Planning the asphalt construction process- towards more consistent paving and compaction operations

C.G. Arbeider[12], S.R. Miller[1] A.G. Dorée[1], M. Oosterveld[2]

1. *University of Twente - Department of Construction Management and Engineering, Enschede, The Netherlands*
2. *BAM Infra, Gouda, The Netherlands*

ABSTRACT

This research addresses the challenge of linking paving and compaction given that they are mostly treated as detached activities, leading to a decrease in the quality of the compacted asphalt layer. The objective was to develop a support tool that can assist decision-making related to equipment allocation and compaction strategies to be followed, such that an asphalt layer- given the prevailing conditions at the construction site- can be compacted efficiently and uniformly within a limited time interval. A basic planning protocol was then developed based on variables such as asphalt cooling, paver characteristics, roller characteristics and road geometry. 12 road construction projects were monitored over a 3-month period. Empirical data on paver speed, roller speed and the number of roller passes served as input for the tool. The monitored projects were evaluated by calculating actual paver output and theoretical and actual roller output on an interval scale and checking whether the output rates were aligned to each other during the whole construction process. The results show that in most cases, paver output, roller output and the available time for compaction were not aligned. The theoretical concepts applied in this research and the developed support tool for decision making appear to be useful for planning and monitoring paving and compaction and for steering it towards a more uniform process. This may lead to an improvement in the quality of the final compacted asphalt layer.

Keywords: Road construction, asphalt compaction, roller capacity, roller output, paver output

1. INTRODUCTION

Since the 1990's innovative contract forms have emerged in the Dutch construction industry [1, 2]. These innovative contract forms are characterized by contractors having to provide design solutions, longer guarantee and warranty periods on the work they deliver, maintenance and damage costs to the contractor and penalties for disturbing traffic flows during maintenance activities [3]. Divergent market dynamics and major changes in the economic environment result in higher risk profiles for the construction companies. Contractors face different "rules of the game" than what they were used to and face a new set of challenges regarding the final quality of the constructed asphalt layers. Challenges include high guarantee-requirements (five years is standard for regular projects) and challenging maintenance periods (twenty years for large highway projects). During these long guarantee - or maintenance periods, every unexpected traffic disruption caused by road damage or repair work will result in severe penalties for closing lanes. During rush hours penalties of 5,000 EUR per traffic lane per hour are normal for highways of strategic importance. This means that one simple pothole in a critical and vulnerable porous surface-layer, for instance as a result of unfortunate local lack of compaction caused by an imperfect paving- or compaction-process, may cost over 20,000 EUR in fines and 2,000 EUR repair-costs if the pothole is not repaired within 4 hours' time. It is easy to imagine that costs will rise enormously when you take into account that contractors are also responsible for the appropriate timing of the surface-replacement, twelve to fifteen years after the initial construction. This requires thoroughly developed risk-assessments which is only possible when circumstances, asphalt-production and paving-quality are at an optimal level.

There is wide agreement that the construction phase is important for achieving the desired quality of the asphalt layer [3, 4]. It is in fact the last opportunity to get it right. Failure to do so may result in extensive variability in the final product which in turn, may lead to early, unplanned maintenance and unnecessary costs to contractors and public clients alike. Given the risks highlighted above, one would expect contractors to focus on and control their primary processes to minimize variability during construction. However, studies conducted over the past decennia have shown that for asphalt construction, work methods are often based on tacit knowledge, experience and craftsmanship and, operational instructions for the asphalt crew are often unclear or even missing. It appears that operators mostly work on the basis of gut feeling and adopt work methods based on experience gained in previous projects [5-8]. A lack of method-based strategies has been shown to result in operational discontinuities and extensive variability in key process parameters such as temperature homogeneity of the asphalt mat and compaction variability [9]. This ultimately results in a decrease in the final quality of the constructed asphalt pavement layers [10].

2. BETTER PLANNING – A NEED TO ALIGN PAVING AND COMPACTION

Imperfect planning from production through to compaction and more specifically, non-alignment of the paving and compaction processes, may lead to discontinuities in the construction process, extensive variability and a lowering of the quality of the final compacted asphalt layer. Also, in order to improve current work methods as used on construction sites and to reduce variability, it is necessary to adopt more method-based operational strategies rather than those based on experience and tacit knowledge [8]. To achieve this, the relevant operational parameters need to be identified and the relationships between them examined. By reducing variability and improving the uniformity and continuity during the construction process, it is likely that this will result in an improved final quality of the asphalt layer [4]. A uniform and continuous paving process is a prerequisite for a good quality asphalt layer [11-14].

This in turn requires proper work preparation and organization of the paving process. An alignment between the four traditional phases of the asphalt construction process – production, transport, paving and compaction – is essential [15]. However, a barrier to good organization and preparation is that the four phases are often seen as distinctly separate phases where little or no alignment is thought of in the planning phase. As an example, studies show that discontinuities in the transport of asphalt to the construction site often results in too few or too many trucks in the logistics cycle [16, 17]. This results in paver stops which in turn, results in variability in temperature homogeneity of the asphalt layer (as illustrated in Figure 1), variability in compaction and ultimately, undesired mechanical properties of the constructed asphalt layer [10, 18, 19].

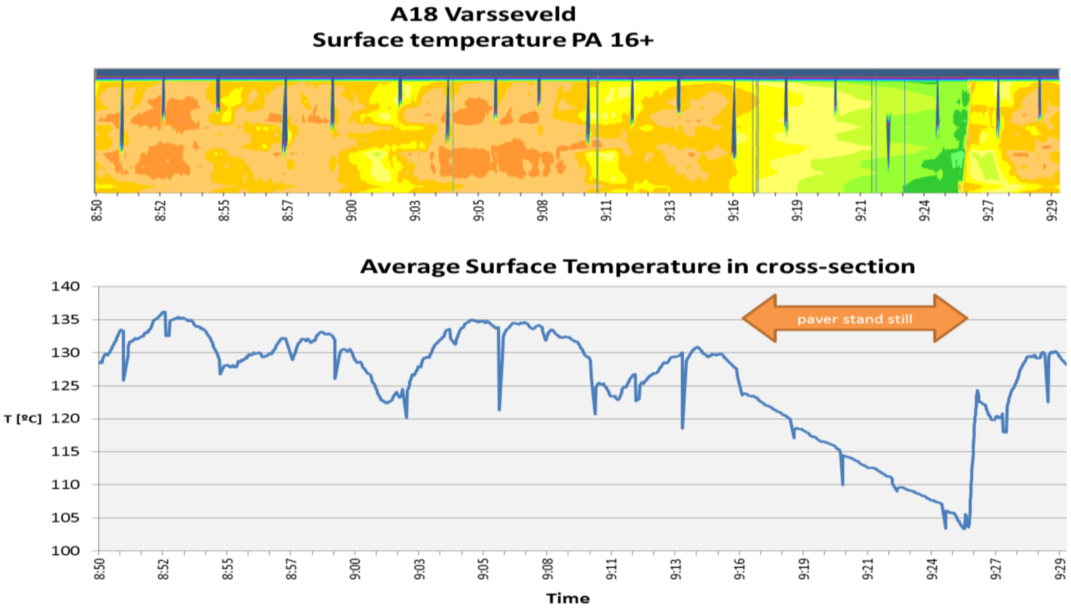


FIGURE 1 Typical temperature variability as result of a paver stop

Also complicating the planning and execution of the asphalt construction process, is the fact that the temperature of the asphalt layer decreases under the influence of several environmental factors [20, 21]. Roller compactor operators therefore have a limited time period in which the compaction process has to be performed [9, 22-24]. According to Kari [1967] as cited by [9], two problems can occur during the compaction of asphalt mixtures. An asphalt mixture can be overstressed (often at too high temperatures) or the mixture can be understressed (often at too low temperatures). In an overstressed situation, a lack of stability of the asphalt layer results in the situation that the layer cannot support the weight of the roller compactor, while in a understressed situation the compaction force is too low to increase the density of the of the asphalt mixture. Both situations result in compaction taking place in a non-optimal temperature and time-frame and therefore may result as mentioned earlier, in undesired mechanical properties of the constructed asphalt layer.

It is clear that the asphalt construction process is complicated and is influenced by several factors. Many operational and environmental variables have to be taken into account [13]. Therefore, proper planning of a rather complex construction process is vital if contractors are to achieve the goal of constructing high quality asphalt layers. The leading question then is what should drive the process? Which process indicator should contractors be paying attention to and using to plan and align the construction process in such a way that variability is reduced and high quality is achieved? There is broad agreement that a continuous paving process results in good overall temperature homogeneity of the asphalt mat whilst a non-homogenous asphalt mat temperature leads to density differentials and undesirable mechanical properties [19, 25, 26].The speed of the paver therefore appears to be a good indicator for the degree of continuity in the paving process [4]. A key issue in determining the speed of the paver is to consider the available roller capacity and to ensure that the roller capacity will not be exceeded. If the output of the paver exceeds the roller capacity, the roller or rollers will fall behind the paver. On the other hand, if the roller output exceeds the paver output, the roller(s) will catch up the paver [27]. Both situations affect the consistency of the paving process negatively. Ideally, the paver output rate should equal the roller output rate [28].

Considering the relationships that exist between optimal compaction, available time for compaction and the quantity of asphalt to be compacted (in m^2 or tons) as a result of the paver and roller output rates, choices have to be made regarding the number, type, dimensions and sequence of rollers and roller speed [15]. For the compaction process, multiple roller types are available and various rolling procedures or strategies can be applied, depending on the geometry of the road [29]. However, as mentioned earlier, the selection of work methods and equipment allocation is largely based on experience, while the choices made will have a major impact on the final quality of the asphalt layer. Making the selection procedure of work methods and equipment allocation more explicit, can lead to a reduction in variability and can contribute to the further professionalization of the road construction sector.

To sum up: Roller operators have to undertake the asphalt compaction process within a limited time and temperature interval in order to achieve desired mechanical properties. With the aim of delivering a good quality asphalt layer, roller operators should make optimal use of this time and temperature “window of opportunity”. However, until now, little is known about how this limited time interval should be used in an efficient and consistent manner with respect to operational variables such as paver speed, number of roller compactors, type of roller compactors, average roller speed, characteristics of the road to be constructed and the relevant relations between these variables. This lack of knowledge complicates the tactical planning of equipment to be used and the compaction strategy to be followed for each specific construction project.

Therefore, this paper presents a method to align paver output with roller capacity based on various operational variables and taking the available time for compaction into account. When paver output and roller capacity are aligned, this will result – at least theoretically – in a more uniform and continuous paving and compaction process. The method should help construction planners with equipment resource allocation decision-making regarding for example, the number of rollers required. It should also be able to generate alternative operational strategies given varying circumstances that the machine operators can apply in their machine settings. This paper is structured in the following way; After this introduction, the objective and approach of this research are described. The fourth section summarises the relevant variables influencing the compaction process and the relations between these variables. Section five describes the proposed paving and compaction alignment procedure, which can be seen as the result of this research. In section six, the monitoring of actual asphalt construction projects is described briefly. Finally, the benefits, main drawbacks and pointers for future research are discussed in a closing section.

3. OBJECTIVES AND APPROACH

The objective of this research was to set up a supportive method which can help decision making in the field of equipment allocation and operational compaction strategies to be followed, such that an asphalt layer – given the prevailing conditions at the construction site – can be compacted efficiently and uniformly within the limited time interval. Overall, the aim was to give more insight in the relevant operational variables and to improve the understanding of the relations between these variables. If these relations are well understood, the consequences for the paving and compaction process can be assessed when values of the different variables are altered.

In order to achieve the objective of this research, relevant variables of four aspects of the asphalt construction process (cooling of asphalt and characteristics of paver, roller and road geometry/design) have been defined based on a literature study. Subsequently, the relations between these variables have been defined both qualitatively and quantitatively. Based on these variables and relations, together with some basic characteristics of the asphalt construction process, a basic planning procedure has been defined. Basically, this planning procedure serves as a Decision Support Tool (DST) for planning asphalt construction works.

4. RELEVANT VARIABLES AND RELATIONS

Based on a literature review, this section describes the most relevant variables and characteristics on four aspects of the asphalt construction process. The variables are presented in Table 1. The variables influencing the cooling of the asphalt layer can be categorized into three categories; mixture characteristics, weather conditions and subsurface conditions. All paver variables defined can be chosen/adjusted (within the limits) by the paver operator. The same applies for the variables of the roller, except for the roller width. All characteristics of the road geometry are set during the design phase and cannot be changed during the construction phase. However, the road design will affect the method of construction in terms of roller patterns [28], mechanical or manual spreading of the mixture [27], and other operational settings of the equipment. Also, it is likely that this in turn will affect the output rate of both the paver and the roller.

TABLE 1 Relevant variables

Cooling		**Paving**		**Compaction**		**Road geometry**	
Variable	*Lit. ref.*	*Variable*	*Lit. ref.*	*Variable*	*Lit. ref.*	*Variable*	*Lit. ref.*
Mixture characteristics (-)	11	Speed (m/min)	28 30	Number of rollers (-)	31	Type of mixture and layer (-)	28 31 32
Layer thickness (mm)	11 12 15 27	Operating width/screed width (m)	30 31	Speed (m/min)	31 32	Layer thickness (mm)	28 31 32
Delivery and paving temperature (°C)	11 12	Areal output (m^2/min)	31	Number of passes (#)	31 32	Width (m)	28 31
Weather conditions, including: ambient temperature (°C), wind speed (km/h), sky conditions (-)	11 12 15 27			Width (m)	31	Length (m)	28
				Overlap (m)	28 31	Curves (-)	28 31
				Length of roller track (m)	31	Longitudinal and transverse joints (-)	28 32
Temperature of subsurface (°C)	11 12			Distance paver-roller (m)	28	Kerbs/obstacles/speedbumps/manual work etc. (-)	28
				Areal output (m^2/min)	31		

Source (Literature reference): [11, 12, 15, 27, 28, 30-32]

We acknowledged that dynamic (vibrating/oscillating) compaction variables (amplitude and frequency) could be a relevant compaction variable. However, in Dutch practise dynamic compaction methods are not (or barely) applied on regular road sections.

The variables as defined in Table 1 are related to each other. In Figure 2 these relationships are illustrated. For example; the areal output of the paver is influenced by the paver speed and the paver width. The paver width in turn is influenced by the width of the road to be constructed. In the centre of the figure, the symbol representing the alignment between available time for compaction, paver output and roller output is placed. In section 4, the relations are defined quantitatively.

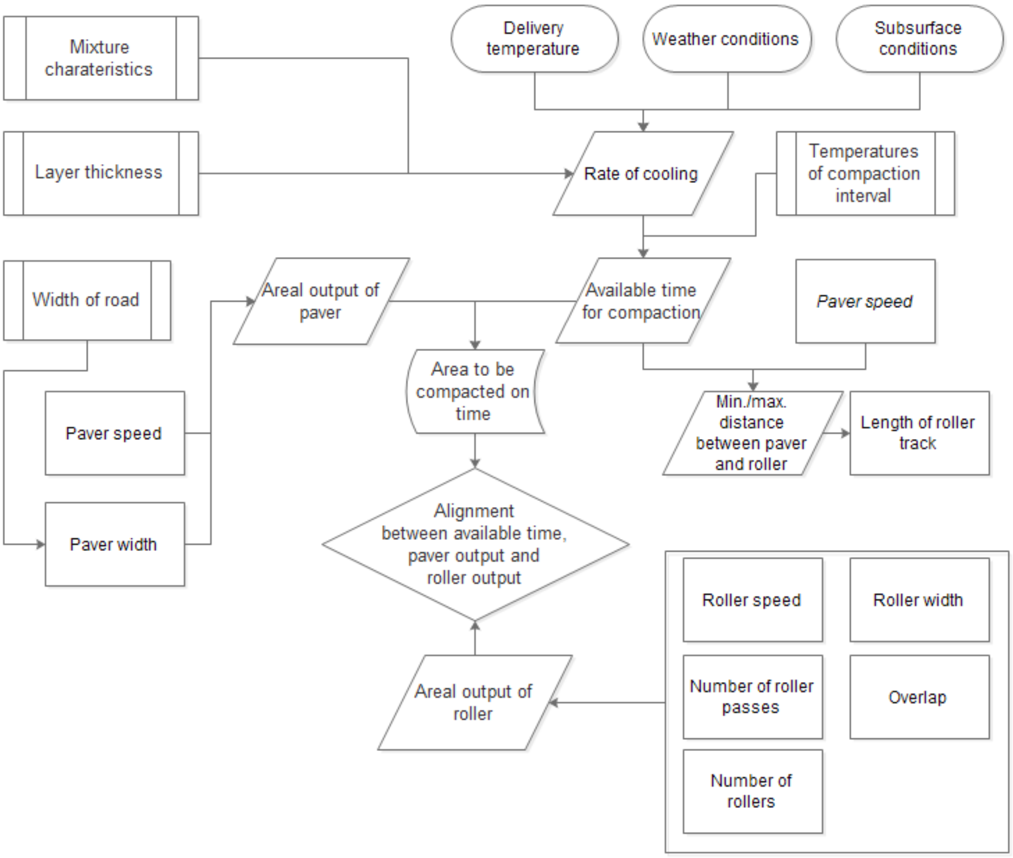


FIGURE 2 Relations between relevant variables

5. BASIC SETUP OF THE PLANNING PROCEDURE

5.1 The leading factor

In the planning/preparation phase, the method for aligning the paver output with the roller output can be applied in two different ways, as can be seen from Figure 2. From two sides, arrows lead to the ‘alignment symbol’. One has to make a choice what will be the leading factor in the DST. The first option is to take the paver output as the leading factor i.e. theoretically the speed of the paver can be chosen freely, without any constraints. As a consequence, the operational values of the roller variables (speed and length of the roller track) will be imposed values in order to match the roller output with the paver output. If the paver speed is leading, one should critically examine whether the intended roller equipment allocation (in most cases the standard roller set) offers sufficient capacity. If not, an extra roller should be allocated to the project. However, availability and cost aspects have to be taken into account as well. The second option is to take the roller output as the leading factor. In this case, the speed of the roller(s) can be chosen freely, without any (theoretical) constraints. As a result, the speed of the paver will have an imposed value. However, in this case one should critically examine whether the productivity targets will be met.

It can debated what the most favourable option is. In general, two rationales have to be balanced. One can increase the paver speed at the costs of the extra resources needed (extra roller, operator, fuel etc.) (rationale underlying option 1) or one can deliberately limit the roller capacity and thus decrease the paver speed, which may result in a reduced productivity (rationale underlying option 2). For each specific project both options have to be assessed. If the alignment calculation has to be made on-site just before the paving and compaction process starts, method 2 should always be applied since roller capacity would be fixed in this case.

It should be mentioned that production rate and delivery rate of asphalt can be leading factors too. However, this research focusses primarily on paving and. The production and transport phases are not within the scope of this paper.

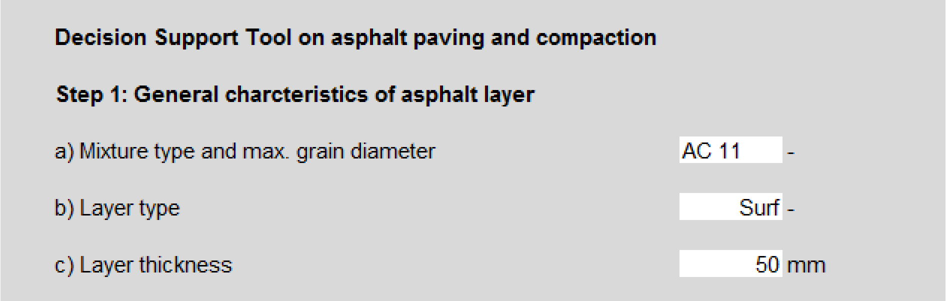
5.2 The six steps of the alignment procedure

The core of the alignment method is formed by a number of equations. Five rather simple equations (eq. 1-5) are drafted by [28]. These equations express most of variables and relationships as defined in section 3 quantitatively. By applying these formulas, the paver output and roller output can be calculated. In order to plan a uniform compaction process, the basic thought is that values should be selected in such a way that the output of the paver equals the output of the roller or rollers. This alignment procedure comprises six steps. The first 4 steps are of a general nature and have to applied for both option 1 and option 2. Starting from step 5, one has to choose whether to follow option 1 or 2.

To assist planners in applying the alignment procedure, an Excel-based interface has been created, in which all relevant formulas are predefined. Thus, planners only have to insert values for a limited number of variables. This increases usability and decreases the time required for applying the method. In the following section, the six steps are explained in more detail. For purposes of illustration, each step in the Excel-based interface is presented. It should be noted that the variables presented on the interface screenshots serve as an example.

5.2.1 Step 1: Definition of type of layer, asphalt mixture and layer thickness

The first step comprises the definition of general characteristics of the asphalt layer. This includes the selection of layer type (base, binder or surface layer), type of asphalt (e.g. asphalt concrete, stone mastic asphalt or porous asphalt) and layer thickness (normally in the range of 20 mm to 90 mm, with 5 mm intervals).



Decision Support Tool on asphalt paving and compaction

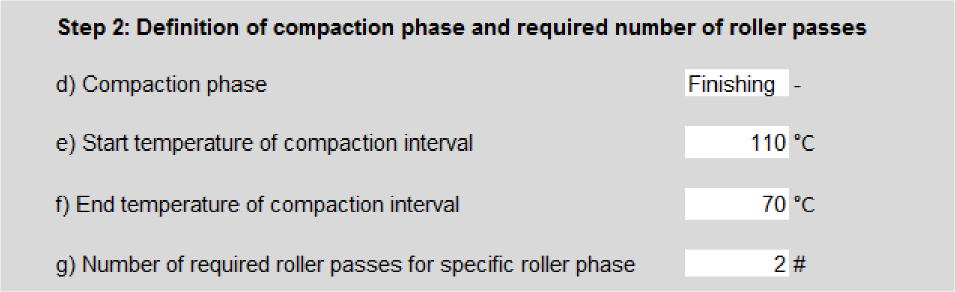
Step 1: General charcteristics of asphalt layer

a) Mixture type and max. grain diameter	AC 11	-
b) Layer type	Surf	-
c) Layer thickness	50	mm

5.2.2. Step 2: Definition of compaction phase and required number of roller passes

In the second step, the different compaction phases have to be taken into account, as the alignment has to be made for each of the three compaction phases. The three compaction phases are; breakdown rolling, intermediate rolling and finishing rolling. Each compaction phase is characterized by a specific temperature interval range. [4, 33]. The temperature boundaries have to be known in order to calculate the available time for compaction for that specific roller phase.

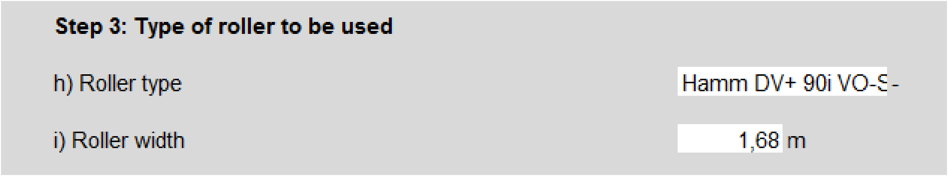
Step 2 also comprises the definition of the required number of passes, taking the characteristics as defined step 1 into account. The required number of passes should be determined with the help of the Quality Control department, by taking nuclear density readings after each roller pass [33]. When determining the required number passes, the type of roller and operation mode have to be taken into account [28]. This makes the presented method an iterative process, as the type of roller is defined in step 3 and the operation mode in step 5.



Step 2: Definition of compaction phase and required number of roller passes		
d) Compaction phase	Finishing	-
e) Start temperature of compaction interval	110	°C
f) End temperature of compaction interval	70	°C
g) Number of required roller passes for specific roller phase	2	#

5.2.3 Step 3: Definition of roller type to be used

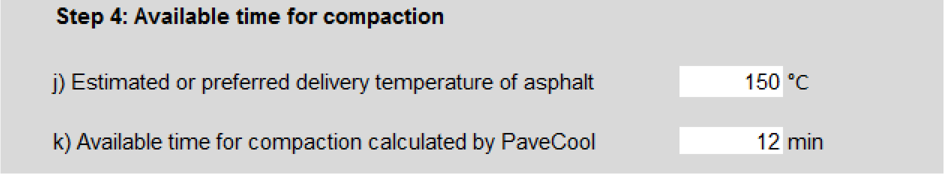
In the third step, the type of roller per specific roller phase must be specified. In particular, the operating width of the roller has to be known, as this variable is required for calculating the roller output rate.



Step 3: Type of roller to be used		
h) Roller type	Hamm DV+ 90i VO-S	-
i) Roller width	1,68	m

5.2.4 Step 4: Determining the available time for compaction (e.g. with aid of PaveCool)

In the fourth step the available time for compaction has to be determined, e.g. with the aid of the PaveCool software tool (developed by [34]). This tool requires among others, weather forecast data input. The available time for compaction should be determined based on the maximum and minimum compaction temperatures for that particular compaction phase. Also, the delivery temperature should be taken into account.



Step 4: Available time for compaction		
j) Estimated or preferred delivery temperature of asphalt	150	°C
k) Available time for compaction calculated by PaveCool	12	min

5.2.5 Step 5a – option 1: Calculation of operational roller variables

Step five encompasses the calculation of the roller speed and the length of the roller track, given the assumption the paver output is leading. This can be done by applying the formulas below. The premise is that $F_{m,o} = F_{w,o}$. These formulas and premise are implemented in the Excel-based interface.

$$F_{m,o} = B * v_m * f_n \qquad \text{Eq. (1)}$$

$$F_{w,o} = \frac{b_{eff} * v_w * f_n}{n} \qquad \text{Eq. (2)}$$

$$b_{eff} = \frac{B}{N} \qquad \text{Eq. (3)}$$

$$N = \frac{B}{b * 0{,}9} \qquad \text{Eq. (4)}$$

Factor 0,9 due to overlap with previous roller track

$$L = \frac{T * v_w}{n * N} \qquad \text{Eq. (5)}$$

$$X_{m-w,min} = \frac{(T_b - T_{maxv})}{C} * v_m \qquad \text{Eq. (6)}$$

$$X_{m-w,max} = \frac{(T_b - T_{minv})}{C} * v_m \qquad \text{Eq. (7)}$$

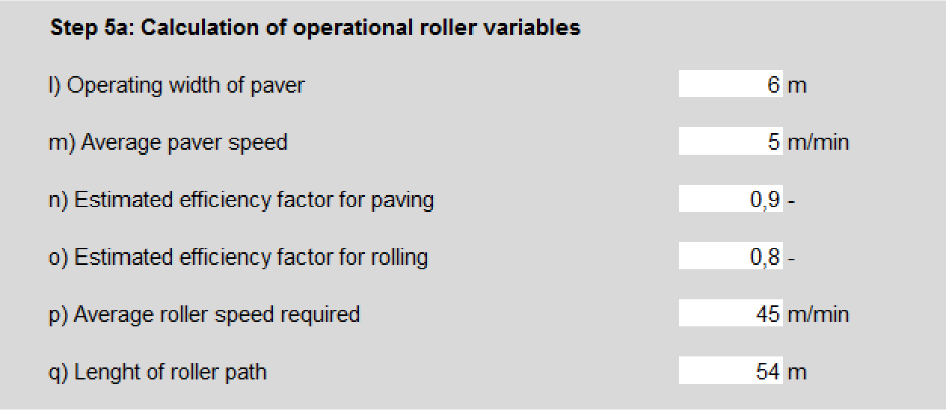
$F_{m,o}$ = Areal output of paver (m^2/min)
B = Operating width of paver (m)
v_m = Average speed of paver (m/min)
f_n = Efficiency factor (-)
$F_{w,o}$ = Areal output of one roller (m^2/min)
b_{eff} = Effective roller width (m)

v_w = Average speed of roller (m/min)
n = Number of roller passes (-)
N = Number of parallel roller tracks (-)

L = Length of roller track (m)
T = Time available for compaction (min)
$X_{m\text{-}w,min}$ = Minimal distance between paver and roller (m)
T_b = Temperature of asphalt behind screed (°C)
T_{maxv} = Maximum asphalt temperature of compaction window (°C)
C = Average cooling rate of asphalt (°C/min)

$X_{m\text{-}w,max}$ = Maximum distance between paver and roller (m)
T_{minv} = Minimum asphalt temperature of compaction window (°C)

For the initial estimation of the desired paver speed, a planner should know the length of the road and the time available for the paving process. For example, if a road with a length of 1,500 meters should be paved within 5 hours, the desired average paver speed is 5.0 meters per minute. Based on the desired paver speed, paver operating width and expected efficiency factor for paving, the average roller speed and length of the roller track can be calculated, given the expected efficiency factor for rolling. Efficiency factors for paving are introduced to capture the effect of decreasing paver speed as a result of changing trucks in front of the hopper or as a result of complex road designs (i.e. manoeuvring the paver). Efficiency factors for rolling are introduced to capture the effect of changing direction laterally and transversally. Paver speeds are generally expressed in meters per minute, while the roller speeds on machine displays are generally expressed in kilometres per hour. To be consistent, roller speeds are also expressed in meters per minute.

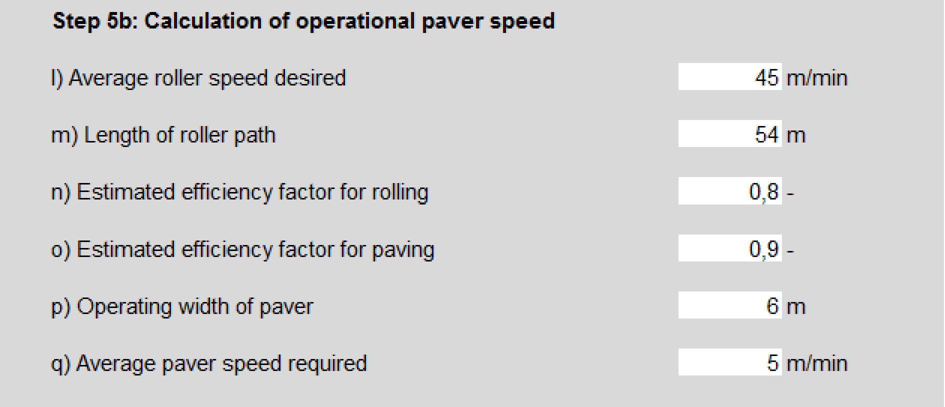


Step 5a: Calculation of operational roller variables

l) Operating width of paver	6	m
m) Average paver speed	5	m/min
n) Estimated efficiency factor for paving	0,9	-
o) Estimated efficiency factor for rolling	0,8	-
p) Average roller speed required	45	m/min
q) Lenght of roller path	54	m

5.2.6 Step 5b – option 2: Calculation of operational paver speed

Step five encompasses the calculation of the paver speed, given the assumption the roller output is leading. This can be done by applying the formulas as presented above. Again, the premise is that $F_{m,o} = F_{w,o}$. These formulas and premise are implemented in the Excel-based interface.

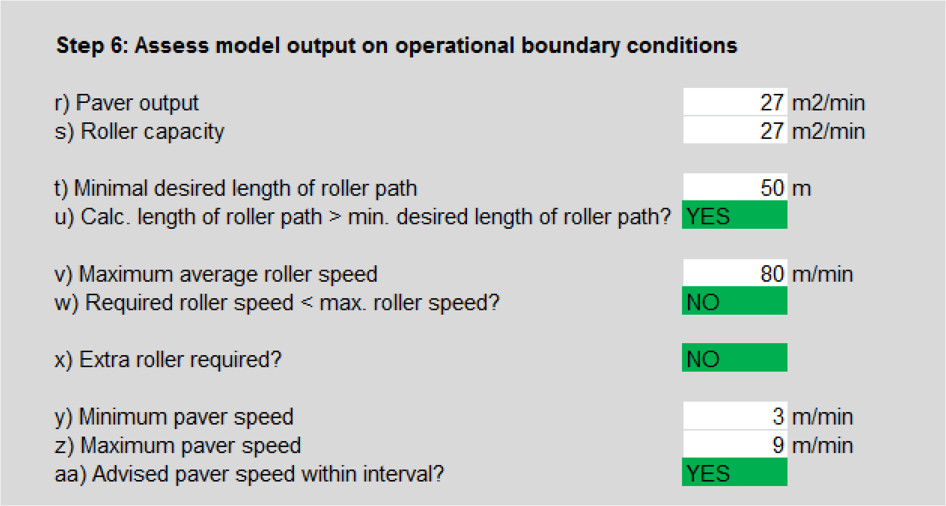


Step 5b: Calculation of operational paver speed

l) Average roller speed desired	45	m/min
m) Length of roller path	54	m
n) Estimated efficiency factor for rolling	0,8	-
o) Estimated efficiency factor for paving	0,9	-
p) Operating width of paver	6	m
q) Average paver speed required	5	m/min

5.2.7 Step 6: Assess model output on operational boundary conditions

The final step in the procedure is to assess whether the calculated values are within the interval boundaries of possible values e.g. if the calculated speed is lower than the maximum operational speed. Criteria can be defined on minimum and maximum paver and roller speeds and minimum length of the roller tracks. If criteria are not met, output rates have to be adjusted or extra capacity has to be allocated, thus applying step 5a or 5b again. Also, one has to check whether the output rates of both paver and roller(s) are equal.



Step 6: Assess model output on operational boundary conditions

r) Paver output	27	m2/min
s) Roller capacity	27	m2/min
t) Minimal desired length of roller path	50	m
u) Calc. length of roller path > min. desired length of roller path?	YES	
v) Maximum average roller speed	80	m/min
w) Required roller speed < max. roller speed?	NO	
x) Extra roller required?	NO	
y) Minimum paver speed	3	m/min
z) Maximum paver speed	9	m/min
aa) Advised paver speed within interval?	YES	

6. MONITORING THE OUTPUT RATES

The method described in section 4 is an appropriate method for planning the paving and compaction process. However, the method is based on single average operational values, while during the actual paving and compaction process, variation in operational values can be expected. Good average results over the entire road section do not immediately imply good results on each subsection of the road. Therefore, when aiming for a consistent process, one has not only to plan the process, but also to regularly monitor the process. Therefore, 12 asphalt construction projects have been monitored thus far for this research project. The aim was to evaluate actual asphalt construction projects on consistency/uniformity in terms of the degree of alignment between paver and roller over the entire road section. When monitoring and evaluating on small discrete time interval scales during (or after) a paving and compaction process, one can check whether the roller output is (or was) in line with the paver output and thus evaluate whether the current process was a consistent process. Monitoring on an interval scale results in more detailed information, more opportunities for analysis and thus more input, recommendations or lessons learned for future projects.

For five (of twelve) projects monitored, the actual interval output rates are calculated. Actual output rates (for both paving and compaction) are defined as the area paved/compacted divided by the time (in hours) elapsed since start of operations. For one particular project (AC16 surf asphalt mix, 5.5 m width, breakdown + intermediate compaction phase) the results are plotted in Figure 3. Also, the theoretical roller output (as a result of the number of passes and speed per section) is plotted in Figure 3. Theoretical roller output is defined as the theoretical productivity in m^2/h based on actual speed, number of roller passes and the effective operating width of the roller (see eq. 2).

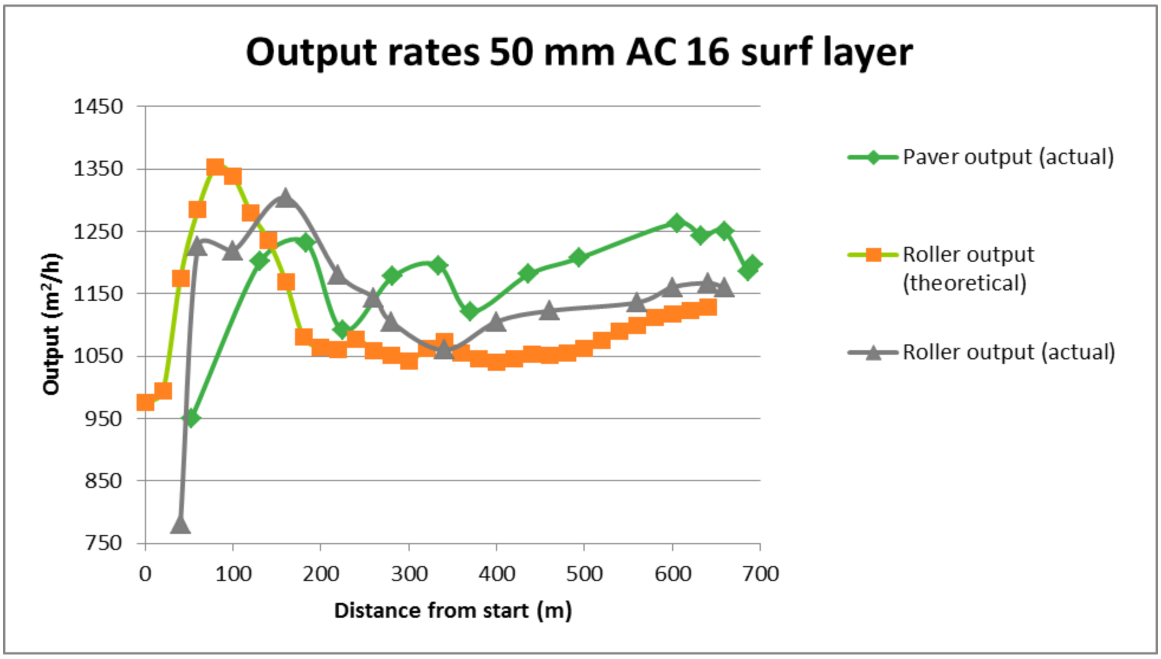


FIGURE 3 OUTPUT RATES OVER LOCATION

From Figure 3, it can be concluded that the output rates vary to a greater or lesser extent during the process. The most variation can be observed in the first 200 meters of the road to be constructed. Thereafter, the output rates are more constant. This pattern can also be observed from the other four monitored projects, where the variation in output rates is highest in the first 200 – 500 meter and output rates are more constant in the remaining 500 – 700 meter. When comparing the theoretical roller output to the actual roller output, in general it can be stated that the lines follow the same pattern. However, it seems that a time lag exists regarding changes in the theoretical output and the moment they can be observed in the actual output. Also - in this case - the actual output is approximately 100 m^2/h higher. Figure 3 shows that the paver output is below the roller output during the first ± 250 m. Thereafter the paver output exceeds the roller output, which means that in this case, the breakdown and intermediate rollers are falling behind the paver. However, at the end of this asphalt construction project, output rates of both paver and rollers are approximately 1150 m^2/h. This implies that overall, the average output rates of paver and roller were aligned to an extent, while clearly a large variation can be observed during the day. This precisely emphasizes the benefit of the interval approach. It also reveals that from the early start until the very end of the day, the output rates should be well aligned. Only a thorough planning in advance will prevent the undesired effects of an increase in variability caused by a misalignment of paving and compacting operations.

7. DISCUSSION AND FUTURE RESEARCH

We succeeded in drafting a method which can help planners with decisions regarding roller equipment allocation and with generating operational compaction strategies in terms of paver and roller speeds and the lengths of the roller tracks. Yet, various aspects need to be addressed.

For simplicity, the method as drafted assumes a standard, fixed rolling pattern. This pattern neglects the time required for changing between the transverse parallel roller tracks and between the longitudinal road sections. Thus, in fact the method overestimates the roller output. Also, it can be debated if and to which extent this pattern is followed under all circumstances. First visual observations confirm this pattern is generally followed, especially on the straight sections. However, additional research could be devoted to the patterns followed on non-standard sections. Also, it may be interesting to study whether operators use different rolling patterns during the three compaction phases.

At this time, no financial aspects are included in the planning/alignment method. However, when operational costs (e.g. costs of operator/crew, fuel usage, depreciation, transport etc.) are included in the method, one can assess the financial impacts of choices made. This in turn allows further optimization of the paving and compaction process, as benefits and costs of increased productivity can be calculated and balanced e.g. a planner can calculate if it is beneficial to allocate an extra roller to the project and whether this will result in reduced overall costs as a result of the increased productivity rate. Moreover, if (weather) conditions for paving and compaction are perceived as not that critical (e.g. high ambient temperatures, low wind speeds, thick layers etc.), a planner can decide to allocate less roller capacity than normal in order to reduce operational costs. Thus, a planner can balance the risk (and consequences) of an insufficient degree of compaction against reduced operational costs. However, one should not forget that final quality always prevail costs. Thus, including operational costs in the method seems beneficial. To achieve this, future research should focus on categorization and quantification of all relevant operational costs.

In order to conduct planning calculations, a planner should be thoroughly acquainted with the operational values for paver speeds, roller speeds, the number of roller passes and efficiency factors under all possible circumstances (e.g. type of layer, roller phase, road geometry etc.). Only then will a planner be able to generate realistic and meaningful paving and compaction strategies. Notwithstanding the fact that some general operational values for general conditions are known in literature (see e.g. [28, 31, 32]), further research effort should be devoted to this issue in order to create insights in operational values under specific conditions.

The proposed method appears appropriate for planning the asphalt paving and compaction process. However, one aspect has to be addressed. The main drawback of the proposed method is that it only generates single “average” values to aim for during the entire paving and compaction process (assuming that the road geometry does not change). Thus, one average paver speed, one average roller speed and one length of the roller track, given the average speeds. However, as a result of the complex interactions with other phases of the asphalt construction process (asphalt production and transport), a large variation in operational variables can be expected when the presented method is based on single average values only. Using single average values also suggests that variation is allowed to a greater or lesser extent as long as the planned average values are achieved. However, good average results over the entire road section do not immediately imply good results on each subsection of the road. Therefore, when aiming for a consistent process, one has not only to plan the process, but also to monitor the process regularly. Future research effort should be devoted to the monitoring of the paving and compaction process.

8. CONCLUSIONS

A uniform and continuous paving process is a prerequisite for a good quality asphalt layer. This in turn requires proper work preparation and organization of the paving process. However, currently the selection of working methods and equipment allocation is largely based on experience, while the choices made will have a major impact on the final quality of the asphalt layer. Further professionalization of the road construction sector can be achieved by making the selection procedure of work methods and equipment allocation more explicit.

This paper describes a method which can help planners with making decisions regarding the number of rollers required and with generating and evaluating operational strategies in terms of different values for different operational variables, based on the alignment between the paver output and the roller output. When paver output and roller capacity are aligned, this will result – at least theoretically – in a more uniform and continuous paving and compaction process. The method comprises six steps, and one has to make the decision whether either the paver output or the roller output will be the leading factor. The method must be applied for each of the three compaction phases and has an iterative character. The first step focuses on the definition of layer characteristics. The second step encompasses the definition of the roller phase and required number of roller passes. In the third step the roller type is stipulated, while in the fourth step the available time for compaction has to be calculated e.g. by means of the PaveCool tool. In the fifth step the operational values for both paver and rollers are defined and calculated. The last step encompasses the assessment of the model output on operational boundary conditions. In order to assist planners in applying the alignment procedure, an Excel-based interface has been created, in which the calculations required for each step are predefined. Thus, planners only have to insert values for a limited number of variables. This increases usability and decreases the time required for applying the method.

As mentioned earlier, the proposed method appears appropriate for planning the asphalt paving and compaction process. However, various aspects require further consideration. These include studying rolling patterns for the various compaction phases and extending the method by including financial considerations. Yet, the most important aspect is the monitoring of paving and compaction processes. The planning method is based on average operational values, while during the actual paving and compaction process, variation in operational values can be expected. Good average results over the entire road section do not immediately imply good results on each subsection of the road. Therefore, when aiming for a consistent process, one has not only to plan the process, but also to accurately monitor the process on each subsection of the of the road. Future research effort should focus on this monitoring aspect and the data gathered during actual paving and compaction operations can serve as a starting point for improving the accuracy of planning calculations.

9. REFERENCES

1. Boes, H., A. Dorée, and B. van der Veen. *First Evaluation of New Scheme for Design and Construct Procurement in The Netherlands*. in *18th ARCOM Conference*. 2002. Newcastle.
2. Dorée, A., J. Caerteling, and E. Holmen. *Co-operation and competition in the construction industry in The Netherlands*. in *ARCOM 2003 - 19th Annual Conference*. 2003. Brighton, UK: ARCOM.
3. Dorée, A.G., S.R. Miller, and H.L. Ter Huerne, *Asfalt, wat bakken we ervan?*, in *CROW Infradagen*. 2008, CROW: Technical University Delft, The Netherlands.
4. Bijleveld, F., *Professionalising the asphalt construction process: aligning information technologies, operators' knowledge and laboratory practices*, in *Construction Management and Engineering*. 2015, University of Twente: Enschede, the Netherlands. p. 217.
5. ter Huerne, H.L. and A.G. Dorée, *Professionalisering asfalt wegenbouw sector*, in *Wegbouwkundige werkdagen*. 2006, CROW: Doorwerth, The Netherlands.
6. Simons, B.J.A.G. and H.L. ter Huerne, *Op weg naar een beter beheerst asfaltverwerkingsproces*, in *Asfalt*. 2008, VBW Asfalt: Zoetmeer, The Netherlands. p. 17-20.
7. Miller, S.R., H.L. ter Huerne, and A.G. Dorée, *Role of action research in dealing with a traditional process*, in *Performance Improvement in Construction Management*, B.

Atkin and J. Borgbrant, Editors. 2010, Spon Press: London, United Kingdom. p. 92-101.

8. Bijleveld, F., S.R. Miller, and A. Dorée, *Making Operational Strategies of Asphalt Teams Explicit to Reduce Process Variability.* Journal of Construction Engineering and Management, 2015. **141**(5): p. 04015002.
9. Miller, S.R., *Hot Mix Asphalt Construction - Towards a more professional approach*, in *Construction Management and Engineering*. 2010, University of Twente: Enschede, The Netherlands. p. 267.
10. Bijleveld, F.R., et al., *Aligning laboratory and field compaction practices for asphalt – the influence of compaction temperature on mechanical properties.* International Journal of Pavement Engineering, 2015: p. 1-14.
11. Asphalt-Institute, *The Asphalt Handbook*. 1989 ed. Vol. Manual series No. 4. 1989, Lexington, USA: The Asphalt Institute. 607.
12. NCAT, *Hot Mix Asphalt Materials, Mixture Design and Construction*. Second Edition, 1996 ed, ed. N.R.a.E. Foundation. 1991: NAPA Research and Education Foundation. 585.
13. Roberts, F.L., et al., *Hot Mix Asphalt Materials, Mixture Design and Construction*. 2nd ed, ed. NCAT. 1996: NAPA Research and Education Foundation. 585.
14. VBW Asfalt, *Het verdichten van asfalt in de praktijk [Compacting asphalt in practice]*. 1992, Vereniging tot Bevordering van Werken in Asfalt: Zoetemeer, The Netherlands.
15. VBW Asfalt, *Asfalt in wegen- en waterbouw [Asphalt in road and water works]*. 10th reprint ed, ed. V.t.B.v.W.i. Asfalt. 2000, Breukelen: VBW Asfalt,.
16. Miller, S.R. and A.G. Dorée, *Improving logistics in the asphalt paving process: what can we learn from the planner's logic?*, in *24th Annual ARCOM Conference*, A. Dainty, Editor. 2008, Association of Researchers in Construction Management: Cardiff, UK. p. 381-390.
17. Boenders, M., *Verbeterd asfaltverwerkingsproces door simulatie? [An improved asphalt paving process through simulation?]*, in *Construction Management and Engineering*. 2008, University of Twente: Enschede. p. 50.
18. Van Dee, R., *Modelling of the compaction of asphalt layers*, in *Road and Rail Engineering Laboratory, Faculty of Civil Engineering*. 1999, Technical University Delft: Delft. p. 137.
19. Willoughby, K.A., et al., *Construction-related asphalt concrete pavement temperature and density differentials.* Construction 2002, 2002(1813): p. 68-76.
20. Stroup-Gardiner, M., J. Nixon, and P. Das, *Automated temperature profiling during hot-mix asphalt construction.* Transportation Research Record, 2004(1900): p. 41.
21. Chadboum, B.A., et al., *An Asphalt Paving Tool for Adverse Conditions*. 1998, University of Minnesota.
22. Vasenev, A., T. Hartmann, and A. Dorée, *A distributed data collection and management framework for tracking construction operations.* Advanced engineering informatics, 2014. **28**(2): p. 127-137.
23. Timm, D.H., et al., *Calcool: A multi-layer Asphalt Pavement Cooling Tool for Temperature Prediction During Construction.* International Journal of Pavement Engineering, 2001. **2**(3): p. 169 - 185.
24. Miller, S.R., T. Hartmann, and A.G. Dorée, *AsphaltOpen - an interactive visualization tool for asphalt concrete paving operations*, in *ASCE International Workshop on Computing in Civil Engineering*. 2009: Austin, USA.
25. Read, S.A., *Construction Related Temperature Differential Damage in Asphalt Concrete Pavements*. 1997, University of Washington: Seattle.

26. Willoughby, K.A., et al., *Comparison of performance and cost between Superpave and conventional hot-mix asphalt in Washington State.* Pavement Rehabilitation, Strength and Deformation Characteristics, and Surface Properties 2004, 2004(1869): p. 32-40.
27. Simons, B.J.A.G., *Op weg naar een beheerst asfaltverwerkingsproces [Towards a more controlled asphalt paving process]*, in *Construction Management and Engineering*. 2007, University of Twente: Enschede. p. 140.
28. Floss, R., *Compaction Technology in Earthwork and Highway and Transportation Engineering*. Vol. 1. 2001, Munich: BOMAG GmbH & Co. OHG. 149.
29. Vasenev, A., *Visualizing Asphalt Roller Trajectories in Context,* in *Construction Management & Engineering*. 2015, University of Twente: Enschede, the Netherlands. p. 167.
30. Bijleveld, F., et al., *Verdichtingstemperatuur en mechanische eigenschappen [Compaction temperature and mechanical properties]*, in *VBW Asfalt*. 2010, VBW Asfalt: Zoetemeer, The Netherlands. p. 8-9.
31. Fischer, A. and R. Schug, *Vögele Booklet on Paving.* . 2012, Ludwigshafen: Wirtgen Group.
32. Schroder, R., *Compaction in asphalt construction and earthworks*. 2010, Tirschenreuth: HAMM AG.
33. Mansell, T., *A practical approach to managing density,* in *World of Asphalt Show and Conference*. 2016: Nashville, TN.
34. Chadbourn, B.A., et al., *An asphalt paving tool for adverse conditions.* 1998.