CEDR Transnational Road Research Programme
Call 2013: Energy Efficiency – Materials and Technology

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CONSISTEND: A tool to assess the impact of construction process quality on the performance of pavements and its implementation in tenders

CONSISTEND: Final report

Deliverable 5.6
Final, June 2016

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CEDR Call 2013: Energy Efficiency
CONSISTEND
A tool to assess the impact of construction process quality on the performance of pavements and its implementation in tenders

FINAL REPORT

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Executive summary

The lifetime of a pavement is highly influenced by the proper quality of the construction process of the road. As both the maintenance costs and carbon footprint of a road construction will be lowered by a higher lifetime, quality control during construction is an important topic to ensure the quality of the construction process. As a first assumption a reduction of at least 10% in both should be possible. Although influence of quality control is recognized as a topic of higher importance by both road authorities and constructers objective knowledge of the influence of better quality of the construction process on the lifetime is scarce.

The CEDR financed CONSISTEND project focused on a method to objectively calculate the influence of construction process quality on lifetime. Quality of road construction is influenced by many factors like weather conditions (low temperatures, rainfall etc.), logistics during construction (stops during construction etc.) and proper handling of the used equipment (poor compaction, cold spots in the truck etc.). The huge number of factors influencing construction quality and the lack of data (measurements) make it almost impossible to perform a robust quantitative analysis. Consequently the CONSISTEND consortium proposed to use expert opinion to (semi) quantify these influences.

The work program of the CONSISTEND project is described below and presented schematically in Figure 1.

- By desk study and interviews a list of quality (lifetime) influencing parameters has been produced. A smaller list of most relevant parameters is derived from this information. This is done by analysis of the input from the interviews and by discussions in workshops (WP1).
- To quantify the influence of the parameters on the service life performance a questionnaire has been developed, which has been send to experts (WP1). The expert opinions gathered from this has been used to quantify the influence of the parameters in a tool (WP2).
- Information on “ready to use” advanced and innovative methods to manage the parameters selected during the construction process have been gathered by interviews and literature study, quantified and implemented in the tool.
- To demonstrate the tool’s potential in practice, information of two trials in which the most influencing parameters are monitored has been used. Furthermore the tool and its use in procurement has been assessed.

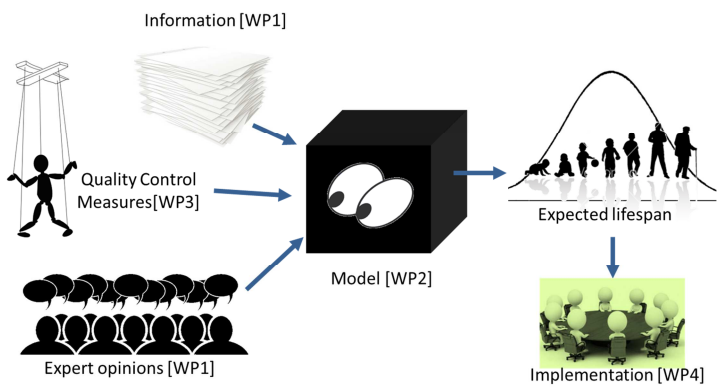

Figure 1 work program CONSISTEND

The project resulted in the following products:

- A list of influencing parameters including an analysis of the most influencing parameters. This list can be used to qualitatively assess the necessity of quality control measures during transport, laying and compaction.
- An inventory of “ready to use” advanced and innovative methods to influence, control and/or measure above mentioned parameters during transport, laying and compaction.
- A tool to quantify the influence on lifetime of above mentioned (most important) parameters.
- A description of use cases in UK and Slovenia.
- Options to use the results of this project in procurement processes.

CONSISTEND project resulted in a model (tool) that is able to calculate a reduction in lifespan for non-optimal circumstances. The model is considered to have potential to be implemented in procurement processes and to further rationalize the cost – benefit ratio of quality control measures during Transport, Laying and Compaction (TLC). Several quite simple ways to implement the tool in procurement processes have been proposed. The project team has formulated a number of specific recommendations to make the CONSISTEND method ready for implementation.

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1 Introduction

The lifetime of a pavement is highly influenced by the proper quality of the construction process of the road. As both the maintenance costs and carbon footprint of a road construction will be lowered by a higher lifetime, quality control during construction is an important topic to ensure the quality of the construction process. As a first assumption a reduction of at least 10% in both should be possible. Although influence of quality control is recognized as a topic of higher importance by both road authorities and constructers objective knowledge of the influence of better quality of the construction process on the lifetime is scarce.

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1.1 Aim of the project

The aim of the CONSISTEND project is to assess the impact of the quality of the construction process on the performance of pavements and the implementation of such an assessment in tender processes. The result of the work is an assessment tool. It is an explicit choice of the CONSISTEND consortium to develop both the assessment tool and the implementation of the tool in the tender process, as these deliverables are mutually dependent.

1.2 Scope of the project

CONSISTEND will assess the impact of the quality of the construction process on the performance of asphalt pavements. In the scope of the project Transport, laying and compaction (TLC) are included.

Material quality is no part of the CONSISTEND scope although we are aware of the importance of this factor in the life span of the final product (road). The assumption is that the material is of good quality. Material quality can be added to the tool in a later stage.

1.3 This report

In this report the work done in and results of the CONSISTEND project are summarised. The report includes references to the deliverables of each Work package in the project. These deliverables further elaborate on the work and the results. In this report is divided in a part that summarises the context and results and a more technical part that summarises respectively the degradation factors, the quality control methods, the tool itself and conclusions and recommendations concerning the tool and quality control measures.

PART 1, CONSISTEND project, context and result

2 Background of the CONSISTEND project

2.1 Context of the project

The CEDR call “Energy Efficiency – Materials and Technology” aims at decreasing the carbon footprint of infrastructure. A longer functional life of a road has an enormous impact on the carbon footprint of a road because it minimizes the use of materials and energy during the life cycle. Therefore CONSISTEND has proposed a project to quantify the impact of construction on the functional life time of a road.

Next to road design and material selection, quality control during the construction process is, an important factor that determines the performance of an asphalt road with respect to service life. CONSISTEND focusses on the possibility to increase the life time by quantifying the influence of the use of state of the art (and / or innovative) measuring and quality control methods during transport, laying and compaction on the life time of the road. The CONSISTEND project results should show the benefits of quality control measures and quantify the benefits in order to stimulate the use. This will stimulate to accept the costs because the benefits are obvious (quantified).

The road construction sector faces a number of changes that have an impact on quality control.

- Firstly, under the impact of new types of contracts like Design, Build, Finance and Maintain (DBFM), the responsibility for quality control moves from road owner to contractors. These types of contracts have changed the quality control from a check made by the client to ensure work was realized according to specifications, to a quality system installed by a contractor to minimize financial risks during the project. As a result of this different perspective, investment in advanced techniques for quality control have now become rewarding for contractors.
- Secondly, the workforce of construction companies is changing more rapidly, people change jobs, companies are taken over, etc. Subsequently road construction teams are subjected to frequent changes, which reduce the total knowledge of the team and the transfer of this knowledge. As the construction quality of asphalt roads is largely dependent on the empirical experience of the construction workers, this lack of continuity has a negative effect on the service life and performance of a road.
- Finally, there are new technologies that have become available over the past decades that can take quality control to a whole new level. With the help of these technologies, a wide selection of parameters can now be monitored during construction in real time. For example, with the use of infrared sensors the temperature of the whole asphalt surface can be monitored just after the screed; through GPS the number of roller passes can be monitored at each location; and the foreman can obtain accurate information about the location and expected arrival time of asphalt trucks, the possibilities are endless.

If quality control is brought to the next level, it is possible to create a population of roads with a longer and much more predictable average service life. As a first assumption a reduction of at least 10% in both should be possible.

However, at this time an important challenge is the limited knowledge available on the influence of the individual construction parameters on the service life of pavements, which makes it difficult to quantify the absolute increase in service life. If it is possible to quantify

the additional service life obtained by installing quality control methods, this will not only be an incentive for contractors to use these methods, but also assist with the planning and management of future maintenance interventions. Additionally, when the influence of the individual construction parameters on the service life of pavements is known, quality control can be focused on controlling these parameters.

2.2 Project outline

In this paragraph the technical idea is introduced.

The qualitative information on lifespan resulting from the tool provides expected values and minimum and maximum values of lifespan. When appropriate quality control methods are implemented, both an increase in mean value of the lifespan as well as a decrease in the uncertainty of the mean value is expected. A schematic representation of this expectation is given in Figure 1.

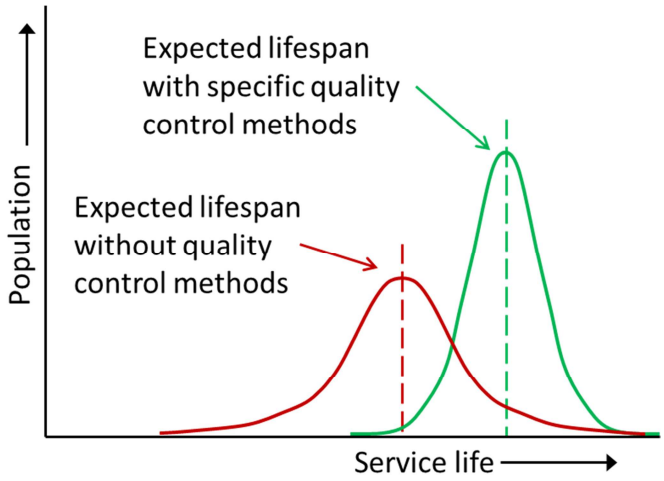


Figure 1: Change in lifespan when using or not using specific quality control methods

Using the insights provided by the tool, contractors and road authorities will be able to build a business case or asses proposals in a Most Economic Attractive Tender (MEAT) assessment process. To urge this development and to accelerate the process of lifecycle analysis of a road becoming common practice, the implementation of the tool in a MEAT tender process has been elaborated in the project.

2.3 Workplan

To reach the aims as described in the previous paragraphs, different Work packages are described in the project plan of the project. A schematic overview of the Work packages and their relations is given in Figure 2.

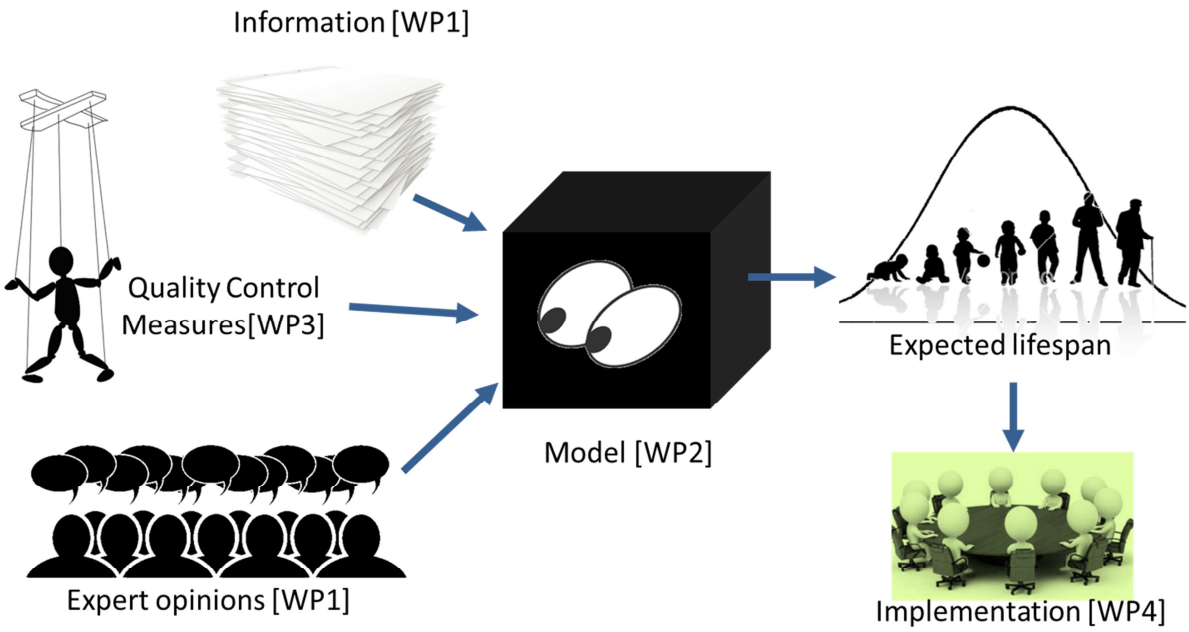


Figure 2: Overview of the project

Work package 1 provides the degradation factors related to the quality of the construction process that influence the lifespan of the pavement, like temperature and compaction. Also, Work package 1 provides expert opinions on expected lifespan of the asphalt road for different values of the degradation factors.

Work package 3 provides information on the available quality control methods, like infrared temperature measurements and intelligent compaction with GPS, and gives a selection of the methods influencing the degradation factors applicable to the project and model. Work package 2 combines the information from Work package 1 and Work package 3 to develop the model. Output from the tool developed in Work package 2 is the expected lifespan, which will be used as input for the implementation in tenders in Work package 4.

3 Implementation of the tool

3.1 Applicability of the tool

To demonstrate the applicability of the proposed tool two pilot studies were organised. The results showed that the application of advanced quality control techniques during construction can provide a much more detailed and more reliable insight into the quality of the actual transport, laying and compaction process, and thus into its influence on the pavement lifespan prediction.

The 'real case' project in Slovenia completed in 2015 identified in detail the benefits of innovative techniques for control of pavement works.

In order to demonstrate the applicability of the proposed tool, the lifespan prediction for this Slovenian project was compared for results of the 'during contract phase', for results of the 'after construction phase 1' , taking into account the results of usual scope of quality control and for results of the 'after construction phase 2', taking into account the results obtained by the devices for automated monitoring of paving process. This comparison demonstrate that the mean value of the predicted lifespan lies between the minimum and maximum lifespan, as expected. However, the change in mean value of the lifespan prediction is relatively small, and smaller than expected by the experts in the CONSISTEND project team.

A first conclusion from the case study is that the response of the model can be increased when significantly less input parameters are defined in a next version of the tool. It is also proposed to introduce weighting factors to individual input parameters.

Furthermore, for some construction parameters, research results have already defined some inter-dependencies, which can be included in the model. However, clear and straightforward inter-dependencies of the parameters, measureable with advanced quality control methods, on the absolute increase or reduction of pavement lifespan are not yet available. Further research is needed in order to be able to calibrate the model and quantify the absolute change in service life taking into account countries' specific technological practices, bituminous mixtures types, and climatic conditions.

Finally, it was found that versions of quality control methods are already available on work equipment as they are factory fitted to several machines. These machines are operated by different companies in the UK and used on a regular basis over a variety of contracts. One major issue identified is that there is a huge amount of information generated over the course of a single day which needs to be verified and interrogated to be of any value. Currently there is little or no drive from the client side for the gathered information, so much of it is collected and then not used. Some work is going on to devise programmes that can do all the interrogation and produce meaningful reports but this is in the early stages.

3.2 The tool in procurement processes

Public procurement practice in paving works differs considerably throughout the EU. Some countries practice pre-qualification of contractors for awarding a 'least price' or 'most economically advantageous' tender (MEAT).

When a road authority chooses to award a contract for paving works based on the MEAT principle, it must define clear criteria linked to the contract works, such as the price and quality criteria on which the evaluation of tenders will be based. The relative weighting of each of those criteria must be specified in advance in the tender documentation. Apart from these obligations, neither of the EU directives 2004/18/EC and 2004/17/EC specifies any evaluation procedure. Road authorities could therefore choose to use the results of the proposed CONSISTEND tool for the weighting of tenders in public procurement in the case when an evaluation model is presented in advance, in a transparent and predictable manner.

The CONSISTEND tool can be used as an objective quantifying tool for a tendering procedure based on the MEAT principle. The expected life span of the asphalt, including the uncertainty, of the tenders of the construction companies can be calculated, priced and compared. The values will depend on the quality control measures proposed by the contractor. The tender with the best value will be contracted. After construction the actual figures can be checked, calculated with the CONSISTEND tool and the final payment can be settled according to a “bonus – penalty” arrangement in the contract.

4 Conclusion

CONSISTEND project resulted in a model (tool) that is able to calculate a reduction in lifespan for non-optimal circumstances. The model is considered to have potential to be implemented in procurement processes and to further rationalize the cost – benefit ratio of quality control measures during Transport, Laying and Compaction (TLC). Several quite simple ways to implement the tool in procurement processes have been proposed. The project team has formulated a number of specific recommendations to make the CONSISTEND method ready for implementation.

PART 2, CONSISTEND project, technical

5 The CONSISTEND tool: degradation factors

5.1 Inventory of degradation mechanisms

The project has started with the collection of information on the influence of the construction process on the service life of asphalt roads (work package 1) This information is gathered by literature review and feedback from experts in industry and road authorities.

The factors that affect the deterioration of a highway pavement can be categorised as follows [Ramaswamy and Ben-Akiva, 1990];

1. Pavement characteristics: pavement strength, layer thicknesses, base type, surface type
2. Pavement history: time since last rehabilitation, total pavement age.
3. Traffic characteristics: average daily traffic, cumulative traffic, traffic mix (percentage of trucks)
4. Environmental variables: average monthly precipitation, number of freeze thaw cycles, average annual minimum temperature, and so on.

For the purposes of this project and development of the model, modes of deterioration will be referred to henceforth as degradation mechanisms. A degradation mechanism is a mechanism that causes degradation of function over time, by changes in properties and/or microstructure of a component material.

5.2 Inventory of degradation factors

Degradation factors are those factors that influence the degradation mechanism (i.e. cause and effect). Each factor is defined by different conditions and each represents a level of acceleration of the speed of degradation. It is recognised that many assumptions are implicit in the design process, over which the design engineer has little or no control [Pearson, 2012]. To achieve the best possible quality in the construction process for an asphalt pavement, a large number of parameters have a strong influence and must be controlled and kept in their optimal range to retain the service life of the asphalt pavement. The degradation factors considered within the scope of this project are taken from literature and do not necessarily represent the view industry in full. After the inventory the degradation factors were prioritised by experts of the project partners and the most important factors have been selected. The selection was presented to experts, the Project Executive Board and reconsidered while building the tool.

After the final selection of degradation factors a questionnaire is send to experts in England, Ireland, Slovenia and the Netherlands, to gather quantitative data on the influence of these degradation factors on the life span of the asphalt. This data has been used in the tool.

5.3 Degradation factors in the model

The result of the procedure described in the previous section is that the following degradation factors have been taken into account in the models for each of the countries. The input is different in two phases (during contract phase and after construction) that have been differentiated in the model:

During contract phase:

1. Temperature of material – during transport
2. Temperature of material – during laying
3. Temperature of material – during compaction
4. Weather – Ambient temperature – during transport
5. Weather – Wind speed – during transport
6. Weather – Ambient temperature – during laying
7. Weather – Rainfall – during laying
8. Weather – Wind speed– during laying
9. Weather – Ambient temperature – during compaction
10. Weather – Rainfall – during compaction
11. Compaction – Void content – during compaction
12. Compaction – Number of roller passes – during compaction
13. Equipment – during transport
14. Equipment – during laying
15. Equipment – during compaction
16. Workmanship – during transport
17. Workmanship – during laying
18. Workmanship – during compaction
19. Travel time and delays – Haulage time from plant – during transport
20. Travel time and delays – Queue to offload (time delay on site) – during laying
21. Travel time and delays – Waiting at paver for next load – during construction
22. Joints – Construction – during laying
23. Joints – Number of joints – during laying
24. Interlayer bond – Amount – during laying

After construction:

1. Temperature of material – during transport
2. Temperature of material – during laying
3. Temperature of material – during compaction
4. Weather – Ambient temperature – during transport
5. Weather – Wind speed – during transport
6. Weather – Ambient temperature – during laying
7. Weather – Rainfall – during laying
8. Weather – Wind speed– during laying
9. Weather – Ambient temperature – during compaction
10. Weather – Rainfall – during compaction
11. Compaction – Void content – during compaction
12. Compaction – Number of roller passes – during compaction
13. Equipment – during transport
14. Equipment – during laying
15. Equipment – during compaction
16. Workmanship – during transport
17. Workmanship – during laying
18. Workmanship – during compaction
19. Travel time and delays – Haulage time from plant – during transport
20. Travel time and delays – Paver stops
21. Travel time and delays – waiting at paver for next load – during construction
22. Joints – Construction – during laying
23. Joints – Number of joints – during laying
24. Interlayer bond – Amount – during laying

The greyed out lines for numbers 4, 16 and 23 of both series, are degradation factors that in the course of the project have become unnecessary and will not be taken into account by the model. However, as the model was already finished when these insights became available, the numbering of the original list was kept. The greyed out line for number 21 of the 'after construction' series, is a degradation factor that in the course of the project has become unnecessary in the 'after construction' lifespan prediction. Line number 20 of the 'after construction' series, is greyed out as it is different from the original degradation factor 20. It contains a new degradation factor, concerning paver stops, which was raised as an important degradation factor when the project was nearly finished. Because of this, unfortunately no expert opinion on this question is available, so the degradation factor is not taken into account in the calculation of the lifespan.

6 Quality control methods

6.1 Introduction

The aim of Work Package 3) is to gather information on quality control methods which can be used to manage the construction parameters during transport, laying and compaction of asphalt surface course. The information gathered has been used as input to the quality assessment tool described in Chapter 4 to quantify the effect of quality control on the construction parameters and hence the service life. Methods which are commercially available and “ready to use” are primarily examined as they are of most interest to roads authorities. However, other methods which are under development are also described. The information was gathered on these methods through an extensive literature review, consultation with industry experts and consultation with road authorities. Information on all aspects of the methods was not always available and in some cases assumptions are made. The source of all information is clearly stated in the report.

The following aspects of each quality control method are examined:

- Description of method.
- Reduction in the variability of construction parameters which can be achieved with this method.
- Energy efficiency and cost are examined to determine the additional energy required to implement the methods and the associated cost.
- Applicability in practice is investigated to identify how suitable the method is practice and under different circumstances.

As part of the review of the available methods, it was found that there are two types of quality control method. The first group measures the construction parameters (temperature, compaction, location, etc) but does not directly influence any of the parameters. These methods generally aim to provide extensive real time information to equipment operators while also saving a permanent record of the construction parameters. These measuring methods require further action to be taken based on the measurements in order to influence the quality and hence the service life of the pavement. The second group of methods directly physically influences the construction parameters (temperature, joints, etc.). The effect of these methods on the construction parameters, and hence the service life, is easier to quantify.

6.2 Input to the tool

As the aim of the tool is to calculate the impact of quality control and measurement during the construction process on the lifespan of the pavement, project specific values of the degradation factors are used as input for the calculation.

These degradation factors are defined by a probability density distribution. The definition of this probability density distribution can be based on information received from quality control methods. However, information from quality control methods is not available before the pavement is actually laid. For this reason, distinction has been made between two phases of the project:

a. during contract phase
b. after construction

During contract phase
During the contract phase, no actual measurements are available that can help define the probability distributions of project values of the degradation factors. The user is asked to for an estimation of the mean project value of the degradation factor. Additionally, the user is asked to indicate which quality control method will be used during the construction process.

Each quality control method has an associated default standard deviation around the estimated mean value the user entered to the model. Further information about the relation between quality control methods and standard deviation around the mean value of a degradation factor can be found in annex E of Deliverable 2.1.

After construction
After construction of the road, information from the applied quality control methods is available. The user is asked to enter this information into the model (mean value and standard deviation). This defines the probability distribution for each of the degradation factors, e.g. temperature during compaction.

7 CONSISTEND Tool: the model

7.1 Service life prediction models

The tool to predict the life span of the pavement based is built in Work Package 2 and described in deliverable D.2.1. The basis of the tool is a model on service life prediction. Many studies on service life and service life prediction have been conducted over the past decades. A considerable amount of information has been contributed through CIB working commission W080, for example Report 295 [Jernberg, P., Lacasse, M.A., Haagenrud, S.E. and Sjörström, C, 2004] and Report 294 [Hovde, P. J. and Moser, K, 2004] of this commission, providing a guide through service life prediction and a report on performance-based methods for service life prediction respectively.

In Report 294 three different levels of complexity of service life prediction models have been described:

1. Research methods, also referred to as Scientific methods, using a probabilistic approach;
2. Simple estimation methods, using a deterministic approach;
3. Engineering methods, combining Simple estimation methods with Scientific methods.

As the requirements of the engineering method as given in Report 294 fit the objectives of the CONSISTEND project, the engineering method is used. Report 294 does not provide a ready-to-use service life prediction model using the engineering approach, but proposes a general principal to find and test a model.

The first step in this approach is to establish an equation. The proposed model is a linear regression model:

$$L = A_{opt} - \left(\sum_{i=1}^{n} A_i\left(x_i - x_{i,opt}\right)\right)^{1/w} + uS \qquad (1)$$

The model describes the degradation of a single degradation mechanism related to a function of the pavement for a given material.

The lifespan L represents the total period of time the degradation mechanism described by the model needs to degrade from a state of no degradation to a state the pavement no longer can fulfil its function. As the variables in the equation are stochastic of nature, the lifespan is formulated within a probabilistic context.
A_{opt} is the lifespan of the degradation mechanism in the case where all considered degradation factors are of optimal value or in optimal condition. The optimal value or condition of the degradation factors is represented by $x_{i,opt}$ and the actual value or condition of a degradation factor is represented by x_i. When the actual value or condition of a degradation factor (x_i) is equal to the optimal value or condition ($x_{i,opt}$), no reduction is applied to the lifespan of the degradation mechanism (A_{opt}). When the actual value or condition of a degradation factor (x_i) is different from the optimal value or condition ($x_{i,opt}$), a reduction is applied to the lifespan of the degradation mechanism: the lifespan reduces. The significance of this reduction is dependent on A_i. The effect of the reduction is dampened by the parameter w. The value of A_i and $x_{i,opt}$ is different for each degradation factor.

Note that optimal values or conditions are not always equal to highest values or conditions. For example the temperature of the material during compaction has a certain optimal value

and both values *lower* as well as values *higher* than this optimal value will result in a reduction of lifespan.

The model will not be perfect. There might be degradation factors not accounted for. Also, linearity is assumed where nonlinearities might play a role as well as there might be parameters now treaded as independent which could be interlinked. Therefore a modelling error is introduced explicitly in equation 1. This error term is modelled to be unbiased (mean zero) with a standard deviation *S*. Variable *S* is also treated as a model coefficient combined with *u*, which stands for a standard normal variable.

After establishing the equation, data is gathered to describe the parameters in the equation. This data is used to represent each parameter as a probability density function. All input needed to describe the parameters of the model is gathered in Work package 1 and Work package 3.

The final steps in the 'Engineering methods approach' are to perform service life calculations and review the results. In the CONSISTEND project this step is used to tune the model to the lifespan expectations given by the experts. Also, the use case studies, which are elaborated by Work Package 4 and described in chapter 5, are used for review of the results.

7.2 Boundary conditions

General information representing the boundary conditions of the model are gathered in Work package 1, Deliverable 1.1a. As boundary conditions are specific per country, three versions of the model have been developed:

1. UK and Ireland
2. Slovenia
3. Netherlands

This also means the model for the Netherlands is not applicable in another country, where other boundary conditions would apply.

7.2.1 Materials

The following materials have been taken into account in the models for the different countries:

- UK and Ireland: HRA 35/14 F surf 40/60
- Slovenia: AC 11 surf B 50/70
- Netherlands: ZOAB+ (deel 7)

7.2.2 Functional requirement

Several functions of the road have been acknowledged in Deliverable 1.1a. The models for all countries govern the total functionality of the road, not one specific function.

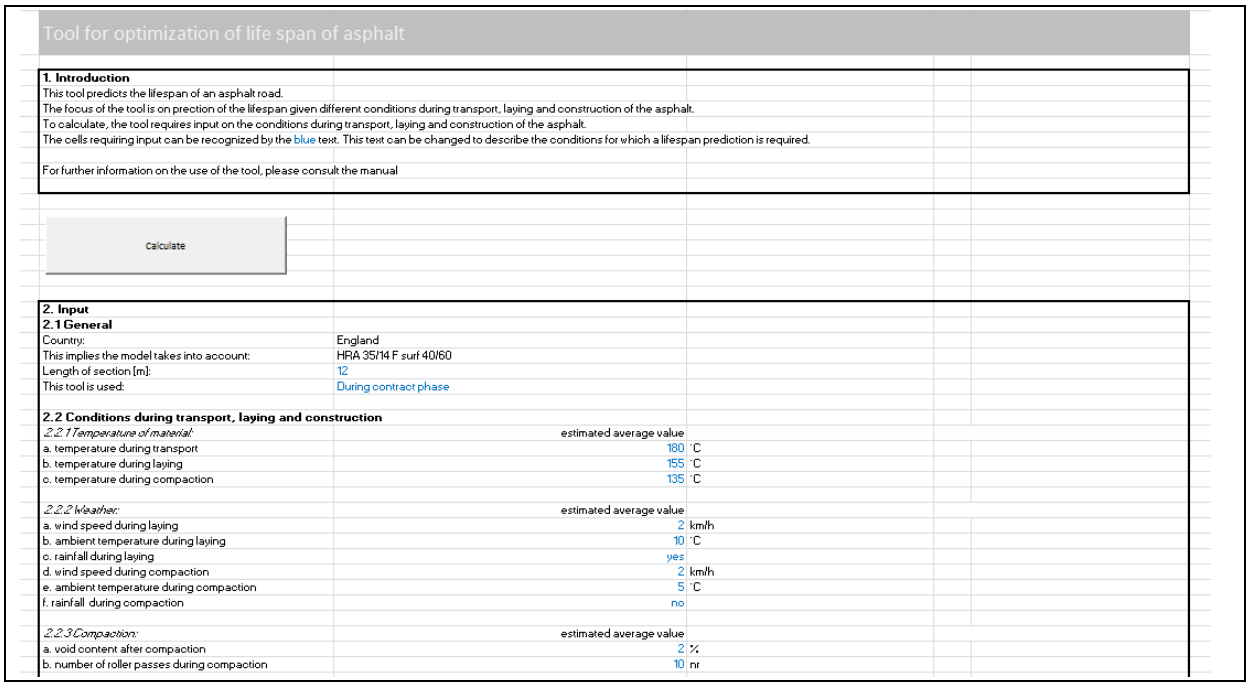
7.2.3 Degradation mechanism

The following degradation mechanisms have been taken into account in the models for the different countries:

- UK, Ireland and Slovenia: Several degradation mechanisms have been acknowledged in Deliverable 1.1a. No specific degradation mechanism is modelled.
- Netherlands: ravelling/fretting

7.3 The tool

The kernel of the probabilistic model itself is programmed in Matlab and deployed as an executable without the need for users to have Matlab installed on their computer. An Excel file functions as a user interface from where the executable of the Matlab model can be ran. In the Excel file a sheet is prepared for the user to enter the project values of the degradation factors (Figure 3). On a second sheet the results of the calculation are presented (Figure 4).



Tool for optimization of life span of asphalt

1. Introduction
This tool predicts the lifespan of an asphalt road.
The focus of the tool is on prection of the lifespan given different conditions during transport, laying and construction of the asphalt.
To calculate, the tool requires input on the conditions during transport, laying and construction of the asphalt.
The cells requiring input can be recognized by the blue text. This text can be changed to describe the conditions for which a lifespan prediction is required.

For further information on the use of the tool, please consult the manual

Calculate

2. Input
2.1 General

Country:	England	
This implies the model takes into account:	HRA 35/14 F surf 40/60	
Length of section [m]:	12	
This tool is used:	During contract phase	

2.2 Conditions during transport, laying and construction

2.2.1 Temperature of material:	estimated average value	
a. temperature during transport	180	°C
b. temperature during laying	155	°C
c. temperature during compaction	135	°C
2.2.2 Weather:	estimated average value	
a. wind speed during laying	2	km/h
b. ambient temperature during laying	10	°C
c. rainfall during laying	yes	
d. wind speed during compaction	2	km/h
e. ambient temperature during compaction	5	°C
f. rainfall during compaction	no	
2.2.3 Compaction:	estimated average value	
a. void content after compaction	2	%
b. number of roller passes during compaction	10	nr

Figure 3: Example of user input worksheet in tool

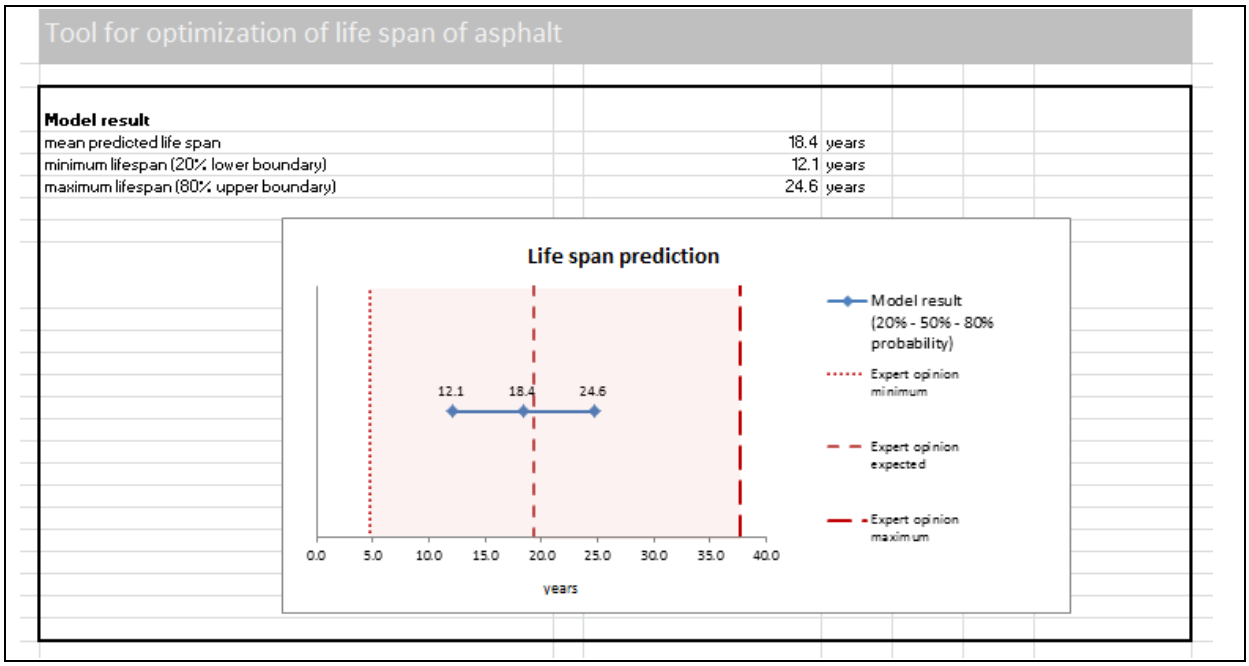


Figure 4: Example of output of the tool

7.4 General impression on the performance of the tool

Anticipating on the use of the tool in the demonstration projects (Work package 4), and considering the results of the calculations performed in order to test and tune the model as described in the previous sections, a general impression on the performance of the tool has developed during the completion of the programming of the model.

When all project values of the degradation factors (x_i) are chosen to be equal to the mean value of the distribution of the optimal value of each degradation factor ($\mu(x_{i,opt})$), the mean value of the lifespan prediction reaches approximately the mean value of the expert opinion on maximum lifespan. This is as anticipated and expected. Also, when the project values of the degradation factors (x_i) are chosen to be non-optimal or when the standard deviation accompanying the project value of the degradation factors is changed, the model responds by changing the mean value of the lifespan prediction to a smaller value. This is also as anticipated and expected.

However, the calculated change in mean value of the lifespan prediction is relatively small, and smaller than expected by the experts in the CONSISTEND project team. The limited response of the model to change in project values of the degradation factors, can be explained by the summation of the influence of the degradation factors in the model ($(\sum_{i=1}^{n} A_{i,1}(x_i - x_{i,opt}))$) in combination with the relative high number of degradation factors. The summation used in the model indicates that the sum of maximum changes in value of each degradation value, is at most equal to the difference between optimal and minimum lifespan as defined by the experts. Within this boundary, the effect of change in value of the individual degradation factors is modelled *relative* to each other.

To increase the response of the model in response to a change in values of the degradation factors, significantly less degradation factors should be defined in the next version of the tool. Also, it can be considered if the summation of influence of the degradation factors is desired considering the discussions on normative degradation factors during the project.

A more extensive insight in the performance of the tool is provided through the use of the tool in demonstration projects and implementation of the tool in the procurement process in chapter 5.

8 Conclusions and recommendations (CONSISTEND tool)

8.1 Conclusions

A model is formulated to predict the lifespan of an asphalt road. Based on expert opinions all variables in this model are defined. An Excel sheet functions as a tool or user interface for the model.

The model responds to non-optimal values of the degradation factors, and to change in the standard deviation accompanying the values of the degradation factors. When all project values of the degradation factors are appointed the optimal value, the lifespan reaches approximately the mean value of the expert opinion on maximum lifespan. This is as expected and as anticipated. When the degradation factors are appointed non-optimal values or their standard deviation is changed, the lifespan is reduced accordingly. This is as expected and as anticipated.

Twenty-four degradation factors are defined and are used in the calculations. This high number of degradation factors, combined with the relative limited bandwidth between minimum and maximum lifespan of the asphalt road defined by the experts, causes the effect of change in the mean value of the degradation factors on the lifespan to be small. The effect of the standard deviation accompanying this mean value (the quality control methods) is even smaller. Consequently the effect described in Figure 1 is difficult to observe.

Combining the fact that the model calculates a reduction in lifespan for non-optimal circumstances with the insight on the origin of the limited extent of this reduction effect, the model is considered to have potential. Section 8.2 gives recommendations to further improve the model.

8.2 Recommendations

8.2.1 Recommendations concerning the model

- The limited response of the model to changing project values of the degradation factors, can be explained by the relative high number of degradation factors. To increase the response of the model in response to a change in values of the degradation factors, significantly less degradation factors should be defined in the next version of the tool.
- In deliverable D2.1, additional possibilities of the model are mentioned. These possibilities can be considered when developing a next version of the model and tool.
- For the current version of the model, the aim of the model is to give insight in the increase in lifespan when using quality control methods. However, only expert opinions on change in lifespan caused by change in the value of the degradation factor are collected. In preparation of a next version of the model, also expert opinions on change in lifespan given the use of different quality control methods can be collected.
- Given the result of the expert opinions on the increase in lifespan that can be accomplished by the use of quality control methods, it should be considered if the indirect influence of quality control (through standard deviation on the value of the degradation factors) can correctly represent this increase.
- In a next version of the model, it should be considered that the quality control methods actually have two benefits:

- They make it possible to improve the quality of the construction process and therefore the quality of the asphalt.
- They make the contractor aware of the optimal conditions for construction and make the contractor aim for these optimal conditions where possible.

8.2.2 Recommendations concerning degradation factors

- During the project, insight is gained on correlation between degradation factors: the value of a degradation factor can only be evaluated in relation to the value of other degradation factors. For example, the use of light weight rollers can be either perfect or deficient, given the value of other degradation factors. These correlations need further study and the results can be incorporated in the next version of the questionnaire and tool.
- During the project insight is gained on the weather related degradation factors. The 'during laying' and 'during compaction' situation of these degradation factors will not differ much. The 'during laying' and 'during compaction' factors can possibly be combined.
- During the project, insight as to the necessity and redundancy of some of the degradation factors has further developed. Degradation factors have been altered, omitted and others added. Also, the description of some of the degradation factors turned out to be unclear or insufficient. Combining this with the limited response of the model due to the large number of degradation factors, careful consideration should be given to the degradation factors to be included in the next version of the model.

8.2.3 Concerning variable definition

- The degradation factor on paver stops in the after construction phase should be defined using expert opinion in a next version of the model.
- The information concerning the length of the section, required in section 2.1 of the tool, should be included in the calculations in a next version of the model.
- Weather is incorporated in the tool as a degradation factor. Also, some of the standard deviations related to the quality control methods are defined based on the weather (outside temperature). This gives weather influence on the predicted lifespan both directly (as a degradation factor) as well as indirectly (by influencing the definition of standard deviation of some of the other degradation factors). When redefining the degradation factors, it should be considered if this is either taking into account the effect of weather twice, or if it is a correct way to model the correlation between weather and some of the other degradation factors.
- It can be considered to predefine weather for the use of the tool in the contract phase. The weather in seasons or months can be predefined and the user only has to choose between winter/spring/summer/autumn or the months of the years.
- All probability distributions describing the degradation factors (both expert opinions as well as project values) are assumed to be normally distributed. Given a new set of degradation factors in a next version of the model, this should be reevaluated.
- When a shorter and adjusted list of degradation factors is available, the expert opinions related to these factors have to be collected.
- In the definition of the quality control methods, various subjective terms are used, like 'best achievable compaction' or 'standard practise'. These should be defined so they can be objectively determined.
- During the definition of the quality control methods, there was much discussion on the fact that some of the quality control methods are actually measuring methods that require additional (correct) actions to control the quality of the asphalt being laid. In a

next version of the model, the terminology ‘quality control methods’ can be reconsidered.

- In the current version of the tool, it is only possible to select one quality control method per heading in the tool. In can be considered to make it possible to select multiple quality control methods in a next version of the tool. When doing so, it should be considered how the tool will calculate with this information: will it only take into account the ‘worst’ quality control method, or will the standard deviation of the degradation factor be calculated taking into account the standard deviation accompanying the different quality control methods used?

8.2.4 In relation to Quality control methods

- Rate of application of bond coat is monitored by computer controlled spraying equipment. Many of these trucks already have GPS equipment on board. It would seem like a logical step to link the recorded rate of application of bond coat with GPS coordinates.
- Parameters which could be considered for inclusion in future versions of the Consistend model:
    a. Layer thickness
    b. Grade and slope
    c. Segregation of aggregate
- There is brief discussion in Deliverable 3.1 of quality control methods which are under development. If these methods become more prevalent, they may need to be included in a future version of the model. The methods discussed include:
    a. Vibration-dampening systems in trucks to reduce aggregate segregation.
    b. Half-shell shaped transport channel around the auger to stop aggregate segregation.
    c. Passive transponders which measure temperature within the asphalt layer.
    d. Low cost expendable RFID tags to track the spatial location of truckloads of asphalt.
- There is limited information available in the literature which quantifies the effect of quality control measures on the variability of construction parameters. Field tests or experiments could be used to get more detailed information on how advanced quality control methods affect the construction parameters. This could also be done in collaboration with other projects mentioned in Deliverable 3.1, e.g. ASPARi or FHWA projects.

9 Definitions and abbreviations

For the purposes of this report European Standards apply, as do the following terms and definitions [Read, 2003 and BSI, 2006]

Pavement, structure, composed of one or more courses, to assist the passage of traffic over terrain

Layer, element of a pavement laid in a single operation

Course, structural element of a pavement constructed with a single material. A course may be laid in one or more layers

Surface course, upper course of the pavement, which is in contact with the traffic

Binder course, part of the pavement between the surface course and the base

Regulating course, course of variable thickness applied to an existing course or surface to provide the necessary profile for a further course of consistent thickness

Base, main structural element of a pavement. The base may be laid in one or more courses, described as “upper” base, “lower” base etc.

Asphalt Concrete, asphalt in which the aggregate particles are continuously graded or gap-graded to form an interlocking structure

Tack coat (or bond coat), light application of bitumen applied between layers of asphalt to create a strong adhesive bond.

Fretting (or ravelling), the progressive loss of interstitial fines from the road surface.

Stripping, the loss of bond between the aggregates and bitumen, resulting in loose material.

Rutting (or deformation), permanent or unrecoverable traffic-associated plastic deformation often restricted to surface layers, can extend throughout the pavement.

Bleeding (or fatting up), occurs when binder fills the aggregate voids resulting in excess binder on the surface

Cracking, occurs when tensile stress and related strain induced by traffic and/or temperature changes exceeds the breaking strength of the mixture.

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