-the-art is analysed of technologies that intend to replace the conventional method of measuring the layer thickness and have to be able to prevent the consequences of a deviation in the layer thickness. In order to be able to identify and assess potential technologies for the purpose of measuring the layer thickness of asphalt, the conventional method and the consequences of a deviation in the layer thickness need to be discussed.

2.1 Conventional layer thickness measurement

The conventional method in road construction for measuring the layer thickness of an asphalt pavement is drilling cores [5]. Several articles mention the disadvantages of the core drilling method [6-7]. One of the main disadvantages is that only local data is obtained through the analysis of cores. The number of measurements (i.e., measurement density) per pavement surface is regulated in

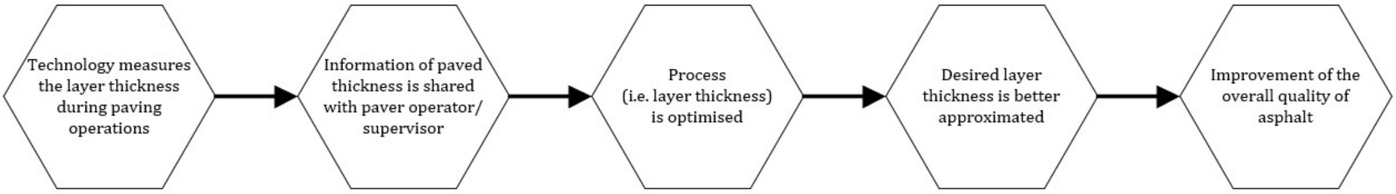

Figure 1: Contribution of the research objective.

standards. As for example, in the Netherlands the highway agency prescribes a measurement per 1000 m² [8]. This prescribed measurement density provides only local data of the quality of the pavement, of which layer thickness is of influence. Although the data represents the local thickness, the data is considered as representative for the whole surface. This disadvantage, and the definition of layer thickness are further discussed in paragraph 4.1.

Another main disadvantage of drilling cores is the timing of the measurement in the paving process. The cores are often drilled after most of the construction phase is completed, which results in deviations being detected too late for corrective layer thickness optimisations. Moreover, the cores are analysed inside the lab mostly after the construction phase is completed. Construction teams therefore often receive feedback about the paved layer thickness days after construction. This has several consequences, which will be discussed in paragraph 4.2. The commonly used method of drilling cores thereby does not align with the trend of monitoring quality parameters during construction.

The destructive character of the core drilling method is important as well. Through the drilling of cores the asphalt is damaged locally, which affects the pavement's durability [5]. Furthermore, the core drilling method has an unreliability. In the research of Al-Qadi et al. [9] the layer thickness of separate cores were measured four times, which resulted in an averaged variation of 2,7%. Although this method thus has a variation in the repeated measurements, core data is mostly seen as 'ground-truth' data [10]. Therefore the performances of other technologies are often referenced to the performances of drilling cores.

2.2 Deviating layer thickness

As previously mentioned, the current practice of measuring the layer thickness often results in a varying layer thickness. This deviation can have many consequences. One of the main consequences is that a possible deviation in the layer thickness is detected too late for corrective measures. This results in structural deviations in the asphalt layer thickness, which are undesired for several reasons. First of all, a structural negative deviation (less thickness than desired) affects the ability to compact the asphalt layer [11]. This is caused by inadequate space for the aggregate particles to be reoriented during compaction. Inadequate compaction is exacerbated by rapid cooling of the layer, which shortens the available time for compaction. A negative deviation in layer thickness is therefore directly related to a shortened lifespan [12]. Secondly, when a structural negative deviation in the layer thickness is detected this can have negative consequences for a contractor. The three most common consequences are: 1) a full replacement of the deviating layer, 2) the addition of an extra asphalt layer, or 3) the payment of contract-bound fines [8]. Thirdly, a positive structural deviation is undesired since it causes the excessive use of materials, which has a negative impact on the profits of a contractor and the environment. Optimising the layer thickness is therefore also a sustainability affair. For most contractors a positive structural deviation is often a response for preventing a negative deviation. They often choose to incorporate a certain 'safety thickness' to the desired thickness in order to prevent the consequences of a fine or corrective measurement.

All of the aforementioned consequences of deviating from the desired layer thickness can be averted by closely monitoring the asphalt layer thickness during the paving process. Monitoring the layer thickness is intended to detect a deviation as early as possible. This data then needs to be presented to the screed operator in real-time, so that the layer thickness can be optimized. The layer thickness therefore needs to be measured as close as possible to the screed of the paver. Getting an overview of the technologies that are able to perform this measurement is therefore the focus of the remaining of this research. Currently there are no technologies available for performing this measurement directly after the screed during paving operations. By identifying the technologies that show potential for measuring the layer thickness during paving operations, the further development and standardisation of layer thickness monitoring is ought to be stimulated. This is expected to result in the ability to detect deviations in the layer thickness earlier in the process, which can be used as feedback data for the process operators to make sure that the layer thickness can be optimised. Eventually, the optimisations need to lead to a better asphalt quality. The contribution to a better asphalt quality is visualised in figure 1.

3. Research Methodology

In this research technologies are identified and reviewed for the purpose of measuring asphalt layer thickness during the paving process. It mainly consists of a semi-systematic literature review study and semi-structured expert interviews for validation of the findings. The semi-systematic literature review is focused on gathering second-hand data regarding potential technologies for measuring layer thickness during the paving process [13]. The gathered state-of-the-art literature is then placed in the perspective of this research, by determining the potential of each reviewed technology for the adoption in practice. The review of each technology is performed in collaboration with experts in the field of road construction. These experts are involved by conducting semi-systematic expert interviews in which the findings of the literature study are validated, and the potential of the technologies are determined.

Preliminary to this research, through the involvement of experts and by conducting a preliminary literature study, a group of six technologies have been identified for their potential contribution to the quality control of layer thickness. These technologies are listed in figure 2. During the research the experts were asked if all technologies were included in this research. They suggested one technology, which registers the consumption of asphalt during the paving process. This technology gives insights in the overall consumption per meter pavement, and thus the layer thickness. Since it does not provide specific point measurements of layer thickness data, the technology is not included in this research. Therefore only the six technologies have been analysed in this research. Each step of the analysis is shortly highlighted in the following section.

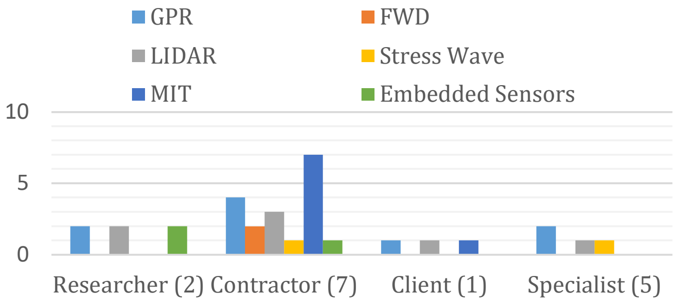

Figure 2: Expert interview contribution and area of expertise

First, a theoretical framework is created which creates the boundaries in which the technologies were analysed in the literature review. Moreover, the theoretical framework serves the purpose of explaining relevant concepts and identifying linkages between the concepts [13]. In the theoretical framework the key concepts 'quality control of layer thickness' and 'monitoring the pavement process' are analysed. Within the concept of 'quality control of layer thickness' it is relevant to discuss the definition of layer thickness, and its interconnections with other (process) quality parameters. Discussing the concept of monitoring key parameters of the pavement process is important since it is essential to determine the ideal timing of measurement in the paving process. Both concepts will be discussed in chapter 4.

By discussing the relevant aspects of measuring the layer thickness during paving operations with practitioners a set of functionalities for the technologies is composed. This set of functional aspects ensures that the technology review results in the differentiation of technologies based on their potential for measuring layer thickness during the paving process.

The next phase consists of collecting second-hand data by performing a semi-structured literature review. This literature review method is selected to collect data of several research groups in a variety of disciplines with different goals [14]. It is recognised for being a suitable method for analysing a subject through its development in time and by a variety of research perspectives. An often-used tool for gathering relevant literature, which is also used in this research, is the 'snowball sampling' method. The name of the method refers to gathering relevant literature through the references of used literature. This method therefore ensures that the snowball (i.e., literature data) keeps on growing while rolling on (i.e., searching through the references). By applying this method in total 84 (review) articles, books and guidelines have been analysed.

After an overview is created of the gathered literature, the findings are validated by experts in the field of road construction. These experts are selected on their role in the road construction sector. Since the research focuses on the improvement of the quality of asphalt by optimising the paving process, most experts are contractors. The most involved experts are employed at the initiator of this research, the Dutch contractor Van Gelder.

In order to review the findings from literature in different perspectives, experts are selected that represent all stakeholders needed in technology adoption. Therefore experts at a client, (multiple) contractors, a research institution and several specialised technology operating firms are interviewed. These interviews were organised in a semi-structured way. This method makes use of a predetermined interview framework, from which can be deviated in case more needs to be asked due to an interesting statement of a respondent. In general, during the interviews respondents are asked about their knowledge base and their experiences with the analysed technologies. According to the technologies mentioned, the findings from literature will be discussed, which will lead to confirmative, contradictive or additive statements. In total 15 expert interviews were conducted, of which the number of experts and their expertise in the technologies are visualised in figure 2.

Eventually the findings from both the literature and expert interviews were gathered in a matrix in order to be able to determine if a technology has potential for the adoption in practice for measuring layer thickness during paving operations. This assessment is based on an elimination strategy. If it appears that a technology is not able, or has low potential to, fulfil a functionality the technology is regarded as 'low potential'. A technology is thus eliminated if it appears that the technology shows low potential (i.e., significant (unrealistic) challenges) to meet a required functionality. The assessment of the technologies is discussed in chapter 5.

If the technology shows potential for meeting all functionalities it is identified as a potential technology for the adoption in practice. The potential technologies have been additionally analysed for the needed developments before they can be used in practice. From these developments a scenario-based roadmap is created to show the sequence of developments in time. A scenario-based (road)mapping method is based on the assembly of possible developments, driven by imagination and the investigation of possible scenario's [15]. Within the roadmap the different technologies can be seen as different scenarios, since the choice for a technology (i.e., scenario) is depended on the uncertainties in time (e.g., contract requirements, technology developments) and the circumstances of each adopter (e.g., knowledge, experience). The conclusion is eventually based on the created roadmap and the supporting recommendations.

4. Theoretical framework

The first step in this research consists of creating a theoretical framework which provides boundaries in which the technologies can be reviewed in the next phase of this research. These boundaries are created by discussing (with practitioners) relevant concepts of measuring layer thickness during the paving process. During this discussion it became apparent that three important aspects of the measurements need to be determined. These aspects are: 1) the desired layer thickness data, 2) the ideal timing of measurement during the process and 3) the required functionalities of a technology for the application on a paver and in the process. All of these three aspects are discussed more in detail.

4.1 Desired layer thickness data

Before conducting a research on the state-of-the-art of technologies that can measure layer thickness, the definition of layer thickness needs to be clear. In general, the layer thickness is a distance measurement between two distinct and subsequent layers. This measurement can be affected by several factors, such as: the roughness of the subbase layer, the roughness of the surface layer and the gradient. An individual point measurement therefore does not provide layer thickness data that is representative of the whole surface. The layer thickness measurements therefore need to be averaged. In general the method of analysing cores and obtaining layer thicknesses is prescribed in standards [8]. In Europe, the regulations about the measurement of layer thickness of bituminous layers are documented in the NEN-EN 12697-36. Averaging layer thickness measurements depends on the type of measurement, the type of data and its measurement resolution (i.e., measurement density). A thickness measurement with a resolution of a cm^2 is more precise than the measured thickness of a m^2. In the research of Telman et al. [16] a different method (than drilling cores) is used for measuring the layer thickness. This method enabled the researchers to measure the layer thickness with a much higher resolution. During the research the resolution of the layer thickness measurements was reduced by averaging all measurements within a roster of 2,25 m^2. This gave a more precise image of the layer thickness of the total pavement and also showed less variability in the results. The actual measurement resolution in the field is also affected by the time it takes to perform a measurement. For example drilling cores has the maximum resolution of 100 mm (standard width of a core) or more, but due to the needed measurement time the actual resolution in practice is much lower [17]. It can therefore be concluded that it is important to consider the factors (e.g., frequency, measurement width, measurement duration) that determine the measurement resolution of the layer thickness per measurement method.

4.2 Timing of measurement

Another important aspect is the timing of measuring the layer thickness during the process. In order to improve the process of paving, a possible structural deviation needs to be detected as soon as possible. According to the practitioners it is thereby important to measure the layer thickness closely to the screed, thus on a paver. The measured layer thickness data can be presented directly to the screed operator. The screed operator then can determine if the height of the screed (thus the layer thickness) needs to be altered.

By measuring the layer thickness in this phase of the paving process, the layer thickness is monitored before the asphalt is fully compacted. This means that the layer thickness is monitored before it has reached its final thickness. It is therefore important to determine what the thickness needs to be behind the screed to obtain the desired final layer thickness after the asphalt pavement is fully compacted. The thickness of the asphalt layer before the compaction phase depends on the extent of pre-compaction (by the paver' screed) and the asphalt type. Acquiring the desired layer thickness data after the compaction phase is therefore a collaboration between the paving and the compaction process. The requisites for measuring the layer thickness close to the screed are discussed in the recommendations.

4.3 Technology functionalities

As mentioned, it is important to consider the required functionalities of a technology for the application on a paver and in the process of paving. The technological functionalities enable the technology to perform its desired task. The functionalities have been identified by discussing the most ideal application of a technology for measuring the layer thickness on a paver during the paving process. Each functionality is discussed below and needs to be taken into consideration during the analysis of possible technologies for measuring the layer thickness during paving operations.

Non-destructiveness: In order to measure the layer thickness with a high resolution and while paving it is important that the technology is non-invasively [10]. This means that it does not affect the quality of the asphalt. A non-destructive measurement therefore keeps the quality of the asphalt pavement intact.

Suitability: The suitability is determined by the possibility of a technology to be applied on a paver. It therefore needs to be able to constantly measure during paving operations, while not being affected by movements (e.g., driving motion, vibrations). Besides, it should be easily (de)mountable for flexibility and transportation reasons.

Usability: This functional aspect relates to the extent to which the data can be used to achieve specified goals with effectiveness and efficiency in a specified context [18]. Suitable data needs to be representative of the whole surface, both in width and in length (i.e., resolution) of the surface. Another important aspect is the ability of the data to be presented in real-time, which is affected by the data size and the interrelated processing/filtering time. The specified context is during the paving process.

Accuracy: This functionality refers to the accuracy of the measured data in comparison to ground-truth data. The data needs to be sufficiently accurate for the purpose of quality (control) monitoring. The accuracy therefore needs to be similar, or even better than the accuracy of the current method (i.e., drilling cores). The accuracy can be expressed in relative or absolute accuracy (according to the user' preference).

Applicability: A technology that has a high applicability is applicable in any situation, and therefore has a higher chance of being adopted than a more specific applied technology. It therefore relates to the number of disturbances by the measured medium (e.g., materials) and the surrounding (e.g., machinery). It relates to disturbances by often occurring paving conditions, such as extreme temperatures, rain, and steam/fog.

Dependency: This functional aspect relates to the required amount of work to perform a measurement. The amount of work increases if actions are needed for preparation, calibration or data collection purposes. A technology should therefore ideally be automated and independent of other technologies/actions in the process.

Maturity: The maturity of a technology is normally expressed in a technological readiness level (TRL) [19]. Since the allocation of a level to the readiness is partly biased by the author, in this research the readiness is expressed by exposing the challenges that withhold it from being fully ready for adoption (i.e., reaching TRL level 9). These challenges can be overcome by developing the technologies in future research in order to be able to successfully adopt the technologies in the paving process.

During the research experts suggested to add two more aspects that had to be considered to assess the potential of the technologies. These suggestions were: data management (e.g., storage, ownership) and costs. Of these suggestions, data management is covered in the functionality 'usability' since the main goal of the researched technologies is to present data in real-time for optimizing the layer thickness. The aspects of storage and ownership of data is relevant for the purpose of layer thickness registration, which is not included in the scope of this research. The suggestion of costs is not included as a criterion since the costs of technologies change over time and therefore depend on the time of adoption. Besides, the sole costs of a technology are found to be of no importance, since the costs have to be analysed in terms of cost per measurement. This is depended on the preferred measurement density, thus on the specific adopter. Nevertheless, the costs of adopting a technology have been discussed in paragraph 6.3.

5 Assessment of potential technologies

The findings from the literature review are validated by experts, which leads to a fully complemented state-of-the-art overview of the reviewed technologies. The overview gives insights in the strong and weak aspects of each technology. Based on of this overview of data per technology, each technology is assessed for its potential for the adoption in practice for measuring layer thickness. This assessment is based on the previously mentioned functionalities. The assessment enables the technologies to be categorised into two groups. The first group consists of the technologies that show low potential for the adoption in practice due to significant limitations. The second group consists of the technologies that have high potential for the adoption in practice. These latter technologies however still have some challenges to overcome in order to be ready for the adoption in practice. Both the low and high potential technologies are listed in the next paragraphs including an explanation for the classification.

5.1 Low potential technologies

In this paragraph the low potential technologies are mentioned including the limitations that cause it to have low potential for the adoption in practice for measuring layer thickness during paving operations. These technologies will be excluded from the remainder of this research. As mentioned before, the potential of a technology is assessed as 'low' if the technology has significant (unrealistic) challenges before it can fulfil all functionalities (as mentioned in paragraph 4.3).

Stress Wave

Stress Wave technologies are a group of similar techniques which make use of different analyses methods. All techniques are based upon sending stress waves (i.e., mechanical energy) through a medium by applying an impact at the surface. In this research the Spectrum Analysis of Surface Waves (SASW), Impact Echo (IE) and Ultrasonic Wave (USW) methods were analysed. All three methods are based upon a different type of analysis of the stress waves that are propagated through a medium. The propagation of a stress wave is depended on the material specific stiffness and propagation speed [20]. Each technology is explained briefly in order to get an understanding of the principles of the Stress Wave methods.

The SASW-method makes use of horizontal surface waves, which propagates through a medium after an impact is applied at the surface [20]. Such an impact can be caused by a hammer or a different impact source. The waves that travel through the medium are expressed in seismic energy, which directly relates to the stiffness of the material.

Another Stress Wave technology makes use of the Impact Echo (IE) method. As the name reveals, it sends an echo (i.e., stress waves) through a medium when an impact is applied at the surface. This method is different than the SASW-method since it analyses vertical stress waves which travel into the medium until they reflect on an interface or object [20]. Eventually the thicknesses can be derived from the elapsed time between the impact and the measured reflected stress waves (see figure 3). The reflected waves, which are propagated through the medium, are measured by nearby accelerometers [21].

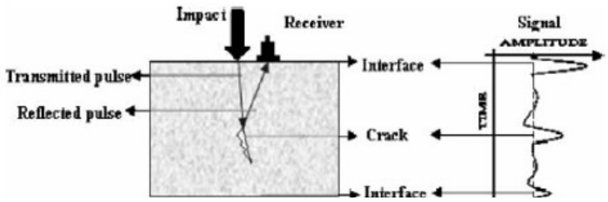

Figure 3: Conceptual description of IE-test [21]

The third and last Stress Wave technology analysed is the USW-method. This method is used to evaluate material properties in the near-surface zone of a medium by transmitting ultrasonic waves through a medium and recording the response of the object at two receivers [22]. The response of the medium is depended on the propagation velocity of the material.

According to Plati et al. [20] all methods have been used for several road construction applications, such as thickness determination. In the article of Edwards and Mason [23] all three methods were tested on asphalt and concrete pavements for thickness measurement. The results of the research indicate that the methods scored low on accuracy and applicability on asphalt pavements. According to the findings in this article this is caused by three characteristics of asphalt. These have been identified as problematic for the application of these methods during the paving process. The three effects that are caused by the characteristics of asphalts are: 1) temperature of the asphalt changes during paving which affects the stiffness of the pavement, 2) asphalt has a relative low stiffness which causes weak reflections of stress waves and 3) (changing) moisture and air contents in the asphalt affect the measurements.

According to an experienced user of the techniques, the technology needs to remain in place and in full contact with the surface while measuring. This makes the technology less suitable to be applied on a paver in motion. Besides, during usage it is experienced that measurements are disturbed by nearby vibrations (e.g., traffic, machinery). This is one of the prominent reasons for the relative low usage in practice [24].

To use the technology during the paving process for quality control purposes it needs to be able to deliver specific thickness results of only the constructed asphalt layer. Although the data is often presented in near real-time, both experts and the literature mention that the differentiation of layers is a challenge. For this reason and the aforementioned reasons this technology shows little potential for the purpose of measuring layer thickness of asphalt during the paving process.

Falling Weight Deflectometer

The falling weight deflectometer (FWD) is based upon applying pressure on a pressure plate by dropping a weight from a specified height in order to simulate a truck load on the asphalt surface [10]. Due to the impact on the plate a deflection (i.e., deflection basin) in the asphalt can be measured with multiple sensors. In general, the FWD is used for static structural assessments of asphalt pavements [25]. More recent developments report on a mobile application, called the Traffic Speed Deflection Device (TSDD) [10].

Normally the technology requires layer thickness as input data in order to back-calculate the pavement material properties [10]. In several studies the process of back-calculation is inversed, and the FWD-technology is used to determine layer thickness [10, 26]. According to Noureldin et al. [26] only the layer thickness data of the entire pavement can be analysed. This is also expressed by an expert in the field of FWD-data processing, since it is currently not possible to differentiate specific layers in the data. This makes the data not suitable for the purpose of monitoring thickness during paving operations.

Another major disadvantage of the FWD-technology is the accuracy, which is reportedly suitable for network level assessment, however not for quality control purposes [10, 26]. The accuracy of the FWD-data is likely to decrease when applied shortly after paving, since the changes in asphalt temperature and moisture content affect the stiffness of the pavement and therefore the deflection measurements. Furthermore, the technology is depended on input parameters for processing the deflection data into layer thickness, which affects the accuracy as well. This technology therefore has similar disadvantages as the Stress Wave methods. In comparison to the Stress Wave methods the FWD is applicable during the construction phase (if the asphalt is cooled down), since it is not disturbed by vibrations in the surroundings (e.g., traffic).

Even if the accuracy could be improved, with calibration measurements for example, the technology is still not capable of measuring close to the screed of the paver due to the changing asphalt characteristics. Therefore, it shows little potential for the adoption in practice for layer thickness quality control purposes.

Embedded Sensors

Embedded sensors have recently been getting attention from scientists for several applications in the road construction sector, such as monitoring asphalt tensions, deformations, and temperatures [27]. In order to measure these parameters, the sensors are placed on the surface before paving or are applied in the asphalt layer after paving. According to a researcher in this field, it is yet to be examined if the placement of sensors in an asphalt layer has an effect on the lifespan and quality of a pavement. Nevertheless, it has been successfully applied for monitoring compaction runs during paving operations according to Yiqui et al. [28].

This technology is taken into consideration in this research since Kara de Maeijer et al. [27] suggested that the data about the tensions in a pavement can be related to the stiffness of the pavement. With this data and a similar back-calculating technique as used for the FWD-technology, the layer thickness could be estimated. This reasoning is validated by an expert (researcher) in the field of embedded sensors. According to the same expert the technology has a major advantage over the other technologies which are examined in this research, which is the possibility to measure quality parameters during the consecutive construction and usage phase. This is possible since the sensors stay active, if they remain intact, in the asphalt layer after the construction phase is complete.

Besides the possibilities of the embedded sensors, there are some substantial challenges. According to the experts and the literature it remains a challenge for the sensors to withstand the high pressures and temperatures of the paving process [27]. Besides, the sensors are mainly tested in research and not in practice. The application of sensors in asphalt is therefore yet to be further developed.

It can be concluded that embedded sensors show potential for the future, however for now the technology is still too relatively new in research and not capable of measuring layer thicknesses in practice. Moreover, it first needs to be investigated what the effects are on the quality of the asphalt pavement (i.e., lifespan) and if the technology can actually play a role in delivering thickness data.

In summary the first group of technologies show little potential for the adoption in practice for measuring the layer thickness of asphalt during the paving process. The technologies are found not to be able to satisfy the predetermined functionalities, because of the following reasons: 1) the technologies are not suitable to be applied on a paver in motion, 2) it is not possible to measure/differentiate individual layer thicknesses, 3) the technologies are not capable of delivering accurate layer thickness data, and 4) the technologies are not applicable to measure layer thickness data of newly paved surfaces. The Stress Wave technologies, the Falling Weight Deflectometer and the Embedded Sensors therefore show low potential for the adoption in practice for measuring the layer thickness during paving operations.

5.2 High potential technologies

The second group of technologies have been identified as potential technologies for further developments. Eventually the developments have to lead to a fully developed technology for the quality control of layer thicknesses during paving operations.

Ground Penetrating Radar

This technology is a non-destructive technology for locating objects and assessing pavement material layer thickness and properties [29]. According to Maser et al. [12] the Ground Penetrating Radar (GPR) is seen as the most established technology, other than coring, for measuring pavement thickness. The GPR-technology is based on sending short electromagnetic pulses into the medium by an antenna. A part of the pulse reflects back to the antenna when a significant change in the dielectric constant of the pavement is encountered [30]. Such a change in the dielectric constant can be caused by a transition in materials or an object inside the pavement. Eventually, the elapsed time between the transmission and reflection of the signal is measured. Based on the dielectric permittivity (i.e., dielectric constant) of the material, the time and amplitude of the signal can be presented as data of the subsurface structure and its layer thickness. This principle is visualised in figure 4.

The GPR-technology can be divided into two categories based on the used antenna: ground-coupled antenna and air-coupled antenna [6]. The difference between the two technologies is the ground-coupled antenna remains in contact with the surface while measuring and the air-coupled antenna can examine the medium from above the ground (appr. 0,3 – 0,5 m1.) [20]. The application above the ground enables it to be applied while driving, which makes it highly suitable for the application on a machine in motion. Another difference is, the ground-coupled antenna usually emits lower frequencies, which makes it suitable for measuring deeper into a medium. On the other hand, higher frequencies are more often used in combination with air-coupled antennas, which results in higher resolutions of the surface layers. According to Shangguan et al. [6] the frequency selection is of high importance. The general rule is that the higher the frequency, the higher the resolution and the smaller the depth of investigation. It can be concluded that it is worthwhile to investigate the ideal type GPR and frequency for measuring layer thickness during paving.

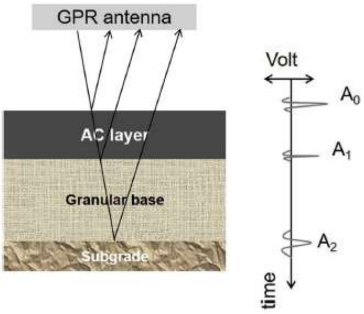

Figure 4: GPR principles [20]

Several studies show the GPR can measure layer thickness with sufficient accuracy for the quality control of asphalt pavements [10, 31]. Al-Qadi et al. [31] states that the accuracy increases with measurements on newer pavements, due to the more homogeneous dielectric constant. To increase the accuracy of the GPR-acquired layer thickness data, the technology needs to be calibrated [10]. The calibration ensures that the correct dielectric permittivity (i.e., dielectric constant) is used in the analysis of the data [32]. Several calibration methods can be applied, such as drilling cores, and laboratory measurements [32].

After the data has been collected the data needs to be processed in order to be suitable for the interpretation of layer thickness. This processing phase, which also requires 'filtering', relies on a high level of expertise of the data-analyst [9, 33]. The goal of filtering is to increase the quality of the data, which is mainly related to an increase in the signal-to-noise ratio (SNR) [33, 34]. In the research of Benedetto et al. [34] an overview is given of the mostly used processing techniques. Despite the dependence on intense processing techniques, Benedetto et al. [35] were able to present layer thickness data from GPR-measurements on a mobile device. Nevertheless, according to experts in the field of GPR-data processing, it remains a challenge to automatise these processing techniques in order to obtain layer thickness data in real-time.

Mitigating the influences of disturbances in the surroundings is another challenge. Measurements with the GPR-technology are disturbed if the dielectric constant of the medium is affected. This occurs when near perfect electrical conductors, such as steel slags, are present in the medium [10, 36]. Moreover, water is highly conductive and can therefore disturb measurements as well [36]. In a paper by Shangguan et al. [6] the GPR-technology was applied during the compaction process in which it was successful in applying a filter to mitigate the signal attenuations by water and air. According to GPR-experts filtering is also necessary for the disturbances of high frequency signals from nearby transmitting towers.

Overall, it can be concluded that the technology is fully developed for the adoption in practice. The next step is to start a pilot project with the application of a GPR for layer thickness quality control during paving operations. Therefore, the most suitable combination of GPR-antenna and frequency need to be examined for the purpose of measuring (top) layer thickness. Eventually the GPR-technology needs to become integrated on the paver in the most suitable location. For this application it is also important that the interferences are reduced, and the data processing process is automated.

Laser scanner

Another potential technology for the adoption in practice for measuring layer thickness during paving operations is the laser scanner. The laser scanner is a mobile surveying technique which can provide accurate, three-dimensional data (i.e., point clouds) [37]. The technology is known as 'laser imaging detection and ranging' (LIDAR). Data is acquired by sending a laser pulse towards an object or surface and by measuring the time of the returned signal [38]. This provides information of the distance of the object in relation to the position of the scanner. Together with the angle and speed of measurement, the height of the object can be determined. In order to generate layer thickness data, the height measurement after paving needs to be compared with the height measurement of the same location before paving [38]. For the alignment of data, the data from the exact corresponding positions need to be aligned. In order to get an exact position with each measurement, a LIDAR system needs to be equipped with a positioning system and an accelero-/inclinometer (e.g., IMU-device).

To process the distance measurement from the LIDAR-technology special processing software needs to be used [38]. With these techniques a virtual core can be extracted from the two aligned surfaces, which provides thickness information (see figure 5). It must be said that the analysis of point cloud data into layer thickness data is difficult and time consuming. The processing time depends on the size of the point cloud and the accuracy of the alignment of the two surface scans on the exact same position. The size of the point cloud depends on the laser frequency used and the desired point cloud density. In general, the more data points (dense point cloud) the more accurate the average layer thickness of a surface [16].

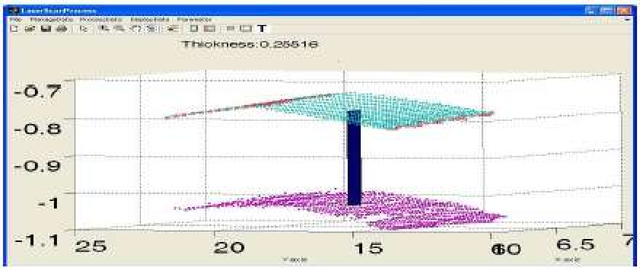

Figure 5: Virtual core [38]

According to the research performed by Puente et al. [37] the absolute accuracy of the technology lies around 7 – 9%. This is dependent on the type of LIDAR-system used. This is supported by the different accuracies that were registered in the research of Yen et al. [40]. In this research commonly used LIDAR-systems have been tested and compared. Besides the differences in accuracy, the different systems showed significant differences in the point density (i.e., measurements per second), range, and costs.

According to an expert in mobile mapping, the accuracy is highly depended on the accuracy of the positioning system for the alignment of the point clouds before and after paving. This might be increased by using fixed points along the surface for the calibration of the data. The accuracy and the range of the scanner are also depended on the reflectivity of the surface [37]. The research of Sluer et al. [5] showed that a wet surface (e.g., rain or a tack coat) caused a disturbance in the measurement. The pulses diffused on the surface instead of reflecting to the scanner.

It can be concluded that the technology has potential for the adoption in practice for the quality control of asphalt layer thickness. It can perform a non-destructive layer thickness measurement with reasonable accuracy. According to a researcher in this field, there are many developments going on for the improvement of the accuracy and the decrease in costs. A major challenge, for the technology to be adopted for real-time quality control, is the need for newly developed software to be able to automatically process the point cloud data into layer thickness data. The main challenge for this development is the accurate alignment of the data before and after paving at the exact same position.

Magnetic Imaging Topography scanner

The last potential technology for the adoption in practice is the magnetic imaging topography (MIT) scanner. This technology is able to detect magnetic reflectors by creating a magnetic field [41]. As most asphalt pavements have no effect on such a magnetic field, metal objects react with an 'answering' magnetic field which can be detected by the technology [17]. With this process the distance to the reflector can be measured through a medium. To make use of this technology, metal reflectors need to be placed on the subsurface before paving the top layer. Those reflectors can be detected after paving, which gives information about the thickness of the layer. This technique is already in use in several countries for the purpose of thickness measurements after the construction phase is complete (e.g., for collecting as-built information) [17].

The reflectors are often standardised, which are made for this purpose and delivered by the technology manufacturers. This ensures a correct and accurate measurement. According to Collier [41] the correct dimensions and type of reflectors have a significant effect on measuring the depth with a solid accuracy. In practice, the same reflectors are used for different measuring depths. McIver [17] mentions in his research that the reflectors have to be attached to the surface in order to ensure that the reflectors remain in place. It is recommended to do this with bitumen and not with nails, in order to keep the reflectors intact. According to Sluer et al. [5] the reflectors can be substituted for a type of aluminium foil. Although this seems a more efficient option, the usage of a foil instead of plates has some practical difficulties.

One of the main advantages of the MIT-scanner is that it is not prone to the varying circumstances in a paving process [41]. It is therefore suitable to be used in wet and dry conditions and with most types of asphalt. However, one disadvantage is often mentioned in the literature. The MIT-scanner interferes with nearby metals, such as machinery, guardrails and steel-toe boots [41]. Other interferences could occur with magnetic materials in the asphalt pavement, such as the use of steel slags as secondary materials. Another disadvantage is the technology depends on the placement of reflectors, which makes it bound to only local measurements. Nevertheless, due to the quick measurements the frequency of measurements can still be relatively high in comparison with taking cores [17].

Despite the aforementioned disadvantages, the technology is often used, partly due to its high accuracy and its ease of use. Several researches report a relative high accuracy (around 1%) in comparison with taking cores [17, 41].

When the pros and cons of the MIT-technology are analysed the technology shows a high potential for the further adoption in practice for measuring layer thicknesses for quality control. According to several experts the technology is sufficiently developed for the sector wide application through pilot projects in which users can get to know the new quality control method. To increase the attractiveness of the technology for this purpose, the technology needs to be fully automated. This means that the placement and detection of the reflectors needs to be performed automatically. For the automation it needs to be clear how many of, and at what positions, the reflectors need to be placed in order to get a representative image of the full pavement. Another option would be to substitute the reflectors for a reflective subsurface or a reflective tack coat. These new strategies for the ideal placement of reflectors, for the MIT-scanner to measure representative layer thickness for the whole surface, have to be investigated. Hereby the effect of the new placement strategy of reflectors on the adhesion between the layers needs to be examined.

In summary the second group of technologies are identified as potential technologies for the adoption in practice for measuring the layer thickness during paving operations. The technologies thus satisfy the predetermined functionalities and therefore show potential for fulfilling the intended tasks. Nevertheless, significant challenges have been identified. These challenges have to be overcome in order for the technologies to become fully ready for the adoption in practice. The remaining challenges will be discussed in the next chapter.

6. Remaining developments

The identified technologies are differentiated on the basis of potential for further development in order to be adopted in practice for measuring layer thickness during the paving process.

The GPR, LIDAR and MIT-scanner are identified as potential technologies for the adoption in practice. Each technology can be chosen for further developments, based on a user's (i.e., company's) preference. This preference can be based on many circumstances, such as the available resources or the desired type of data.

From the findings in paragraph 5.2 several challenges (i.e., future developments) have been identified that withhold the technologies from being fully ready for the adoption in practice. These challenges are transformed into future developments. The future developments have been mapped in a roadmap (see figure 6). A roadmap can be seen as a useful tool to link goals and actions in a stepwise plan [42]. The roadmap is based on the 'scenario-driven roadmapping' method [42]. This method makes use of the strengths of a roadmap, while taking the uncertainties of the future into account [15]. In the roadmap the adoption of each of the three technologies is seen as a separate scenario that is depended on the uncertainties in the future. The uncertainties in this research consist of the uncertainties of future technological developments, contract requirements, and an organisation's preference. By presenting three scenarios (i.e., three technology adoption roadmaps) the uncertainties in the future are of less importance and the roadmap remains usable.

The actions (i.e., developments) in the roadmap have been categorised into short-, mid- and long-term developments. By implementing these developments, the intention is to fulfil all the technological functionalities listed in paragraph 4.3. All identified developments have been categorised into technological developments (category A), software developments (category B) and developments in the stimulation of adoption (category C).

The categories, and the developments, are captured in a roadmap (see figure 6). In general, most developments are applicable to all three technologies. However, some developments are specific for one technology, which are therefor visualised in a colour which correspond to that technology. The developments in the roadmap will be described in paragraph 6.1 according to the identified milestones (A1, B1, etc.).

The roadmap differentiates developments on the short, medium and long term in order to show the developments in time. For the completion of all developments per category some requisites have to be present. These requisites are described in paragraph 6.2.

In the last paragraph of this chapter, several supporting recommendations are made to ensure that a fully developed technology is adopted with success. These supporting recommendations consider the link with the other quality control measurements and the needed preparatory work.

6.1 Roadmap milestones

The roadmap, as is displayed in figure 6, will be discussed according to the milestones. The milestones have been coded to systematically describe each milestone per category.

Category A, *'Technology development'*, is focused on the future developments that enable the current technologies to measure layer thickness during the paving process with ease of use. The category contains the developments which aim to make the technology; 1) suitable to be applied on a paver, 2) able to provide accurate data (including an accurate position), and 3) widely applicable with minimal interferences while measuring. Each of these targets have to be accomplished by several developments, which are grouped in milestone 'A1'. By reaching this milestone the technology becomes fully ready for the integration on a paver.

According to the findings in literature and the experts' input, before the integration can start it is important that some issues are examined first. An issue that needs to be examined is the most suitable setup of the technology, which consists of the selection of a suitable type, the settings (e.g., frequency) and the most effective position on the paver. An additional issue is the number of measurements that are needed to get a representative image of the thickness of the entire pavement width and length. The number of measurements can be altered by the number of aligned measuring points and the rate of measurements per timeframe (points/sec.). For the MIT-scan too many measurements can lead to a decrease in the adhesion between layers (due to the presence of reflectors), which weakens the structural quality of the asphalt pavement. Therefore, effects of reflectors on the adhesion between layers has to be examined first.

Together with the technological developments an accurate positioning system (relative or absolute) needs to be selected for the purpose of coupling a position to the data. Besides the position coupling, to obtain an accurate measurement the possible interferences of the technology need to be mitigated. These interferences are different for each technology, except for the interference of high conductors (e.g., metals) since this interferes with the measurements of both the MIT-scanner as the GPR. After the technology has gone through these developments (milestone A1) it becomes ready for the integration on the paver.

For the integration on a paver the technology needs to be coupled with a suitable positioning system and placed close to the screed on the pre-examined, most effective, position. For the LIDAR technology a positioning system also needs a coupling with an IMU-device (accelero-/inclinometer). When this milestone (A2) is reached it is possible to further optimise the technology.

Optimisations are necessary to create an economic viable application which will stimulate a sector-wide adoption in practice (milestone A3). According to the experts, a sector wide adoption necessitates that the accuracy and applicability of the positioning system (e.g., in covered areas) need to be improved as well.

For the next category, *'Software development'*, the developments are focussed on creating the needed software for measuring layer thickness and presenting it in real-time. These developments are different for each of the three technologies. The MIT-scanner is already fully developed for the automatic processing of layer thickness data. The LIDAR-technology on the other hand, needs to be combined with software that automatically compares the height data before and after paving. This then provides data about the paved thickness. A development in software for the GPR-technology consists of automating the process of differentiating layer transitions in order to determine the layer thickness of the paved layer. These developments combined lead to milestone B1.

Following the achievement of this milestone, the software needs to be expanded to filter interferences (e.g., nearby or underground interferences). This ensures a more accurate measurement of the pavement's thickness. The only development remaining is the development of software that can present the data in real-time. To

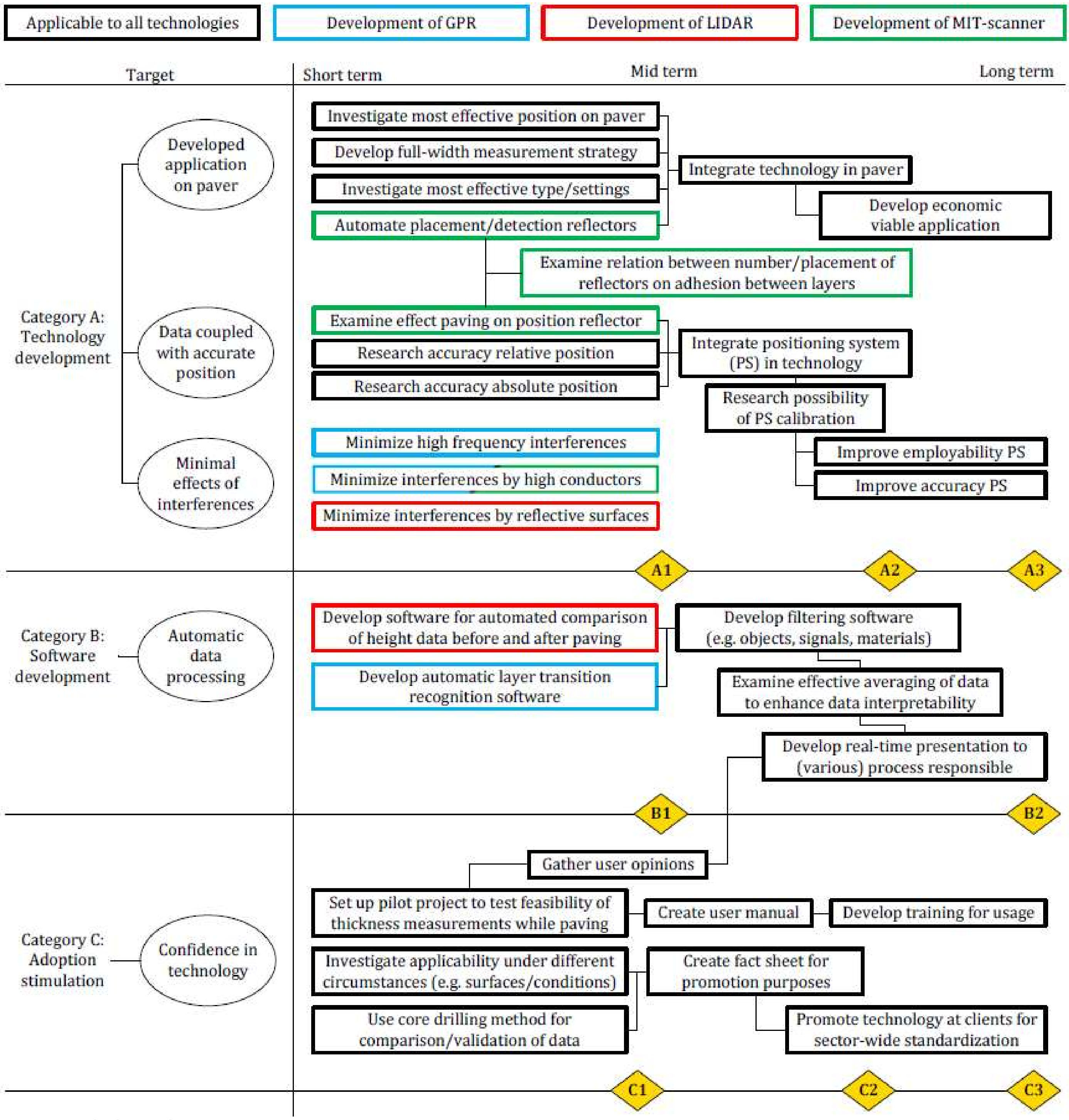

Figure 6: Technology roadmap

enhance the interpretability of the data it is important to determine if, and how, the data needs to be averaged to give only structural layer thickness data. Averaging might also be needed since structural deviating layer thickness is often undesired, while a local deviating thickness can be beneficial for the smoothness of the pavement. Eventually all software developments lead to a technology that is ready to be used for measuring and presenting layer thickness data in real-time (milestone A3).

The last category, 'Adoption stimulation', focuses on ensuring that the technology will be standardised (sector-wide) and accepted by clients. For this milestone it is important to introduce the technology in a pilot project. In such a pilot project the practitioners can get used to the new method of quality control. This might also expose new challenges which have to be addressed. According to the experts, it is important to compare the results of the new method with the conventional method (i.e., drilling cores) until enough confidence is found to replace the conventional method. The added value of the new technology also needs to be confirmed by testing it under different conditions, such as different weather types and asphalt surfaces. In general, a pilot project also gives an opportunity to gather user opinions, which can be used to create the desired data presentation interfaces and the desired controls. Involving users increases the support for the innovation as well. In the end the technology is fully examined and introduced (milestone C1) and can be further integrated.

In order to produce similar (reliable) outcomes at different applications it is important to create a user manual (i.e., standard/ protocol) (milestone C2) by gathering information from the pilot project(s). This manual can also be used in special trainings to teach users the purpose of the technology and how to work with the technology (e.g., demounting, calibrating). Besides the users, also the clients, and advisors need to be convinced of the added value of the technologies. This can be accomplished by gathering information in the pilot project(s) which form a fact sheet of the performances (e.g., accuracy, applicability, costs). Eventually the technology must be supported by clients, advisors and other stakeholders. This will further stimulate the development of the technologies and the sector-wide standardization (milestone C3).

6.2 Requisites for development

In order for the technologies to be developed some requisites have to be present. This paragraph discusses the main requisites per category of developments.

For the technological developments (category A) the technology itself and the available supporting systems (e.g., GPS, LPS, IMU) need to be available. These can be integrated on the paver and used for further developments. For some of these, more specific, developments possibly the developers of the technology and supporting systems must be involved.

Category B (software development) primarily needs the presence of human resources to develop the software of the technology. Therefore, sufficient knowledge/experience in software development and data processing is needed. This can also be outsourced to experienced third parties.

The third category, which focuses on stimulating the adoption of a technology, depends on the acceptance of practitioners (e.g., users, project leaders) and clients. This category therefore needs an open-minded construction crew that is willing to pilot with the project. An organisation needs to have adequate resources to purchase a technology and its supportive systems. Furthermore, a representative from the company should be appointed to guide this stimulation phase (e.g., correct testing, creation of standards, promotion at clients).

6.3 Standardisation of asphalt layer thickness measurements during paving operations

Besides the recommendations for developing a technology that can monitor layer thickness, other supportive recommendations have been identified from the literature and the expert interviews. These recommendations must be taken into consideration in order to standardise the measurements of the layer thickness of asphalt during paving operations. They can therefore be seen as supportive recommendations.

The already mentioned developments are derived from the current state-of-the-art literature and expert opinions. This data can change over time, if the circumstances alter (e.g., market conditions, quality requirements). The identified developments, which are mentioned in the roadmap (figure 6), are therefore recommendations for this specific moment in time and remain applicable if the circumstances remain the same.

As mentioned before, it is important to first think of which technology suits the organisation/sector the best. This could be based on the purpose(s) of the dataset, the current knowledge/experience, or the available resources. It could also be based on the most suitable interaction/connection with the other technologies present in the paving process (e.g., temperature scanner, compaction monitoring). Eventually all systems need to work together to improve the quality of the paving process and eventually the quality of the asphalt pavement.

One more consideration that has to be taken into account, which can alter the choice for a technology, is the amount of desired data. Insufficient data gives only insight in the local layer thickness and excessive data can cause the datasets to become unmanageable. The amount of data is sufficient if it gives a representative image of a pavement's layer thickness in both the width and the length.

Representative data eventually needs to be presented to the practitioners. A screed operator therefore needs a different presentation of data than the project leader. It should therefore be considered how the data is presented to each stakeholder.

Most desirably the measurement takes place as close to the screed of the paver as possible to detect a deviation as early as possible. This means that the measurement is performed in an insufficient compacted layer, since the compaction phase is yet to begin. The asphalt at this moment in the process is pre-compacted by the screed. Data of the desired pre-compacted layer thickness therefore needs to be gathered in order to get the desired layer thickness after the pavement is fully compacted. In order to determine the change in layer thickness before and after compaction, conversion factors per type of asphalt and for each screed need to be provided. This can be provided from laboratory tests and should be documented in a standard.

The measurement close to the screed focuses on paving the desired layer thickness before compaction. To deliver the desired layer thickness after compaction the compaction phase also needs to be in full control and executed as it is intended. It is therefore a general recommendation to focus on the adoption of compaction monitoring technologies alongside the adoption of technologies that monitor the layer thickness. Besides, the thickness before compaction should be determined per type of asphalt. The thickness closely behind the screed can also be depended on the extent of pre-compaction of the screed. These factors should be taken into consideration for the development of a technology for the purpose of measuring the layer thickness behind the screed during paving operations.

Eventually, for a sector-wide adoption of a technology it is evident that the price of the technology needs to be within boundaries. This could be viewed from the perspective of the cost per measurement. Experts in the field of these technologies have been seeing a significant decrease in costs and an increase in performance over the last couple of years. This is substantiated in the literature according to the noticeable changes over time in the performances. A technology is therefore never fully developed, since technology developers always strive for optimisations.

7. Discussion

In this research a certain strategy is chosen to obtain the data for the analysis of each technology. This eventually helps to fulfil the

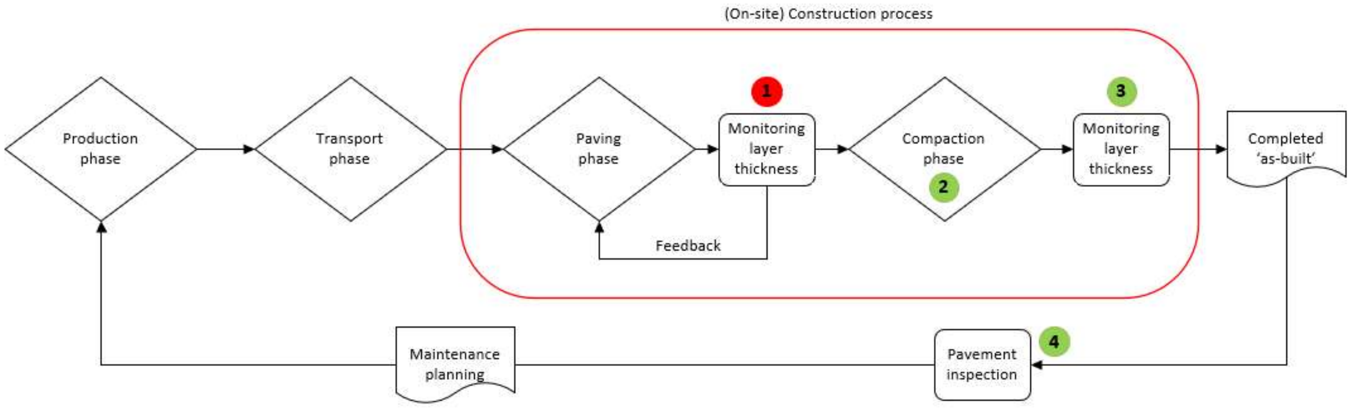

Figure 7: Construction process applications

goal of this research, getting an overview of the readiness of technologies for measuring layer thickness during the paving process. By choosing this strategy some limitations arose. These limitations are discussed in paragraph 6.1.

As mentioned, this research focuses on the application of a technology close to the screed to detect deviations in the layer thickness as early as possible. Therefore, it is also interesting to discuss what the other purposes are of a fully developed technology. This multi-purpose view on the technologies' potential might stimulate the developments for future adoption even more.

7.1. Research Limitations

The limitations of this research primarily consist of the unbalanced focus on certain technologies in comparison to the other technologies. Eventually this might result in an incomplete dataset, since not enough focus is put in gathering all state-of-the-art data about each of the technologies. The following limitations have been identified:

- *Gathered data is incomplete*. The data is gathered by reviewing literature and conducting expert interviews. This research is performed in a timeframe of 20 weeks. Due to this limited amount of time it might occur that not all findings in literature are gathered and that not enough experts have been interviewed to validate all findings.
- *Difference in focus*. This research is depended on the gathered literature and the input of experts. Therefore, a difference is noticed in the amount of literature and experts per technology. For instance, the GPR is further developed and therefore has more scientific publications and user experts. This causes an unbalance in the data, which might influence the results. Nevertheless, the focus has been to gather as much literature as possible for each technology and to involve as many, and at least one, experts per technology.
- *Experts' knowledge and experience differs*. The findings from literature have been validated by experts which have knowledge regarding the technology or have experience using it. It is questionable if the knowledge and experience of each expert is sufficient to validate the data from literature. This could have resulted in erroneous validations and/or an incomplete validation of the data.
- *Promotional behaviour experts*. Since experts have practical experience or knowledge from a technology, they are involved to validate the data. Some of these experts are employed by companies which rely on selling the service of employing such a technology for the assessment of pavements, therefore they could benefit from a positive outcome. It might have occurred that their input mainly consisted of positive validations instead of negative validations. This has been mitigated by confronting each expert with both the negative as positive statements out of the literature.

7.2 Opportunities for other purposes

The goal of this research is to obtain an overview of technologies that are able to measure layer thickness as close to the screed as possible. This position in the process is chosen in order to detect a deviation in the layer thickness as early as possible.

During the review of literature and the expert interviews other possibilities have been identified for applying a non-destructive technology which measures layer thickness. These possibilities will be discussed according to the overview of the different construction phases of an asphalt pavement. The position which is focused on in this research is pointed in red (see figure 7) and the other positions are visualised in green. The positions are discussed in the sequence of the numbers.

1. The first position is the position close to the screed (during paving). Besides gathering layer thickness data for providing feedback to the screed operator, the measurements can also be used to determine the consumption of asphalt for a certain constructed pavement length. With this insight in the production/consumption of asphalt for the constructed pavement, the needed amount of asphalt can be calculated for the remaining length of the surface. This data helps with planning the right amount of asphalt to be produced and transported.

   Layer thickness data behind the screed can also be used to better predict the process of cooling of an asphalt pavement. With the combination of layer thickness data, and temperature data behind the screed (temperature scanner), a better prediction of the cooling rates of asphalt can be made. This can lead to more accurate estimations of the time window in which the asphalt has the right temperature to be compacted.
2. An additional possible application is to position the layer thickness measuring technology on a compactor. By applying it on a compactor the layer thickness data can assist in determining the density of the pavement. The density is derived from the layer thickness, so the data is very useful and applicable for this purpose as well. This

eventually needs to result in a better compacted asphalt pavement.

3. By applying the layer thickness measuring technology on the last compaction run, or even later in the process (e.g., on a cleaner), data can be gathered for the as-built drawings. These drawings are a representation of what has been constructed and are often required by the client.
4. The last possible application is to apply the technology on a vehicle in order to measure layer thickness while inspecting the road. In case a road is identified as in need of maintenance, the inspected layer thickness can be used to better prepare the maintenance and the corresponding contract.

8. Conclusion

In this research an overview is created of the technologies with the most potential of being adopted in the future for measuring layer thicknesses during the paving process. These measurements can be used as feedback to the screed operator to optimise the layer thickness in case a deviation is detected. For this purpose, a total of six technologies have been reviewed. It appeared that not all technologies had high potential for being adopted, since the challenges that had to be overcome were too difficult or were inherent to the nature of the measurement for some technologies. Eventually, assessing the technologies on the basis of their potential for the future adoption in practice led to the identification of three potential technologies.

The technologies which were identified as potential for the future adoption in practice are: the GPR, the LIDAR and the MIT-scanner. All three technologies can measure the layer thickness of asphalt in a non-destructive manner. For the application of measuring the layer thickness for quality control purposes, challenges were identified for each technology to be addressed.

These challenges have been converted into future developments and have been gathered in a roadmap. In this roadmap three scenarios are displayed, corresponding to the development of each of the three technologies. In general, most developments are generic for all three technologies. These are mainly focused on:

- Developing an application which is suitable to be integrated on a paver.
- Coupling the thickness data with an accurate position.
- Minimising the effects of interferences.
- Automating the processing/filtering of data.
- Stimulating the adoption of the technology.

The developments have been divided in short-, mid- and long-term developments. By following the stepwise developments according to the roadmap (see figure 6), each technology will be fully developed to become ready for the adoption in practice.

During the gathering of data out of literature and the expert interviews a trend is identified in which contractors are increasingly interested in monitoring key parameters in the construction process. Their main motivation for their increasing interest is that if the process is more in control, the quality of the product will be improved, which results in a higher profitability, less impact on the environment and a higher durability of the product. This motivation has to be further propagated throughout the sector, and by all stakeholders (e.g., clients), in order to stimulate the adoption of monitoring technologies and to improve the overall quality of the asphalt pavements.

It can be concluded that several technologies show potential for detecting a deviation in the layer thickness during the paving process. These technologies can therefore be used to assist the paving crew with achieving the desired layer thickness, and therefore to prevent the occurrence of the negative consequences of a deviating layer thickness. Since the negative consequences are significant and evident, the monitoring of layer thickness during paving operations should therefore be standardised in the road construction sector.

The identified technologies can replace the local thickness measurements and can provide both the client and the contractor with useful information about the quality of the construction process and the asset. Before the current practice can be substituted, some challenges must be met and overcome. The challenges identified can be solved by following the proposed roadmap. Eventually the monitoring of layer thickness becomes another addition to the trend of monitoring key parameters of the paving process. It can therefore be included in the PQi-methodology. In the end this all leads to more durable, more financially viable and higher quality asphalt pavements.

9. Acknowledgements

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