GUIDANCE

MMOPP DESIGN PROGRAM FOR ROAD PAVEMENTS

CONSTRUCTION AND PLANNING

SEPTEMBER 2017

DISCLAIMER

The translation into English of Road Standards (Vejregler) and Tender Specifications is to be regarded entirely as a service. In the event of any discrepancy or shortcomings in the translation, the Danish version will prevail. At any time the Danish versions of Road Standards (Vejregler) and Tender Specifications are those in force.

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1 Introduction

MMOPP is a design program that is linked to the Road Standard for the Design of Pavements and Reinforcement Surfacings and has been developed by the Road Standards Group for the Design of Road Pavements.

The Road Standard contains guidelines for designing pavements on roads and constructions used by ordinary heavy vehicles which may travel on public roads. Thus, MMOPP cannot be used to design pavements for aircraft or vehicles for handling containers, for example.

The program can design the following types of pavements by the analytical method:

- Flexible pavements (asphalt layer laid on unbound base course of gravel layers)
- Semi-rigid pavements (asphalt layer laid on typical hydraulically bound base layers)
- Rigid pavements (concrete laid on asphalt base layers, hydraulically bound materials or unbound materials)

The program can also be used for designing reinforcements of flexible and semi-rigid pavements. Finally, the program allows for the simulation of degradation processes for new-laid and reinforced flexible pavements.

The user manual provides a basic description of the program's features, as well as examples of how to enter input data and extract results from the program's various functions.

Section 2 is a theoretical section describing principles, models and formulas used in the program.

Section 3 provides information about installing the program.

Section 4 reviews all the functionalities and screens in the program. Special attention is paid to the series of examples which show common design challenges:

Analytical design:

- Section 4.3.1: Default design
- Section 4.3.2: User-defined design
- Section 4.3.3: Manual analytical design
- Section 4.3.4: Parallel design of pavements with hydraulically bound base layers (HBB)
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- Section 4.4.3: Designing a reinforcement layer by simulation

Section 5 examines the printing options and the documenting of the calculations.

Section 6 specifies references.

2 The program's principles

2.1 The program's design methods

The purpose of the program is to enable the user to design pavements, whilst taking traffic, materials and climate conditions into account. Calculations are made in MMOPP with the WESDEF program, which has been integrated as a DLL sub-routine. WESDEF is a linear elastic program on a par with BISAR [ref. 5], ELSYM5 [ref. 7] and CHEVRON [ref. 10].

The designing of pavements can be done by two fundamentally different methods:

- Analytical design
- Simulation, where a number of simulations are made of the degradation of the pavement, which determines when the pavement ceases to comply with certain predefined requirements (lifespan criteria) for asphalt degradation, evenness and rutting

For analytical design, MMOPP ensures that the desired lifespan is observed for all layers in the pavement and for the subgrade. If the user manually adjusts layer thicknesses or the E values of the materials, the user must check that the desired lifespan is still complied with for all layers in the pavement and for the subgrade themselves.

For simulations with the same thicknesses of the layers in the pavement, various lifespans will be available until the criteria are not met. Based on this, one can assess the surety according to which the construction meets the criteria.

As stated in the foreword of the handbook for the Design of Pavements and Reinforcement Surfacings, [ref. 11], the following three levels of design are defined:

- Level 1, Catalogue road pavements - the pavement is determined based on a printed catalogue
- Level 2, Analytical-empirical Design - the pavement is designed based on design criteria based on pre-defined or user-chosen traffic and material parameters
- Level 3, Design by simulation - the pavement is designed based on simulated breakdown processes to meet standard or use-chosen requirements for durability and reliability

Flexible and semi-rigid pavements may be designed according to level 1.

At level 2, flexible, semi-rigid and rigid pavements can be designed and at this level, reinforcement of flexible and semi-rigid pavements can also be designed.

At level 3, new flexible pavements as well as their reinforcement can be designed, and it is also possible to optimise construction costs of new flexible pavements. However, this method is not so evolved yet that it can be considered more correct than level 2 design, which is why design at level 3 should be regarded as indicative for the time being.

2.2 Analytical design

The critical loads in the individual layers of a pavement depend on the material properties of the layers as well as on the amount of load.

Analytical design calculates critical loads in the pavement for a design load (E10 load) and the size of the critical loads are controlled in relation to the permissible loads. For bound materials, such as asphalt, concrete and HBB, the critical load (p) is the horizontal strain on the underside of the layer (indicated by index "h" for horizontal), whereas, for unbound materials, the vertical pressure is on the upper side of the layer (indicated by index "z").

A design criterion of a material is given by a mathematical correlation between the permissible loads (p) and the number of design loads (N_{E10}) and can be specified in the following generic form:

$$p = A \times (E / E_{ref})^{B} \times (N_{E10}/10^{6})^{C} \qquad \text{(I)}$$

Where the parameters are:

p	The (maximum) permissible load for a given number of design loads
E	E value of the material
E_{ref}	Reference E value for the material type
N_{E10}	The number of E10 loads during the design period
A, B, C	Material parameters for the material type.

A historical background to the design criteria for unbound materials and asphalt materials used in the Road Standard is given in [ref. 3].

Designing of layers constructed of hydraulically bound base layers are based on analytical design criteria determined from VI Report 138, "Mechanistic Design of Semi-Rigid Pavements", [ref. 4], based, among other things, on the full-scale fatigue tests carried out in 2003 with six experimental trials.

The E10 load is defined as a 10-tonne axle with twin wheels. In MMOPP, only one set of twin wheels is modelled as two circular load points with a centre-centre distance of 350 mm and a tire pressure of 0.70 MPa. The load is 6 tonnes, which corresponds to the weight of one set of wheels plus a shock allowance of 20%, which takes into account the unevenness of the surfacing.

2.2.1 Design criteria for unbound materials

For unbound materials, the critical load is the vertical stress on the upper side of the layer, denoted as σ_z. The form of the design criteria depends on the E value of the material, as indicated in the following equation for the permissible load:

$$\sigma_z = 0.086\ MPa \times (E/160\ MPa)^{1,06} \times (N_{E10}/10^6)^{-0.25} \qquad \text{(II)}$$

The background to this equation is given in [ref. 3].

2.2.2 Design criteria for asphalt materials

For asphalt materials, the critical load is the horizontal strain in the underside of the layer, denoted as ε_h. The design criterion for the permissible load is given in the following equation:

$$\varepsilon_h = -0.000250 \times (N_{E10}/10^6)^{-0.191} \quad \text{(III)}$$

The background to this equation is given in [ref. 3].

2.2.3 Design criteria for hydraulically bound base layer materials

In the handbook for the Design of Pavements and Reinforcement Surfacings [ref. 11], the following two, different types of hydraulically bound base layers (HBB) are included:

- HBB-A: uniform-sized, sanded aggregate
- HBB-B: graded, gravelly aggregate

The difference between the two types of HBB is described in the tender specification for hydraulically bound base layers [ref. 12].

Repetitive loads from traffic will inevitably degrade HBB materials over time. With this degradation, the E value of the HBB layer is continuously reduced and thus the Road Standard operates, respectively, with E values for the HBB materials in "initial state" and "terminal state".

In the Road Standard, the following E values are used in the terminal state, depending on the type of HBB:

- HBB-A, $E_{terminal}$: 1,500 MPa
- HBB-B, $E_{terminal}$: 2,000 MPa

The design criteria for HBB materials determine the largest permissible horizontal strain on the underside of the layer, denoted as ε_h. This value depends on the material's initial E value, (E_{INIT}), as well as the degree of degradation which as acceptable at the end of the design period. The degree of degradation is characterised by the material terminal E value, (E_{TERM}).

The design criteria for HBB used in the Road Standard are shown in Table 1 below.

Material	Strength class (MPa)	E_{INIT} (MPa)	E_{TERM} (MPa)	Design criteria	
HBB-A	$C_{5/6}$	7,500	1,500	$\varepsilon_h = -0.000048 \times (N_{E10}/10^6)^{-0.201}$	(IV)
HBB-A	$C_{6/8}$	9,000	1,500	$\varepsilon_h = -0.000060 \times (N_{E10}/10^6)^{-0.180}$	(V)
HBB-A	$C_{8/10}$	12,000	1,500	$\varepsilon_h = -0.000086 \times (N_{E10}/10^6)^{-0.148}$	(VI)
HBB-B	$C_{5/6}$	11,800	2,000	$\varepsilon_h = -0.000066 \times (N_{E10}/10^6)^{-0.149}$	(VII)
HBB-B	$C_{6/8}$	13,000	2,000	$\varepsilon_h = -0.000075 \times (N_{E10}/10^6)^{-0.139}$	(VIII)
HBB-B	$C_{8/10}$	15,000	2,000	$\varepsilon_h = -0.000090 \times (N_{E10}/10^6)^{-0.125}$	(IX)
HBB-B	$C_{9/12}$	15,900	2,000	$\varepsilon_h = -0.000098 \times (N_{E10}/10^6)^{-0.119}$	(X)
HBB-B	$C_{12/16}$	18,300	2,000	$\varepsilon_h = -0.000118 \times (N_{E10}/10^6)^{-0.107}$	(XI)
HBB-B	$C_{15/20}$	20,500	2,000	$\varepsilon_h = -0.000137 \times (N_{E10}/10^6)^{-0.098}$	(XII)
HBB-B	$C_{18/24}$	22,500	2,000	$\varepsilon_h = -0.000156 \times (N_{E10}/10^6)^{-0.090}$	(XIII)
HBB-B	$C_{21/28}$	24,300	2,000	$\varepsilon_h = -0.000173 \times (N_{E10}/10^6)^{-0.085}$	(XIV)

Table 1 Design criteria for Hydraulically Bound Base Layers.

The selected E values in the terminal state ensure that the HBB materials will retain a high load-carrying capacity after the design period.

The background to these design criteria for HBB is described in [ref. 7].

2.2.4 Design criteria for concrete

For concrete surfacings, using an E value of 35,000 MPa and a Poisson's ratio of 0.15, a design criterion can be used of the form:

$$\varepsilon_h = -0{,}000038 \times (N_{E10}/10^6)^{-0{,}118} \qquad \text{(XV)}$$

A theoretically correct design of concrete surfacing is ensured by comparing the tensile stresses in the concrete from the E10 load and comparing these with the concrete flexural tensile strength. The stresses are calculated either by means or Westergaard's formulas or Finite Element calculation, which have not been integrated in MMOPP. The chosen "equivalent" criterion ensures that approximately the same thicknesses are determined as in the diagram method in the original Road Standard 7.10.03 [ref. 13], and the background to determining the design criterion is given in [ref. 6].

In Road Standard 7.10.03, the design of concrete surfacings was based on a 20-year design period. In addition, recommendations for the choice of base layer materials were specified based on the traffic intensity.

These recommendations for selecting base layer materials have been translated into current traffic classes and shown in the table below:

Traffic load class	Recommended base layer material
T1	SG, SKM, SIM, KB or HBB-A
T2, T3, T4	HBB-A
T5, T6, T7	HBB-B

Table 2 Limits for use of base layer materials under concrete (strength class of the HBB materials must be in accordance with Table 1).

Minimum and maximum thicknesses of these base layer materials under concrete are listed in the following table:

Material	E value [MPa]	Thickness [mm]	
		Minimum	Maximum
HBB-A, all strength classes	1,500	150	300
HBB-B, all strength classes	2,000	150	250
Stone macadam (SKM)	1,000	120	130
Shingle macadam (SIM)	600	120	130
Base course of gravel I (SG I)	350	120	250
Base course of gravel II (SG II)	300	120	250
Crushed concrete (KB)	350	120	250

Table 3 Minimum and maximum thicknesses of base layer materials under concrete (strength class of the HBB materials must be in accordance with Table 1).

When designing concrete pavements with MMOPP, no sheet size, possible reinforcement, load transfer between sheets or joint sizes and types are taken into account. These things should be determined based on the relevant standards and codes of practice.

2.3 Design by simulation

2.3.1 Overall

Simulation of a road pavement's degradation under traffic takes place by mathematically letting a wheel travel over a pavement of a given length under varied climatic and speed conditions.

Unlike more traditional designs, which can also take seasons into account by calculating the degradation contributing factors for the traffic volume which occur throughout the lifespan of the individual climatic periods, the simulation method makes the calculations seasonal in order to analyse a number of uniform climate events using the current annual traffic volume.

This results in a recursive effect of the previous year's degradation, so that the increasing unevenness results in heavier impact loads which, in turn, lead to accelerated degradation, etc.

In determining degradation models, the road standards group assumed that the pavements, which, according to the Road Standard 7.10.03 of 1984, were designed for 10 years, had an average lifespan of 15 years. This corresponds to the pavements being able to comply with the evenness criterion for 10 years with a probability of 70% - 90%. The prior assumption also corresponds to the degradation model for evenness, which is integrated into the vejman.dk program, which is used to prioritise maintenance works on major roads in Denmark.

2.3.2 Models

The simulation program is based on a number of mathematical models of the interaction between wheel and surfacing and the impacts which the loads cause in the pavement.

The following models shall be used:

a) <u>Pavement model</u>, which defines the characteristics and layer thicknesses of the individual layers, as well as the surface of the surfacing

b) <u>Load model,</u> which defines the correlation between the geometry of the road surface and the wheel's movements and loads on the road surface

c) <u>Climate model,</u> which defines the correlation between the deformation properties of the materials and the climate

d) <u>Response model,</u> which describes how a load on the road surface is distributed down throughout the pavement. For this simulation, Odemark-Boussinesq's theory is used.

e) <u>Structural degradation (cracks),</u> which defines the correlation between dynamic loads and the degradation of the asphalt layer

f) <u>Permanent deformations (evenness and rutting)</u>, which defines the correlation between dynamic loads and permanent deformations

2.3.3 Pavement model

The pavement model consists of two parts, namely a geometric part that defines the surface of the pavement and the thickness of the individual layers, as well as a material part that defines the E values at each individual point.

The length of the section can be varied. The default value in the program is 30 m, approximately equal to the length of the AASHO test's observation sections of 100 feet. Sub-sections of 300 mm are considered as uniform elements for which the surface, layer thicknesses and E values are specified, as shown in the figure below.

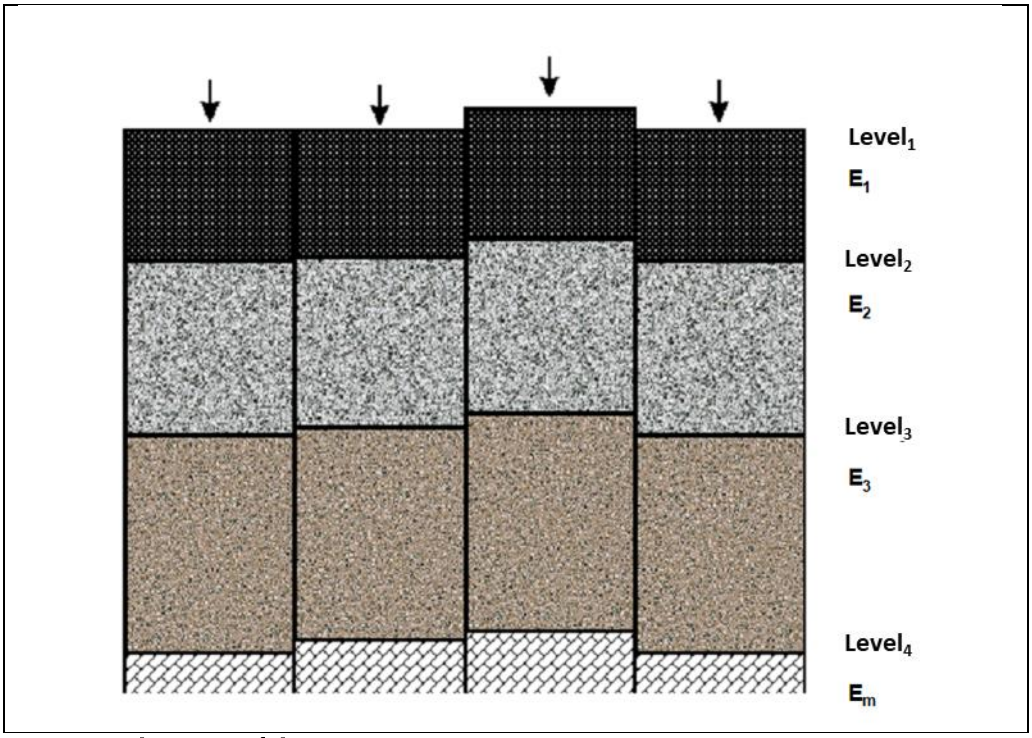


Figure 1 Elements of the pavement.

All layer surfaces and material properties are determined by a "second-order autoregressive process" where the value of a given element depends on the value of the two preceding points, based on a so-called autocorrelation (a high autocorrelation coefficient indicates a very little variation from point to point).

For each layer, a mean layer thickness, spread on the surface, as well as a 1st and 2nd autocorrelation coefficient for the surface is indicated. The surfaces are generated based on these values.

The surface evenness, IRI value, is calculated from the surface levels in the middle of the individual element.

The deformation properties will not follow the usual normal distribution for the material descriptions, but, on the contrary, a logarithmic normal distribution, i.e. that the logarithms of the E values will follow a normal distribution. In a normal distribution, the dispersion indicates how much to add/subtract in order to reach, respectively, 84% and 16% fractiles. For logarithms of values, addition/subtraction equals multiplication/division of the actual values. The dispersion of the logarithms of E values therefore corresponds to distribution factors (sdf, Standard Deviation Factor) for the actual E values.

The values which are added to the program correspond to the values normally used in the Road Standards. These, however, are not the averages for layers, but correspond to the 25% fractiles, i.e. that 75% of the E values of the layer on the section are higher than the specified value. The program makes the necessary conversions itself.

2.3.4 Load model

The interaction between wheels and road surface is described by a single-wheel or twin-wheel 2-mass viscoelastic system, in which the user can define the masses of wheels, incl. axle and body weight, as well as the spring and damping constants between wheels and road surface (covered), as well as wheel+axle and coachwork (suspension system).

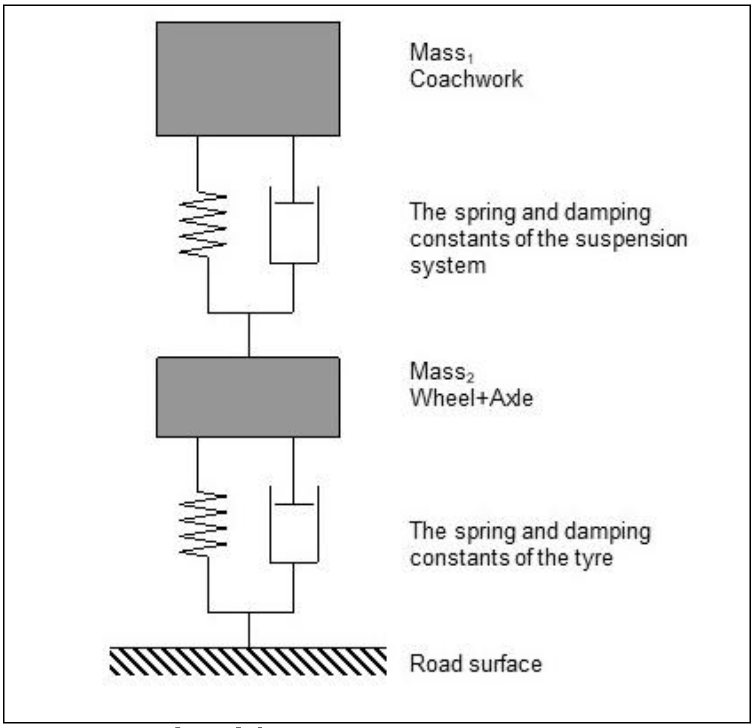


Figure 2 Load model.

2.3.5 Climate model

The climate model contains two sub-models which, respectively, determine the E values of the materials in the different seasons and calculate the depth of frost penetration during the winter period.

E value model

Simple table functions are used for the E values of the materials in the different climatic periods (seasons). Slightly modified versions of the Swedish Road Standard's climate parameters for Skåne are used. The table below indicates period lengths and relationships between the E values in the respective periods. It is seen that the E values given as inputs to the program correspond to the summer period conditions, with a factor of 1.0 for all layers specified.

Period	Days	Temperature	E_1	E_2	E_3	E_m
-	-	°C	factor	factor	factor	factor
Winter	49	-2	4	4.2	10	20
Winter thaw	10	1	3.7	0.33	10	20
Sudden thaw	15	1	3.7	0.67	0.7	0.6
Late spring	46	4	3.1	1.0	0.85	0.8
Summer	143	20	1.0	1.0	1.0	1.0
Heatwave	10	35	0.3	1.0	1.0	1.0
Autumn	92	7	2.6	1.0	1.0	1.0

Table 4 Parameters in climate simulation.

Frost penetration model

Frost penetration in the pavement is calculated from a model specified in the Swiss standards:

$$Frost\ penetration = 45mm \times subzero\ temperature\ days^{0.5} + \frac{k}{2} \qquad \text{(XVI)}$$

k Pavement thickness in mm

Sub-zero temperature days are calculated based on a time series of the years 1873 to 2003 registered by DMI at Tranebjerg (station 27080). The last 24-hour period's maximum and minimum temperatures are specified on a daily basis. Assuming that the average of max and min is also the average of the day, the cumulative sub-zero temperature days are calculated for all periods with negative temperatures, and the highest number of sub-zero temperature days for each year are stored as the sub-zero temperature days of the year, as shown in the figure below.

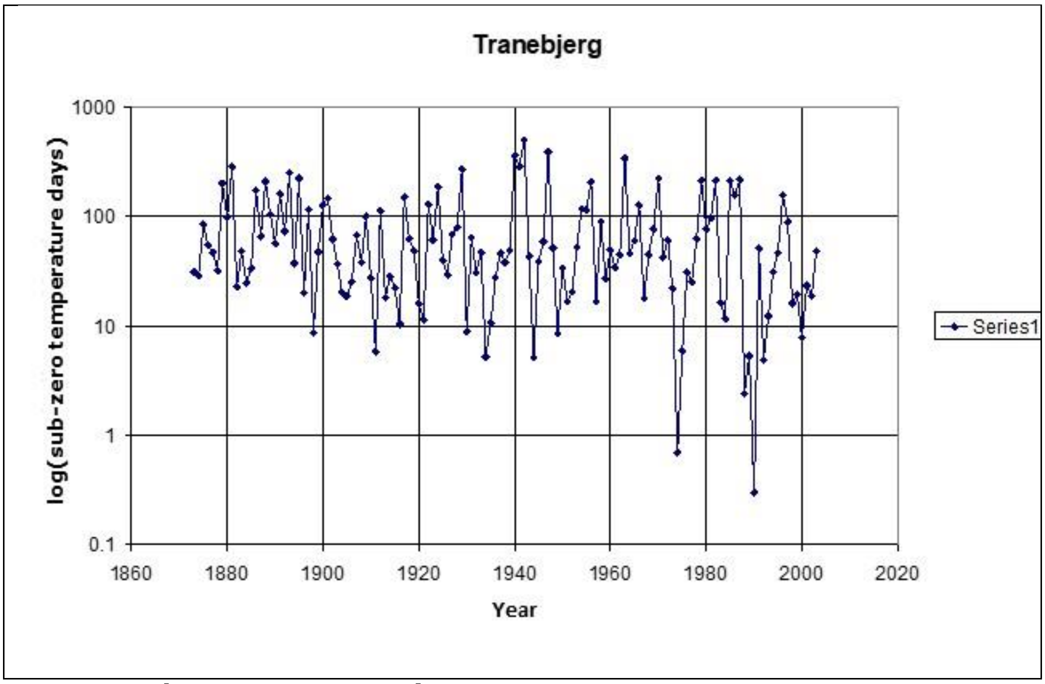


Figure 3 Sub-zero temperature days 1873-2003.

This series of sub-zero temperature days can be described by a logarithmic normal distribution of an average of 1.64 (43.9 ºC×days) and a dispersion of 0.53 (standard deviation factor (sdf) of 3.39).

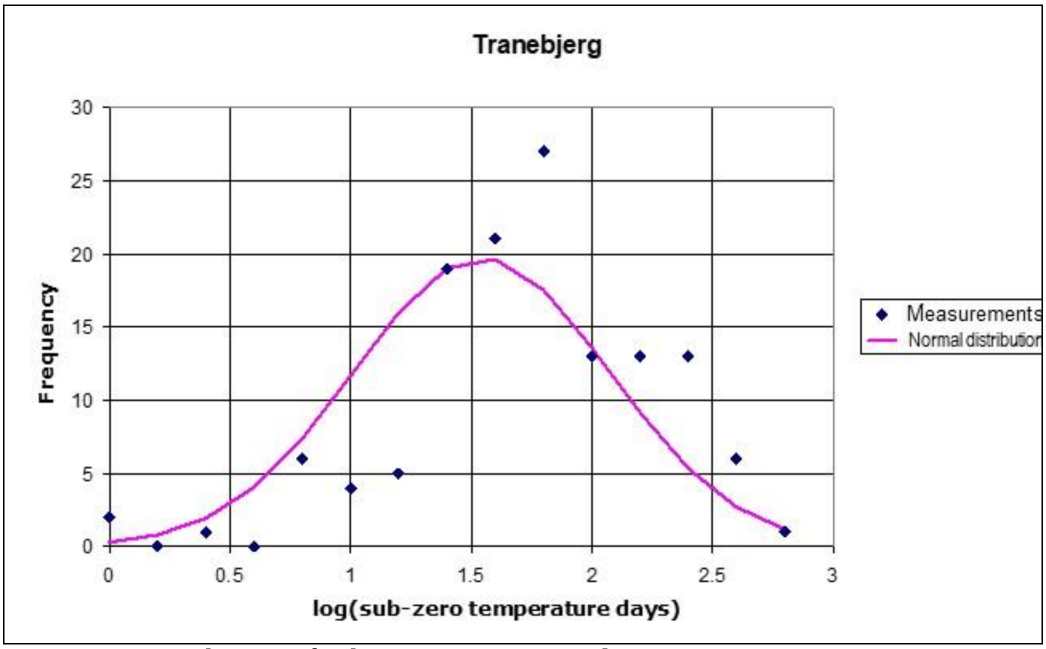


Figure 4   Distribution of sub-zero temperature days.

Based on the logarithmic normal distribution, the program selects a random number of sub-zero temperature days each year and calculates the frost penetration based on the previously stated formula.

2.3.6 Response model

The Equivalent Thickness Method is used by default. The correction factors in the calculations vary as a function of material properties and layer thicknesses, as indicated in the following table:

Pavement type	2-layer		3-layer		4-layer	
Condition	$h_e<0.6a$	else	$h_e<0.6a$	else	$h_e<0.6a$	else
f_1 Condition	calc. $\frac{E_{øvre}}{E_{nedre}}<2$	0.8 else	calc. $\frac{E_{øvre}}{E_{nedre}}<2$	0.8 else	calc. $\frac{E_{øvre}}{E_{nedre}}<2$	0.8 else
f_2			1	0.92	1	0.92
f_3					1	0.92
f_m	1	0.82	1	0.82	1	0.82

Table 5   Correction factors in calculations using the Equivalent Thickness Method.

Definitions of the symbols in the above table:

h_e The equivalent depth

a Radius of the load area

E_{upper} E value of the layer above the joint surface, where the impacts are calculated

E_{lower} E value of the layer below the joint surface where the impacts are calculated

f_n The correction factor in the nth joint surface for the conversion between the pure third root calculated depth of z ($z = t_{upper} \times (E_{upper}/E_{lower})^{1/3}$) and the equivalent depth, h_e ($h_e = f_n \times z$)

f_m	The correction factor for the subgrade
t_{upper}	Thickness of the layer above the joint surface, where the impacts are calculated
calc.	Indication of the fact that the correction factor f_1 is calculated from the formula $f_1 = 1 + 0.6\times(a/z)^2$

2.3.7 Structural degradation of the asphalt layer

A model is used which, based on calculated stresses in the underside of the asphalt, determines the crack initiation in accordance with the traditional design criteria developed, for example, from a three-point flexural test. The spread up through the layer is then calculated in accordance with simplified models for fracture mechanics. As the cracks are spread, the E value of the layer is reduced. In this context, the asphalt layer of the pavement as a whole is considered to be of material parameters corresponding to a weighted average of the wearing course, binder course and base layer.

Fracture mechanics is a relatively complicated analytical method which calculates the development of cracks through a uniform material by using the stress concentrations around the tip of the crack. Both the effects of shearing stresses and flexural stresses are considered, so that different development patterns can occur for pavements with the same type of course, but with different supportive factors. However, for all developments, they will run relatively slowly in the beginning and then accelerate to a certain level that remains constant until the crack has reached right through the layer.

In MMOPP, the effect is expressed by a recording of the asphalt layer E value pursuant to a formula constructed as follows:

$$E_{before} = E_{after} \times \left(1 - 0{,}5 \times \left(\frac{\varepsilon_{actuel}}{\varepsilon_{permissable,1million} \times (VB/10\%)}\right)^n \times \frac{dN}{k_{temperature} \times CP_{factor}}\right) \qquad \text{(XVII)}$$

Definitions of the symbols in this formula are:

E_{before}	E value at the start of the period to be calculated
E_{after}	E value after the period of the design load dN
$\varepsilon_{current}$	The calculated strain in the underside of the asphalt layer
$\varepsilon_{permissible,\ 1\ million}$	The permissible strain in the underside of the asphalt layer v. 10^6 passages
VB	The bitumen content in the volume percentage
n	Exposure model exponent, Kirk's exponent is used here at 5.62
dN	Number of design loads during the period
$k_{temperature}$	A temperature correction which makes the material less susceptible to fractures at high temperatures
CP_{factor}	A set constant which calibrates the process to actual conditions

The factor $k_{temperature}$ is calculated by $k = C1 \times 10^{[(T+C2)/C3]}$

The constants C1, C2 and C3 depend on the temperature, T, as shown in the following table and figure:

	T ≤ 16º C	16º C < T < 21º C	21º C ≤ T
C1	0.0005	0.22	1
C2	17.8	-16	-21
C3	12.8	7.6	3

Table 6 Constants in the temperature correction factor.

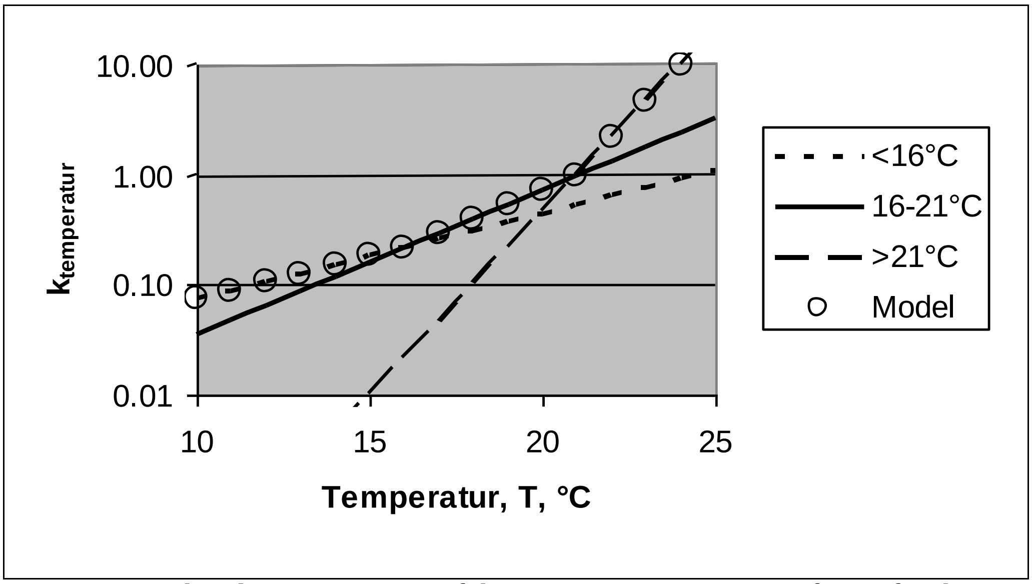


Figure 5 Graphical representation of the temperature correction factor for the model.

2.3.8 Permanent deformation

Permanent deformation comes from plastic strain. Plastic strains are calculated based on the E values of the materials and dynamically calculated stresses using the Equivalent Thickness Method.

The permanent deformation of a material can take place in up to 3 phases:

Phase 1 The plastic strain rate of the material is decreasing
Phase 2 The plastic strain rate of the material is constant
Phase 3 The plastic strain rate of the material is increasing

The transition between the three phases typically occurs at constant levels of permanent deformation, as indicated in the figure below. Phase 3 does not occur under normal operating conditions, as it corresponds to the pavement being in a collapse situation. Phase 3 is, consequently, not included in the program.

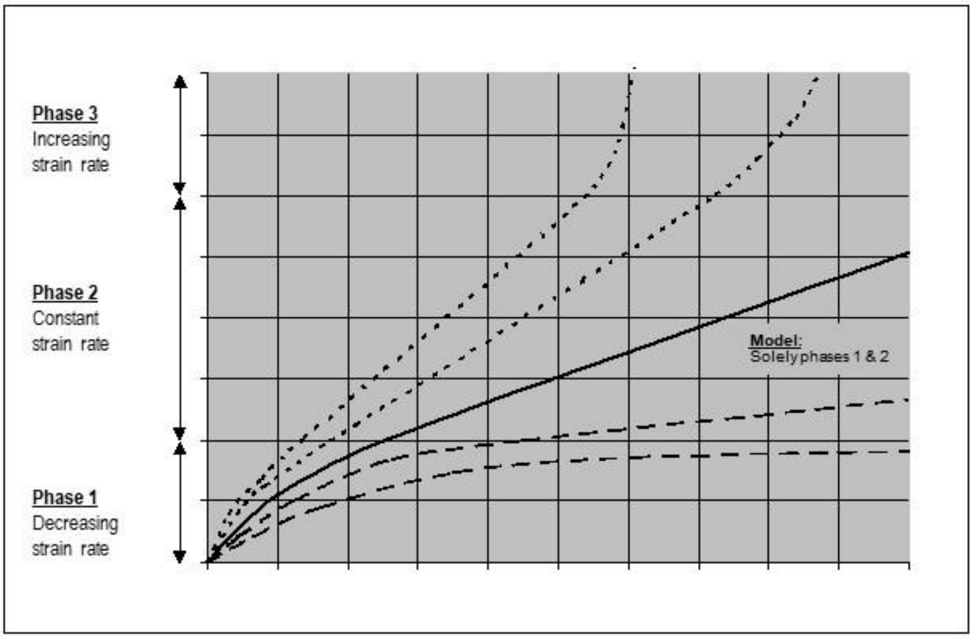


Figure 6 Model for permanent deformation.

The general form of Phase 1 is:

$$\varepsilon_p = A \times N^B \times \left(\sigma/\sigma_{ref}\right)^C \qquad \text{for } \varepsilon_p < \varepsilon_0 \qquad \text{(XVIII)}$$

and for Phase 2:

$$\varepsilon_p = \varepsilon_0 + (N - N_0) \times A^{1/B} \times B \times {\varepsilon_0}^{1-1/B} \times \left(\sigma/\sigma_{ref}\right)^{C/B} \qquad \text{for } \varepsilon_p > \varepsilon_0 \qquad \text{(XIX)}$$

in which

$$N_0 = {\varepsilon_0}^{1/B} \times A^{-1/B} \times \left(\sigma/\sigma_{ref}\right)^{-C/B} \qquad \text{(XX)}$$

Here the formula parameters are as follows:

ε_p	Plastic strain
ε_0	The level of strain which indicates the transition from phase 1 to phase 2
N	The number of design loads (refer to the elaboration in the text below)
N_0	The number of design loads until the transition from phase 1 to phase 2
σ	Current stress (refer to the elaboration in the text below)
σ_{ref}	Reference value for stress
A, B, C	Material constants

The input stresses are the values calculated at any given time in the top and bottom of the individual layer of the pavement, such that the seasonal variations of the materials are taken into account, as well as the degradation of the asphalt layer.

In MMOPP, the permanent deformation counter (N) in the simulations is reset after each sudden thaw phase, as frost/thaw cycles, from experience, lead to a certain repositioning of the microstructure similar to the disturbance that occurs during the filling of a road.

The reset occurs only if there has been a frost penetration of at least 10mm in the layer, where the total frost penetration is calculated as indicated in section 2.3.5.

In order for this reset not to lead to excessive permanent strains, the part of the deformation originating from the first 1,000 passages is ignored. As with structural degradation, the asphalt layer of the pavement is considered as one unit.

Finally, it should be noted that the deformations calculated in the program are those caused by normal post-compaction and limited displacement in layers not subject to structural "flow". The heavy ruts which can occur when one exceeds the shear strength of the materials for given layers, such as, for example, in asphalt materials during extremely hot periods or in uniform-sized sanded materials which are overloaded and thereby break down, cannot be taken into account by the program. Protection against this degradation type can be ensured by, among other things, performing rutting tests.

3 Program installation

3.1 System requirements

The program can be run on all Windows 32-bit and 64-bit operating systems up until Windows 10 at the end of 2016.

If you want to go directly into the MMOPP program's database, this can be done in Microsoft Access 7 or higher.

3.2 Installation

The program has been gathered into a self-extracting file that can be downloaded from:

www.vejdirektoratet.dk/DA/vejsektor/ydelser/programmer/Sider/Dimensioneringsprogram.aspx

By default, the program will be installed in the BASIS2017 folder, under the following path:

C:\Users\Public\MMOPP\BASIS2017\

By installing under C:\Users\Public\ it is ensured that the Windows operating system doesn't limit the user in editing files, and that the application can write to the database and generate temporary files in the folder.

The two "lowest" folders in this path, \MMOPP\BASIS2017\, cannot be changed by the user. The purpose of this design is to allow the user to create parallel folders for separate projects under the MMOPP folder by copying the BASIS2017 folder and giving the new folder a name related to the current project. In the copied .INI file (see Figure 15), the path should be corrected to fits with the current folder name. In this way, you can safeguard against an insurmountable amount of surfacing alternatives in the database, and this can be stored together with the project's other documentation. When copying a project, you should save a copy of the entire application folder, as it is not guaranteed that future versions of MMOPP can run on old databases.

On computers with Danish Windows, the path C:\Users\Public\MMOPP\BASIS2017\ will instead be c:\brugere\delte filer\MMOPP\BASIS2017\. Windows makes the necessary conversion itself. The English-language "\Users\Public\" can still be used in .INI files.

The following installation instructions require that the user (even temporarily) has administrator rights on the computer.

The MMOPP installation file is called SetupMMOPP2017.exe. The program's installation is started by double-clicking the downloaded file.

You must then confirm that you allow the SetupMMOPP2017.exe program to make changes to your computer. This requires administrator rights. Click "Yes", then the following screen will appear:

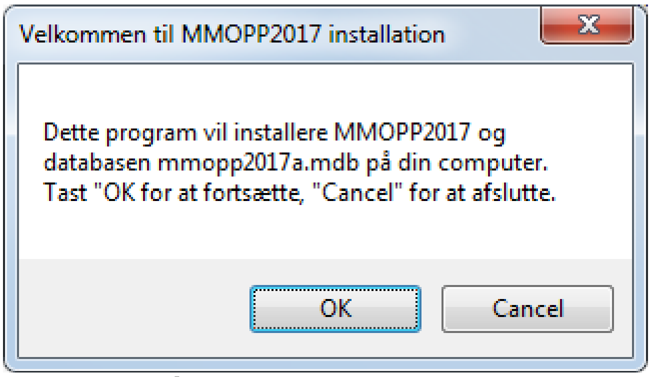


Figure 7 Welcome screen

Pressing "OK" displays the following screen:

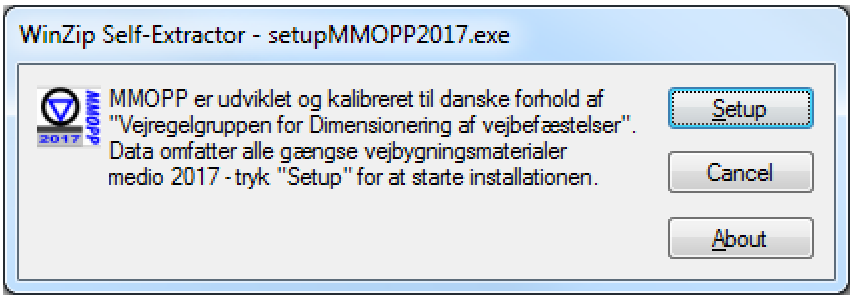


Figure 8 Start setup

By clicking "Setup", the following screen is displayed on a blue background:

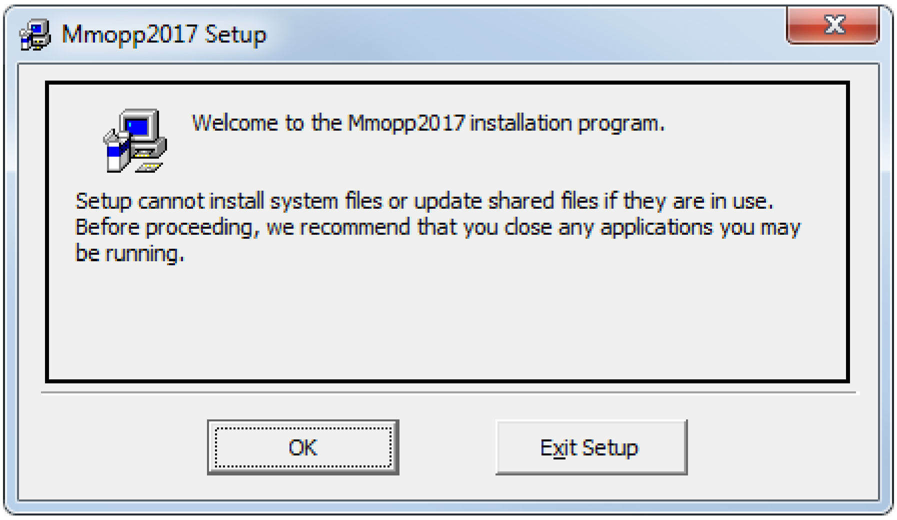


Figure 9 Remember to close other programs

Pressing "OK" leads to the following screen:

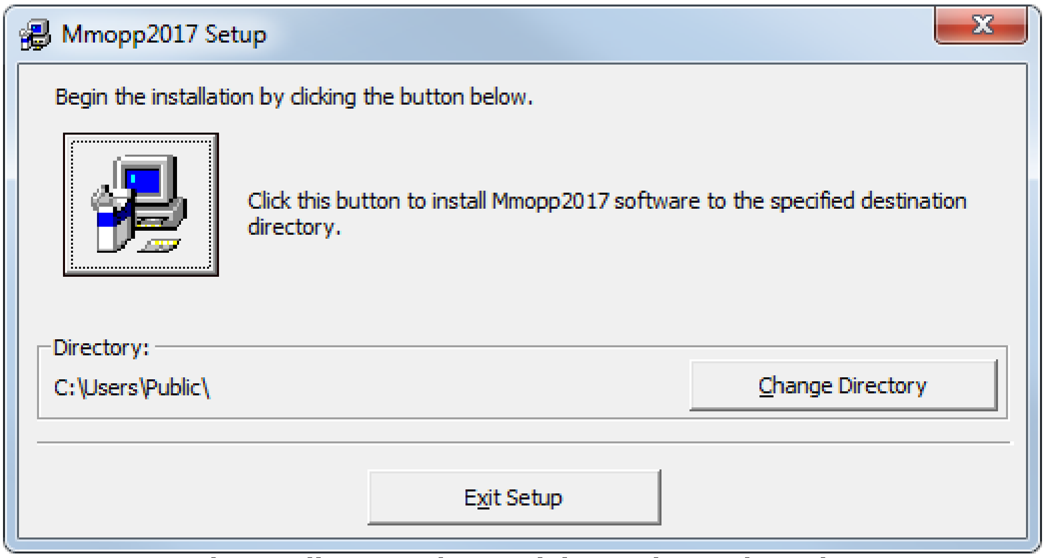


Figure 10 Start the installation or the possibility to change the path

The installation is started by clicking the big button with the image of a desktop PC. This produces the screen in Figure 12.

You can choose another path within \MMOPP\BASIS2017\ by clicking "Change Directory". You'll be presented with the screen below, where one can enter the path you'd like in the field "Path", but without the \MMOPP\BASIS2017\.

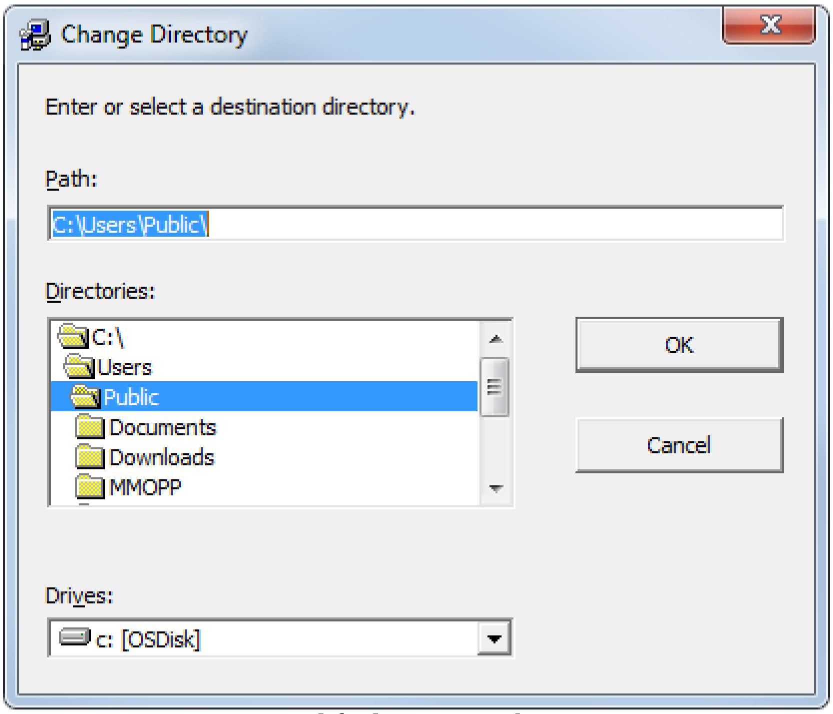


Figure 11 Entering a modified parent path

After entering a possible change of path, you will return to Figure 10 by clicking "OK". The changed path will then be displayed in Figure 10.

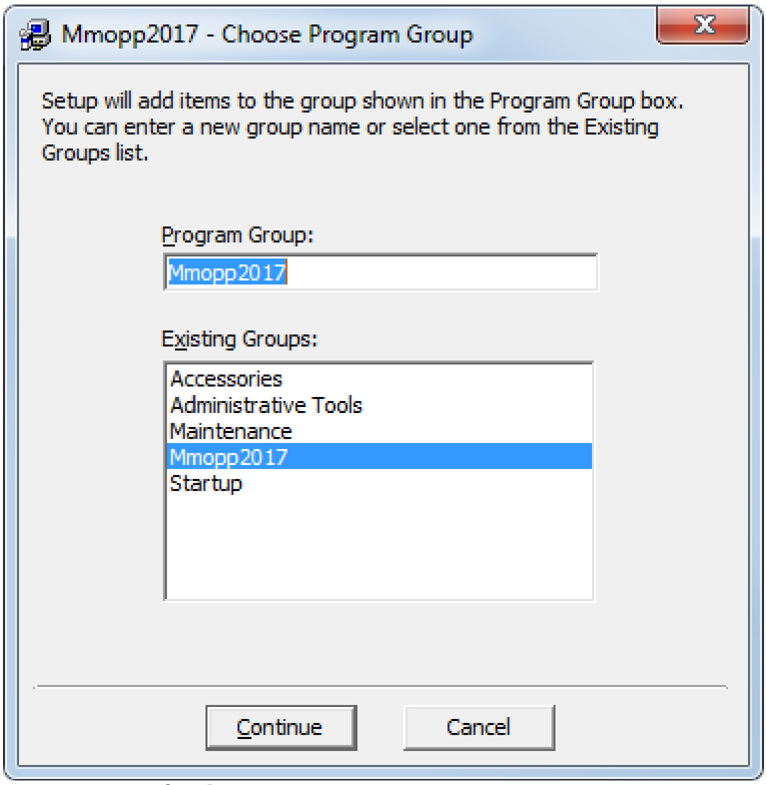


Figure 12 Info about creating a program group

Click "Continue" to accept the creation of a "Mmopp2017" program group. The installation is performed after this.

Questions can be asked during the installation regarding whether you want to overwrite newer files, such as shown below. Click "Yes" to keep existing versions.

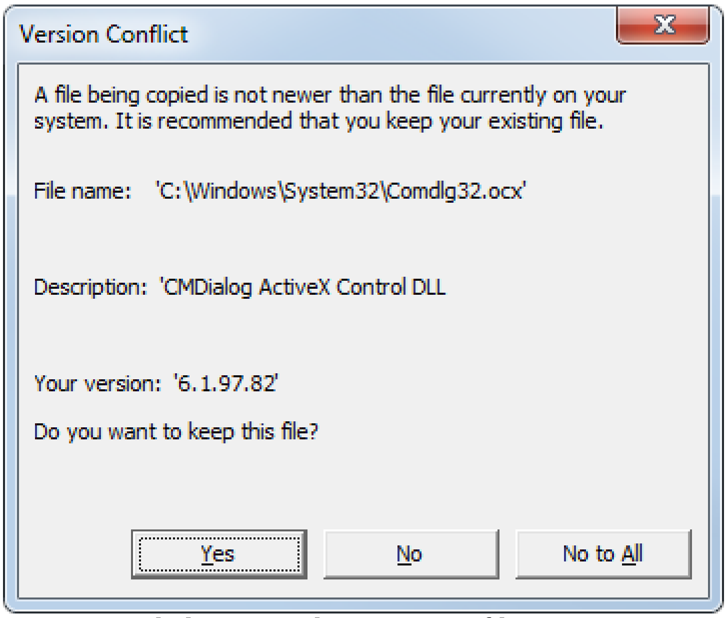


Figure 13 Click "Yes" to keep existing files

When the installation is complete, the following is displayed - click "OK" to exit.

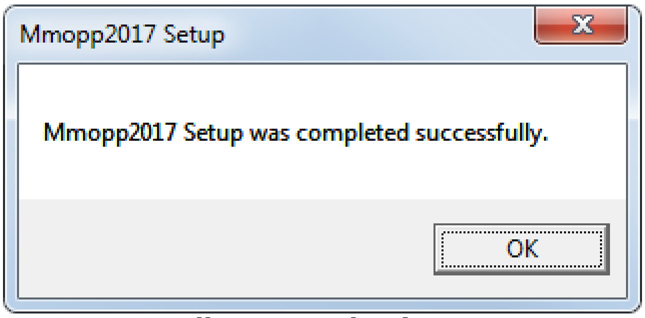


Figure 14 Installation completed

After completion of the installation, make sure that the MMOPP.INI file's third line contains the address of the current directory if one different than the default was selected.

The INI file can be edited in Notepad. The name of the database used in the calculations is stated in the second line of the file.

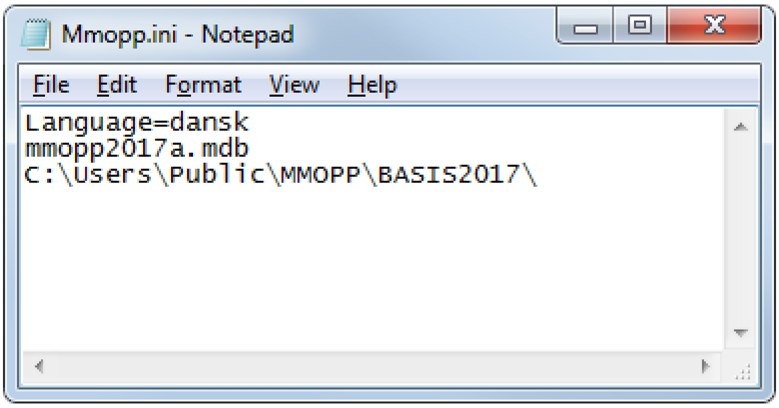


Figure 15 MMOPP.INI file specifies the database and path

After that, the program should be ready to run by double-clicking the MMOPP2017.exe program in the current application folder or on the MMOPP2017 icon in the start menu (if this was created).

The program is installed with a database called mmopp2017a.mdb. The name indicates that this is a version "a". Adding or altering the material and design parameters of the road standards will allow for revised databases later on, named according to the same principle.

3.3 Known issues

Problems may occur when installing MMOPP. Known issues are described in a dynamic document, which is available on the Danish Road Directorate's website and can be downloaded from:

www.vejdirektoratet.dk/DA/vejsektor/ydelser/programmer/Sider/Dimensioneringsprogram.aspx

4 Using the program

4.1 General

The MMOPP program has two basic operating methods:

- Designing according to the traditional analytical method, either with simple traffic and material options or with user-defined inputs
- Designing the degradation process by simulation, either by checking the lifespan(s) of a given pavement or by optimisation, where the most economical pavement that will meet the required lifespan requirements of the construction is ascertained

The program uses conventional SI units. In the program's "main window", "Input parameters" (see page 24), the current units for data that is not dimensionless are displayed when the mouse pointer is brought over that particular field.

When designing, MMOPP calculates the required layer thicknesses to achieve a theoretically expected lifespan that meets the desired design period. This often results in "slanting" layer thicknesses, which the user can subsequently round off appropriately, after which it should be checked that the desired theoretical lifespan is still present.

The program ends by clicking the "End" button found in the "Input parameters" window (see section 4.2.1), as well as in all the material selection windows which lead to "Input parameters".

4.2 The program's screens

An explanation is given below of the basic input values in MMOPP's screens. These screens are:

- Input parameters
- Layer
- Climate (disabled by default)
- Load (disabled by default)
- Limits (disabled by default)

Some of these screens are disabled and are thus hidden for users in the Road Standard Edition of MMOPP, in order to ensure that only inputs which are in accordance with the prerequisites of the Road Standard are used. Information on how these screens can be enabled can be obtained from the Chairman of the Road Standards Group for the Design of Road Pavements.

4.2.1 The "Input parameters" window

The "Input parameters" window can appear in two calculation modes, depending on the calculation situation, which can be one of the following:

- Analytical design
- Design by simulation

Transition between the two calculation situations takes place by means of the two "option buttons" respectively labelled "Analytical" and "Simulation" in the right side of the screen.

Figure 16 and Figure 17 show the window "Input parameters" for, respectively, analytical design and design by simulation:

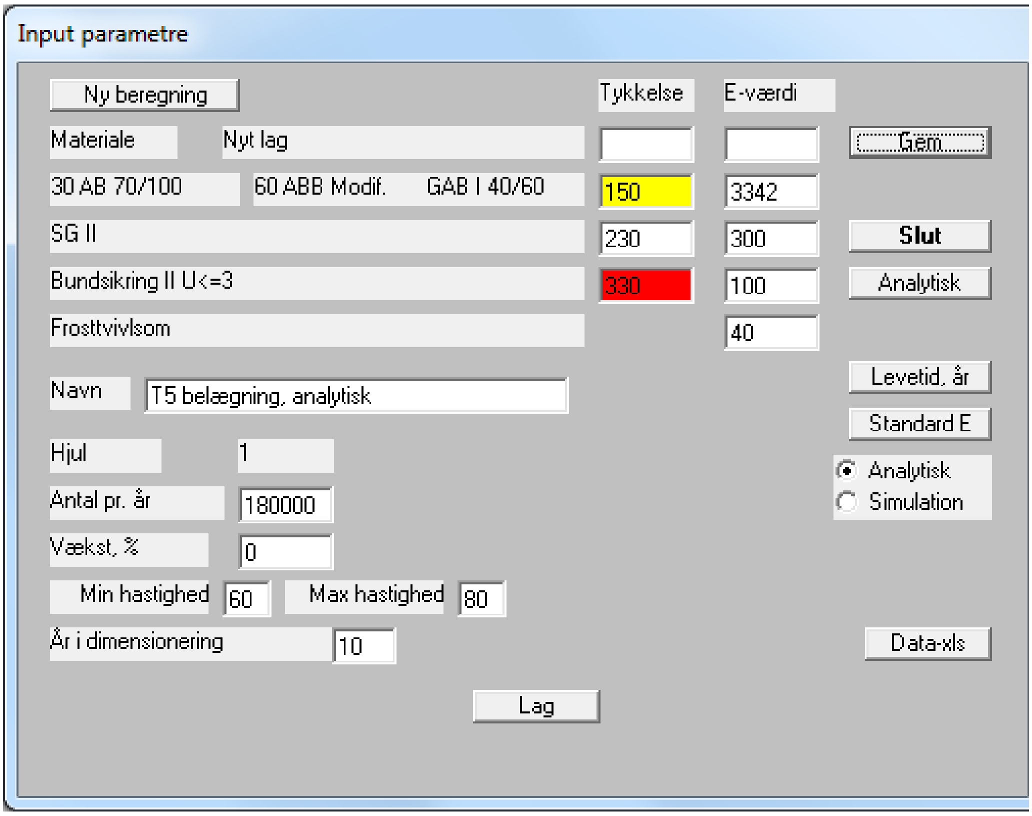


Figure 16 Input parameters - analytical calculation mode.

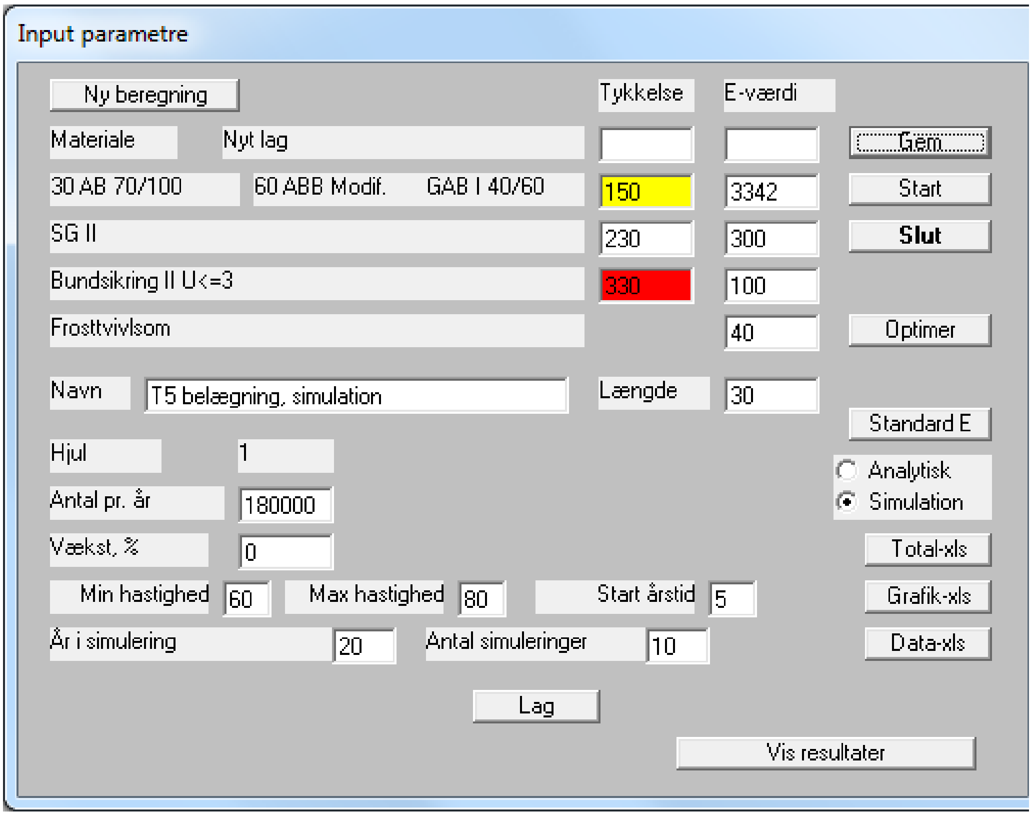


Figure 17 Input parameters - simulation calculation mode.

As can be seen from Figure 16 and Figure 17 over the background in the "Thick-ness" input fields can have different colour, with the meaning therefore being de-scribed below:

- White background: No comments
- Yellow background: The minimum thickness of the material is used cf. Table 8 and 9 of [ref. 11] => it should be investigated whether another layer can be selected which provides for a thinner construction
- Red background: Thickness of a material greater than the recommended maximum when laid in a layer, cf. Table 8 and 9 of [ref. 11] => the layer must, thus, be laid in several stages (selection of a material that can be laid thicker in one layer may possibly result in an overall cheaper price for the pavement)

Selection of other materials is described in the example below, see section 4.3.2.

In both calculation situations, there are usually the following four layers in a pavement (indicated from top to bottom):

- Reinforcement layer
- Bound wearing course/binder course/base layer
- Unbound base layer
- Subbase

In addition, there is also always a subgrade that can be calculated to have an infinite area.

There is, generally, no reinforcement layer (New layer). This only occurs if the user enters values for the layer or displays a previous calculation where there is a reinforcement layer themselves.

If a user has chosen the subgrade as "Frost-proof", there will not be a subbase layer.

The "Input parameters" screen contains a number of input fields for both calculation situations; both "Analytical" and "Simulation":

- Thickness: Thickness of layers (see below for an elaboration on the thickness of bound layers)
- E value: E value of layers (see below for an elaboration on the E value of bound layers)
- Name: User-defined name for the design/simulation
- Quantity per year: Annual design traffic
- Growth, %: Annual traffic growth (MMOPP uses the formula for increasing traffic growth, as specified in section 2.2 of [ref. 11]. When using decimals it is important to use decimal characters which match the computer's configuration).
- Min. speed and Max. speed: Minimum and maximum speeds for vehicles in the design
- Years of design or Years of simulation: Design period/number of years of the simulation
- Number of simulations: Number of simulations of degradation (only for "Simulation", where the default is 10 simulations - see also section 4.4)
- Starting season: Season at the start of simulations (only for "Simulation", where the default is five - which corresponds to "Summer" - cf. Figure 20)
- Length: Length of the section modelled in MMOPP (Simulation only, where the default is "30" metres - see also section 2.3.3)

For the materials, the bound layers are listed on one line with the up to three layers which can be used in MMOPP at one time. On this line, the selected thicknesses for the first two bound layers are specified (the wearing and binder course selected by the user), while the thickness of the third bound layer is the difference between the first two bound layers and the total thickness in the "Thickness" input field.

If there are three bound materials, a mouse click on the light grey line, with the bound binder course and base layer, will open a new window where thicknesses of each of the three layers are specified (see the figure below):

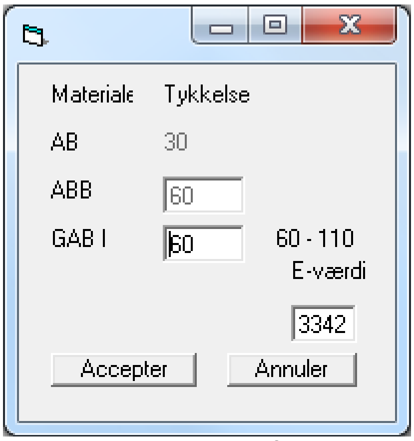


Figure 18 Indication of the thickness of the three layers which make up the total thickness of bound wearing courses/binder courses/base layers.

In the "E value" field on the line with the bound layers, the combined E value of the bound materials is specified. This combined E value is based on Odemark's Equivalent Thickness Method, with the formula for the combined E value being written as indicated below:

$$E_{equivalent} = \left(\frac{\Sigma\left(h_i \times \sqrt[3]{E_i}\right)}{\Sigma h_i}\right)^3 \quad \text{(XXI)}$$

An example of a calculation of the combined E value of bound materials is included in section 4.3.4.

By reinforcing existing pavements, the thickness and E value of the reinforcement layer appears in the input fields next to the "New layer" line. Examples of analytical reinforcement design and the design of reinforcement by simulation are included in sections 4.3.6 and 4.4.3.

As described in the handbook for the Design of Pavements and Reinforcement Surfacings, cf. section 3.4 of [ref. 11], the viscoelasticity of the asphalt means that the E value of the asphalt is reduced at speeds below 60 km/h.

MMOPP can perform this adjustment automatically, based on the average value of "Min speed" and "Max speed" on the "Input parameters" screen. An interval should be specified, especially if you will be performing a simulation afterwards, as a uniform speed in all simulations will cause unrealistic results due to resonance in the calculation procedure.

With such an adjustment of speeds, the value of the asphalt is not immediately changed in the data field, as this value is the basis for the simulation calculations (see section 4.4). Instead, the speed-adjusted asphalt E value appears to the right of the heading "E value" in the "Input parameters" screen.

The "Input parameters" screen contains a number of buttons for both calculation situations; both "Analytical" and "Simulation":

- New calculation: Switches to the start screen, so that a new or previous pavement can be selected
- Save: Saves the current pavement with the name displayed in the "Name" input field (Previous calculations with the same name will be overwritten without notice!)
- Start: Starts the simulation and a screen appears showing the number of the current simulation, see also section 4.4 (only with "Simulation")
- End: Closes MMOPP without notice
- Analytical: MMOPP performs an analytical design, see also sections 4.3 (only with "Analytical")
- Optimise: Optimises the pavement based on user-entered unit prices, see also section 4.4.2 (only with "Simulation")
- Lifespan, years: MMOPP calculates the theoretical lifespan in years of each layer in the pavement and displays the result in a new screen, see also section 4.3.1 (only with "Analytical")
- Default E: Opens a new screen where the user can specify whether default or user-defined values are to be used for the individual materials, see also section 4.3.2
- Total xls: Opens Excel and displays a printout of the results of all the calculation data for each individual simulation, including the parameters in the basic calculation routines (only with "Simulation").

- Graph xls: Opens Excel and displays a printout of all the calculation data for each individual calculation step of each individual simulation, including the parameters in the basic calculation routines, as well as graphs with the different degradation processes, see also section 4.4.3 (only with "Simulation")
- Data xls: Opens Excel and displays an overview of results for each individual simulation, as well as the construction of the pavement (this overview can usually be considered as adequate documentation for a design of required layer thicknesses)
- Display results: Opens a new window with results from each individual simulation, as well as the averages and spread of results, see also section 4.4.1 (only with "Simulation")
- Layer: Opens a new screen where the user can select other materials or another thickness of bound wearing and/or binder courses, but it is not possible to remove or add layers, see also section 4.3.2

4.2.2 The "Layer" window

This window is enabled by the "Layer" button in "Input parameters".

Figure 19 Data for each type of layer (the pavement displayed is a copy of the pavement in the "Input parameters" screen, before any potential user changes).

This window is enabled by the "Layer" button in "Input parameters".

This window shows the default parameters for the application and the properties of the materials, with these being indicated by the following terms:

- Material: A description of materials, in accordance with the relevant Road Standard
- Layer type: Wearing course, binder course, bound base layer, unbound base layer, subbase layer, subgrade
- Maximum stone size: Only relevant for asphalt materials and not necessarily specified

- Penetration of base bitumen: A description of the bitumen hardness, in accordance with the tender specification for hot mixed asphalt (only relevant for asphalt materials)
- Thickness: Minimum thickness of a given material
- Evalue1: The E value of a given layer, used for the top 100 mm of the layer measured from the top of the combined pavement
- Evalue2: The E value of a given layer, used for a material located below the top 100 mm of the layer, measured from the top of the combined pavement ("Evalue2" only differs from "Evalue1" for asphalt materials)
- Min E10: The lowest recommended E10 load per day per lane for the material
- Max E10: The highest recommended E10 load per day per lane for the material

The above parameters are used in both analytical design and design by simulation and are in accordance with the handbook for the Design of Pavements and Reinforcement Surfacings, [ref. 11].

By clicking the given layer in the pavement in Figure 19 a list of material types for this layer is displayed.

Once the desired layer is selected, click the "Back" button.

4.2.3 The "Climate" window

This window is disabled in the Road Standard Edition of MMOPP.

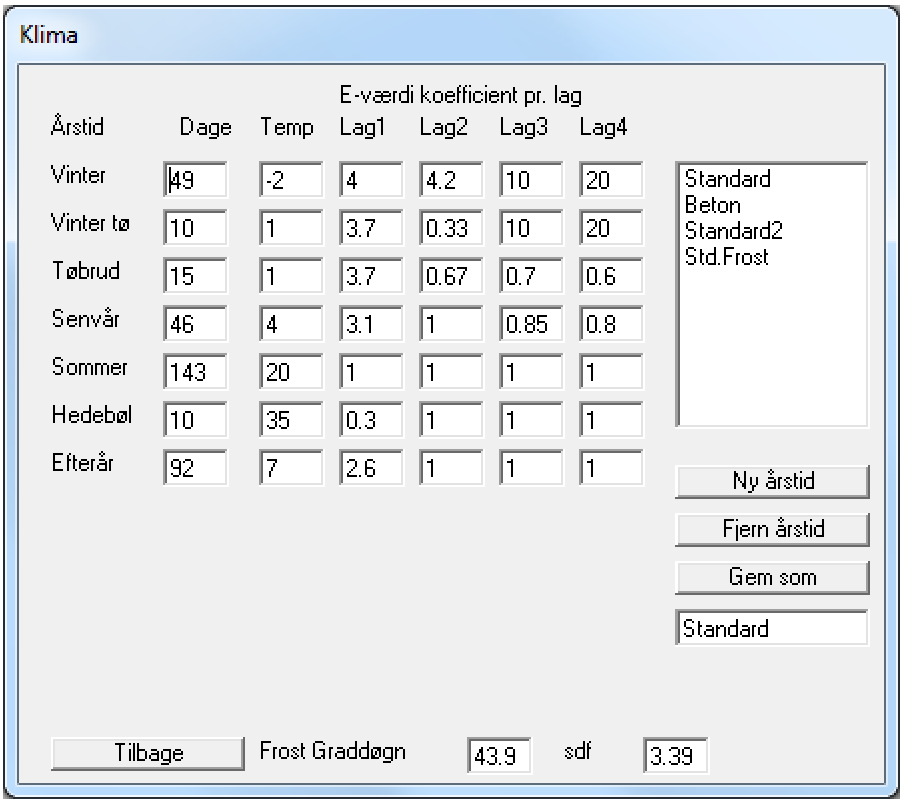


Figure 20 Climate data.

This window appears by clicking the "Climate" button in "Input parameters" after having enabled the advanced settings.

The window contains a number of seasons with the following parameters:

- Days: The number of days in the given season (the sum of the days in all the seasons tallies up to 365)
- Temperature: The average daily temperature for the given season
- E value coefficient per layer: The coefficient which the E value of any given layer must be multiplied by for the given season (Layer 1: Bound wearing course/binder course/base layer, Layer 2: Unbound base layer, Layer 3: Sub-base, Layer 4: Subgrade)

The above parameters are only used in design by simulation, for example, for layer 2 (e.g. SG II, default E value of 300 MPa) in the winter period; an E value of 300 MPa × 4.2 = 1,260 MPa.

The temperature indication serves as a calculation of the asphalt materials' susceptibility to crack initiation. At high temperatures, asphalt materials are less prone to cracking, thereby reducing the susceptibility to crack initiation (the asphalt layer can be subjected to greater strain without causing cracks when the asphalt is soft) - see also section 2.3.7.

The specified temperatures are air temperatures. These are converted to asphalt temperatures by the program, taking into account the layer thickness, in accordance with a model based on the "Shell pavement design manual" [ref. 1].

Changed temperature conditions can be given a new name in the field under the "Save as" button.

The fields "Sub-zero temperature days" and "sdf" contain the parameters which determine the stochastic calculated frost penetration, as specified in section 2.3.5.

Once the climate has been selected, click the "Back" button.

4.2.4 The "Load" window

This window is disabled in the Road Standard Edition of MMOPP.

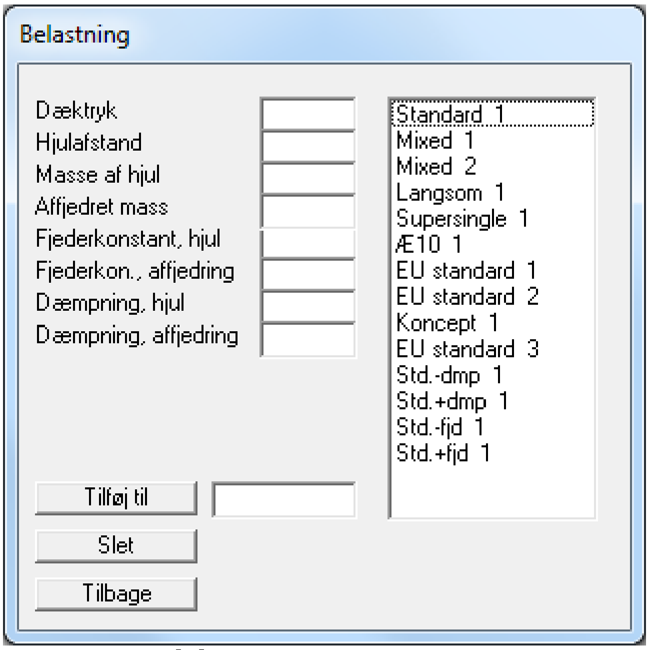


Figure 21 Load data.

This window appears by clicking the "Load" button in "Input parameters" after having enabled the advanced settings.

The window contains tire pressure, masses, spring constants and damping constants and is used for both analytical design and design by simulation.

For a given simulation, load combinations of loads from a total of six different single or twin wheels can be applied. These are defined in "Load windows" where they are inserted into the required load combination by clicking the "Add to" button.

If a combination of multiple loads is selected, the "Input parameters" window must indicate the first year's traffic (quantity per year) and the traffic growth (growth, %) separately for the individual loads in the combination.

In the analytical design, MMOPP, by default, calculates a 20% shock allowance in addition to the load displayed (the sum of "Wheel mass" and "Sprung mass").

If you want to make an analytical design with, for example, only a 10% shock allowance, then the wheels' "Wheel mass" and "Sprung mass" must be reduced by a factor of (100 + 10)/(100 + 20) = 0.92. This load can only be used during analytical design, seeing as with simulation calculations, dynamic effects are automatically calculated, based on the speed and the evenness of the pavement, which is why the full load without a shock allowance must be used.

Once the load is selected, click the "Back" button.

4.2.5 The "Limits" window

This window is disabled in the Road Standard Edition of MMOPP.

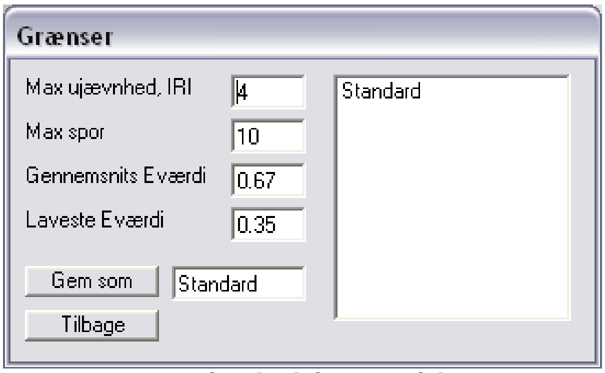


Figure 22 Limits for the lifespan of the pavement.

This window appears by clicking the "Limits" button in "Input parameters" after having enabled the advanced settings.

The window contains the constants which, in connection with design by simulation, determine when the lifespan has been reached in accordance with the following criteria:

- Maximum permissible unevenness (IRI)
- Maximum permissible rutting
- Minimum ratio of the average E value of asphalt to intact asphalt
- Minimum ratio of the lowest E value of asphalt to intact asphalt

The above four parameters are only used in design by simulation.

Changed limits can be given a new name in the box next to the "Save as" button.

Once the limits are selected, click the "Back" button.

4.3 Analytical design

When the program is started, a screen will be presented with the choice between "New calculation" or "Previous calculation". By selecting "New calculation" one is taken through to options for the following parameters:

- Traffic load class: Select traffic class T1 to T7
- Pavement type: Select the type of wearing course
- Pavement: Select the thickness (mm) and, if so desired, the bitumen hardness of the wearing course
- Binder course: Select the thickness (mm) and, if so desired, the type as well as the bitumen hardness of the binder course or "None"
- Bound base layers: Select the type of bound base layer, including the bitumen hardness of asphalt materials and the type of HBB materials or "None"
- Unbound base layer: Select the type and quality of unbound base layers or "None"
- Subgrade: Select the type of subgrade ("frost-proof", "frost-susceptible" or "splitting frost-susceptible")
- If the subgrade is specified as "frost-susceptible" or "splitting frost-susceptible", for the sake of risk of frost heaving, please state whether the pavement has been drained (by using kerbstones, as well as culverted drains or paved verges) or "undrained" (water may penetrate the pavement from ditches, unpaved verges or the like)

Below are a few examples of analytical design in MMOPP.

4.3.1 Default design

Below is an example where a pavement is desired to be designed based on the following options:

- Select "New calculation"
- Select traffic class "T3"
- Select "PA" as an asphalt wearing course
- Select "25 PA 250/330 E = 500" (25 mm powdered asphalt with a bitumen hardness of 250/330, which has an E value of 500 MPa at 30°C by default)
- Select "50 GAB.0 70/100 E = 2000" (50 mm hot-mix asphalt concrete base, type 0, with a bitumen hardness of 70/100, which has an E value of 2,000 MPa at 30°C by default) as the asphalt binder course
- Select "GAB.I 70/100 "(hot-mix asphalt concrete base, type I, with a bitumen hardness of 70/100) as the asphalt base layer
- Select "SG II" as the unbound base layer
- Select "Frost-susceptible" as the type of subgrade
- Select "No", as this example does not use kerbstones, culverted drains and paved verges, so there is a risk that water can penetrate the pavement

These selections are illustrated in the following figure:

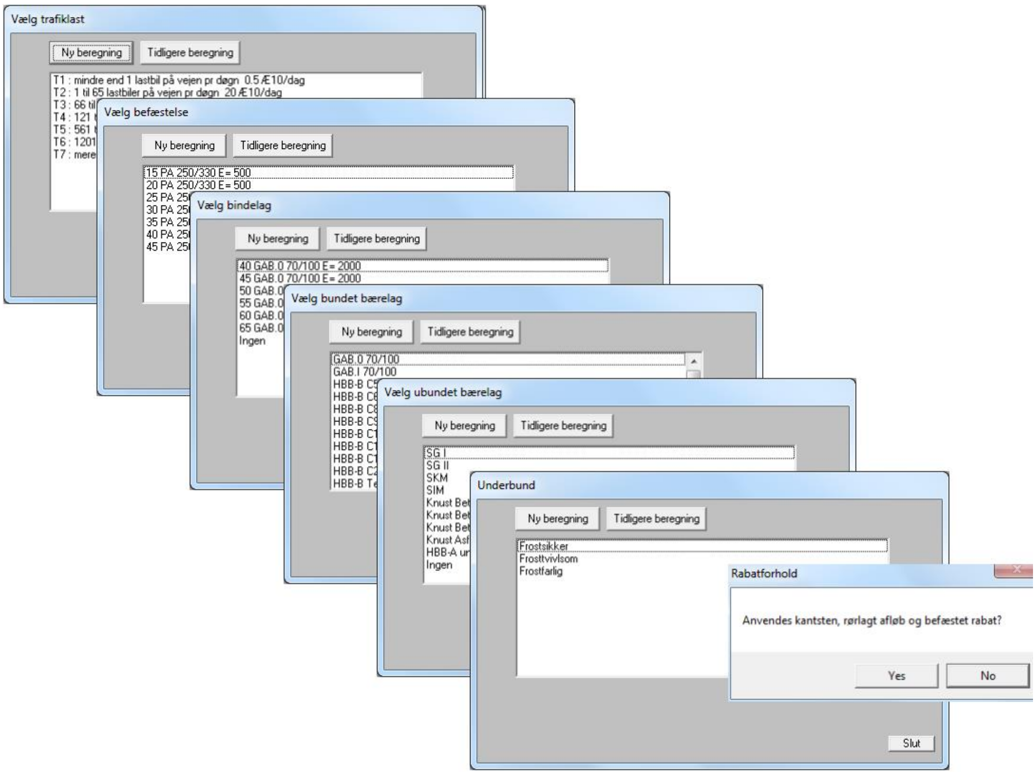


Figure 23 Default design - data input sequence.

Once all the necessary selections have been made, MMOPP performs an analytical design in accordance with the design criteria in section 2.2 and the use of a 5-tonne twin-wheel + 20% shock allowance as the design load, and the "Input parameters" screen is presented, with reference to the following figure:

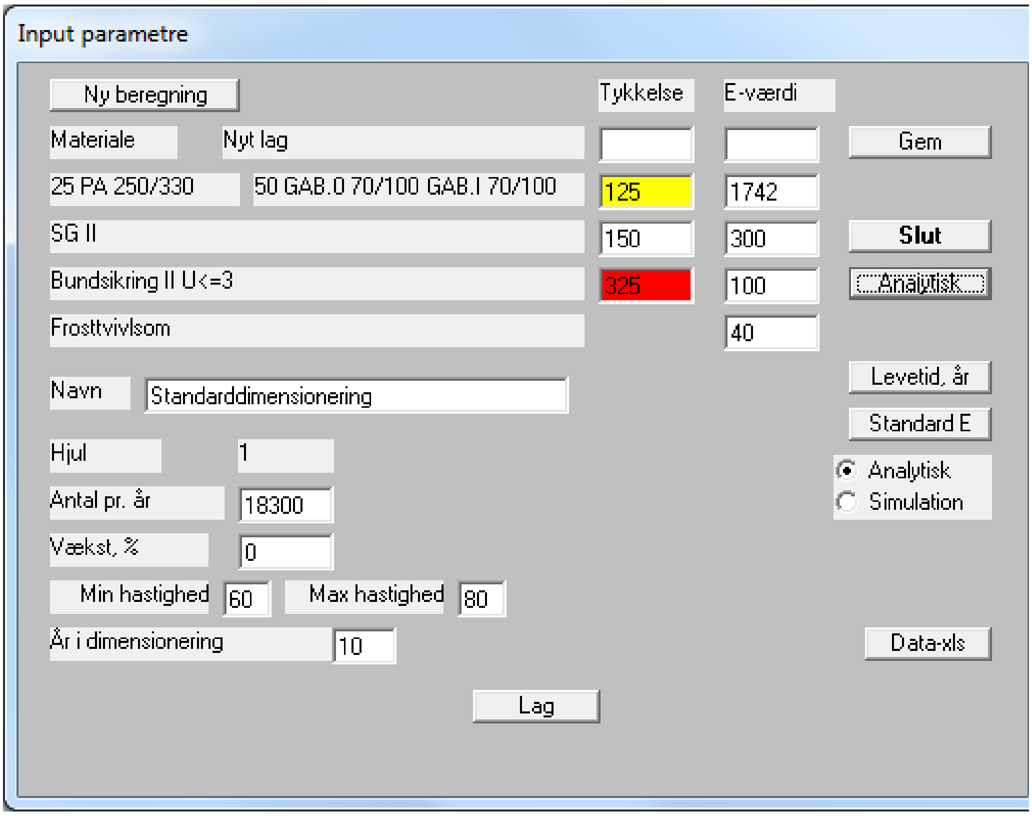


Figure 24 Default design - the main screen "Input parameters".

As displayed in the figure above, the total asphalt thickness is 125 mm, of which 25 mm is made of wearing course and 50 mm is made of binder course, which means that the base layer should be 50 mm thick. MMOPP has thus designed the following pavement:

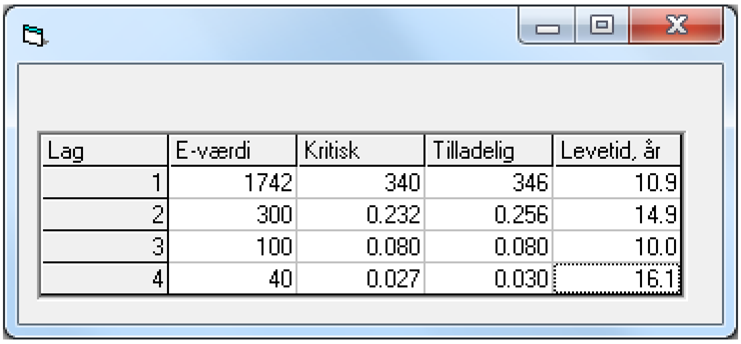
- 25 mm PA 250/330
- 50 mm GAB 0 70/100
- 50 mm GAB I 70/100
- 150 mm SG II
- 325 mm BL II, U ≤ 3

This design has been made based on the following default inputs:

- Design traffic: 18,300 E10/year (default for traffic class T3)
- Annual traffic growth: 0%
- Speed: 70 km/h (average of minimum and maximum speed)
- Design period: 10 years
- Type of subgrade: Frost-susceptible (that is to say, the pavement thickness is at least 600 mm for the given traffic class, in accordance with the handbook for the Design of Pavements and Reinforcement Surfacings (cf. Table 10 in [ref. 11]), as there is a risk that water can penetrate the pavement)
- Rigidity of the subgrade: 40 MPa (default for frost-susceptible subgrade)
- Subbase: BL II, U ≤ 3 (default material for subbase)

If the above default input is correct, the design is complete - otherwise you must change the default input, as described in the next example, see section 4.3.2.

Clicking the "Lifespan, year" button presents a new window with a range of information for each layer, with reference to the figure below:



Lag	E-værdi	Kritisk	Tilladelig	Levetid, år
1	1742	340	346	10.9
2	300	0.232	0.256	14.9
3	100	0.080	0.080	10.0
4	40	0.027	0.030	16.1

Figure 25 The E value, as well as the calculated values for the individual layers in the pavement.

The above figure shows the following for each layer (Layer 1: Bound wearing course/binder course/base layer, Layer 2: Unbound base layer, Layer 3: Subbase, Layer 4: Subgrade):

- E value: The E value of layers (same values as on the "Input parameters" screen)
- Critical: The calculated value of the critical parameter, based on the given traffic load and E value of individual layers
- Permissible: The calculated permissible value of the critical parameter, based on the traffic load in relation to design criteria for individual layers, see section 2.2
- Lifespan, years: The calculated theoretical lifespan based on the calculated value of the critical parameter in relation to design criteria for individual layers, see section 2.2

The critical parameter depends on the material type in the individual layer - horizontal strain on the underside of bound materials and vertical stress on the top of layers for unbound materials, cf. section 2.2.

The layer with the shortest lifespan is called the critical layer.

4.3.2 User-defined design

In connection with a design in MMOPP, the following default inputs and selection of materials can be changed in the "Input parameters" screen:

- Name
- Design traffic
- Speed
- E value
- Material

These options for changes are described below:

Name changing
You can enter a name for a given design in the "Name" input field. By clicking the "Save" button, the current "Input parameters" screen with the given design will be stored in the MMOPP folder and can be retrieved by clicking the "Previous calculation" button on the startup screen.

By clicking the "Save" button, previous calculations with the same name will be overwritten without notice!

Design traffic changes
The total design traffic is a combination of data in the following input fields:

- Quantity per year: The traffic load as the number equivalent to E10 loads in the design
- Growth, %: The annual growth of traffic load in the design
- Years of design: The length of the design period

Often users will have made a calculation of the total design traffic based on the handbook for the Design of Pavements and Reinforcement Surfacings, [ref. 11]. The annual number of E10 loads, as well as the length of the design period are entered in the "Quantity per year" and "Years of design" input fields. If the calculation of the total design traffic already contains traffic growth, the value "0" is retained in the "Growth, %" input field.

The design is then made by clicking the "Analytical" button.

In the example of a default design, see section 4.3.1, a pavement was designed based on default inputs.

In the following example, the total design traffic throughout the design period is calculated as 400,000 E10 loads. With a design length of 20 years, this gives 20,000 E10/year. This is entered manually in the "Input parameters" screen, after which the "Analytical" button is clicked and the following screen appears, with reference to the figure below:

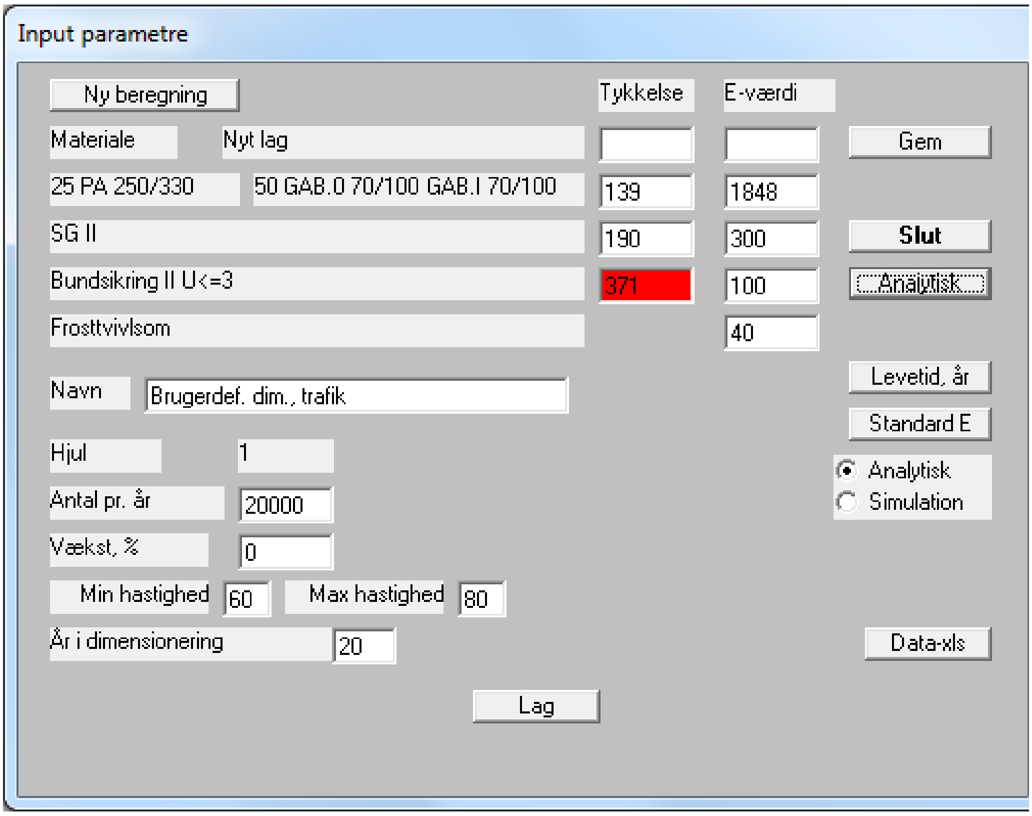


Figure 26 User-defined design - changed design traffic.

Compared to the default design example, where the traffic load was less, see Figure 24, the total thickness of the asphalt layers is increased by 14 mm, while the thickness of the unbound base layer and subbase is increased by 40 mm and 46 mm, respectively, so the total pavement thickness is 700 mm, which corresponds to the current traffic class, cf. Table 10 of [ref. 11].

Seeing as the thickness of the wearing and binder courses has been determined, the increase in total asphalt thickness has taken place in the asphalt base layer. In this way the thickness has now reached the minimum thickness, and therefore the yellow background has disappeared.

In order to show the effect of increased traffic, a design is now made of double the quantity of traffic loads (2 × 20,000 E10/year = 40,000 E10/year), with reference to the figure below:

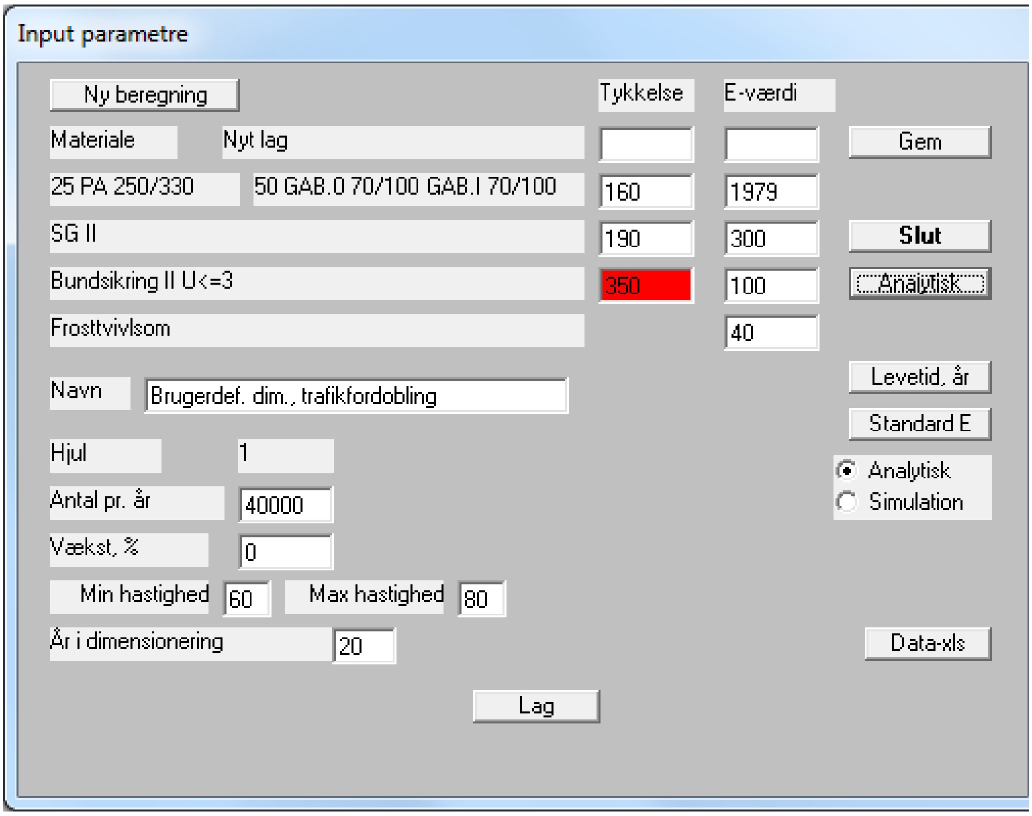


Figure 27 User-defined design - doubled design traffic.

By doubling the design traffic when compared to previously, see Figure 26, the total thickness of the asphalt layers is increased by 21 mm, while the thickness of the unbound base layer is unchanged and the thickness of the subbase layer is reduced with the increase of the asphalt thickness, so that the total pavement thickness still corresponds to the minimum for the current traffic class.

Change of speed

As described in section 4.2.1, speeds below 60 km/h causes the E value of the asphalt to be reduced (MMOPP can make this deduction automatically).

In the following example, the speed is reduced from above 60 km/h, see Figure 27, to 10-20 km/h (an average of 15 km/h) and its effect is shown in the figure below:

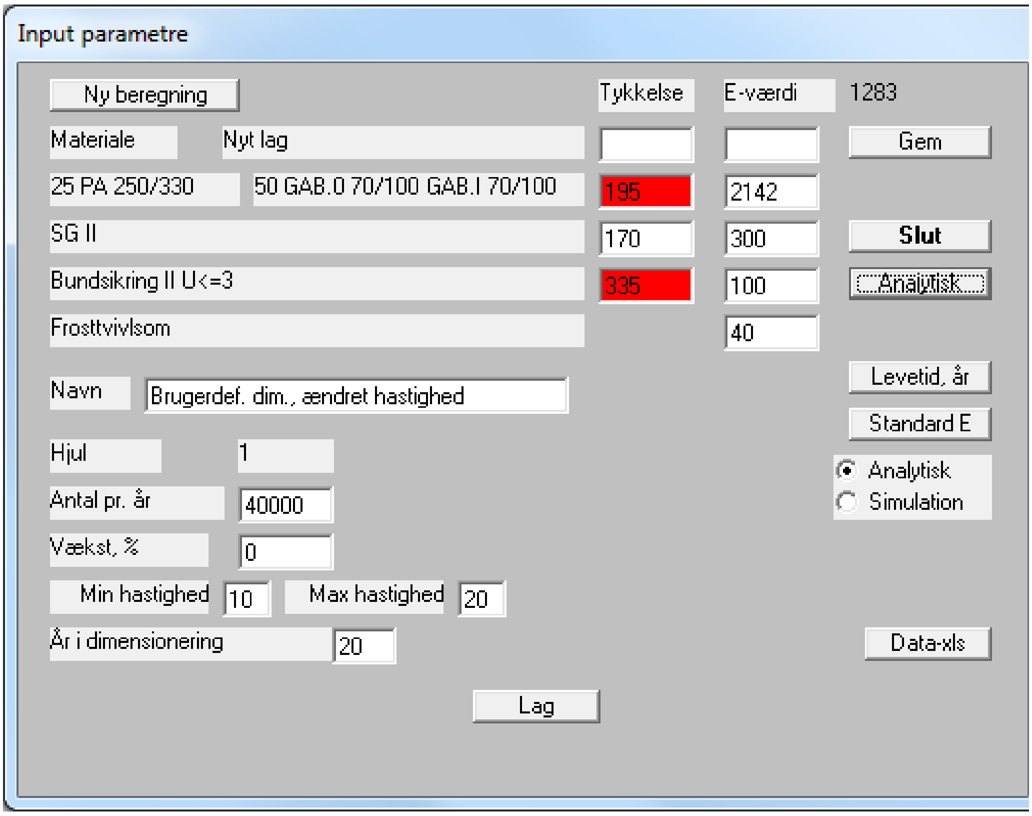


Figure 28 User-defined design - reduced design speed.

A reduction in the design speed can be due to signs or the road's geometry (narrowing of the lanes, intersections, slip roads, bus stops or the like) and, as seen from the above figure, the reduced E value of the asphalt layers is shown next to the heading "E value".

Compared to the example above of doubled design traffic, see Figure 27, the total thickness of the asphalt layers is increased by 35 mm, while the thickness of the unbound base layer and subbase is reduced by 20 mm and 15 mm, respectively, so that the total pavement thickness still corresponds to the minimum for the current traffic class.

E value changes
Clicking the "Default E" button gives the user the following options:

- Use E values for default materials (selected by default)
- Use E values from the input form
- Use default E values for bound layers

Selections are made with the option buttons and, after selecting, by clicking the "OK" button.

Generally speaking, default values are selected for the individual materials, including the subgrade, and MMOPP automatically reduces the asphalt's E value (if applicable), based on the average of the minimum and maximum speed.

By selecting "Use E values from the input form", MMOPP uses the user's input E value for the individual layers, thus reducing the E value of the asphalt, even though the average speed is less than 60 km/h.

By selecting "Use default asphalt E values", MMOPP still automatically reduces the E value of the asphalt (if applicable), while the user's input for E value for the unbound layers as well as the subgrade is used by MMOPP.

By clicking the "Default E" button, the user's selection is retained in the subsequent designs, until a new selection is made or MMOPP closes.

In the figure below, "Use default E values for bound layers" is selected after clicking the "Default E" button, after which the rigidity of the subgrade is changed to 70 MPa and the "Analytical" button is clicked:

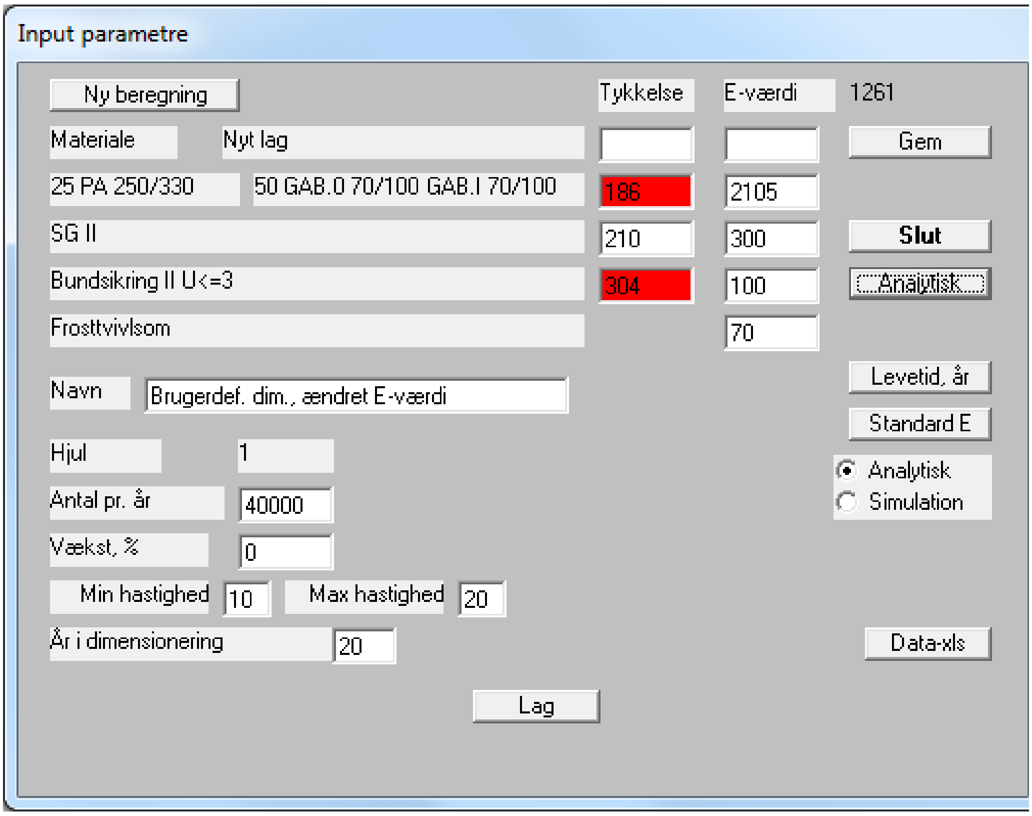


Figure 29 User-defined design - changed E value of the subgrade.

With a more rigid subgrade (higher E value of the subgrade), the total thickness of the asphalt layers can be reduced, but on the other hand, the thickness of the unbound base layer must be increased while the subbase layer is adjusted to comply with the required pavement thickness.

It may seem paradoxical that a more rigid subgrade doesn't cause the thickness of all layers in the pavement to be reduced, but it is completely in line with the linear elastic calculation model, as well as with practical conditions. The more rigid a subgrade, the lesser the deflection of the pavement, but also the lesser the distribution of pressure down through the pavement, as the pressure depth narrows. For a given pavement, the strain in the underside of the layers will thus be reduced, while the vertical stress in the upper side of the layers will increase with a more rigid subgrade.

For the unbound layers, it is the vertical stress across the layer which is the critical parameter, cf. 2.2.1, and, in this example with a more rigid subgrade, there is thus a need for an increased layer of base course of gravel to protect the underlying subbase layer, as well as the subgrade.

Material changes

In MMOPP you cannot remove or add materials to the pavement (if you wish to do this, you must start over again by clicking the "New calculation" button).

However, one can select another material, which can be relevant for when a given material has the minimum thickness or has a thickness greater than the maximum thickness.

In the above example, see Figure 29, both the bound layers and the subbase layer are highlighted in red, as the thickness of, respectively, the asphalt base layer and the subbase layer is greater than the maximum thickness for laying in one layer. However, there can seemingly be done nothing about the subbase layer, as it is this layer thickness that is needed based on the traffic load and rigidity of the subgrade, but, on the other hand, the asphalt materials can be changed.

The user must be aware of the fact that, when using MMOPP, one is guided through the design process step by step, and, based on the selected traffic class, one only receives the option to select the types of materials recommended for this traffic load. Thus, you will never have the option to select, for example, "OB" for a road in traffic class T7.

If you want to replace a material with another, you will be presented with all materials of the same type (all types of wearing courses, if you'd like to change wearing courses and so on), and it is then the user's own responsibility to select a suitable material. With regard to the selection of suitable asphalt materials, one can rely on, for example, Table 8 or 14 in the handbook for the Design of Pavements and Reinforcement Surfacings, see [ref. 11].

To select another material, click the "Layer" button and a new window will open showing the individual layers in the current pavement. By clicking the layer where you want to change the material, a new window opens with all the different types of this type of material. The figure below shows that the asphalt base layer "GAB I 70/100" has been replaced with the material "GAB II 40/60":

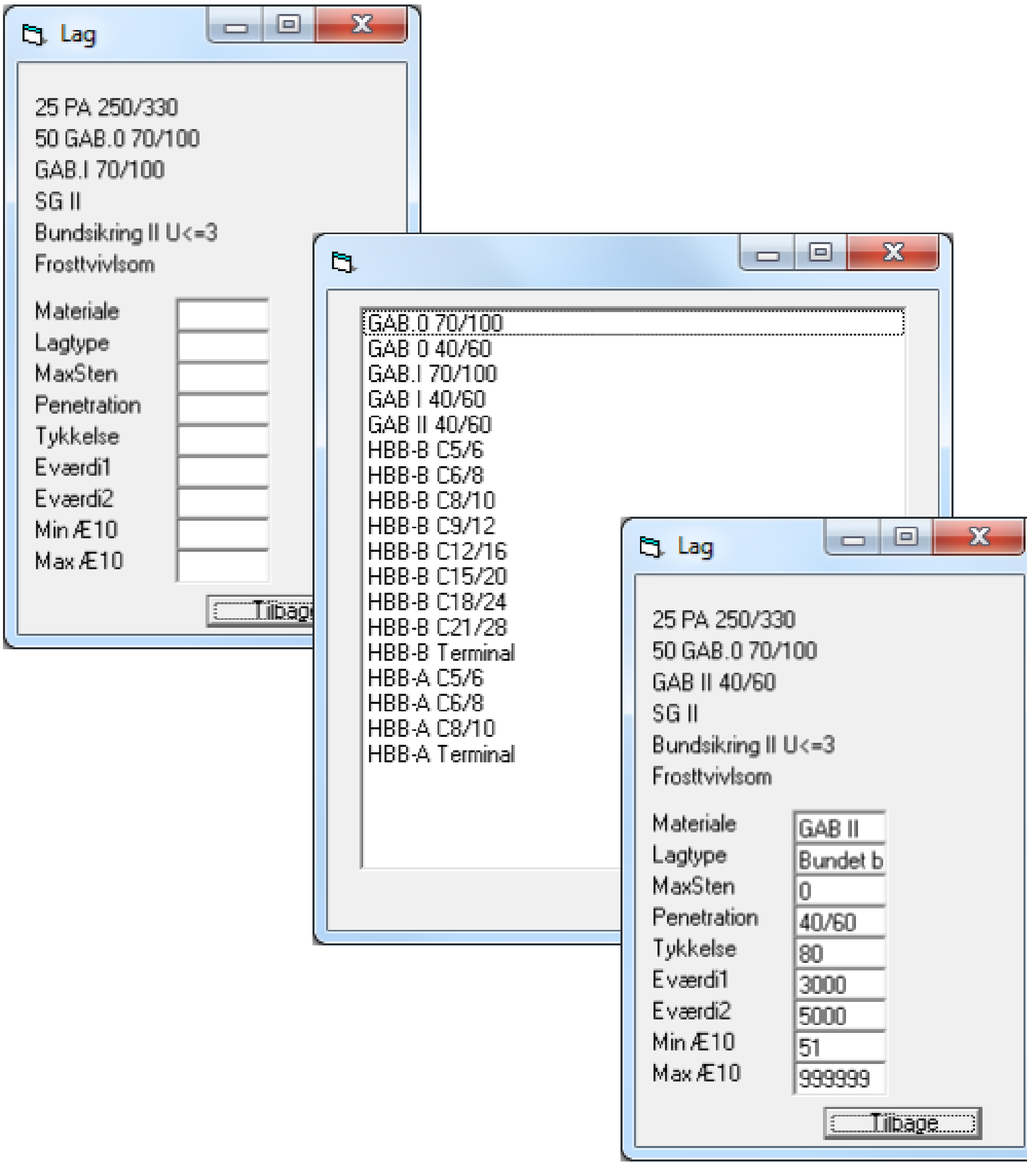


Figure 30 User-defined design - changing the asphalt base layer.

By clicking the "Back" button one returns to the "Input parameters" screen.

When replacing bound materials, MMOPP cannot update the combined E value, which MMOPP otherwise automatically calculates, based on the Equivalent Thickness Method (see also section 4.3.4). This happens where there is a big difference between the E value of the original bound material and the new bound material.

When clicking the mouse on the light grey line with bound binder course and base layers, a new window will appear, where thicknesses of each of the three asphalt layers are specified, and MMOPP uses this to calculate the combined E value automatically.

After replacing one or more layers, click the "Analytical" button to create a design with the new layer(s) - see the figure below:

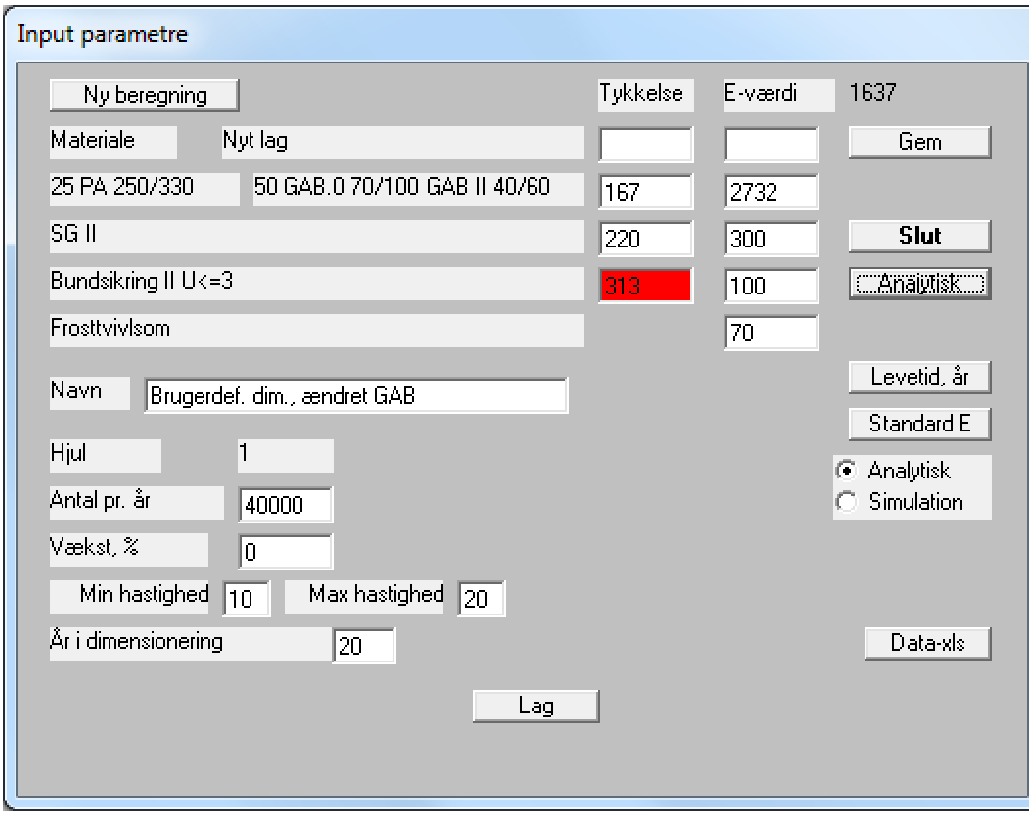


Figure 31 User-defined design - changed asphalt base layer.

As can be seen from the above figure, the red background has now disappeared from the input field with the required overall layer thickness of the asphalt layer.

The asphalt base layer GAB II can be laid with a greater thickness than GAB I, but, in this example, the bitumen hardness was also increased from a penetration of "70/100" to "40/60". The more rigid bitumen also results in a higher E value, cf. Table 8 of [ref. 11], thereby reducing the total asphalt thickness.

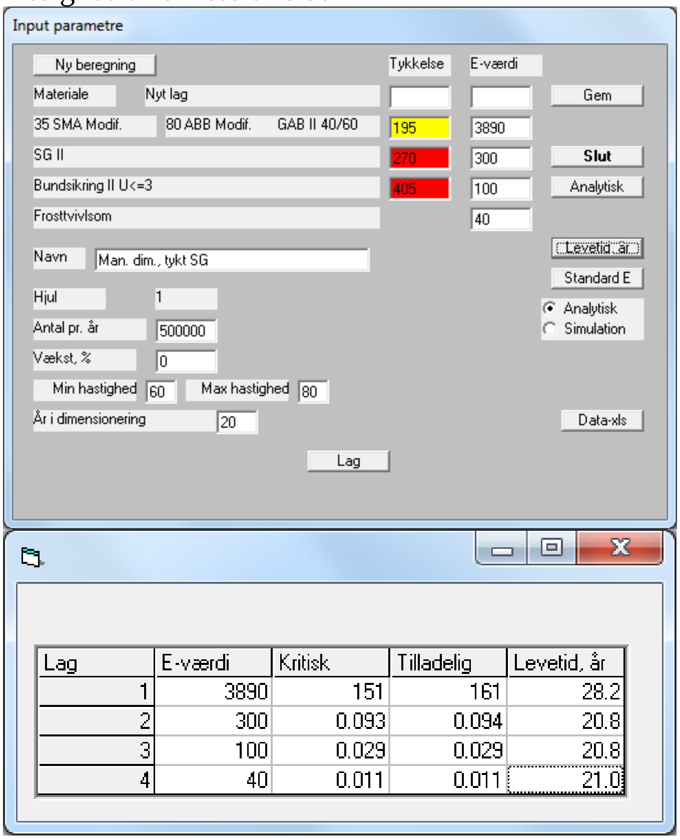
4.3.3 Manual analytical design

In certain situations, the analytically determined layer thicknesses can be inappropriate. This may apply, for example, to road widenings, where a certain pavement thickness and/or asphalt thickness are desired or if the analytically determined thickness of the base course of gravel becomes too much for the layer to be built into one layer.

As described in section 4.3.1, a new window will appear by clicking the "Lifespan, year" button, cf. Figure 25. By manually adjusting the layer thickness of the individual layers, one can, by clicking the "Lifespan, year" button, check that the desired lifespan is present for each individual layer.

Below is an example of a pavement with a base course of gravel layer which exceeds the recommended maximum thickness of 250 mm, cf. Table 9 of [ref. 11]. In this example, the desired theoretical lifespan is manually ensured by increasing the thickness of the asphalt base layer after reducing the thickness of the base course of gravel layer:

Designed thickness of SG:



Adjusted thickness of SG:

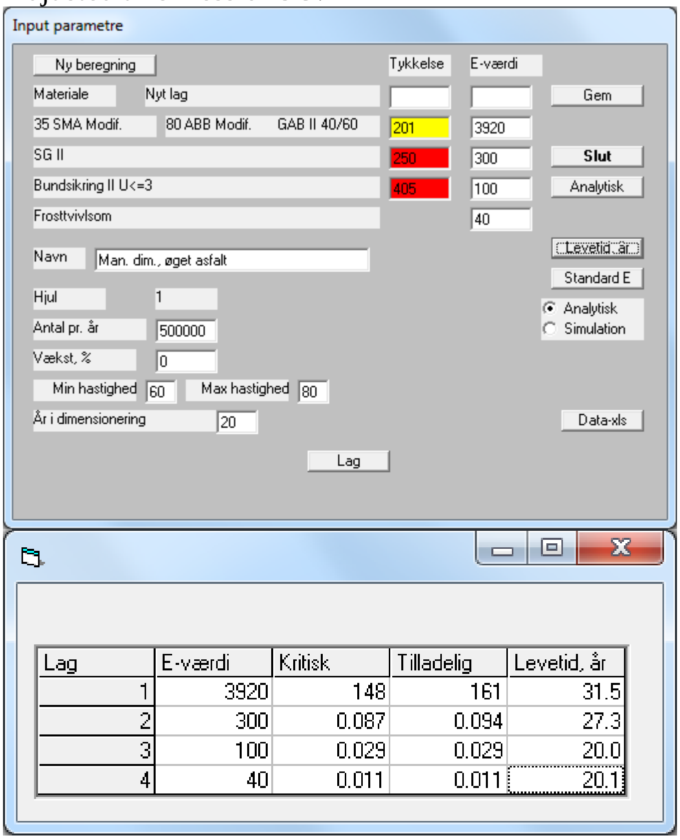


Figure 32 Manual analytical design - the thickness of the base course of gravel layer is reduced by an increased thickness of the asphalt base layer.

With a default analytical design (top screen in the above figure), the background is yellow for the total asphalt thickness, because the thickness of the GAB II layer is set to the minimum thickness. This means that the pavement as a whole is oversized to a certain extent,as the theoretical lifespan of all the layers is longer than the 20-year design period.

Similarly, the background is red for both the unbound base layer and subbase, because the thickness of both layers is greater than the maximum thickness, so these materials will have to be integrated into multiple layers.

With the manual analytical design (bottom screen in the above figure), the thickness of the base course of gravel layer is manually changed to 250 mm, after which the total asphalt thickness is increased until the theoretical lifespan complies with the design period for all layers. Once the thickness of the asphalt wearing and binder course is determined, the thickness of the asphalt base layer is increased.

When performing a manual analytical design and one does not click the "Analytical" button, MMOPP does not perform the usual default checks with regard to the following:

- Compliance with the minimum pavement thickness for the given traffic class, in accordance with the handbook for the Design of Pavements and Reinforcement Surfacings, cf. Table 10 of [Ref. 11]
- Minimum and maximum thicknesses for the individual layers

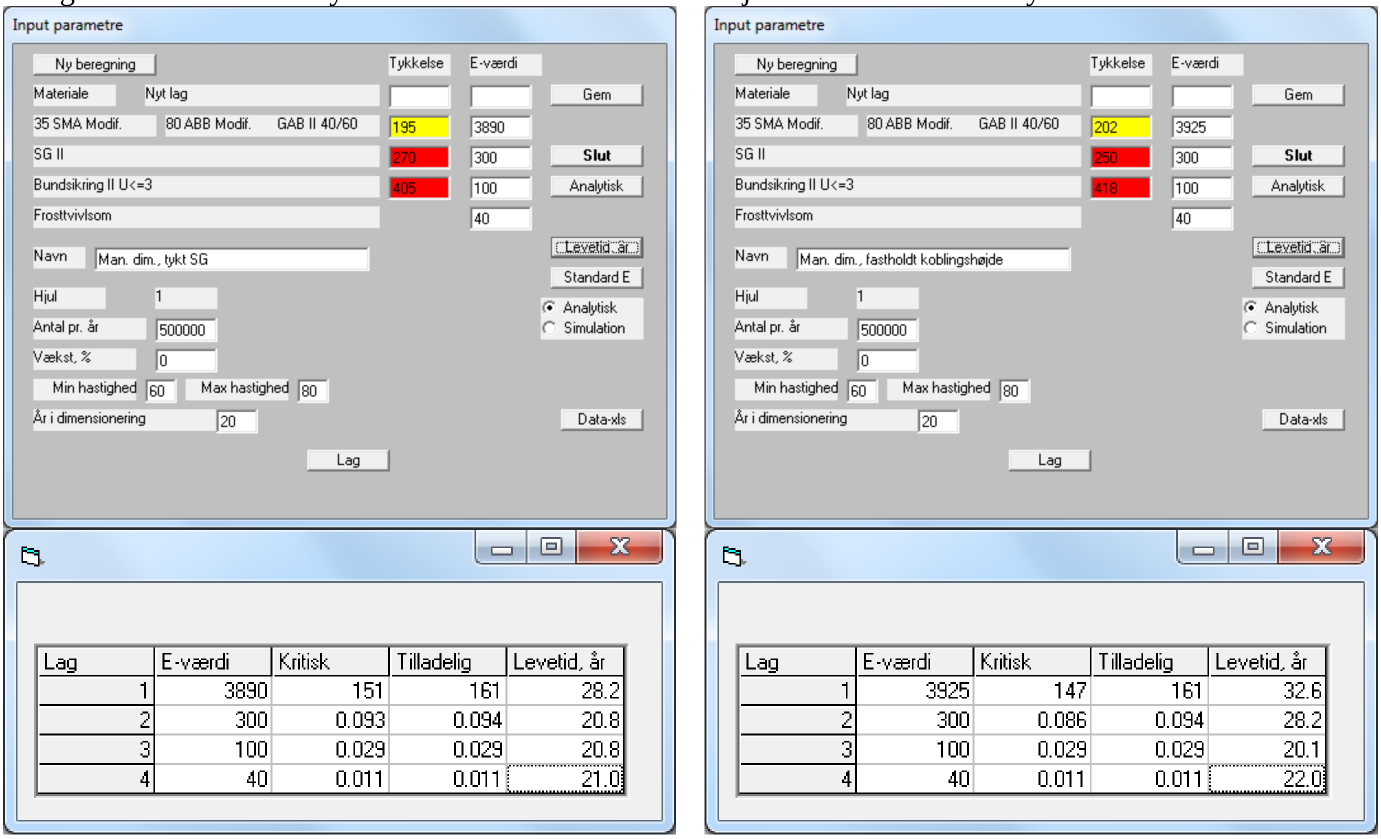
The user must be aware of and check this themselves.

In the bottom screen of the above figure, the background is still yellow and red for the total asphalt thickness and for the thickness of the unbound base layer, even though the asphalt base layer no longer has the minimum thickness and the base course of gravel layer is no longer thicker than the maximum.

In the above example, the total pavement thickness is reduced, which is due to the fact that asphalt has a higher E value than base course of gravel. In certain cases, however, it can be advisable to maintain the pavement thickness, even if a manual analytical design is performed.

In the example below, a manual analytical design is made where the pavement thickness is maintained by increasing the thickness of the subbase layer, with reference to the figure below:

Designed thicknesses of layers: Adjusted thicknesses of layers:



Lag	E-værdi	Kritisk	Tilladelig	Levetid, år
1	3890	151	161	28.2
2	300	0.093	0.094	20.8
3	100	0.029	0.029	20.8
4	40	0.011	0.011	21.0

Lag	E-værdi	Kritisk	Tilladelig	Levetid, år
1	3925	147	161	32.6
2	300	0.086	0.094	28.2
3	100	0.029	0.029	20.1
4	40	0.011	0.011	22.0

Figure 33 Manual analytical design - the thickness of the base course of gravel layer is reduced by an increased thickness of the asphalt base layer, as well as the subbase layer, in order to maintain the pavement thickness.

As seen from the above figure, an increase in the subbase layer causes the total asphalt thickness to also increase marginally. As described earlier, with reference to the example of "E value changes" in section 4.3.2, a more rigid subgrade causes the vertical stress in the upper side of the layers to increase (in this case, the subbase layer (Layer 3) is the critical layer).

In order to comply with the design criterion for the subbase layer, the thickness of one or more of the overlying layers should be increased, but, in this case, the thickness of the base course of gravel layer cannot be increased, as this layer already has the maximum thickness. Thus, only the total asphalt thickness can be increased to ensure that the design criteria for all layers are met.

4.3.4 Parallel design of pavements with hydraulically bound base layers (HBB)

Pavements with hydraulically bound base layers (HBB) are referred to as semi-rigid pavements. In the handbook for the Design of Pavements and Reinforcement Surfacings, cf. [ref. 11], two different types of HBB materials, with varying strength classes, have been included. HBB-A, which is a sandy material, and HBB-B, which is a gravelly material, see section 2.2.3.

In 2003 a full-scale test, as well as a follow-up assessment of the load-carrying capacity of existing Danish motorways with the HBB layers were carried out, see [ref. 4]. The full scale test showed that the E value of the HBB layer is relatively rapidly being reduced to a level significantly lower than the initial state, with reference to the figures below.

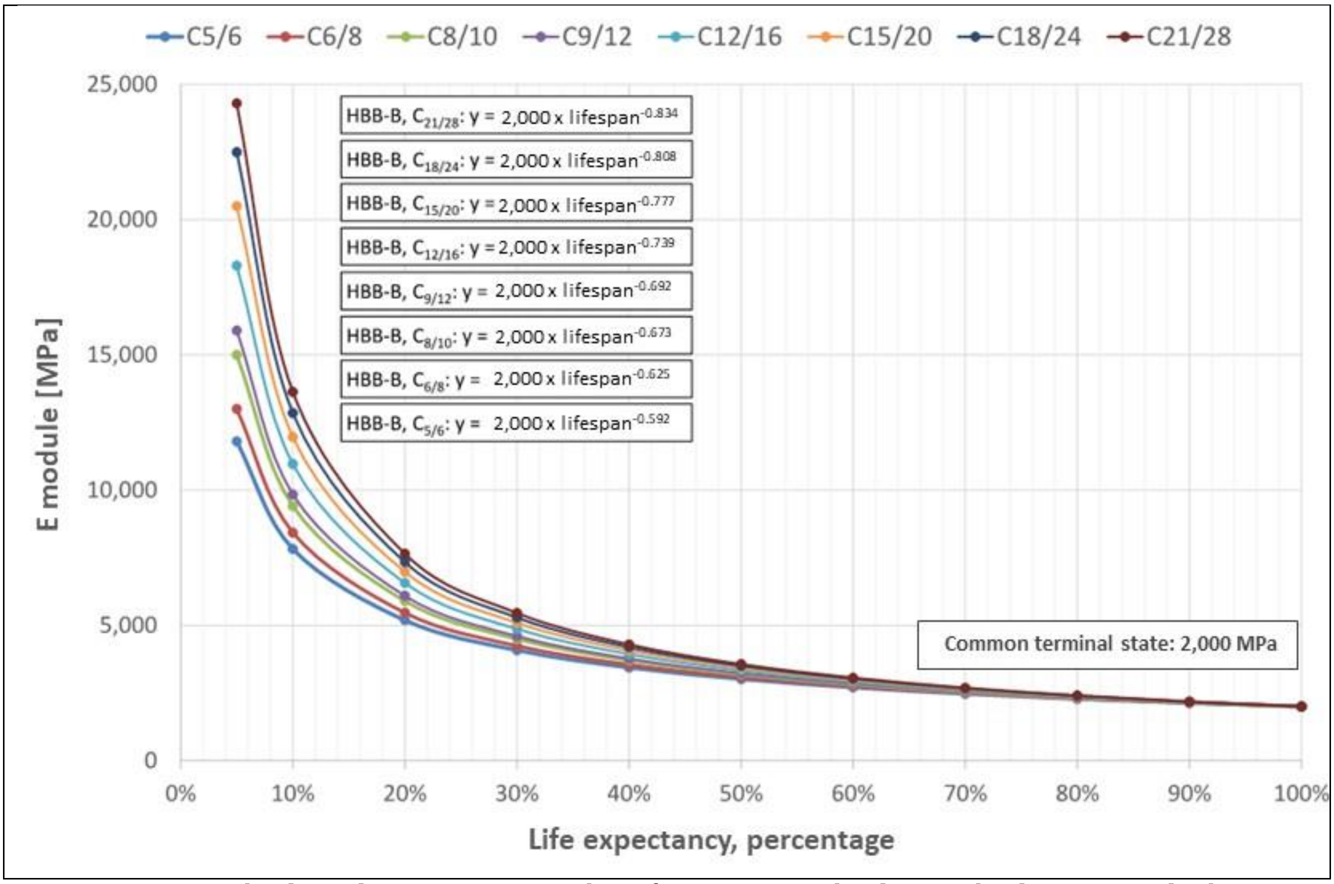


Figure 34 <u>*HBB-B:*</u> *The degradation process resulting from repetitive loads over the design period - the lifespan has been inserted in pure numbers, so "100%" is equal to 1.00 (in accordance with [ref. 4]).*

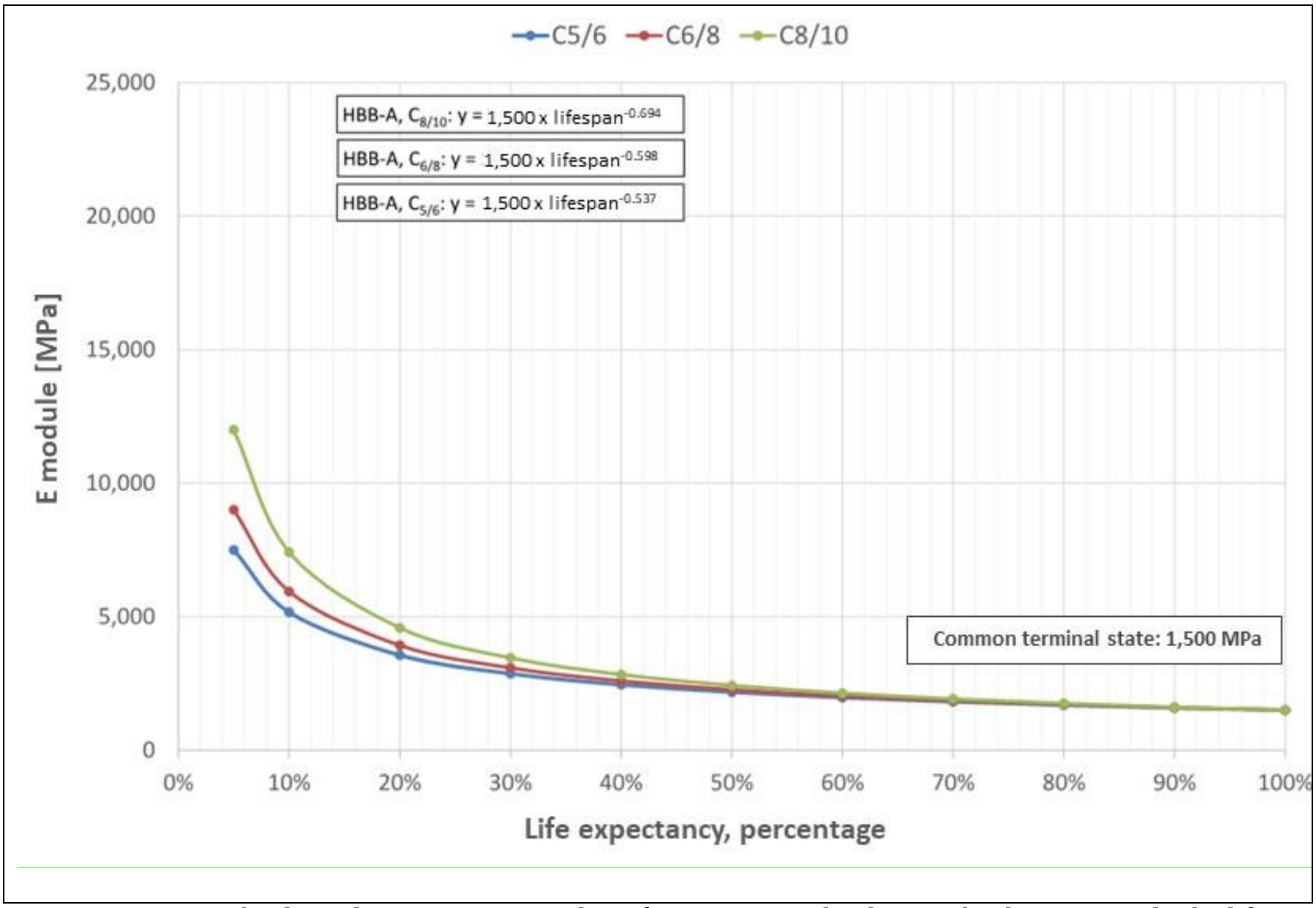


Figure 35 HBB-A: The degradation process resulting from repetitive loads over the design period - the life-span has been inserted in pure numbers, so "100%" is equal to 1.00 (in accordance with [ref. 4]).

Due to the rapid reduction of the HBB layer's E value, the semi-rigid pavements differ from normal flexible pavements, in that, for the most part, the HBB layer has a significantly lower E value than with new structures. In order to ensure the functionality of the pavement during the entire desired lifespan, it is necessary to assess the pavement with the HBB layer in both "initial state" and "terminal state".

Thus, the initial state describes the HBB layer at the time of construction, while the terminal state describes the HBB layer once it has been degraded at the end of the design period. During the intermediate period, the HBB layer is gradually degraded due to the traffic load and the layer's E value follows a degradation process, as illustrated in the two figures above.

In the initial state of the HBB material, the required thickness of the HBB layer in MMOPP is designed based on the critical horizontal strain in the underside of the layer.

In the terminal state, the design criterion for the HBB material is so lenient that it will never be critical. The required thickness of the HBB layer is thus determined for the sole purpose of protecting the underlying layers.

In both cases, the underlying layers are designed in accordance with the usual design criteria in MMOPP, while overlying asphalt layers are not designed. The user should make sure with their MMOPP selections that the total thickness of the asphalt layer is at least 90 mm, cf. the hydraulically bound base layer tender specification [ref. 12].

The design of semi-rigid pavements with the HBB layers is best done by opening two MMOPP calculations side by side - one with the HBB material in the initial state and the other with the HBB material in the terminal state. By using the same input parameters (type of subgrade, drainage conditions, E value of other materials, traffic load), as well as to manually ensure that layer thicknesses are the same in both MMOPP calculations, the theoretical lifespan of the pavement can be assessed in both modes at the same time. This is the principle of parallel design of pavements with HBB.

The parallel design can be used for both HBB-A and HBB-B materials and can be done using the following two methods:

- Simple analytical design in initial and terminal state
- Manual analytical, iterative design

The parallel design with both of the above methods will be discussed below, based on the same input parameters.

Simple analytical design in initial and terminal state
A pavement is desired to be designed based on the following inputs:

- A traffic load of 280,000 E10/year, corresponding to traffic class T6, in accordance with Table 1 in [ref. 11]
- HBB-B, C8/10 is to be used as a bound base layer with a minimum of 120 mm total asphalt thickness
- The rigidity of the subgrade is 15 MPa, which means that it must be considered "Splitting frost-susceptible," unless laboratory investigations show that this is not the case, see Table 10 of [ref. 11]
- Kerbstones, culverted drains and paved verges are used
- The design period is 30 years
- The average speed is greater than 60 km/h, so MMOPP will not reduce the asphalt's E value

Based on traffic class, type of subgrade and drainage conditions, the required pavement thickness is, thus, at least 800 mm, cf. Table 10 in [ref. 11].

Two parallel MMOPP calculations are opened and the desired pavement is modelled in its initial and terminal state, respectively, with the following options in MMOPP (new screens for both MMOPP calculations will be opened in the same spot on the screen, so one should continuously organise the corresponding screens, so that one keeps up with which respectively belong to the initial and terminal states):

- Select "New calculation"
- Select traffic class "T6"
- Select "SMA" as an asphalt wearing course
- Select "35 SMA Modif. E = 3000" (a 35 mm stone mastic asphalt with modified bitumen, which has an E value of 3,000 MPa at 30°C by default)

- Select "85 ABB Modif. E = 3000" (an 85 mm asphalt concrete binder course with modified bitumen, which has an E value of 3,000 MPa at 30°C by default) as an asphalt binder course
- When selecting the bound base layer, different types must be selected in the two MMOPP calculations
    - MMOPP calculations with the HBB material in the initial state: Select "HBB-B C8/10" (hydraulically bound base layer, type B, with strength class $C_{8/10}$ in the initial state) as a bound base layer
    - MMOPP calculations with the HBB material in the terminal state: Select "HBB-B Terminal" (hydraulically bound base layer, Type B, in the terminal state) as a bound base layer
- Select "SG II" as the unbound base layer
- Select "Splitting frost-susceptible" as the type of subgrade
- Select "Yes", as this example assumes that kerbstones, culverted drains and paved verges are used, so there is no risk that water can penetrate the pavement
- Click the "Default E" button and select "Use default E values for bound layers"
- Customise the input (in this example, input for traffic load, design period, as well as the subgrade's E value)
- Click the "Analytical" button in both screens with "Input parameters" so that the two MMOPP calculations separately design the required layer thicknesses in the pavement
- Click the "Lifespan, year" button on both screens with "Input parameters" so that the theoretical lifespans of the two MMOPP calculations are displayed.

The above selections result in the following two screens with "Input parameters", as well as the associated table of theoretical lifespans, with reference to the two figures below:

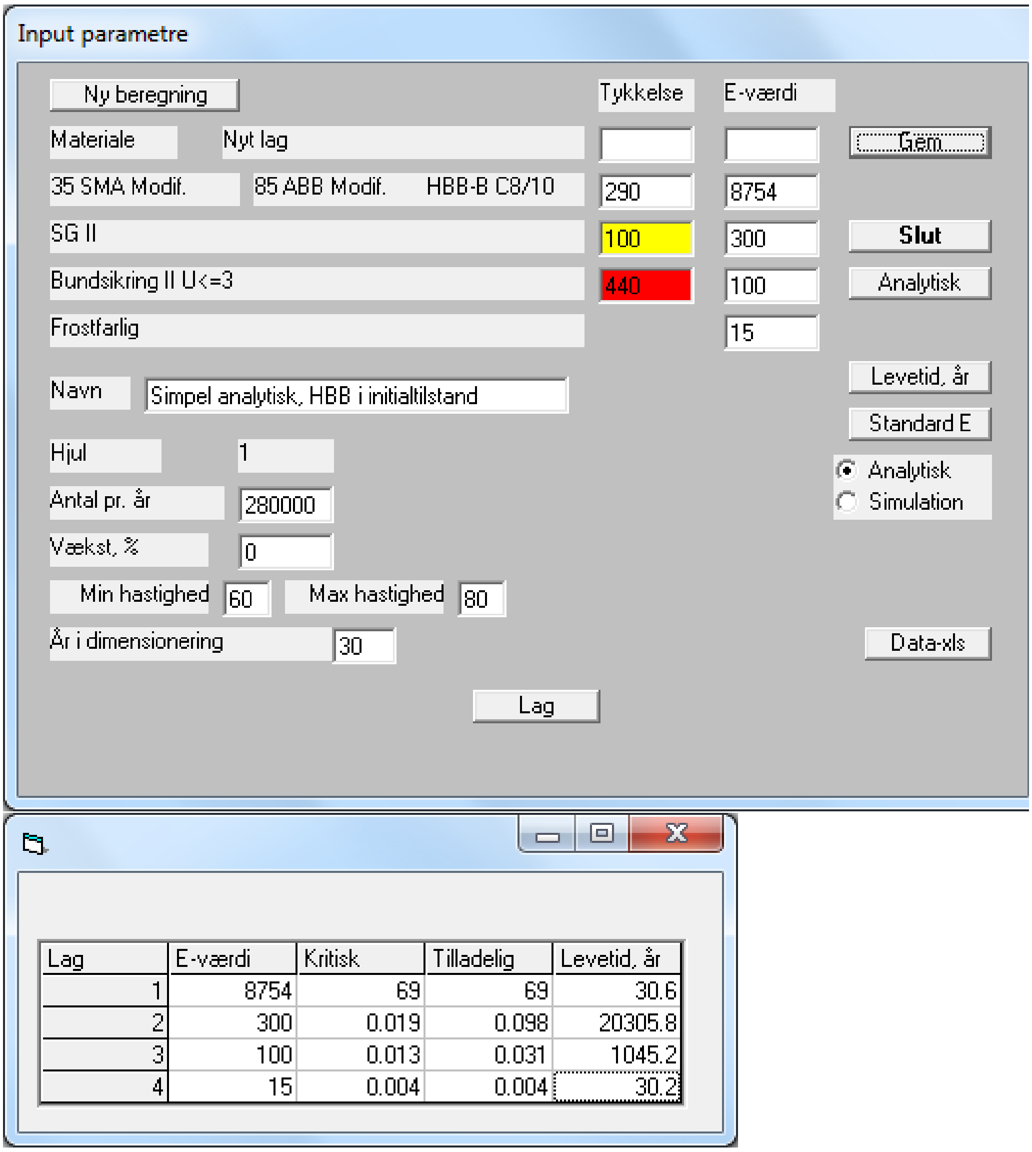
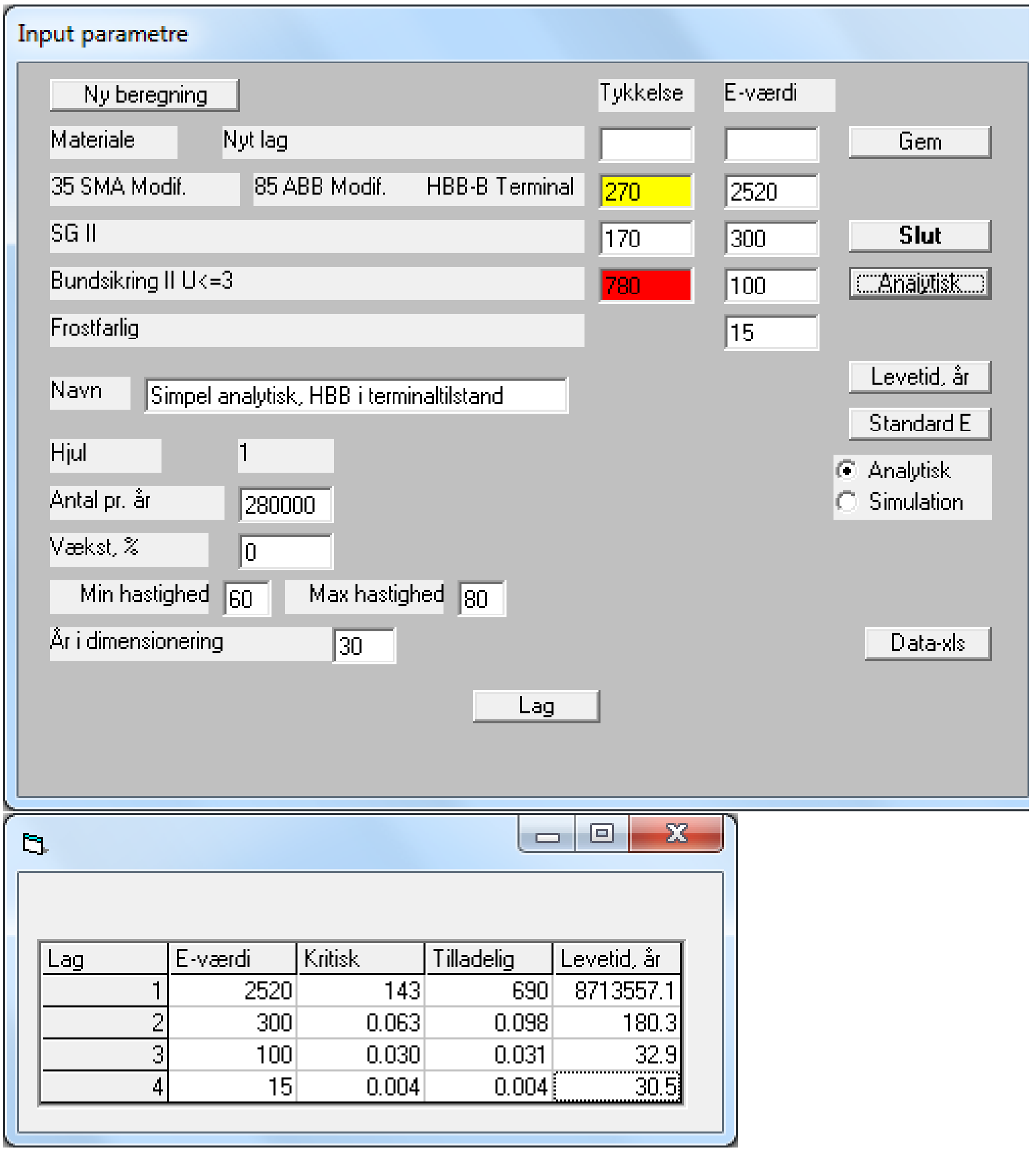


Figure 36 Initial state of the HBB: Simple analytical design - initially, separate design.



Lag	E-værdi	Kritisk	Tilladelig	Levetid, år
1	2520	143	690	8713557.1
2	300	0.063	0.098	180.3
3	100	0.030	0.031	32.9
4	15	0.004	0.004	30.5

Figure 37 <u>Terminal state of the HBB:</u> Simple analytical design - initially, separate design.

In the initial state of the HBB material, the combined E value of "Layer 1" (the asphalt layer and HBB) is 8,754 MPa (cf. Figure 36) while the value is only 2.520 MPa when the HBB material is in the terminal state (Figure 37). This is because HBB-B, $C_{8/10}$ has a default initial state of 15,000 MPa, while the terminal state at the end of the design period is expected to have a default value of 2,000 MPa, cf. Table 1.

The lifespan of Layer 1 is only calculated for the HBB layer, as critical strains are only checked for the bottom of the bound layers. The fact that MMOPP does not check the lifespan of the asphalt layer is as a result of the fact that, for semi-rigid pavements, experience tells us that it is not the asphalt layers which are the critical layers.

As described above, the initial state describes the HBB layer at the time of construction. Due to the traffic load, the HBB layer will gradually be degraded until it reaches the terminal state at the end of the design period. In order for the calculated theoretical lifespan of the HBB layer to be correct, it is necessary that the underlying layers, including the subgrade, also have a sufficiently useful lifespan when the HBB material is in the terminal state.

Because the design criterion for the HBB material in the terminal state is very lenient, the calculated theoretical lifespan of the HBB layer in the terminal state is, thus, not a realistic expression of this layer's lifespan. Therefore, the calculated theoretical lifespan of the HBB layer in the terminal state can only serve as an indication that, with the given construction, the HBB layer is not the critical layer.

The above initial designs will result in the following two constructions, with reference to the table below:

Layer	Layer thickness [mm]	
	Initial state of the HBB material	Terminal state of the HBB material
Asphalt wearing course, SMA mod.	35	35
Asphalt binder course, ABB mod.	85	85
Bound base layer, HBB-B, $C_{8/10}$	170	150
Unbound base layer, SG II	100	170
Subbase, BL II, U ≤ 3	440	780
Pavement thickness:	**830**	**1,220**

Table 7 Simple analytical design in initial and terminal state - initial construction by separate design (from Figure 36 and Figure 37).

As can be seen from the above table, there is a difference in the required thickness of the HBB and base course of gravel and subbase layers, depending on whether the HBB material is in the initial or terminal state. The goal of the parallel design is to find a construction that has the desired lifespan in both the initial and the terminal state of the HBB material.

For the HBB material in the terminal state, the table above shows that a thicker layer of base course of gravel is needed to protect the underlying subbase layer, as well as a thicker subbase layer to protect the subgrade. The same protection could be achieved by increasing the thickness of either the asphalt layers or the HBB layer, but base course of gravel and subbase are the most immediate cheapest materials.

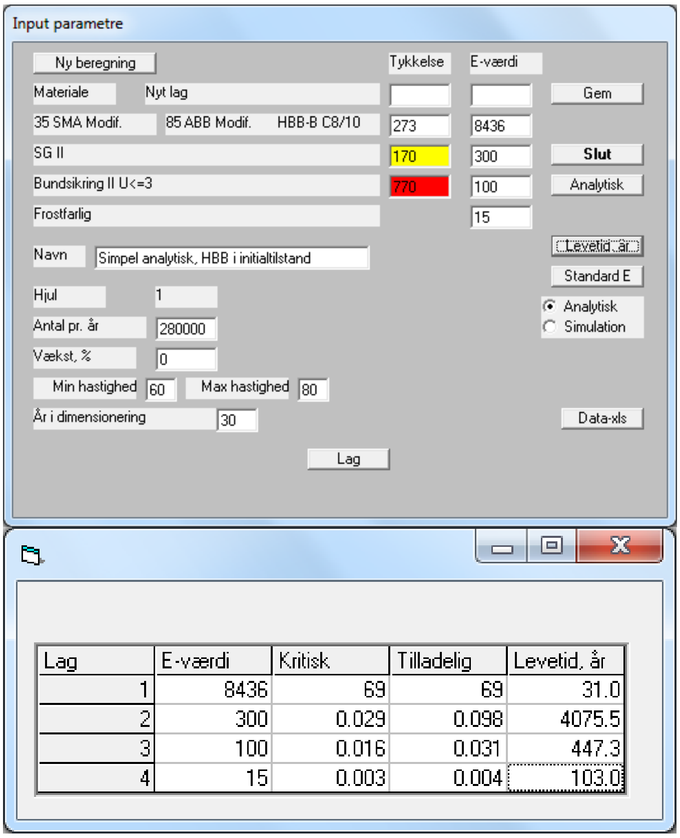
In this example there are two options, both of which provide a pavement with the desired theoretical lifespan in both the initial and the terminal state:

- Alternative 1:
  - In the MMOPP calculation with the HBB layer in the initial state, the required layer thickness for base course of gravel and subbase is inserted from the parallel design with the HBB layer in the terminal state
  - With the thicker layers of base course of gravel and subbase, the required layer thickness of the HBB layer in the initial state can be manually reduced until the desired theoretical lifespan has just been met
  - The thickness of the unbound layers is reduced if possible, so that the desired theoretical lifespan is still observed (in this example, it is desired that the total asphalt thickness should be at least 120 mm, otherwise this thickness could also be reduced)
  - The theoretical lifespan of all layers in this pavement is subsequently checked in the terminal state for HBB

- Alternative 2:
  - In the MMOPP calculation with the HBB layer in the terminal state the required layer thickness for HBB is inserted from the parallel design with the HBB layer in the initial state
  - With the thicker layer of the HBB in the terminal state, the required layer thickness of the base course of gravel and subbase layers can be manually reduced until the desired theoretical lifespan has just been met
  - The thickness of the HBB layer is reduced if possible, so that the desired theoretical lifespan is still observed (the same remark as in Alternative 1 regarding the possible reduction of the asphalt layer applies)
  - The theoretical lifespan of all layers in this pavement is subsequently checked in the initial state for HBB

The above two alternative pavements are shown in the following two figures:

Initial state of the HBB:



Terminal state of the HBB:

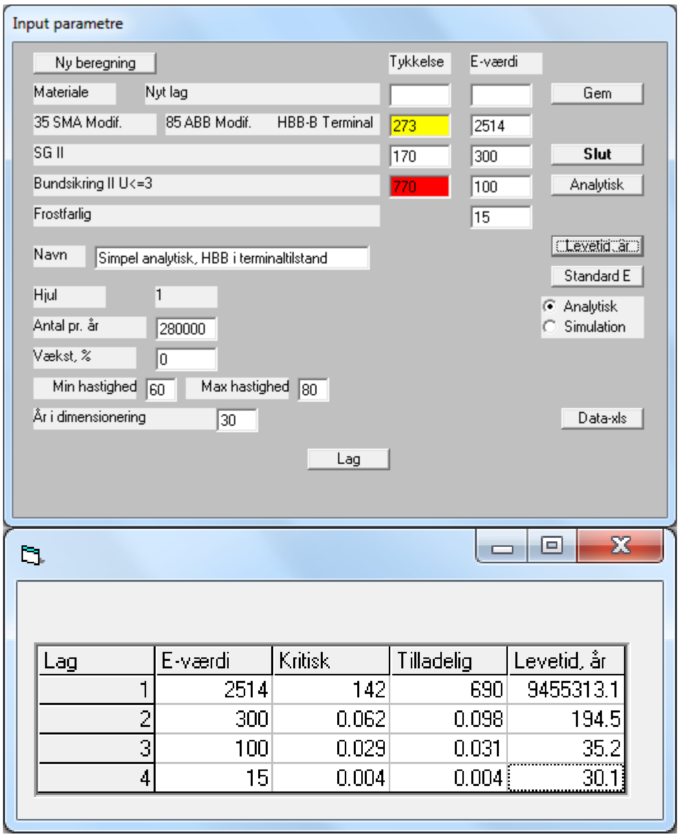


Figure 38 Alternative 1: Simple analytical design - a manually customised pavement.

Initial state of the HBB: Terminal state of the HBB:

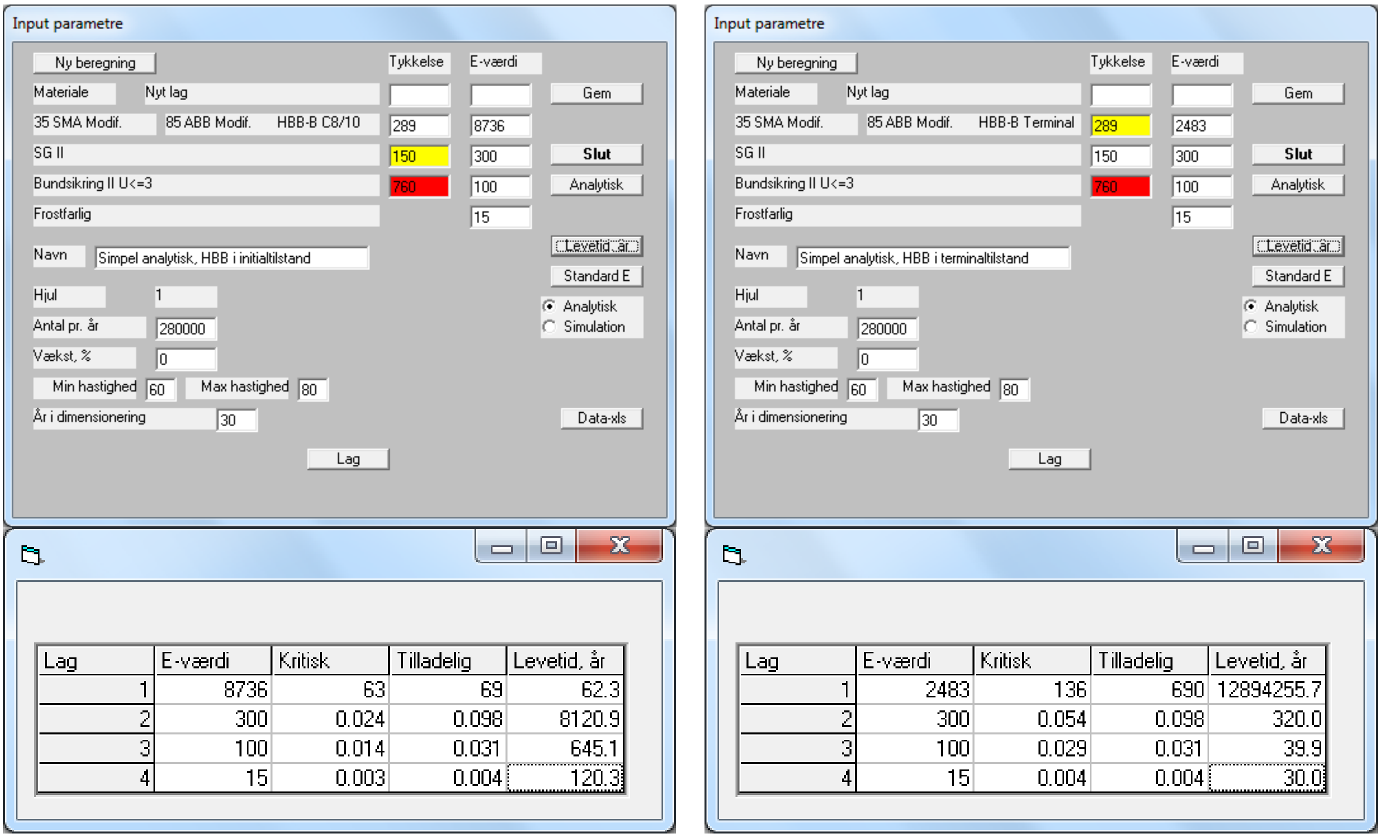


Figure 39 Alternative 2: Simple analytical design - a manually customised pavement.

The above two alternative constructions have been summarised in the below table:

Layer	Layer thickness [mm]	
	Alternative 1	Alternative 2
Asphalt wearing course, SMA mod.	35	35
Asphalt binder course, ABB mod.	85	85
Bound base layer, HBB-B, $C_{8/10}$	153	169
Unbound base layer, SG II	170	150
Subbase, BL II, U ≤ 3	770	760
Pavement thickness:	**1,213**	**1,199**

Table 8 Simple analytical design in initial and terminal state - two alternative constructions, both of which have the desired theoretical lifespan in both the initial and the terminal state (from Figure 38 and Figure 39).

Both alternative constructions in the above table have the desired theoretical lifespan. As can be seen, there is not such a big difference in layer thicknesses of the two alternatives (by comparing unit prices for the individual layers, as well as expenditure on appropriate excess widths of the individual layers, as well as possible excavation, the cheapest construction can be determined).

Both alternatives have a reasonable pavement thickness, but if one desires this to be reduced, one can do the following, either separately or in combination:

- Increase the thickness of the bound layers
- Increase the strength class of the HBB material
- Increase the rigidity of the subgrade by means of, for example, lime and/or cement stabilisation

Compliance with the desired theoretical lifespan is naturally checked in MMOPP, as described above.

If the conditions during construction do not require a drivable subgrade in the form of a base course of gravel, then, as an alternative to the pavements in Table 8, one can also try with a pavement without an unbound base layer - such a design (denoted as "Alternative 3") is done, below, in MMOPP after clicking on the "New calculation" button. Input parameters are as before, but where "SG II" was previously selected as the unbound base layer, now "No" is selected, which brings about the following two screens with "Input parameters", as well as a table with theoretical lifespans, with reference to the following two figures:

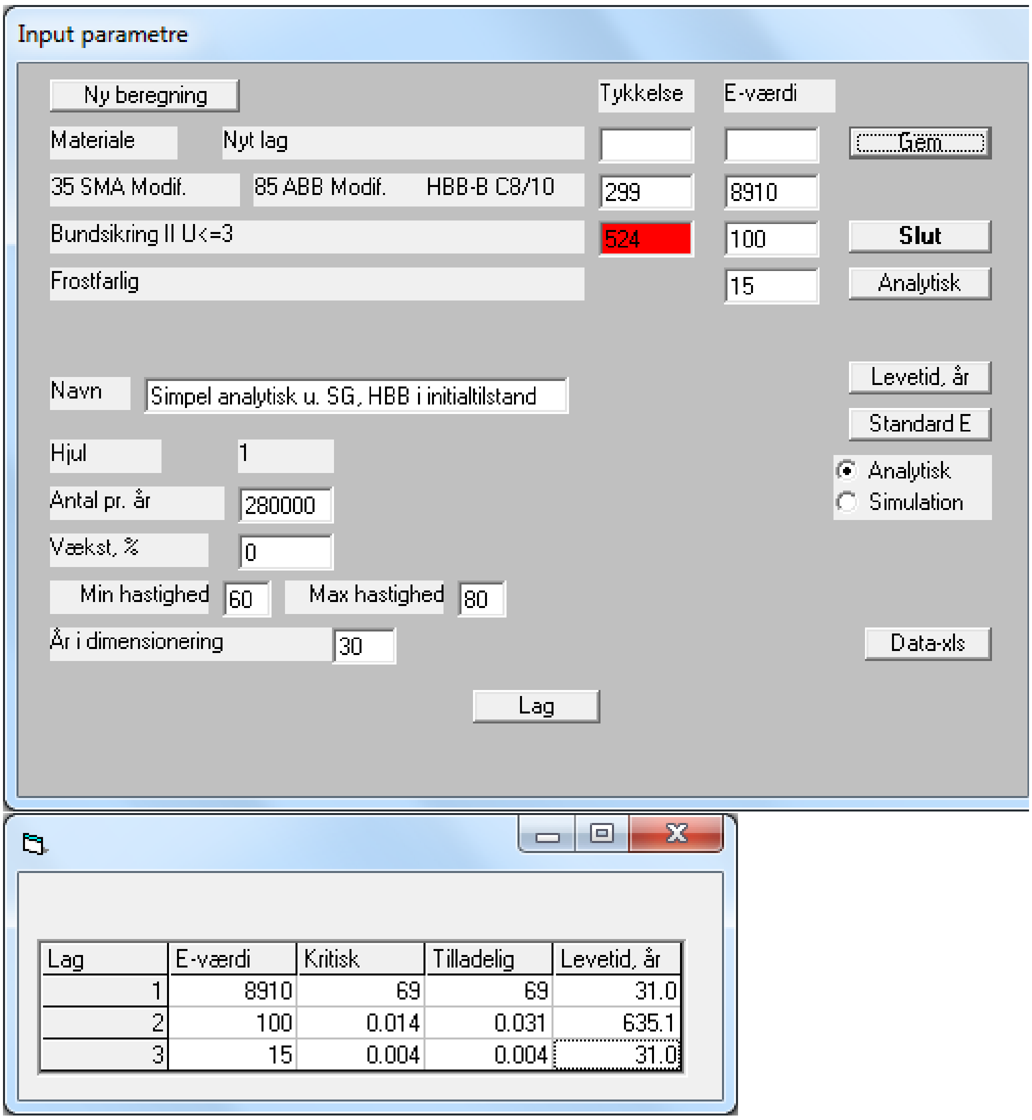


Figure 40 <u>Initial state of the HBB:</u> Simple analytical design - initially, separate design for Alternative 3 without SG as the unbound base layer.

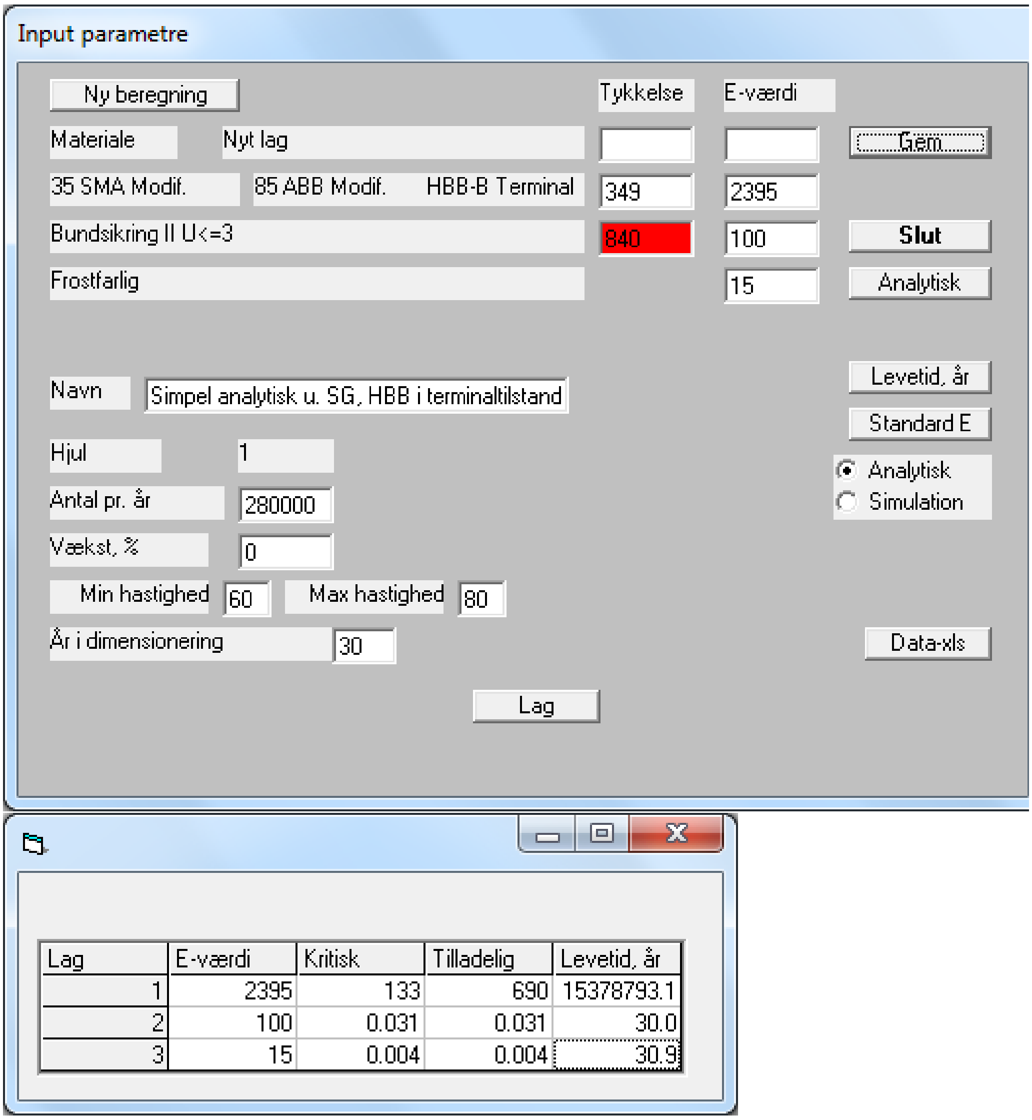


Figure 41 <u>Terminal state of the HBB:</u> Simple analytical design - initially, separate design for Alternative 3 without SG as the unbound base layer.

This initial design without SG as the unbound base layer results in the following two constructions, with reference to the table below:

Layer	Layer thickness [mm]	
	Initial state of the HBB material	Terminal state of the HBB material
Asphalt wearing course, SMA mod.	35	35
Asphalt binder course, ABB mod.	85	85
Bound base layer, HBB-B, $C_{8/10}$	179	229
Subbase, BL II, U ≤ 3	524	840
Pavement thickness:	**823**	**1,189**

Table 9 Simple analytical design in initial and terminal state - initial construction by separate design for Alternative 3 without SG as the unbound base layer (from Figure 40 and Figure 41).

As can be seen from the above table, for this alternative too, there is a large difference in the required thickness of both the HBB and subbase layers, depending on whether the HBB material is in the initial or terminal state. However, for this alternative, both the HBB and subbase layers are the thickest in the terminal state, and thus none of these layers can be immediately reduced.

In an attempt to reduce the total pavement thickness for Alternate 3, one can also try to increase the thickness of the bound layers, to increase the strength of the HBB material or to increase the rigidity of the subgrade by means of, for example, lime and/or cement stabilisation, as described above, and thereby to check both the initial and the terminal state in MMOPP.

Thus, for the given input parameters, the following three alternative constructions have been obtained, with reference to the table below:

Layer	Layer thickness [mm]		
	Alternative 1[1)]	Alternative 2[1)]	Alternative 3[2)]
Asphalt wearing course, SMA mod.	35	35	35
Asphalt binder course, ABB mod.	85	85	85
Bound base layer, HBB-B, $C_{8/10}$	153	169	229
Unbound base layer, SG II	170	150	-
Subbase, BL II, U ≤ 3	770	760	840
Pavement thickness:	**1,213**	**1,199**	**1,189**

[1)] Layer thicknesses from Table 8 for the two alternatives.

[2)] Layer thicknesses from the critical pavement in Table 9.

Table 10 Simple analytical design in initial and terminal state - three alternative constructions, all of which have the desired theoretical lifespan in both the initial and the terminal state.

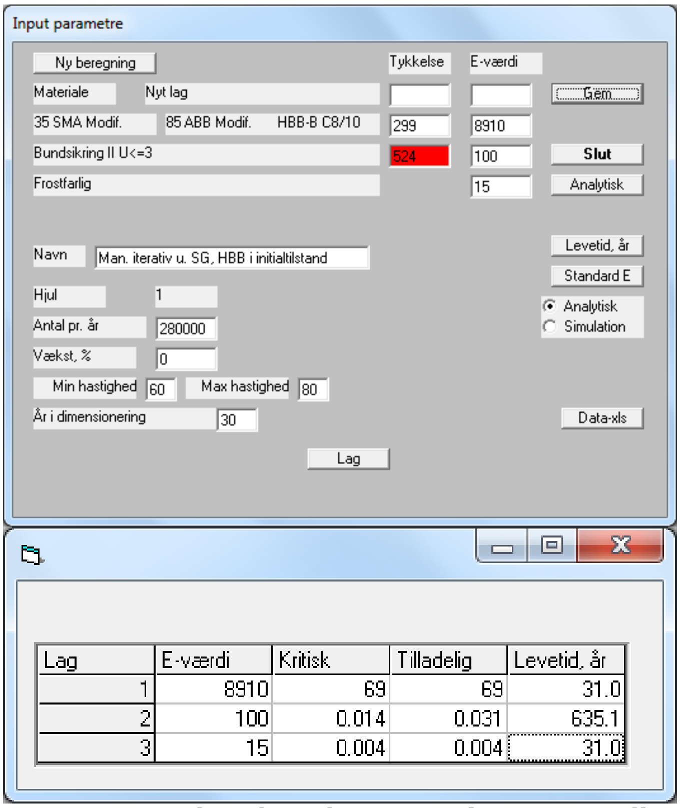
All three alternative constructions in the above table have the desired theoretical lifespan (by comparing unit prices for the individual layers, as well as expenditure on appropriate excess widths of the individual layers, as well as possible excavation, the cheapest construction can be determined).

By using the calculation method "Simple analytical design in initial and terminal state", as described above, it is ensured that the pavement theoretically has the desired lifespan in both the initial and the terminal state. In some cases, the calculation method "Manual analytical, iterative design" results in a thinner pavement, and, in the following, this is shown for Alternative 3 in the above table.

Manual analytical, iterative design
This calculation method also opens two side by side MMOPP calculations.

Input parameters are as before for Alternative 3, and the following two screens with "Input parameters" are presented again, as well as the table of theoretical lifespans, with reference to the below figure:

Initial state of the HBB:



Terminal state of the HBB:

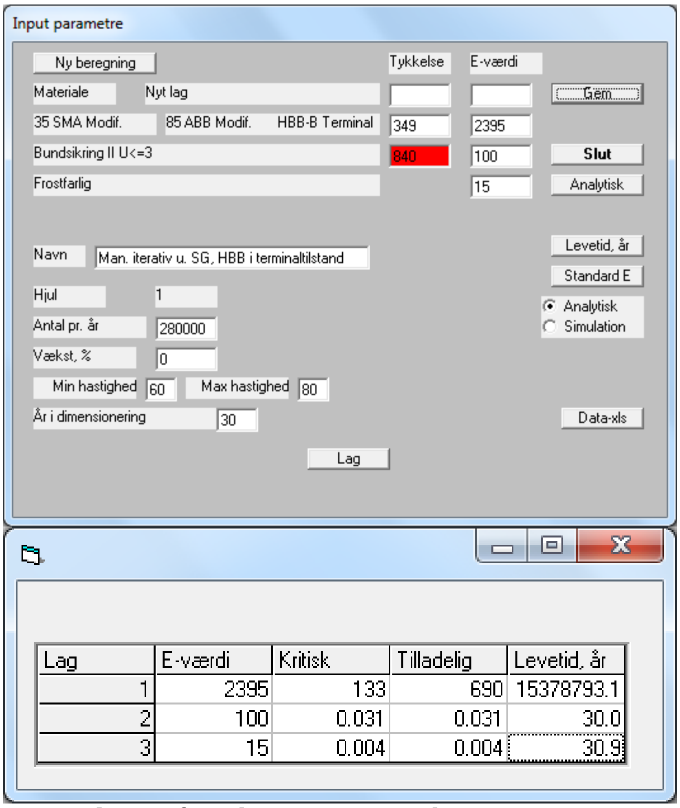


Figure 42 Manual analytical, iterative design - initially, separate design for Alternative 3, without an unbound base layer.

As described earlier, the terminal state is critical for this alternative, as both the HBB and subbase layers are thickest when the HBB material is in this state. However, in both the initial and the terminal state, default E values have been used for the different materials, which means that MMOPP expects the HBB layer in the terminal state to be degraded, so the E value is reduced to 2,000 MPa, cf. Table 1.

By using thicker layers in the pavement than calculated in MMOPP with the HBB material in the initial state, the HBB material will not be completely degraded to the terminal state within the desired design period and therefore a higher E value for the HBB layer can be considered in the terminal state than the default value.

In this example, 349 mm combined asphalt and HBB layers and a 840 mm thick subbase layer are required when the HBB layer is in the terminal state, with reference to the screen on the right in Figure 42. This is how these thicknesses are used in the MMOPP calculation with the HBB layer in the initial state, as illustrated in the figure below:

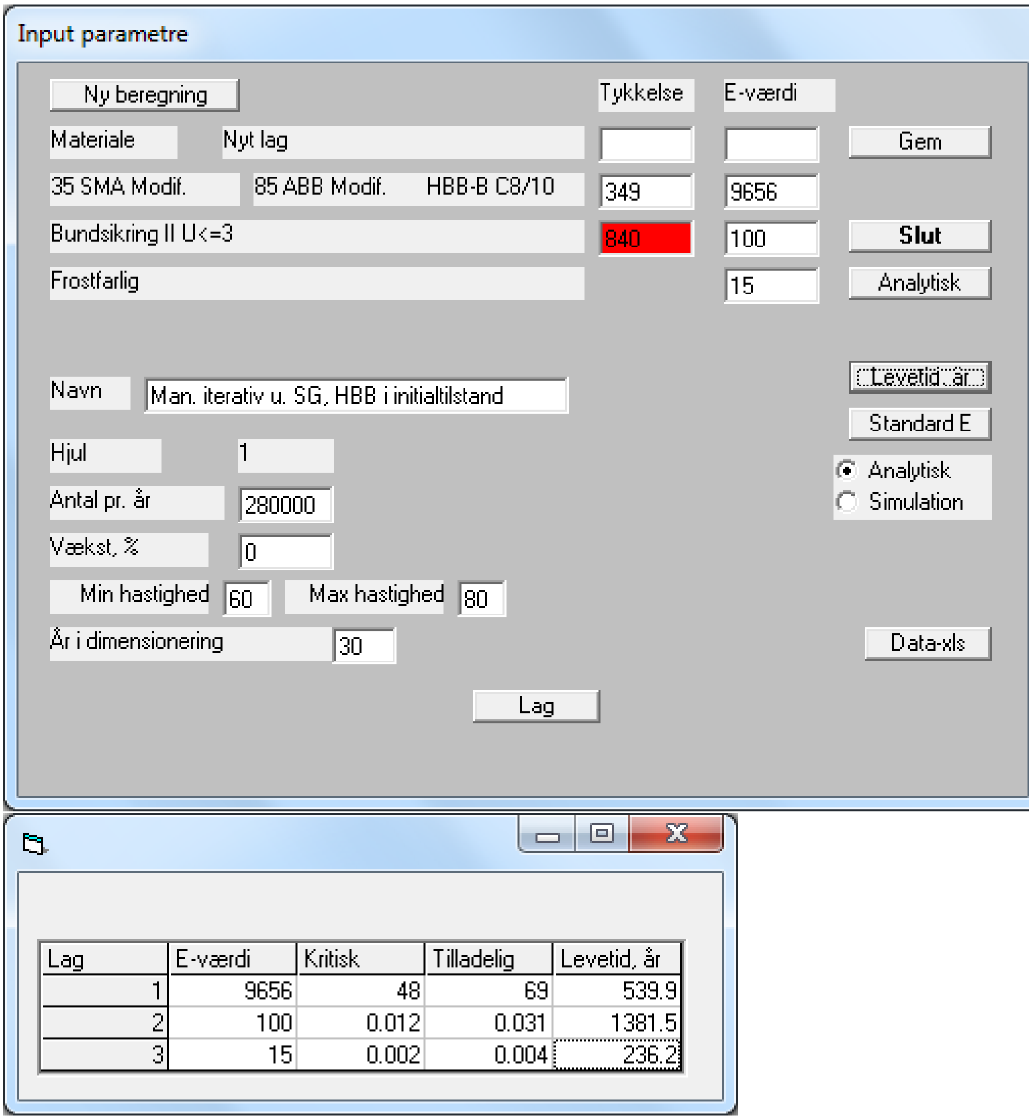


Figure 43 <u>Initial state of the HBB:</u> Manual analytical, iterative design - the effect of an increased thickness of the HBB and subbase layers with the HBB in the initial state.

When designing the pavement with the HBB layer in the initial state, the expected theoretical lifespan was 31.0 years (cf. the left screen in Figure 42), but, as seen from the above figure, the expected theoretical lifespan of the HBB layer increases to 539.9 years using the thick layers of the HBB and subbase required in the MMOPP calculation with the HBB layer in the terminal state.

By expiry of the design period after 30 years, the HBB layer is thus only degraded (30/539.9 = 0.056 =) 5.6% with these thick layers of the HBB and subbase.

The degradation of the HBB-B materials is illustrated in Figure 34, and using the regression equation for HBB-B, $C_{8/10}$, the real E value of the HBB-B material in a partially degraded state after 30 years can be calculated to (2,000 × $0.056^{-0.673}$ =) 13,916 MPa, which is significantly higher than the default value of 2,000 MPa.

In MMOPP, the combined E value of the asphalt layers and the HBB layer are calculated automatically from the Equivalent Thickness Method (see formula (XXI)), based on <u>default</u> E values. For this example, this combined E value of the asphalt layer and the HBB layer can be calculated manually using the following formula:

$$E_{comb.} = \left(\frac{h_{asphalt,upper} \times \sqrt[3]{E_{asphalt,upper}} + h_{asphalt,lower} \times \sqrt[3]{E_{asphalt,lower}} + h_{HBB} \times \sqrt[3]{E_{HBB}}}{h_{asphalt,upper} + h_{asphalt,lower} + h_{HBB}} \right)^3 \qquad \text{(XXII)}$$

In terminal state, the total thickness of the bound layers is determined as 349 mm, spread out over 120 mm asphalt and 229 mm HBB, cf. the screen on the right of Figure 42. The two different types of asphalt have the same E value - 3,000 MPa for the top 100 mm and 5,000 MPa for the asphalt material located lower down, cf. Table 8 of [ref. 11] (this is because the upper part of the asphalt is warmer and therefore less rigid than the lower part). By inserting the corresponding E values and layer thicknesses (100 mm of 3,000 MPa, 20 mm of 5,000 MPa and 229 mm of 13,916 MPa) in the formula above, the combined E value can be calculated to 9,123 MPa.

If this combined E value for the asphalt layers and the HBB layer is used in the MMOPP calculation with the HBB in a partially degraded state, the following result is obtained by clicking the "Lifespan, year" button, with reference to the following figure:

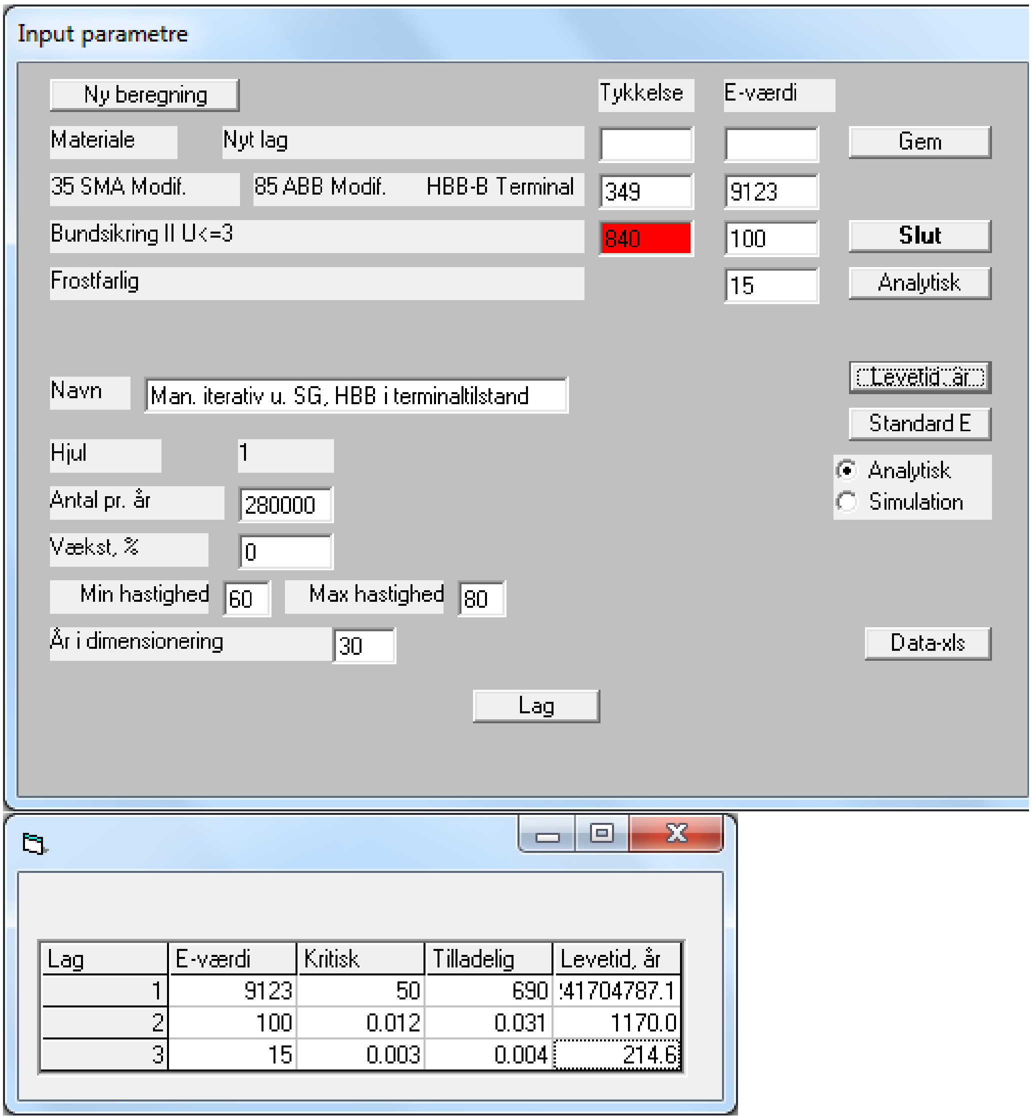


Figure 44 <u>The partially degraded state of the HBB:</u> Manual analytical, iterative design - the effect of an increased E value of the HBB material in a partially degraded state.

As can be seen from the above figure, the expected theoretical lifespan of the pavement with the HBB layer in a partially degraded state is significantly longer than the 30-year design period. This is how the required thickness of the HBB layer and potentially also the thickness of the subbase layer can be reduced.

During a number of iterative steps, the pavement can manually be optimised to ensure that the expected theoretical lifespan is achieved in both the initial and the partially degraded state - thus, the "Lifespan, year" button is used instead of the "Analytical" button.

In this calculation process, it should be noted that, as a rule, MMOPP automatically adjusts the combined E value of the asphalt and HBB layer when the thickness of the bound layers is changed. MMOPP will do this in the MMOPP calculation with the HBB in the initial state, but in the MMOPP calculation with the HBB in a partially degraded state, one actually just wants to use a combined E value which differs from the default value in MMOPP.

Thus, in the MMOPP calculation with the HBB layer in a partially degraded state, you must either always change the layer thickness first and then manually enter the combined E value of the bound layer or you can click the "Default E" button and select "Use E values from the input form", so MMOPP no longer automatically changes the E values to default values, but uses the user’s inputs.

For this example, the iterative process is illustrated in the table below, where both pavements, E values and expected theoretical lifespans in both the initial and the partially degraded states are given:

	Thickness [mm]	HBB, initial		HBB, partially degraded	
		E value [MPa]	Lifespan[1)] [year]	E value [MPa]	Lifespan[1)] [year]
Iteration 1 - Point of departure w/ 229 mm of HBB and 840 mm of BL (Alternative 3):					
Asphalt, upper	100	3,000	-	3,000	-
Asphalt, lower	20	5,000	-	5,000	-
HBB	229	15,000	-	13,916[2)]	-
Bound layers	**349**	**9,656[3)]**	**539.9**	**9,123[4)]**	**≥ 1,000**
Subbase	**840**	**100**	**≥ 1,000**	**100**	**≥ 1,000**
Subgrade	**-**	**15**	**236.2**	**15**	**214.6**
Degradation rate of the HBB[5)] [%]:			5.6%	-	-

	Thickness [mm]	HBB, initial		HBB, partially degraded	
		E value [MPa]	Lifespan[1)] [year]	E value [MPa]	Lifespan[1)] [year]
Iteration 2 - assume that HBB can be reduced to 200 mm:					
Asphalt, upper	100	3,000	-	3,000	-
Asphalt, lower	20	5,000	-	5,000	-
HBB	200	15,000	-	5,699[2)]	-
Bound layers	**320**	**9,247[3)]**	**142.1**	**4,691[4)]**	**≥ 1,000**
Subbase	**840**	**100**	**621.0**	**100**	**94.3**
Subgrade	**-**	**15**	**138.5**	**15**	**50.4**
Degradation rate of the HBB[5)] [%]:			21.1%	-	-
Iteration 3 - assume that HBB can be reduced to 190 mm:					
Asphalt, upper	100	3,000	-	3,000	-
Asphalt, lower	20	5,000	-	5,000	-
HBB	190	15,000	-	4,109[2)]	-
Bound layers	**310**	**9,092[3)]**	**87.4**	**3,777[4)]**	**≥ 1,000**
Subbase	**840**	**100**	**464.2**	**100**	**42.6**
Subgrade	**-**	**15**	**114.5**	**15**	**32.8**
Degradation rate of the HBB[5)] [%]:			34.3%	-	-
Iteration 4 - assume that HBB can be reduced to 188 mm:					
Asphalt, upper	100	3,000	-	3,000	-
Asphalt, lower	20	5,000	-	5,000	-
HBB	188	15,000	-	3,842[2)]	-
Bound layers	**308**	**9,059[3)]**	**79.1**	**3,619[4)]**	**≥ 1,000**
Subbase	**840**	**100**	**437.3**	**100**	**36.5**
Subgrade	**-**	**15**	**110.1**	**15**	**30.3**
Degradation rate of the HBB[5)] [%]:			37.9%	-	-
Iteration 5 - assume that HBB can be reduced to 187 mm:					
Asphalt, upper	100	3,000	-	3,000	-
Asphalt, lower	20	5,000	-	5,000	-
HBB	187	15,000	-	3,718[2)]	-
Bound layers	**307**	**9,043[3)]**	**75.3**	**3,545[4)]**	**≥ 1,000**
Subbase	**840**	**100**	**424.5**	**100**	**33.8**
Subgrade	**-**	**15**	**108.0**	**15**	**29.1**
Degradation rate of the HBB[5)] [%]:			39.8%	-	-

	Thickness [mm]	HBB, initial		HBB, partially degraded	
		E value [MPa]	Lifespan[1)] [year]	E value [MPa]	Lifespan[1)] [year]
Iteration 6 - assume that BL can be reduced to 830 mm:					
Asphalt, upper	100	3,000	-	3,000	-
Asphalt, lower	20	5,000	-	5,000	-
HBB	188	15,000	-	3,809[2)]	-
Bound layers	**308**	**9,059[3)]**	**78.1**	**3,599[4)]**	**≥ 1,000**
Subbase	**830**	**100**	**443.5**	**100**	**36.3**
Subgrade	**-**	**15**	**106.5**	**15**	**28.8**
Degradation rate of the HBB[5)] [%]:			38.4%	-	-

[1)] Where the theoretical lifespan is above 1,000 years, "≥ 1,000" is stated.

[2)] Calculated using the regression equation for HBB-B, $C_{8/10}$, based on the degradation rate of the HBB, cf. Figure 34.

[3)] Automatically calculated by MMOPP based on default E values.

[4)] Calculated using the formula of Equivalent Thickness Method, see formula **(XXII)**, where the HBB layer is in a partially degraded state.

[5)] Calculated based on the length of the design period in relation to the expected theoretical lifespan of the HBB layer in the initial state.

Table 11 Manual analytical, iterative design - results from the iterative process with a different thickness of the HBB layer with the HBB in both the initial and the partially degraded state (the cells with a grey background indicate that the expected theoretical lifespan has not been met).

As can be seen from the above table, iteration 4 gives the thinnest pavement where the expected theoretical lifespan is met with the HBB layer in both the initial and the partially degraded state.

The following table lists the three alternatives from "Simple analytical design in initial and terminal state" displayed together with the above result from "Manual analytical, iterative design" (the latter is denoted as "Alternative 4 "):

Layer	Layer thickness [mm]			
	Alt. 1[1)]	Alt. 2[1)]	Alt. 3[1)]	Alt. 4[2)]
Asphalt wearing course, SMA mod.	35	35	35	35
Asphalt binder course, ABB mod.	85	85	85	85
Bound base layer, HBB-B, $C_{8/10}$	153	169	229	188
Unbound base layer, SG II	170	150	-	-
Subbase, BL II, U ≤ 3	770	760	840	840
Pavement thickness:	**1,213**	**1,199**	**1,189**	**1,148**

1) Layer thicknesses from Table 10 for the three alternatives determined by "Simple analytical design in initial and terminal state", with the HBB layer in both the initial and the terminal state.

2) Layer thicknesses from iteration 4 in Table 11 determined by "Manual analytical, iterative design", with the HBB layer in both the initial and the partially degraded state.

Table 12 Comparison of the calculation methods - four alternative constructions, all of which have the desired theoretical lifespan in both the initial and, respectively, the terminal and partially degraded state.

All four alternative constructions in the above table have at least the desired theoretical lifespan. By comparing unit prices for the individual layers, as well as expenditure on appropriate excess widths of the individual layers, as well as possible excavation, the cheapest construction can be determined.

The calculation method "Simple analytical design in initial and terminal state" is relatively quick to use."Manual analytical, iterative design" is more time consuming, but can lead to a thinner HBB layer.

4.3.5 Stops in the city area with bus and regular traffic

A stop without a bus bay is partly exposed to regular traffic and partly to stopping/starting buses.

Seeing as the two traffic types drive at different speeds - taken to be 40 km/h for heavy vehicles and 2.5 km/h for buses - it is necessary to calculate the two traffic types' lifespan usage separately and, subsequently, to combine the lifespan usage from the two parallel calculations in order to check the total lifespan usage. In MMOPP, the speed of heavy vehicles is, for example, entered at 30 km/h - 50 km/h and for buses at 2 km/h - 3 km/h.

On one road there are altogether 90 bus passengers per day in both directions. The average annual daily traffic is 28,000 vehicles and the proportion thereof of heavy vehicles is 10%. The road has two lanes in each direction, but all buses will drive in the innermost lane. It is designed for a lifespan of 40 years, and there will be no traffic increase during this period for the particular road section. Bus traffic is channelled with an E10 factor of 0.55. The heavy vehicles are considered without channelling with an E10 factor of 0.45. These E10 factors correspond to the middle range of the two vehicle types, according to Tables 6 and 7 of [ref. 11]. The road section is a municipal road where some heavy traffic can occur, and, on this basis, the supersingle factor is set to 1.5 for both types of traffic.

The calculation of the designed traffic loads, N_{E10} for the two types of traffic load is calculated from the Road Standard's formula:

$$N_{E10} = P \times K_F \times K_K \times K_R \times F_{SS} \times \Sigma(F_{E10} \times L)$$

Factor	Description	Buses	Heavy vehicles
P	Growth factor = Years of the design period with a traffic increase of 0%	40	40
K_F	Distribution factor (two lanes for buses and four lanes for heavy vehicles)	0.50	0.45
K_K	Channelling factor (buses drive all the way to the kerbstone each time)	2.0	1.0
K_R	Correction factor for roundabouts and intersections (an even road without torsion)	1.0	1.0
F_{SS}	Supersingle factor - municipal road in the city, heavy traffic	1.5	1.5
F_{E10}	E10 factor - municipal roads	0.55	0.45
L_{Buses}	Number of buses/year = 90 × 365	32,850	
$L_{Heavy\ vehicles}$	Number of heavy vehicles/year = 28,000 × 365 × 10% × 0.86		878,920
N_{E10}		1,084,052	10,678,878
N_{E10}/year (rounded)		27,101	266,972
Total traffic class		T6	

Table 13 Design affected traffic load, N_{E10}.

The pavement is designed in several steps:

Step 1: First, the pavement for the two types of traffic is determined separately.

Step 2: Thereafter, a pavement is selected, composed of the thickest layers for the two constructions decided on in "Step 1". The lifespan of the two traffic types is determined and the total lifespan usage is checked.

Step 3: The thickness of the SG layer is reduced to 250 mm and the asphalt layer thickness is increased until the total lifespan usage is below 100% in all layers.

The following layers are chosen for the construction:

Layer	Material	Thickness
Wearing course	Semi-flexible	40 mm
Binder course	ABB modified	55 mm
Asphalt base layer	Hot mix gravel II (GAB II)	Variable
Unbound base layer	SG II	Max. 250 mm in one layer
Subbase layer	BL II, U ≤ 3	Variable

Table 14 Selection of layers for a bus stop.

It is assumed that the subgrade is "Frost-susceptible," with a rigidity of 40 MPa, as well as that "kerbstones, culverted drains and paved verges or pavements" are used.

<u>Step 1:</u> The pavement is analytically designed for each of the two traffic types.

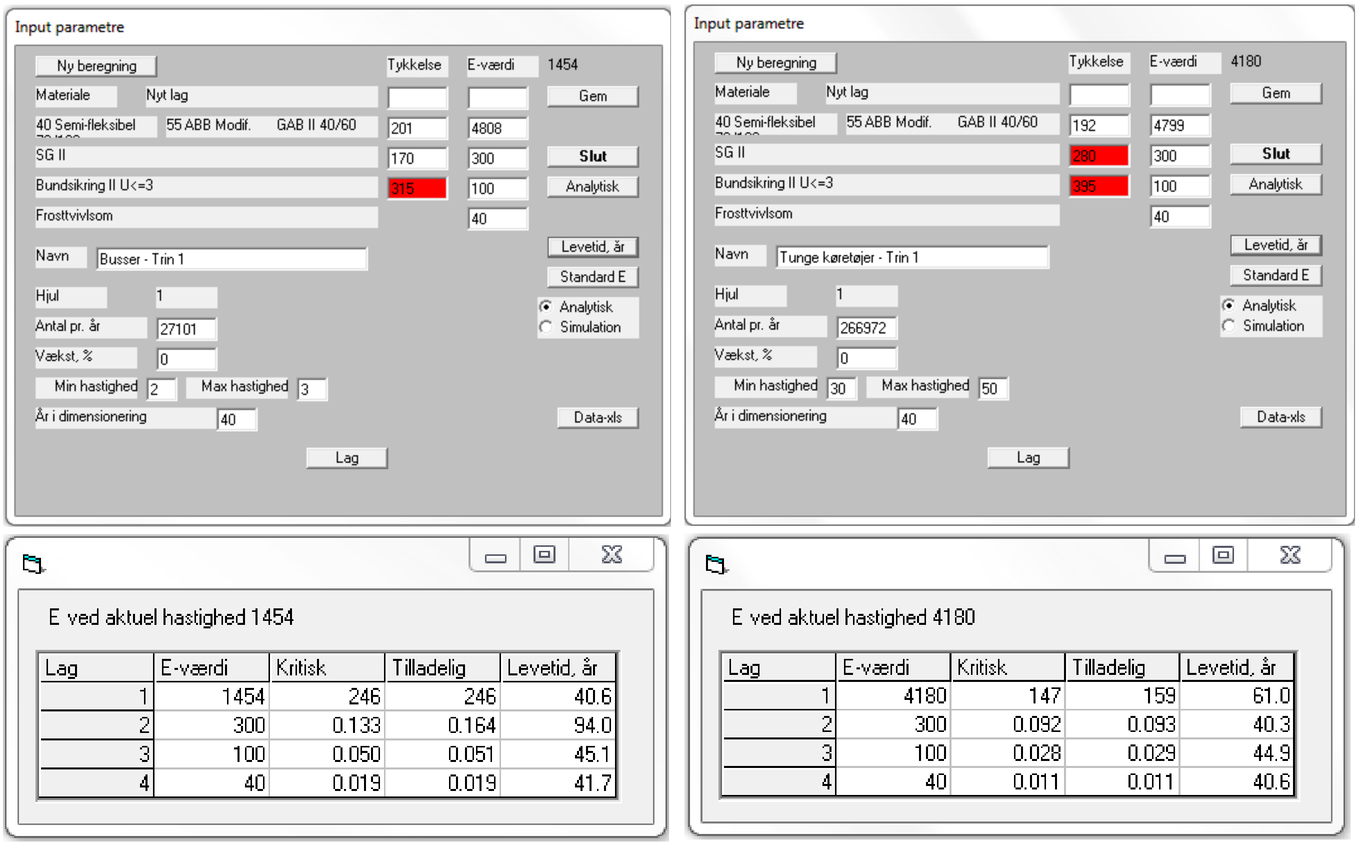


Figure 45 <u>Step 1:</u> Bus stop - separate calculations.

It is seen that the required asphalt thicknesses in the two cases are almost the same, but for different reasons:

- For the buses, the thickness of the asphalt layer is required in order to ensure the lifespan of the asphalt.
- For the heavy vehicles, the thickness of the asphalt layer is required in order to protect the SG layer.

Since the two designs have fairly similar asphalt thicknesses, it is chosen to start with a pavement with the largest asphalt thickness, the thickest base course of gravel layer and the thickest subbase gravel layer.

Step 2: The pavement chosen is now checked for "Lifespan" in the two load instances.

Figure 46 Step 2: Bus stop - separate calculations for a common pavement.

The lifespan usage for each of the two types of traffic over a 40-year period can now be calculated by percentage and it is checked that the total lifespan usage of each layer does not exceed 100%:

- Asphalt (40/70.7) + (40/77.7) = 57% + 51% = 108%
- Base course of gravel (40/66.3) + (40/54.2) = 60% + 74% = 134%
- Subbase (40/143.6) + (40/56.0) = 28% + 71% = 99%
- Subgrade (40/199.4) + (40/47.3) = 20% + 85% = 105%

The calculations show that the overall load-carrying capacity of the chosen pavement is not sufficient to achieve 40 years of lifespan, with a total lifespan usage exceeding 100% in one or more layers. This is adjusted in "Step 3" by increasing the thickness of the asphalt base layer.

Step 3: In this step, layer thicknesses are optimised so that the SG layer does not exceed 250 mm and the asphalt layer thickness is adjusted until the total lifespan usage is less than or equal to 100% in all layers.

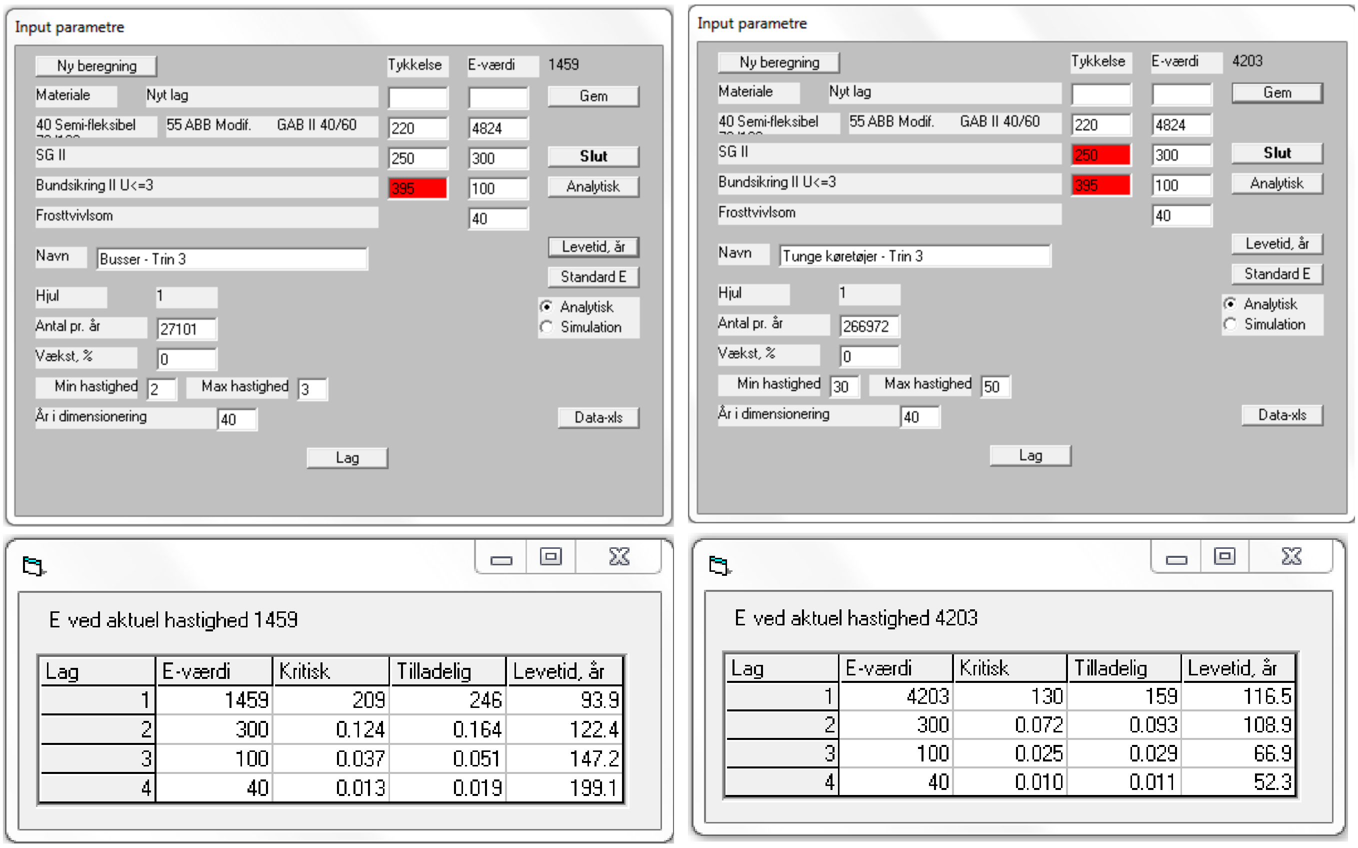


Figure 47 Step 3: Bus stop - optimisation of a common pavement.

It is checked again for each layer as to whether the lifespan usage of the two traffic volumes doesn't exceed 100% over a 40-year period:

- Asphalt (40/93.9) + (40/116.5) = 43% + 34% = 77%
- Base course of gravel (40/122.4) + (40/108.9) = 33% + 37% = 69%
- Subbase (40/147.2) + (40/66.9) = 27% + 60% = 87%
- Subgrade (40/199.1) + (40/52.3) = 20% + 76% = 97%

It can be seen from the above calculation that total lifespan usage is less than 100% for all layers. A quick check of the total pavement thickness (220 mm + 250 mm + 395 mm =), 865 mm, indicates that it is greater than the required pavement thickness, based on the traffic load and rigidity of the subgrade, cf. Table 10 in [ref. 11].

Therefore, a construction consisting of 40 mm of SFB 70/100, 55 mm of modified ABB, 125 mm of GAB II 40/60, 250 mm of SG II and 395 mm of BL II could be used at a bus stop with the current traffic load and subgrade rigidity.

4.3.6 Analytical reinforcement design

MMOPP can perform analytical reinforcement calculations based on data of the existing pavement.

For a reinforcement calculation, an existing pavement which has been used for a number of years is located. The pavement is now in a degraded state as a result of traffic or another load (for example, the weather) and there is a need for reinforcement of the pavement so that it can have a lifespan of a new road again. The inputs for the reinforcement design are the corresponding layer thicknesses and E values of the individual layers in the road pavement.

Information about layer thicknesses exists either from "as performed" data or can be obtained, for example, from drillings, diggings or ground-penetrating radar measurements.

Information about E values of the individual layers can be obtained from, for example, measuring with a falling weight.

Both layer thicknesses and E values from an existing pavement can be expected to vary and in order to take this variation into account, it is recommended to use the following statistical procedure:

- Layer thicknesses: Divide into uniform sub-sections if the thickness of the individual layers varies greatly => use the average thickness for each individual layer within each individual uniform sub-section
- E values: Divide into uniform sub-sections if the E values of the individual layers vary greatly => use the lower 25% fractile of the E value for each individual layer within each individual uniform sub-section

By using the lower 25% fractile of the E values for each individual layer it, in a purely statistical sense, means that the E values for the given layer of the range are below the design value 25%, while 75% are above (this requires that the measurements are evenly distributed throughout the area).

In the example below, an existing pavement has the following construction:

Layer	Average layer thickness [mm]	E value (MPa)		
		Average	Dispersion	Lower 25% fractile[1)]
Asphalt	140	3,390	652	2,950
Base course of gravel	220	345	40	318
Subbase	390	130	18	118
Subgrade	-	43	9	37

[1)] For a normal distribution with the average value "0" and the dispersion "1", the lower 25% fractile has a value of "-0.674". The lower 25% fractile is then calculated as "Average" + "Dispersion" × -0.674.

Table 15 Information from the existing pavement for a uniform sub-section.

The above pavement is desired to be reinforced such that it can carry a traffic load of 200,000 E10/year in a 15-year design period and the general speed is above 60 km/h. Due to the traffic volume (traffic class T6, in accordance with Table 1 in [ref. 11]), a wearing course type with either a bitumen hardness of 40/60 or modified bitumen is selected, cf. Table 14 in [ref. 11]. For a wearing course with this type of bitumen, the E value is generally 3,000 MPa, cf. Table 8 of [ref. 11].

With regard to the selection of the construction of the pavement in MMOPP, it is less important which options are used, seeing as you will type in the thicknesses and E values for a specific pavement afterwards yourself. Rules regarding appropriate asphalt types and minimum pavement thicknesses based on user selection are thus set aside (all that the user needs to keep in mind is that if the subgrade is chosen as "frost-proof", the subbase layer is omitted).

In MMOPP, the following steps are performed in the analytical reinforcement design:

- Select the construction of the pavement (in this case, asphalt layer, base course of gravel and subbase)
- Click the "Default E" button and select "Use default E values for bound layers"
- Enter the thickness and E value of the existing pavement manually
- Enter the design traffic, speed, and design period
- Enter the value for thickness (e.g. 10mm), as well as the E value of the reinforcement layer in the input fields next to the line with "New layer"
- Click the "Analytical" button.

By entering a thickness and an E value of the reinforcement layer, the general calculation method of MMOPP is disabled and only the layer thickness of the reinforcement layer is changed until the design criteria for all layers are met. The entered thickness of the reinforcement layer is only used as a point of departure for the analytical design.

The following figure shows the completed reinforcement design after having clicked the "Analytical" button:

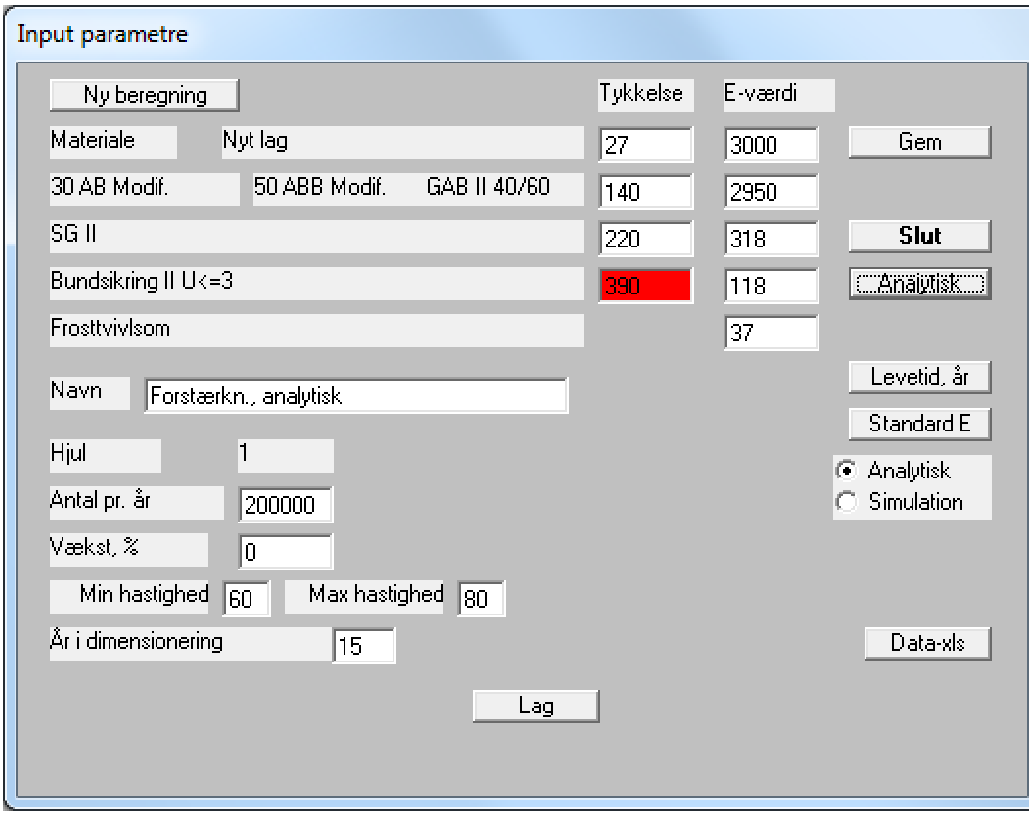


Figure 48 Analytical reinforcement design - required reinforcement.

As can be seen from the above figure, the required thickness of the reinforcement is 27 mm. This thickness is suitable for laying a new wearing course in one layer. In order to achieve a good result, however, it is assumed that the existing pavement is in good condition (any potholes and cracks are to be repaired appropriately) and also sufficiently even.

If the existing pavement is uneven, milling can be done, which is done in MMOPP by reducing the thickness of the existing asphalt and then clicking the "Analytical" button again. For example, if 50 mm of existing asphalt is milled off, the reinforcement thickness increases to 77 mm (this is not surprising, as the existing asphalt and reinforcement layer have approximately the same E value).

Such a thick reinforcement layer can be advantageously divided into, for example, an asphalt binder course and an asphalt wearing course, which provides good conditions for a smooth surface.

4.3.7 Designing a concrete surfacing

Concrete surfacings can advantageously be used on heavily loaded areas, while less easily managed areas are rarely economically cost-effective.

Below is an example of a design of a pavement for a freight terminal with 20 years of desired lifespan. The traffic load is made up of ordinary heavy vehicles which also travel on the other road network (it should be emphasised that MMOPP cannot be used to design pavements for vehicles for, for example, the handling of containers, as these vehicles have axle loads which are significantly higher than ordinary heavy vehicles).

The freight terminal area consists of the following two sub-areas:

- The port area, where all heavy vehicles have to pass, in order to get in/out of the freight terminal
- Driving routes between rows of stacked containers, where port cranes handle the containers to/from the heavy vehicles carrying their cargo to/from the freight terminal

The total traffic load is 150,000 E10/year in and out of the freight terminal. It is assumed that this traffic volume is evenly distributed, such that half drives in and half drives out. The port area has a separate entry and exit, and thus the design traffic is 75,000 E10/year for this sub-area (this corresponds to traffic class T5).

At the freight terminal, traffic is distributed into the area's roadways. Some roadways are more "popular" and receive more traffic than others, and these most loaded roadways have a design traffic of 30,000 E10/year (this corresponds to traffic class T4).

In Table 1 the recommended base layer material under concrete is specified. For traffic class T5, HBB-B is specified, while HBB-A is specified for traffic class T4.

The subgrade has a rigidity of 10 MPa (which means that the subgrade is to be deemed "splitting frost-susceptible"). Kerbstones and culverted drains are used, which means that there is no risk that surface water would penetrate the pavement. Options for the port area by analytical design in MMOPP are shown below:

- Select "New calculation"
- Select traffic class "T5"
- Select "Concrete" as a wearing course
- Select "150 Concrete E = 35000" (150 mm of concrete, which has an E value of 35,000 MPa by default)
- Select "None" as the asphalt binder course
- Select "None" as the bound base layer
- Select "HBB-B under concrete" as the unbound base layer
- Select "Splitting frost-susceptible" as the type of subgrade
- Select "Yes", as this example uses kerbstones, culverted drains and paved verges, so there is no risk that water can penetrate the pavement

These selections are illustrated in the following figure:

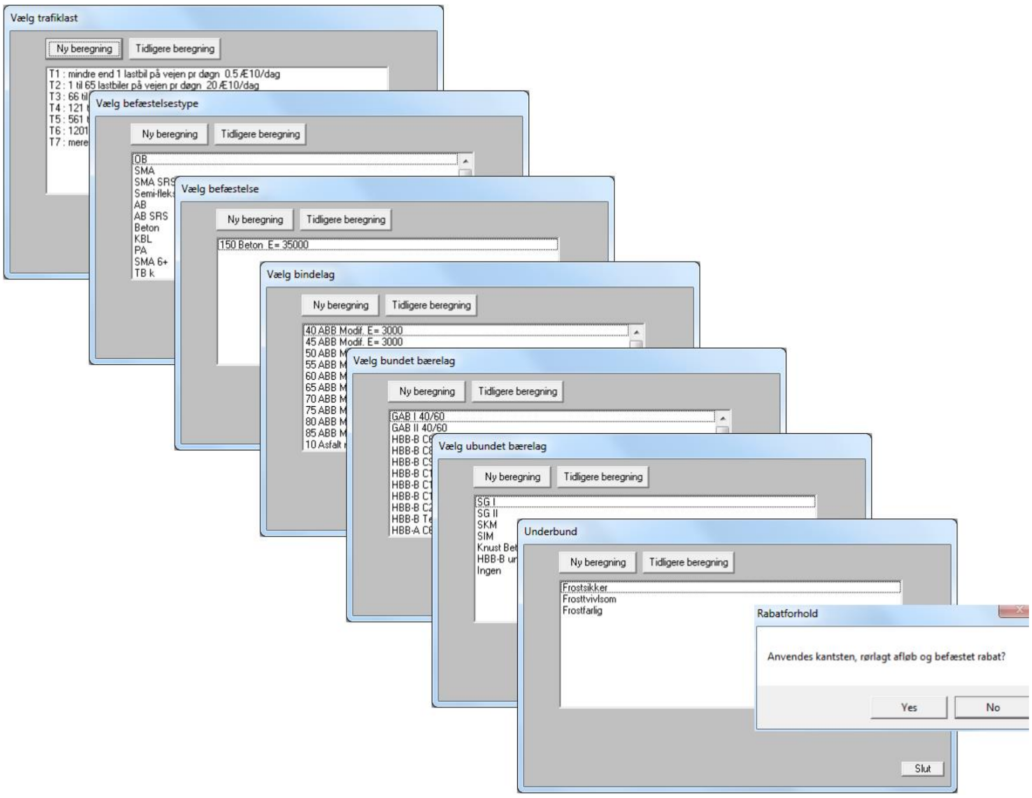


Figure 49 Designing a concrete surfacing - data input sequence.

Hereafter, MMOPP performs an analytical design in accordance with the design criteria in section 2.2 and the use of a 5-tonne twin-wheel + 20% shock allowance as the design load, based on the following default inputs:

- Design traffic: 180,000 E10/year (default for traffic class T5)
- Annual traffic growth: 0%
- Speed: 70 km/h (average of minimum and maximum speed)
- Design period: 10 years
- Type of subgrade: Splitting frost-susceptible (i.e. the pavement thickness is at least 800 mm for the current traffic class (T5), in accordance with the handbook for the Design of Pavements and Reinforcement Surfacings (see Table 10 in [ref. 11]) as there is no risk that water can penetrate the pavement)
- Rigidity of the subgrade: 20 MPa (default for splitting frost-susceptible sub-grade)
- Subbase: BL II, U ≤ 3 (default material for subbase)

The rigidity of the subgrade in the example does not correspond to the default E value of splitting frost-susceptible subgrades, therefore, click the "Default E" button and select "Use default E values for bound layers".

By changing the design traffic to 75,000 E10/year, the design period to 20 years, as well as the subgrade’s rigidity to 10 MPa, the following pavement is obtained after clicking the "Analytical" button, with reference to the following figure:

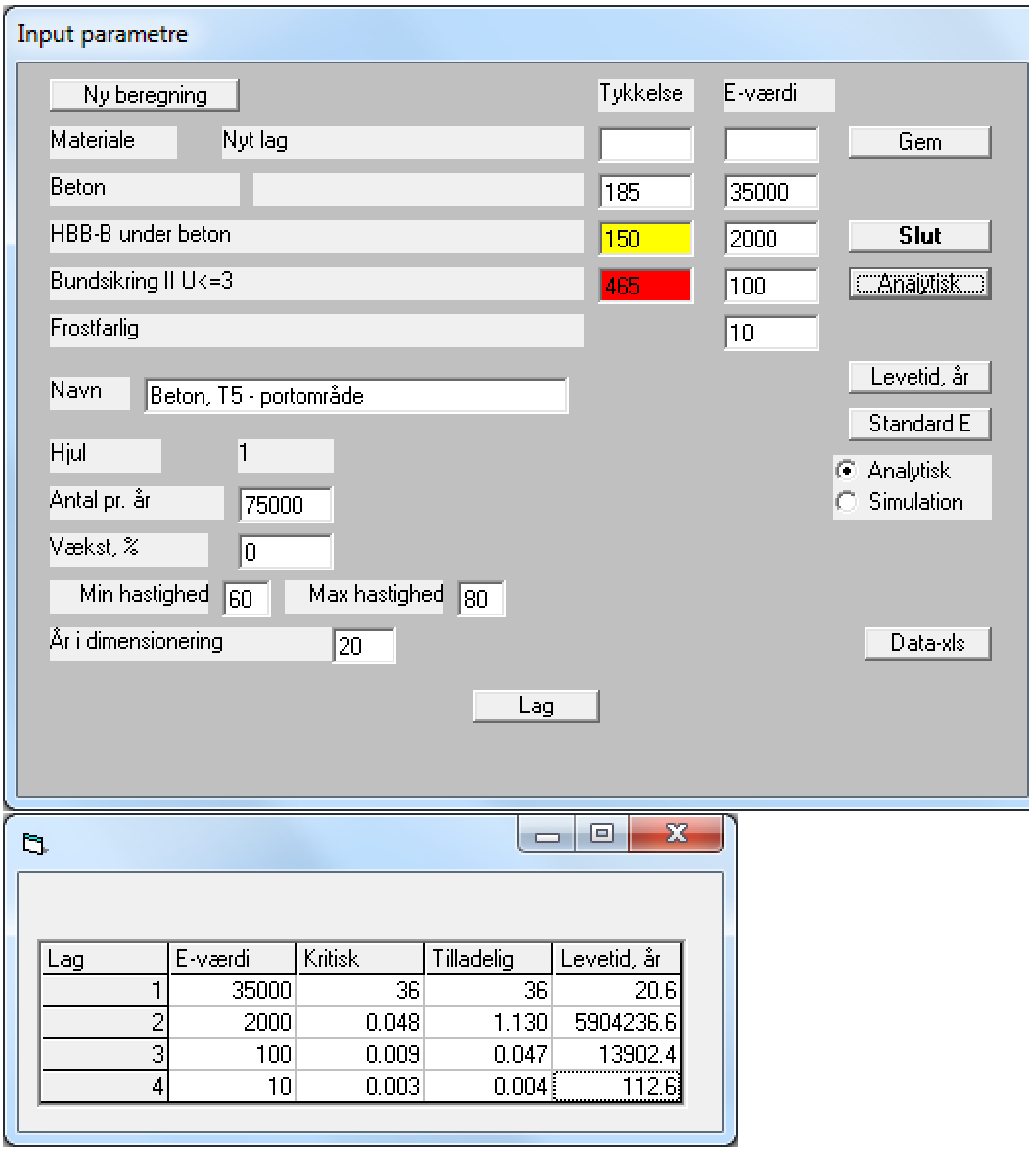


Figure 50 Designing a concrete surfacing - port area with HBB-B as the base layer material under the concrete.

This completes the design of the pavement for the port area.

For the roadways, one can use HBB-A as a base layer material under the concrete, and, in the following figure, analytical designing for the roadways is displayed:

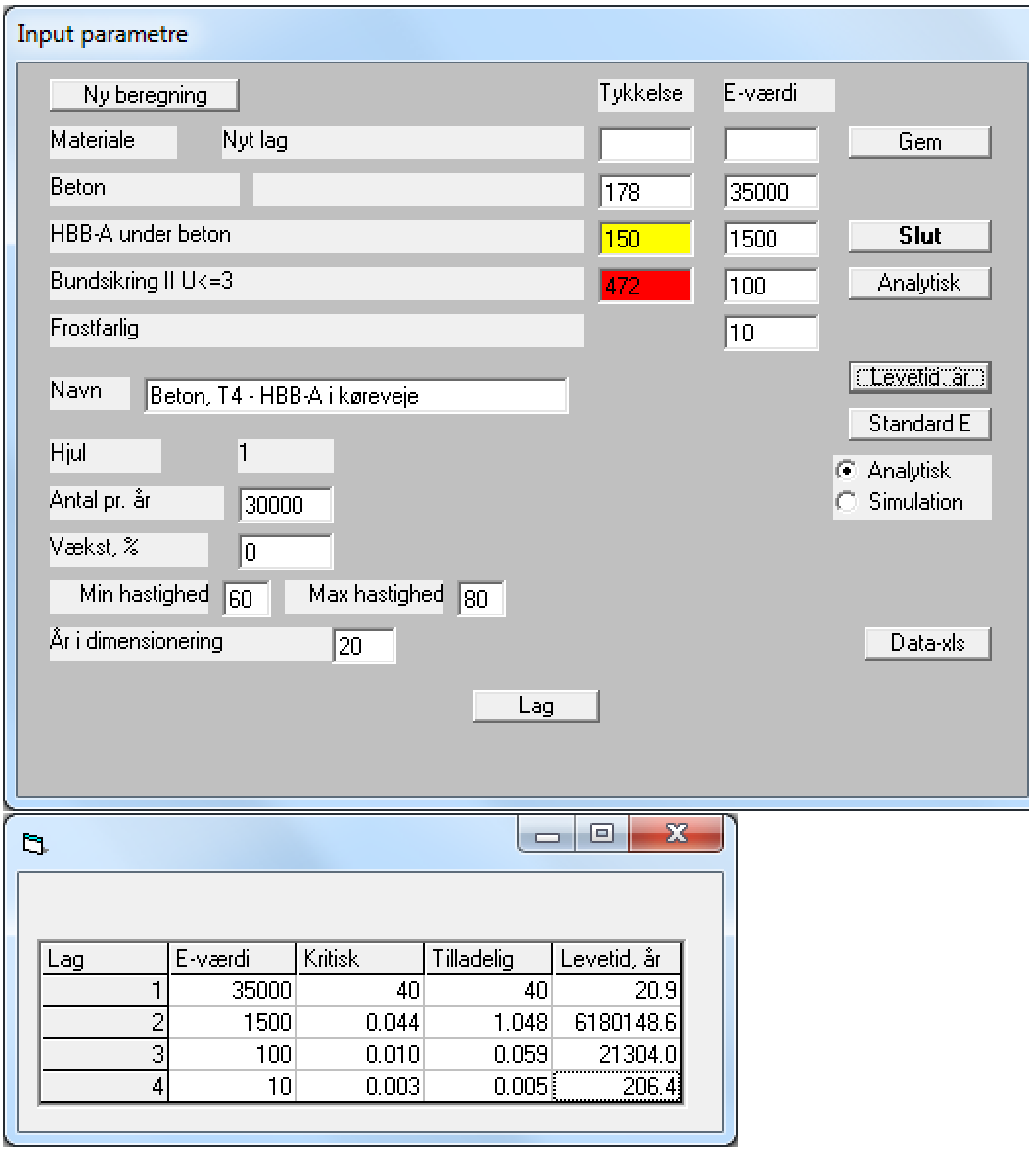


Figure 51 Designing a concrete surfacing - roadways with HBB-A as the base layer material under the concrete.

The above can be summarised in the table below:

Layer	Layer thickness [mm]	
	Port area with HBB-B under the concrete	Roadways with HBB-A under the concrete
Concrete	185	178
HBB-B	150	-
HBB-A	-	150
Subbase	465	472

Table 16 Designing a concrete surfacing - Port area and roadways with HBB-B and HBB-A, respectively, as the base layer material under the concrete.

As can be seen from the table above, the pavement thickness of both pavements is 800 mm, which corresponds to the current traffic classes (T4 and T5) and to the splitting frost-susceptible subgrade, when using kerbstones, culverted drains and paved verges, cf. Table 10 in [ref. 11].

As expected, a thinner layer of concrete can be used in the roadways, as the traffic load here is less.

It complicates the construction work to use both HBB-A and HBB-B. Thus, from a construction point of view, it is desirable to only use one HBB material, and therefore HBB-B can, of course, be used for both the port area and roadways. If a stronger/more rigid subgrade for the concrete (HBB-B instead of HBB-A) is used for the roadways, the required thickness of the concrete layer can be slightly reduced, but the required pavement thickness must still be met (less concrete => more subbase). It will require a comprehensive consideration of the financial aspects to be able to determine which of the two pavements is the cheapest to construct.

4.4 Design by simulation

Simulation of degradation processes is performed on pavements loaded a given number of times with a default load, after which the simulated degradation is compared with default acceptance limits for degradation, with reference to Figure 21 for the default load and Figure 22 for default acceptance limits.

Simulation can only be performed for pavements consisting of flexible layers. This is due to the fact that the road standards group is of the opinion that the introduction of correct HBB degradation models requires a reprogramming that is best done in conjunction with a more extensive upgrade of the program, which will make it possible to model pavements with significantly more than five layers. Finally, the experience base for concrete pavements has been found to be too weak to be able to serve as the basis for the development of degradation models.

Based on the road standard group's experience and data from, among other things, the vejman.dk system, the degradation models are adapted to the following conditions:

- Over the course of 15 years, the pavements reach an average IRI of 2.8 m/km, corresponding to the roadman.dk degradation model.
- The asphalt layers are degraded, so that 75% of the pavements have an average E value after 15 years that is higher than 2/3 of the initial value.

It should be pointed out that the simulation part in MMOPP has been calibrated to Danish conditions. As a result, the simulation calculations must be carried out with the database default parameters to comply with the Road Standard.

The mmopp2017a.mdb database contains default values for all of these parameters.

As stated in section 2.1, designing by simulation cannot be considered more accurate than analytical design. However, designing by simulation can advantageously be used to compare different alternatives or with optimisation, where the most economical pavement that will meet the required lifespan requirements of the structure is ascertained.

The simulation calculations determine four different theoretical lifespans, all of which are stated by year. These lifespans are based on the following criteria for the permissible state of the pavement, cf. section 4.2 of [ref. 11]:

- IRI: The evenness of the surface of the pavement
- Rutting: The average lane depth
- Eave: The relation between the average E value of the asphalt layer and an intact asphalt layer with the default E values of the current materials.
- E min: The relation between the lowest E value of the asphalt layer and an intact asphalt layer with the default E values of the current materials.

Below are a few examples of design by simulation in MMOPP.

4.4.1 Default design by simulation

Simulation calculation is a stochastic process where the estimate of the "true" values of average and dispersion of the various lifespan targets becomes more accurate the more simulations which are made. Assessment of an outcome or a comparison of two alternative road pavements should, however, always be based on a high number of simulations.

In purely statistical terms, a design value can be specified with a given reliability in accordance with the following expression for normally distributed values:

$$Design\ value_{normaldistributed} = "Average" + "Dispersion" \times q \qquad \text{(XXIII)}$$

In this regard, "q" is the given fractile for a normal distribution with the average value "0" and the dispersion "1".

In the example below, two alternative road pavements are desired, compared with the help of a simulation. Both pavements contain the same three asphalt layers, as well as an unbound base layer and subbase. The one pavement is based on a traditional analytical design (alternative 1), while the other has been designed in a manual analytical manner, where the thickness of the unbound base layer and subbase has been reduced and the total asphalt thickness has been increased in order to achieve a limited pavement thickness (alternative 2).

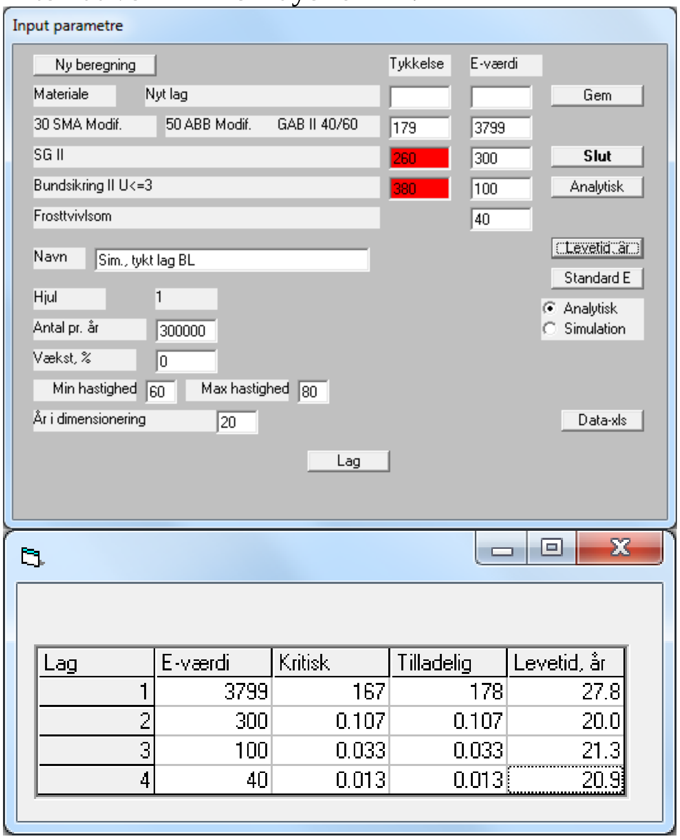
The design prerequisites are as follows:

- Traffic load class T6
- Frost-susceptible subgrade
- No kerbstones, culverted drains and paved verges have been used
- A design period of 20 years
- An assessed theoretical lifespan at 85% reliability

Based on traffic class, type of subgrade and drainage conditions, the pavement thickness is, thus, at least 700 mm, cf. Table 10 in [ref. 11].

The figure below lists the two alternative pavements, both of which meet the above design prerequisites on the basis of analytical design:

Alternative 1 - Thick layer of BL:



Alternative 2 - Reduced layer of BL:

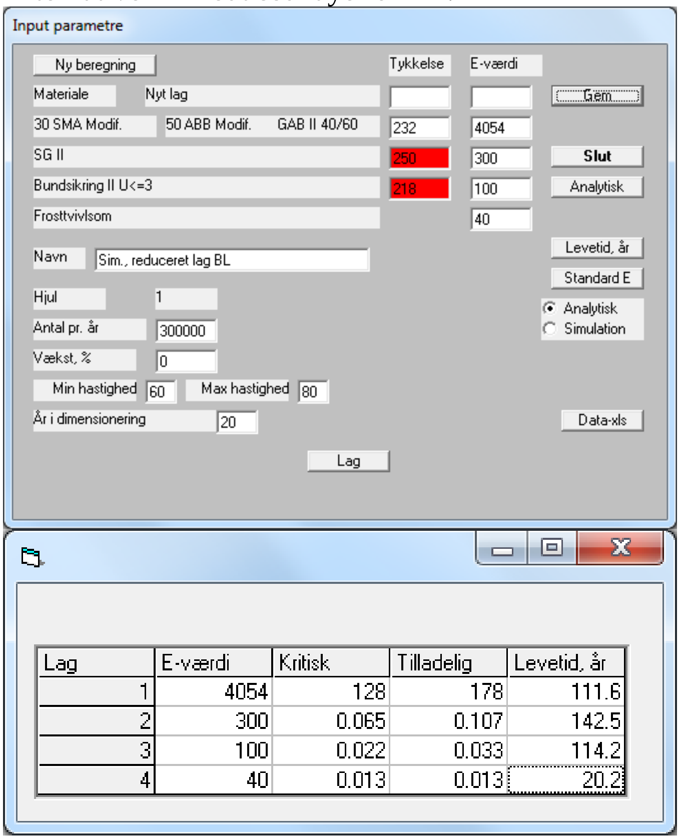


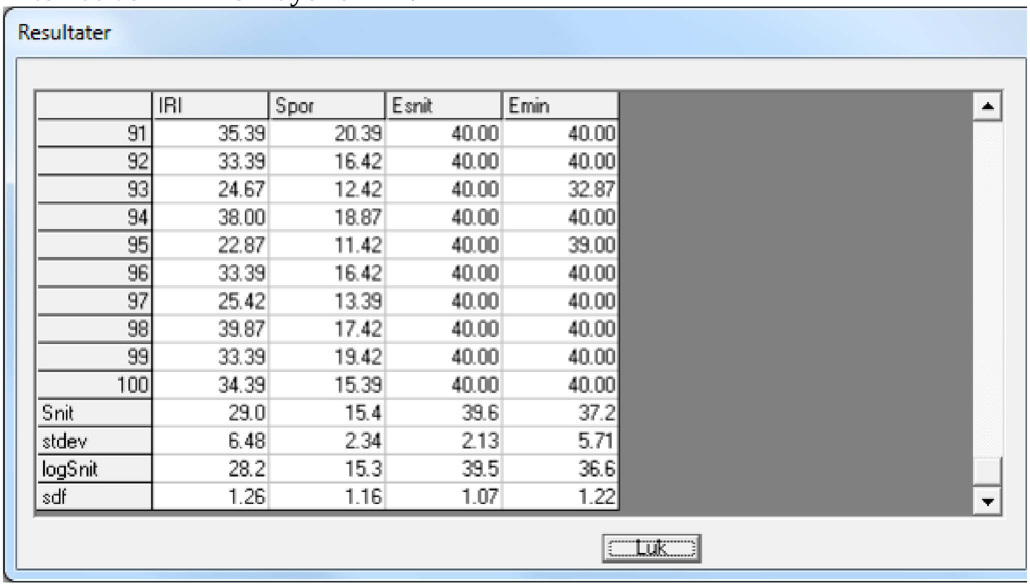
Figure 52 Design by simulation - a specification of two alternatives which have been analytically designed.

As can be seen from the above figure, the base course of gravel layer is the critical layer with a theoretically expected lifespan of 20.0 years as per the traditional analytical design (top screen with Alternative 1), while the subgrade is critical with a theoretically expected lifespan of 20.2 years as per the manual analytical design (bottom screen with Alternative 2). Both pavements can thus be expected to have the same theoretical lifespan, even though different layers are critical.

By selecting "Simulation" on the option buttons on the right of the screen, a number of buttons and input fields are presented. Purely for computational reasons, it is necessary to have a longer simulation period than the desired design period - generally, the simulation period should be twice as long as the design period, which, in this case, means that 40 years are used in the simulation (this is changed manually). 100 simulations are selected in the same manner. Then click the "Start" button, which opens a new screen that displays the number of the current simulation. Calculations can be interrupted by clicking "Stop".

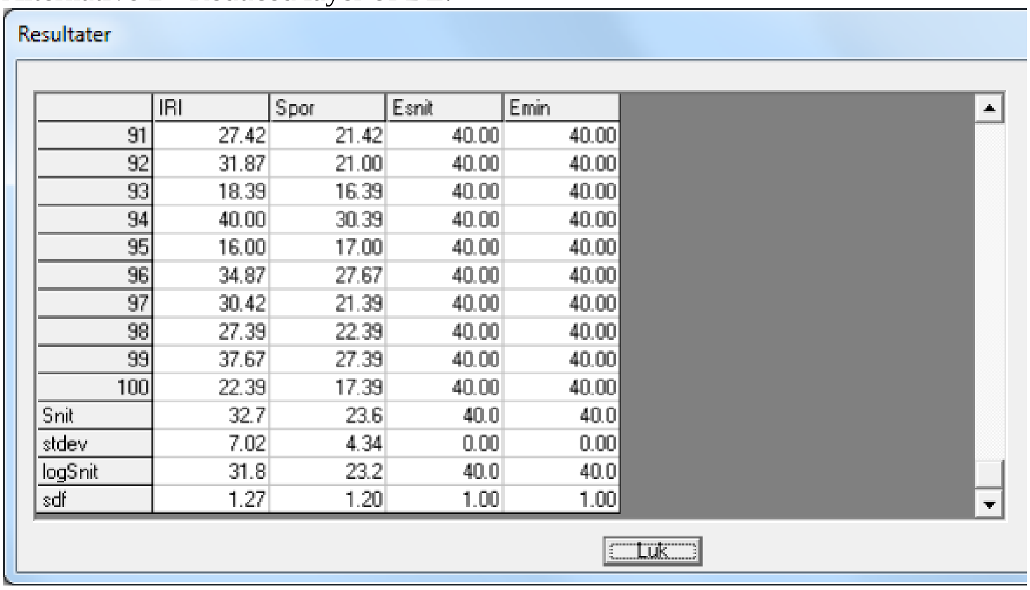
Once the simulation has ended, you will automatically return to the "Input parameters" screen and, by clicking the "Show results" button, a table of theoretical lifespans is displayed by year for each of the four criteria (evenness (IRI), rutting, as well as the average and minimum E value of the asphalt layers) for each individual simulation. At the bottom of this table, the average and spread of these calculated theoretical lifespans by simulation are shown, with reference to the figure below for the result of the simulation of the two alternative pavements:

Alternative 1 - Thick layer of BL:


Resultater

	IRI	Spor	Esnit	Emin
91	35.39	20.39	40.00	40.00
92	33.39	16.42	40.00	40.00
93	24.67	12.42	40.00	32.87
94	38.00	18.87	40.00	40.00
95	22.87	11.42	40.00	39.00
96	33.39	16.42	40.00	40.00
97	25.42	13.39	40.00	40.00
98	39.87	17.42	40.00	40.00
99	33.39	19.42	40.00	40.00
100	34.39	15.39	40.00	40.00
Snit	29.0	15.4	39.6	37.2
stdev	6.48	2.34	2.13	5.71
logSnit	28.2	15.3	39.5	36.6
sdf	1.26	1.16	1.07	1.22

Alternative 2 - Reduced layer of BL:


Resultater

	IRI	Spor	Esnit	Emin
91	27.42	21.42	40.00	40.00
92	31.87	21.00	40.00	40.00
93	18.39	16.39	40.00	40.00
94	40.00	30.39	40.00	40.00
95	16.00	17.00	40.00	40.00
96	34.87	27.67	40.00	40.00
97	30.42	21.39	40.00	40.00
98	27.39	22.39	40.00	40.00
99	37.67	27.39	40.00	40.00
100	22.39	17.39	40.00	40.00
Snit	32.7	23.6	40.0	40.0
stdev	7.02	4.34	0.00	0.00
logSnit	31.8	23.2	40.0	40.0
sdf	1.27	1.20	1.00	1.00

Figure 53 Design by simulation - the "Show results" button displays a table with results after the simulation of two alternative pavements.

The column at the far left of the above figure shows the simulation number first (in the above section only the last 10 simulations are shown), followed by four columns with the corresponding calculated theoretical lifespans for the four criteria. The bottom four lines indicate the following:

- Average: The average of the calculated theoretical lifespan for all the simulations
- stdev: The spread of the calculated theoretical lifespan for all the simulations
- logAverage: The average of the logarithmic value of calculated theoretical lifespan for all the simulations
- sdf: The spread of the logarithmic value of calculated theoretical lifespan for all the simulations

The following table shows the result of the simulation for the two alternative pavements:

	Calculated theoretical lifespan [year]			
	IRI	Rutting	Eave	Emin
Alternative 1 - Thick layer of BL:				
Section	29.0	15.4	39.6	37.2
stdev	6.48	2.34	2.13	5.71
Design value[1)]	**22.3**	**13.0**	**37.4**	**31.3**
Alternative 2 - Reduced layer of BL:				
Section	32.7	23.6	40.0	40.0
stdev	7.02	4.34	0.00	0.00
Design value[1)]	**25.4**	**19.1**	**40.0**	**40.0**
[1)] For a normal distribution with the average value "0" and the dispersion "1", the lower 15% fractile has a value of "-1,036". The lower 15% fractile is then calculated as "Average" + "Dispersion" × -1.036, which corresponds to an 85% reliability.				

Table 17 Design by simulation - determination of the design value for the theoretical lifespan of two alternative pavements.

As can be seen from the above table, the pavement with the thick layer of subbase (alternative 1) has a calculated theoretical lifespan which is shorter than the desired 20 years for rutting on <u>average</u>. An calculated average theoretical lifespan of 15.4 years means that, after this number of years, one can expect half of the road section to be rutted to a critical level, but for the worst parts of the road, this critical rutting may have occurred earlier.

As the design value indicates in the table above, both alternatives will have critical rutting of approximately 15% of the section after, respectively, 13.0 and 19.1 years (purely computationally).

It should be remembered that this is a mathematical simulation of the degradation, and with the general uncertainty regarding the design of pavements (the projection of traffic, variations of the rigidity of the subgrade and variations of materials), the calculated theoretical lifespan by simulation should not be taken to be the "truth".

As can be seen from Figure 52, both alternatives have a calculated theoretical lifespan by analytical design which corresponds to that desired. As mentioned initially in section 2.1, designing by simulation cannot be considered more accurate than analytical design. So in this example, the simulation should only serve to make it possible that alternative 2, with a reduced BL and, thus, thick asphalt layer, has a theoretically longer lifespan than Alternative 1 with a thick layer of BL.

4.4.2 Optimisation by simulation

A pavement is desired optimised from a financial point of view, based on requirements for the theoretically expected lifespan, with the following unit prices being used:

Materials	Unit price [DKK/m^3]
Asphalt	3,667.00
Base course of gravel, SG II	370.00
Subbase, BL II, U ≤ 3	140.00

Table 18 Optimisation by simulation - unit prices for the individual materials.

The design prerequisites are as follows:

- Traffic load class T4
- Frost-susceptible subgrade
- No kerbstones, culverted drains and paved verges have been used
- The theoretical lifespan with an 85% reliability must be at least 15 years for evenness and rutting and at least 20 years for other criteria

Based on traffic class, type of subgrade and drainage conditions, the pavement thickness is, thus, at least 700 mm, cf. Table 10 in [ref. 11].

In the example, the requirement for lifespan for evenness and rutting is lower than for the two E value criteria. This is because it is expected that a new layer of wearing course will be introduced within these years, whereby the evenness and rutting will be "reset".

For analytical design and 20 years of design, the following setup is found, with reference to the figure below:

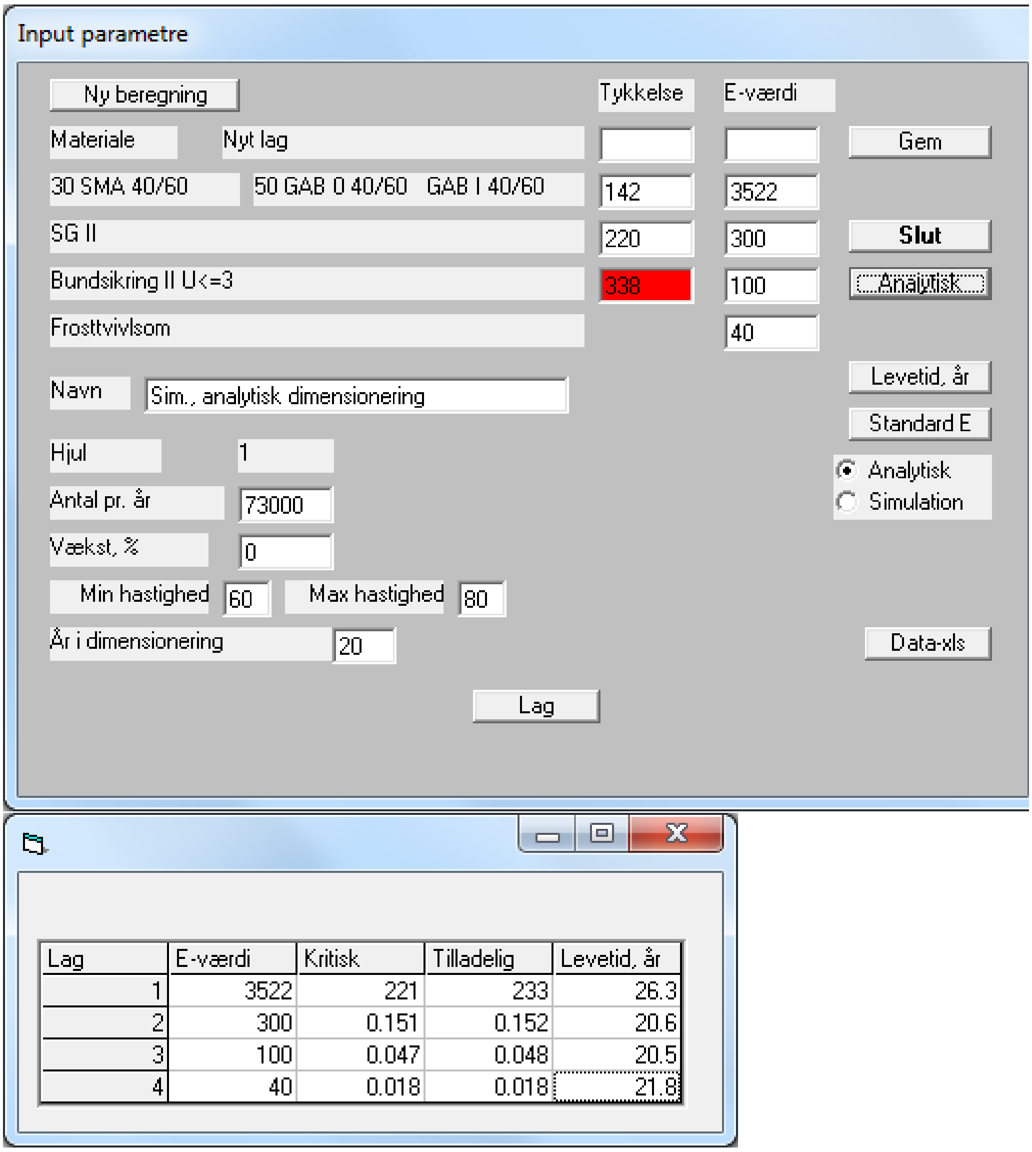
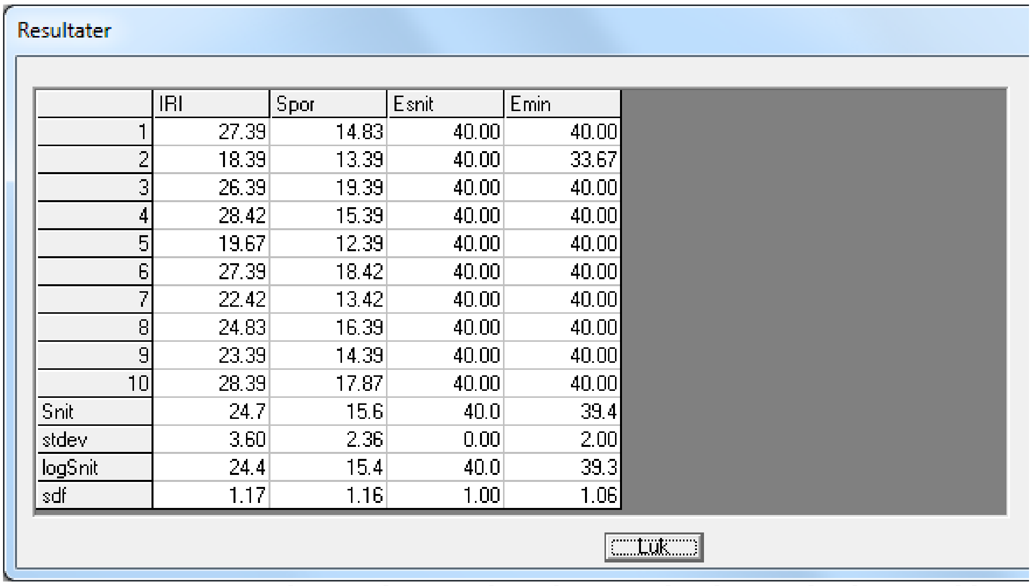


Figure 54 Optimisation by simulation - construction of a pavement by analytical design.

As can be seen from the above figure, by analytical design, this pavement has an expected lifespan of more than 20 years for all layers. Now the "Simulation" option button is selected and 10 simulations are performed over 40 years. By clicking the "Start" button, the calculations start and when these are finished, a table can be seen with the calculated expected lifespan by clicking the "Show results" button - this table is shown in the following figure:



	IRI	Spor	Esnit	Emin
1	27.39	14.83	40.00	40.00
2	18.39	13.39	40.00	33.67
3	26.39	19.39	40.00	40.00
4	28.42	15.39	40.00	40.00
5	19.67	12.39	40.00	40.00
6	27.39	18.42	40.00	40.00
7	22.42	13.42	40.00	40.00
8	24.83	16.39	40.00	40.00
9	23.39	14.39	40.00	40.00
10	28.39	17.87	40.00	40.00
Snit	24.7	15.6	40.0	39.4
stdev	3.60	2.36	0.00	2.00
logSnit	24.4	15.4	40.0	39.3
sdf	1.17	1.16	1.00	1.06

Figure 55 Optimisation by simulation - the "Show results" button displays a table with results after the simulation of the pavement in Figure 54.

As can be seen from the figure above, it can be expected that, on average, rutting will become critical after 15.6 years (it must, thus, be expected that half of the section has critical rutting after this number of years).

This does not meet the requirement of a minimum of 15 years theoretical lifespan for rutting with an 85% reliability (average dispersion × q = 15.6 years + 2.36 years × (-1.036) = 13.16 years < 15 years). Thus, the pavement is manually adjusted until the simulation yields the desired result, which gives the following construction, with reference to the figure below:

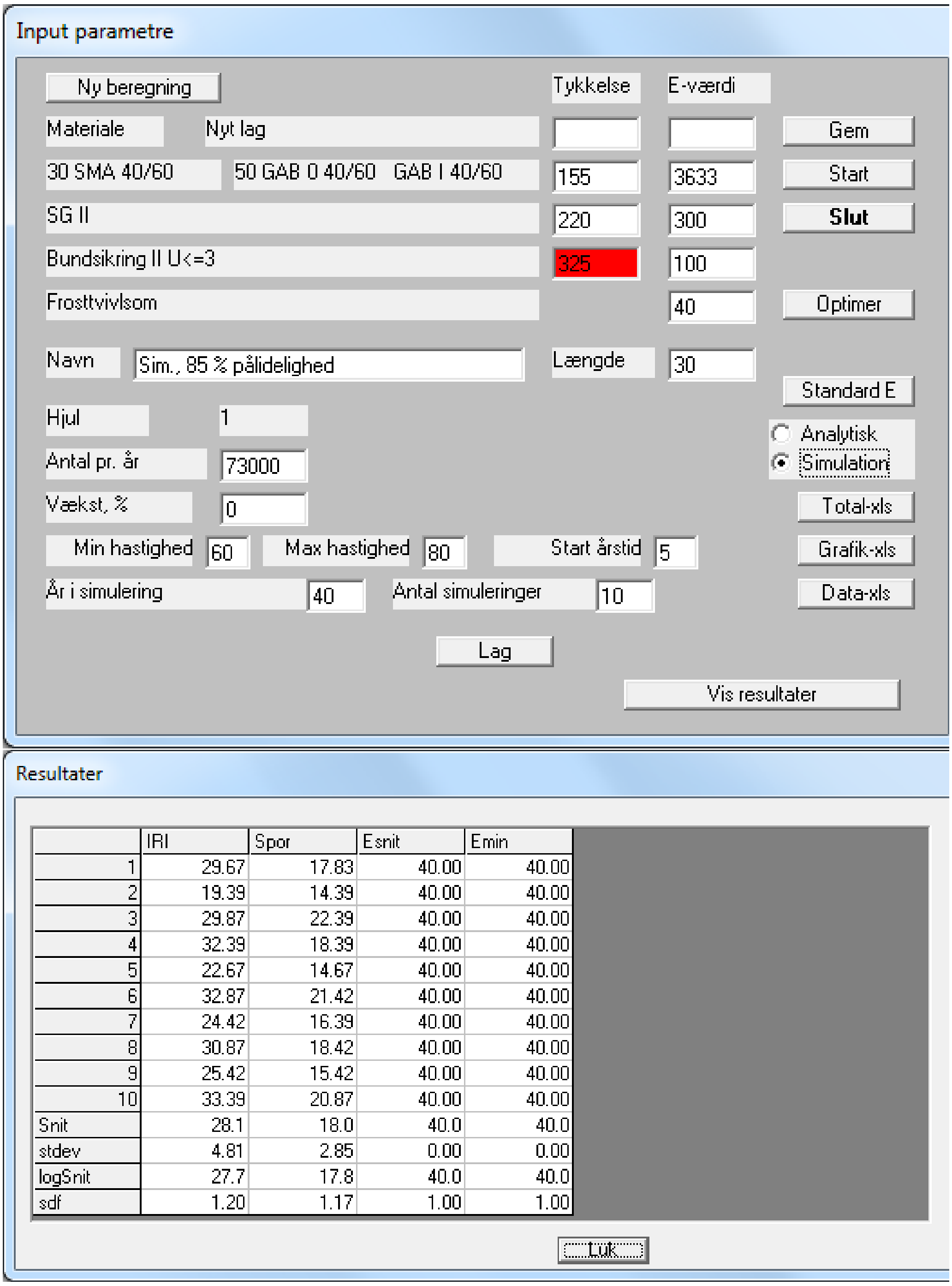


Figure 56 Optimisation by simulation - a pavement which meets the desired minimum of 15 years theoretical lifespan for rutting with an 85% reliability ("Average" - "stdev" ≥ 15.0 years).

The total asphalt thickness is 155 mm, while the thickness of the base course of gravel layer is 220 mm, and the subbase is adapted so that the total pavement thickness is 700 mm.

However, the base course of gravel layer can be laid in thicknesses from 100 mm up to 250 mm, cf. Table 9 of [ref. 11], in order for it to be possible to save on the asphalt or that more asphalt can further reduce the thickness of the base course of gravel layer. Therefore, an optimisation is run where the asphalt layer is varied from 145 mm to 155 mm in 1 mm increments (i.e. 10 steps), while the base course of gravel layer is varied from 100 mm to 250 mm in 10 mm increments (i.e. 15 steps). The thickness of the subbase layer is not varied, as this will automatically be adjusted in order to achieve the required pavement thickness of at least 700 mm. By clicking the "Optimise" button, the following screen opens, where the interval of thicknesses, the number of steps for an interval procedure, as well as the unit price for each material can be entered:

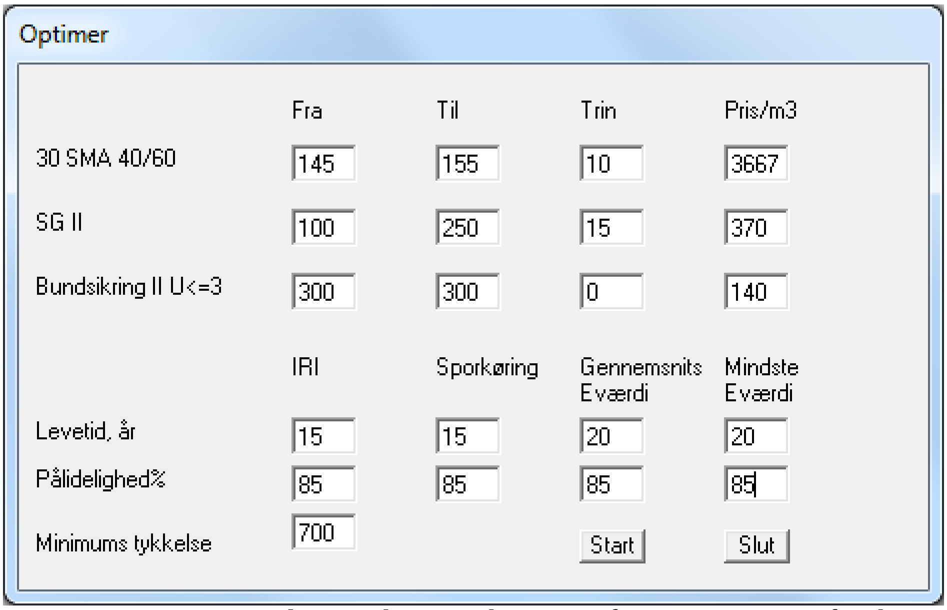


Figure 57 Optimisation by simulation - the inputs for optimisation after having clicked the "Optimise" button.

By clicking the "Start" button the optimisation process begins, simulating the different combinations of layer thicknesses with the number of simulations specified in the "Input parameters" screen. The more the simulations and the more the steps for each layer, the longer the optimisation (optimisation in this example is expected to take 30-60 minutes, but it depends very much on the processor speed - and during that time, one cannot use MMOPP in order not to interrupt simulations).

When the optimisation has been completed, the "Optimise" screen automatically closes and the "Input parameters" screen displays the financially optimal pavement which meets the lifespan requirement with the given reliability. In this example, the following results are obtained, with reference to the figure below:

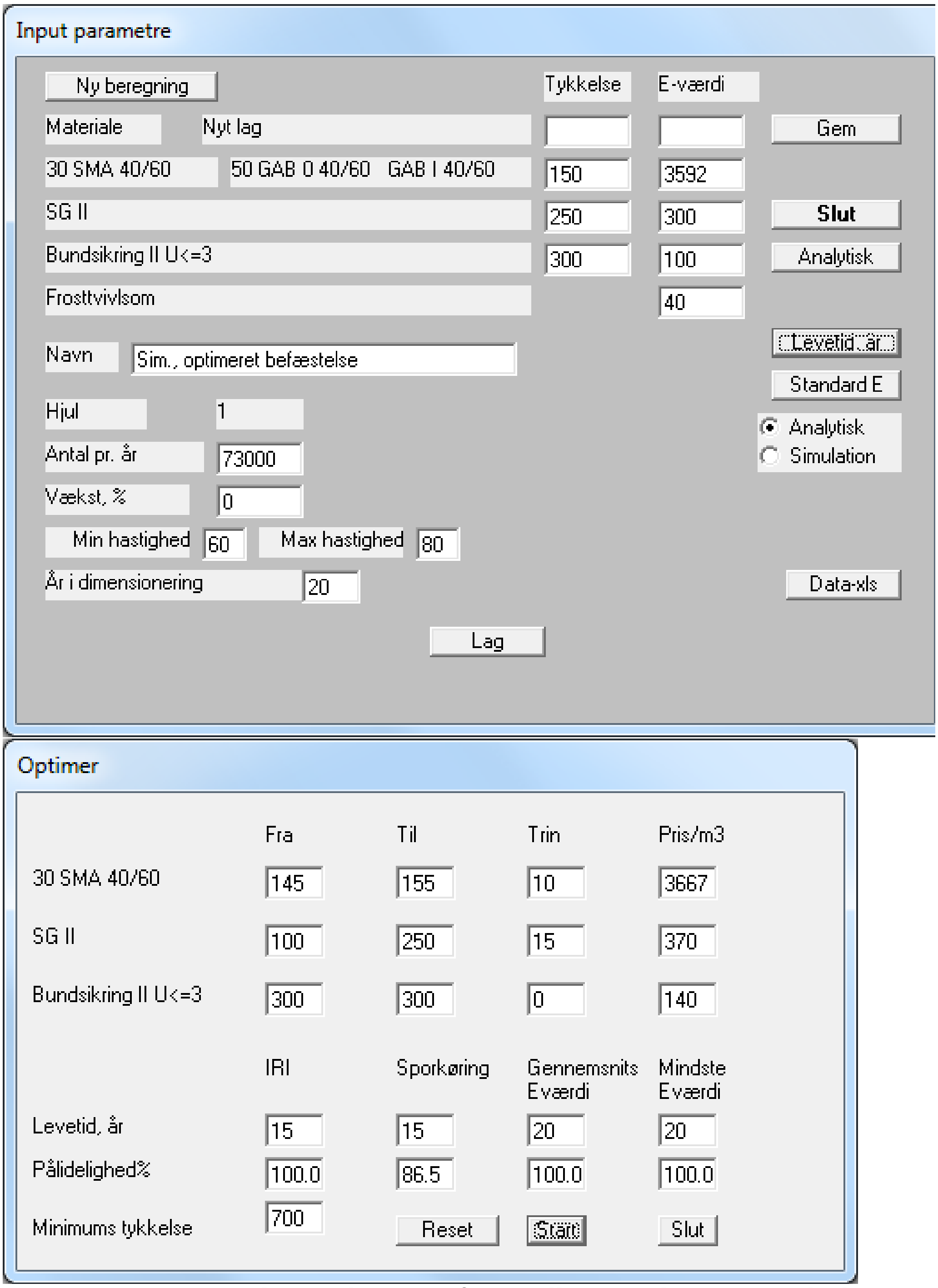


Figure 58 Optimisation by simulation - a financially optimal pavement which meets the desired minimum of 15 years theoretical lifespan for rutting with at least 85% reliability.

The financially optimal pavement is thus 150 mm of asphalt (30 mm SMA 40/60, 50 mm GAB 0 40/60, 70 mm GAB I 40/60), 250 mm SG II and 300 mm BL II, U ≤ 3 - this pavement has 15 years of theoretical lifespan with an 86.5% reliability, cf. the above figure.

If it had not been possible to meet the requirement for the lifespan with the given reliability, then a window would have been presented with the text: "No solution". After having closed this window, in the "Optimise" screen one can see the degree of reliability you can achieve for the desired theoretical lifespan.

4.4.3 Designing a reinforcement layer by simulation

MMOPP can perform the design of a reinforcement layer by simulation, based on data about the existing pavement.

For a reinforcement calculation, an existing pavement which has been used for a number of years is located. The pavement is now in a degraded state as a result of traffic or another load (for example, the weather) and there is a need for reinforcement of the pavement so that it can have a lifespan of a new road again. The inputs for the design of a reinforcement layer by simulation are corresponding layer thicknesses and E values of the individual layers in the road pavement, as well as the values for evenness (IRI) and rutting.

Information about layer thicknesses exists either from "as performed" data (including information about previous willing works and reinforcement layers) or can be obtained, for example, from drillings, diggings or ground-penetrating radar measurements.

Information about E values of the individual layers of the degraded pavement can be obtained, for example, from measuring with a falling weight, while evenness and rutting can be measured using appropriate laser equipment.

In preparation for the design of a reinforcement layer by simulation, the road section is divided into sub-sections, which can be classified as homogeneous in terms of materials, layer thicknesses, E values, as well as degradation states.

Layer thicknesses, as well as E values, evenness and rutting from an existing pavement can be expected to vary, and in order to be able to take this variation into account, a degraded pavement, which represents the condition which corresponds to the measured properties on the road, is computationally modelled in MMOPP.

In the example below an existing pavement has the following construction for a homogeneous sub-section:

Layer	Average thickness [mm]	E value (MPa)		
		Average	Dispersion	Lower 25% fractile[1)]
Asphalt	140	3,390	652	2,950
Base course of gravel	220	345	40	318
Subbase	390	130	18	118
Subgrade	-	43	9	37

[1)] For a normal distribution with the average value "0" and the dispersion "1", the lower 25% fractile has a value of "-0.674". The lower 25% fractile is then calculated as "Average" + "Dispersion" × (-0.674).

Table 19 Information from the existing pavement for a homogeneous sub-section.

For the same homogeneous sub-section, an evenness (IRI value) of 4.9 m/km, as well as a 22.5 mm of rutting has been measured on average.

The above pavement is desired to be reinforced such that it can carry a traffic load of 200,000 E10/year in a 15-year design period with an 85% reliability and the overall general is above 60 km/h. Due to the traffic volume (traffic class T6, in accordance with Table 1 in [ref. 11]), a wearing course type with either a bitumen hardness of 40/60 or modified bitumen is selected, cf. Table 14 in [ref. 11]. For a wearing course with this type of bitumen, the E value is generally 3,000 MPa, cf. Table 8 of [ref. 11].

The first step in the design of a reinforcement layer by simulation is to model a computationally degraded pavement in MMOPP. To achieve this, one starts with a whole new pavement, where one simulates degradation over time until you achieve the desired degradation.

With regard to the selection of the construction of the pavement in MMOPP, it is less important which options are made, seeing as you will type in thicknesses and E values for a specific pavement afterwards yourself. Rules regarding appropriate asphalt types and minimum pavement thicknesses based on user selection are thus set aside (all that the user needs to keep in mind is that if the subgrade is chosen as "frost-proof", the subbase layer is omitted).

In MMOPP, the following steps are included in the design of a reinforcement layer by simulation:

- Select the construction of the pavement (in this example, an asphalt layer, base course of gravel and subbase - the traffic load in the example indicates that the bitumen hardness in the original pavement has been at the high (rigid) end, that is to say, 40/60 or modified, which is why these have been chosen)
- Click the "Default E" button and select "Use default E values for bound layers"
- Manually enter the average thickness for all layers and a 25% fractile for the E value of unbound layers in the existing pavement, but use the default asphalt layer E value
- When a pavement has been degraded, the asphalt’s E value is gradually reduced as the layer cracks. At present, a new pavement will be used, which will be used as a basis for simulating the degradation over time with MMOPP, and therefore the default E value for new asphalt is used.
- Due to the traffic load, unbound layers will become rutted and uneven over time, but the E value will not change. That is why the 25% fractile of the measured E values of the unbound layers, as well as of the subgrade is used, as it is assumed that the unbound layers as well as the subgrade of the original pavement had these rigidities when newly constructed.
- Enter the design traffic and speed
- Select the "Simulation" option button, as well as an appropriate number of simulations over a long period of time - 10 simulations and 40 years have been used in this example.

The "Input parameters" screen, in accordance with the above selection, is displayed in the following figure:

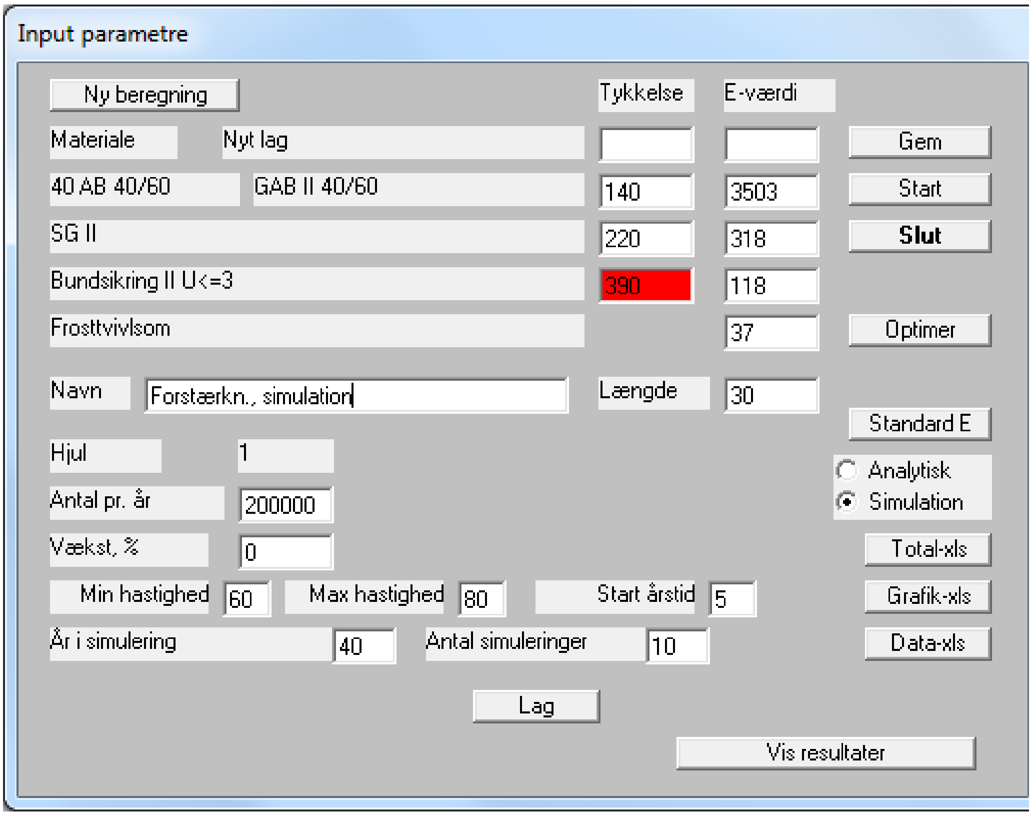


Figure 59 Design of a reinforcement layer by simulation - a new pavement modelled in MMOPP prior to the simulation.

The "Start" button should then be clicked and then, once the simulations have been completed, click the "Graph xls" button, after which data is transferred to an Excel spreadsheet (it takes 20-30 seconds, in which time it is important not to use the computer in order not to interrupt the data transfer). Transferring the data to this Excel spreadsheet also automatically includes the generating of a number of graphs for evenness (IRI), rutting, as well as the average and minimum E value of the asphalt layers.

When laying a reinforcement layer, evenness and rutting is to be "reset", so the main parameter in the design of a reinforcement layer by simulation is the average E value of the asphalt layers in the degraded pavement, which MMOPP has created and which is called "Eave" in the spreadsheet.

On the "Eave" tab, the average E value of the asphalt layers is given for each individual simulation and for each individual season in the 40-year long simulation period (with reference to the length of the seasons in Table 4). Using the calculation functions in Excel, calculate the following for all the simulations for each individual season throughout the simulation period:

- The average of the average E value
- The lower 25% fractile (for a normal distribution with the average value "0" and the dispersion "1" the lower 25% fractile has a value of "-0.674" - the lower 25% fractile is then calculated as "Average" + "Dispersion" × (-0.674))

This average and this lower 25% fractile are listed in the figure below, respectively, as the terms "Average" and "25% fractile":

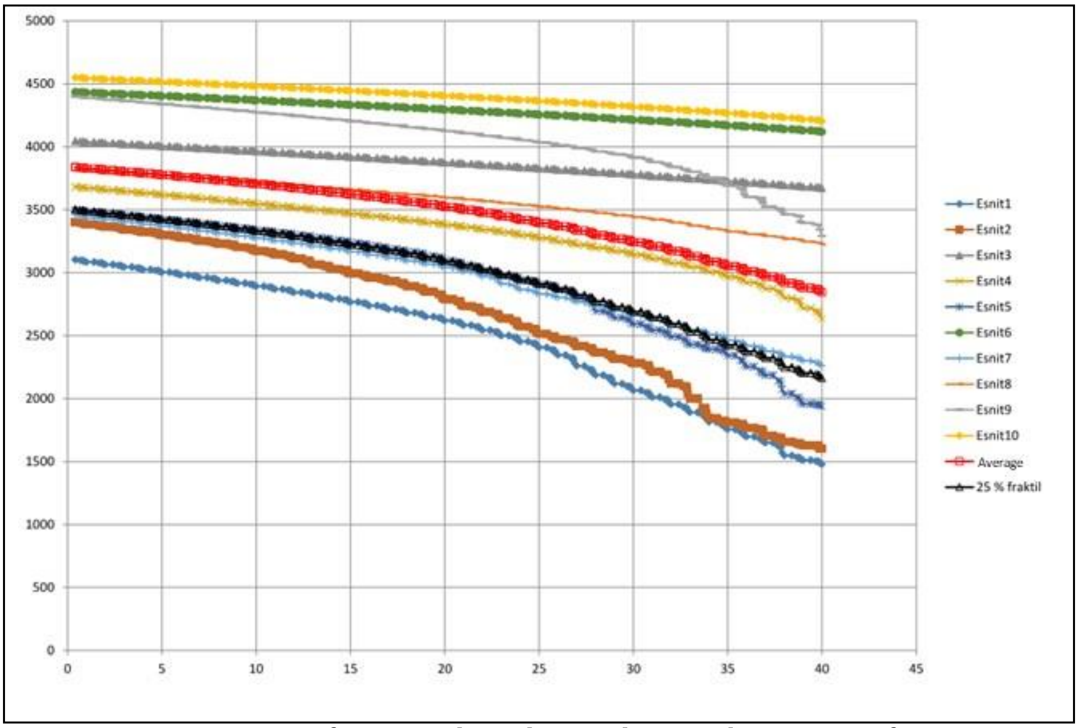


Figure 60 Designing a reinforcement layer by simulation - the average of "Eave" is shown in the colour red and the lower 25% fractile of "Eave" is shown in the colour black (the x axis represents the simulation period by "year", while the y axis represents the average E value of the asphalt layers in MPa).

As can be seen from the figure above, the asphalt layer's average E value decreases as the pavement gets older and has been exposed to more and more traffic. However, neither the point of departure nor the degradation process are exactly the same, seeing as MMOPP, based on the user's input, automatically generates a number of pavements which vary slightly with respect to both the layer thicknesses as well as the E value of the individual layers, cf. section 2.3.3.

This automatic variation in MMOPP follows a set "random generator", such that all users will get the same "random" varied range of pavements by using the same point of departure (material types, layer thicknesses, E values and number of simulations).

An average E value of the asphalt has been measured at 3,390 MPa on the degraded pavement, cf. Table 19, and, as can be seen from the above figure, the asphalt layers are degraded to this value after about 25 years on average (with reference to the line for "Average" in Figure 60). In theory, a pavement with the given construction and traffic load can thus be expected to be in a degraded state, similar to that measured, after about 25 years. The 25 years are therefore used as a simulation period in the calculation which follows.

At the same time, as the required simulation period is determined as described above, one should also record the lower 25% fractile of the asphalt layers' E value when starting the simulations (with reference to the "25% fractile" line in Figure 60), as this will be used later. In this example this value is 3.503 MPa.

The values read on Figure 60 which need to be used in the further design of a reinforcement layer by simulation have been summarised in the following table:

Parameter	Value
Number of years of simulation in order to achieve the registered, degraded state [years]	25
The lower 25% fractile of the asphalt layer's E value at the start of the simulations [MPa]	3,503

Table 20 Inputs in the further design of a reinforcement layer by simulation (read from Figure 60).

In MMOPP, the number "1" is to be entered in the "Number of simulations" field, as well as a simulation period of 25 years, with reference to the figure below:

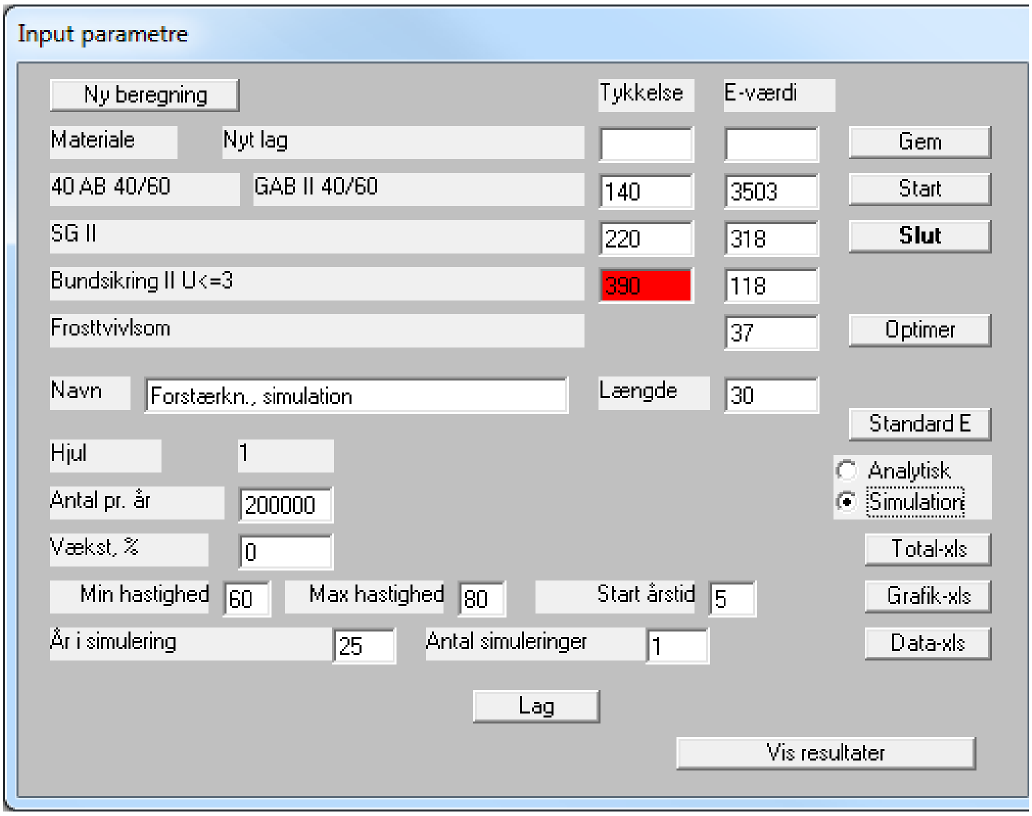


Figure 61 Designing a reinforcement layer by simulation - the establishment of a computationally degraded pavement.

By clicking the "Start" button, a new window opens where the measured values for the degraded pavement must be entered - i.e. the average values for evenness and rutting, as well as the 25% fractile of E values, cf. Table 19 as well as the text under this table. It cannot be expected that exactly the same values will be found by simulation and, therefore, you must enter an acceptance interval as a percentage, with reference to the figure below:

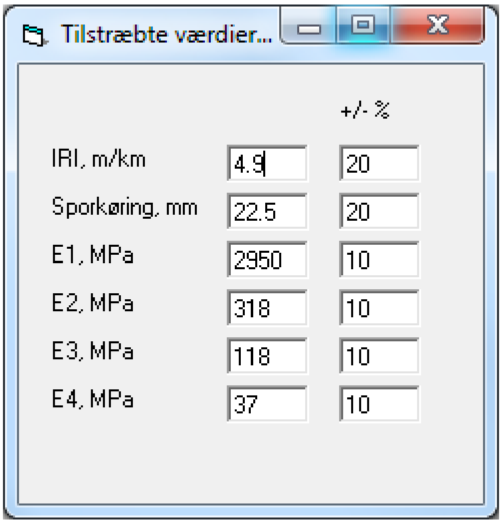


Figure 62 Designing a reinforcement layer by simulation - the desired degradation values (the average values for evenness and rutting, as well as the 25% fractile of E values), as well as the acceptance interval.

The "Continue" button should then be clicked and MMOPP will perform up to 20 individual simulations, where MMOPP will automatically change input values a little while attempting to hit the specified state after 25 years (if it does not succeed within the first 20 individual simulations, one will be asked if you'd like to try again).

Once the terminal state has been hit within the desired acceptance intervals for all parameters, the loop of individual simulations is stopped and the results are displayed in a new window, with reference to the following figure:

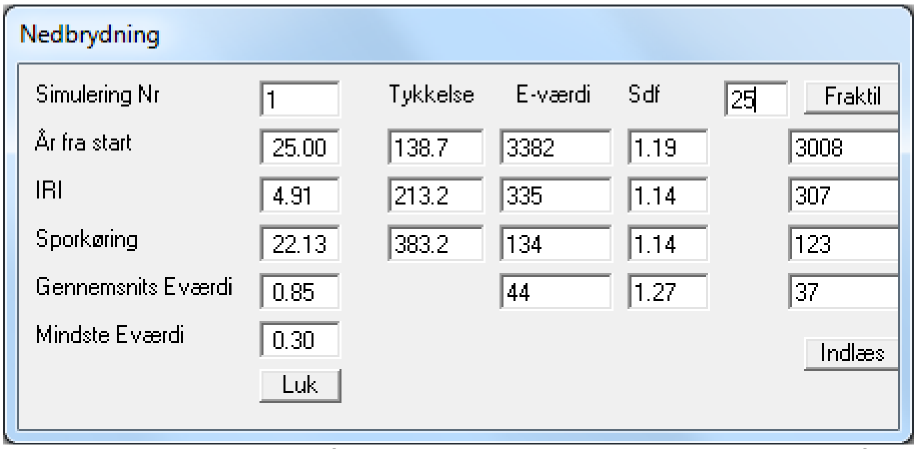


Figure 63 Designing a reinforcement layer by simulation - the result of an individual simulation which satisfies the desired values for a degraded pavement within the acceptance interval of after 25 years (corresponding simulations can be expected to give a different result).

If you are not satisfied with the values, click the "Close" button, then click the "Start" button again in the "Input parameters" screen in order to let MMOPP try again.

If you are satisfied with the degraded pavement (a 25% fractile of the individual layers' E value roughly corresponds to the measured 25% fractiles, cf. Table 19), click the "Load" button and return to the "Input parameters" screen, where the values for layer thicknesses and E values from the degraded pavement are loaded and the number of simulations is automatically changed to 10.

Manually enter the following:

- The required number of simulations, as well as the number of years in the simulation (as a minimum, double the number of years of the desired design period - in this example, thus, a minimum of 30 years)
- The E value of the reinforcement layer, as well as "0" mm of reinforcement

The "Start" button should then be clicked. This initial simulation "without reinforcement" is important, as MMOPP does not automatically take into account the degradation of the original pavement in the first simulation round.

In the subsequent simulation rounds, a guesstimate should be entered for the required reinforcement needs, after which one can display a window for entering "Intact asphalt E module" by clicking on the "Start" button (this is if the asphalt layers' E value from the simulation where a degraded pavement is generated is lower than the default value of the materials in MMOPP). Here you must enter the lower 25% fractile of the asphalt layers' E value in the original pavement (this value will use MMOPP as a point of departure for the degradation of the original pavement at the time of reinforcement). In this example, this value was 3.503 MPa, cf. Table 20.

The following figure shows the "Input parameters" screen for the example where a simulation with a 30 mm reinforcement layer is desired:

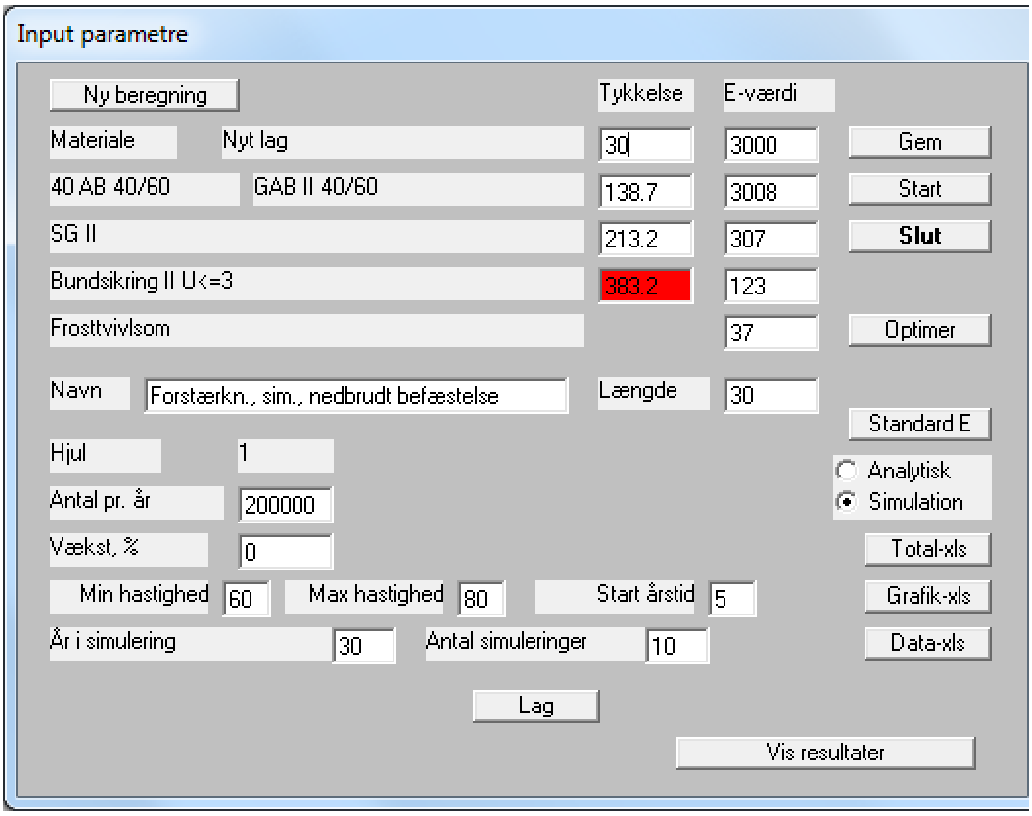
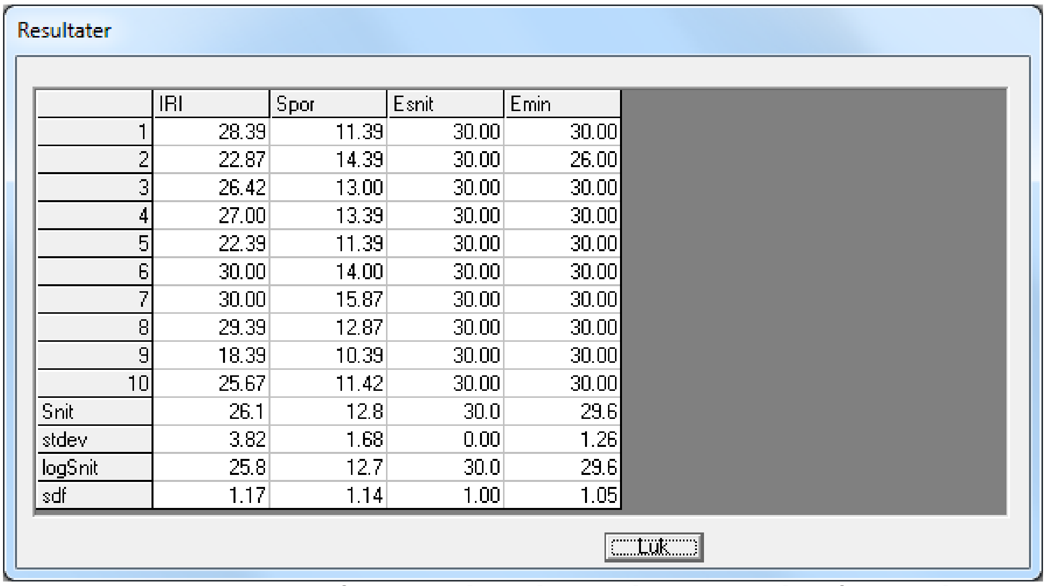


Figure 64 Designing a reinforcement layer by simulation - guesstimates of the required thickness of the reinforcement layer of the degraded pavement (thicknesses for layers, as well as E values for unbound layers in the existing reinforcement have been fed in from Figure 63).

By clicking the "Start" button, MMOPP simulates the degradation of the already partially degraded pavement after a reinforcement layer has been laid. The result of these simulations is best seen by clicking the "Show results" button when MMOPP has finished simulating, with reference to the following figure for results after a simulation with a 30 mm reinforcement layer:



	IRI	Spor	Esnit	Emin
1	28.39	11.39	30.00	30.00
2	22.87	14.39	30.00	26.00
3	26.42	13.00	30.00	30.00
4	27.00	13.39	30.00	30.00
5	22.39	11.39	30.00	30.00
6	30.00	14.00	30.00	30.00
7	30.00	15.87	30.00	30.00
8	29.39	12.87	30.00	30.00
9	18.39	10.39	30.00	30.00
10	25.67	11.42	30.00	30.00
Snit	26.1	12.8	30.0	29.6
stdev	3.82	1.68	0.00	1.26
logSnit	25.8	12.7	30.0	29.6
sdf	1.17	1.14	1.00	1.05

Figure 65 Designing a reinforcement layer by simulation - results after simulation with a 30 mm reinforcement layer on a degraded pavement.

After repeated simulation rounds (where you, after each round, change the thickness of the reinforcement layer, enter the value for "Intact asphalt E module", as well as check the results from the simulations) the required thickness of the reinforcement layer can be determined.

In the table below, the results are displayed for a number of simulations with different thicknesses of the reinforcement layer:

	Calculated theoretical lifespan [year]			
	IRI	Rutting	Eave	Emin
30 mm reinforcement layer:				
Section	26.1	12.8	30.0	29.6
stdev	3.82	1.68	0.00	1.26
Design value[1)]	**22.1**	**11.1**	**30.0**	**28.3**
50 mm reinforcement layer:				
Section	28.5	14.7	30.0	30.0
stdev	2.62	1.71	0.00	0.00
Design value[1)]	**25.8**	**12.9**	**30.0**	**30.0**
70 mm reinforcement layer:				
Section	29.9	16.8	30.0	30.0
stdev	0.19	1.99	0.00	0.00
Design value[1)]	**29.7**	**14.7**	**30.0**	**30.0**

	Calculated theoretical lifespan [year]			
	IRI	Rutting	Eave	Emin
72 mm reinforcement layer:				
Section	29.9	17.0	30.0	30.0
stdev	0.19	2.02	0.00	0.00
Design value[1)]	**29.7**	**14.9**	**30.0**	**30.0**
73 mm reinforcement layer:				
Section	29.9	17.2	30.0	30.0
stdev	0.19	1.96	0.00	0.00
Design value[1)]	**29.7**	**15.2**	**30.0**	**30.0**
[1)] For a normal distribution with the average value "0" and the dispersion "1", the lower 15% fractile has a value of "-1,036". The lower 15% fractile is then calculated as "Average" + "Dispersion" × -1.036, which corresponds to an 85% reliability.				

Table 21 Designing a reinforcement layer by simulation - results from simulating with a variety of thicknesses of the reinforcement layer (cells with a grey background indicate that the theoretical lifespan has not complied with the desired 85% of reliability).

As can be seen from the table above, rutting is the critical parameter and the required thickness of the reinforcement layer is 95 mm.

Such a thick reinforcement layer can be advantageously divided into, for example, an asphalt binder course and an asphalt wearing course, which provides good conditions for a smooth surface.

It is not possible to make a simulation calculation of reinforcement needs after having milled off a portion of the existing asphalt, as this is calculated on the basis of a specific pavement and its predetermined variation of thicknesses and E values.

5 Documentation

MMOPP prints different types of documentation of inputs and outcomes of the completed calculations.

5.1 Documentation - analytical design

Below is the printout of the user-defined analytical design in Figure 28, transferred to Excel by clicking the "Data xls" button:

Project:	User defined dim., changed speed		Date:	15/04/2016
C:\Program Files (x86)\Work tools\MMOPP2015\mmopp20160405.mdb				
Load:	Type:	Standard	Number:	800000

Pavement

Layer	Thickness, mm	E value, MPa	Material
1	195	1283	25 PA 250/330 + 50 GAB.0 70/100 + GAB.I 70/100
2	170	300	Base course of gravel II
3	335	100	Subbase II U<=3
4		40	Frost-susceptible

Critical and permissable load

Layer	Type	Critical	Permissable		Lifespan
1	el	260.8	260.9	microstrair	20
2	zz	0.1472	0.1771	MPa	41.9
3	zz	0.054	0.0553	MPa	22
4	zz	0.0195	0.0209	MPa	26.7

Figure 66 Documentation transcript, analytical design.

5.2 Documentation - design by simulation

Below is the printout of the user-defined design by simulation in Figure 54, transferred to Excel by clicking the "Data xls" button:

Project:	Sim., analytical dimensioning	Date:	15/04/2016
C:\Program Files (x86)\Work tools\MMOPP2015\mmopp20160405.mdb			
Climate:	Standard		
Load:	Standard		
Limits:	Standard		

Wheel	Number	Growth, %
1	73000	0

Length, m:	30
Minimum speed, km/h:	60
Maximum speed, km/h:	80
Start season:	5
Years in simulation/ dim.	40
No. of simulations	10

Pavement

Layer	Thickness, mm	E value, MPa	Material
1	142	3522	30 SMA 40/60 + 50 GAB 0 40/60 + GAB I 40/60
2	220	300	Base course of gravel II
3	338	100	Subbase II U<=3
4		40	Frost-susceptible

Lifespan (years)

Number	IRI	Rutting	Eave	Emin
1	27.4	14.8	40	40
2	18.4	13.4	40	33.7
3	26.4	19.4	40	40
4	28.4	15.4	40	40
5	19.7	12.4	40	40
6	27.4	18.4	40	40
7	22.4	13.4	40	40
8	24.8	16.4	40	40
9	23.4	14.4	40	40
10	28.4	17.9	40	40

Figure 67 Documentation transcript, design by simulation.

The Excel printout can optionally be combined with the plots of the degradation processes for IRI, Rutting, Average and Minimum E value of the asphalt layer, with reference to the following figure:

Project:	Sim., analytical dimensioning			Date:	15/04/2016
C:\Program Files (x86)\Work tools\MMOPP2015\mmopp20160405.mdb					
Climate:	Standard				
Load:	Standard				
Limits:	Standard				

Wheel	Number		Growth, %
	1	73000	0

Length, m:	30
Minimum speed, km/h:	60
Maximum speed, km/h:	80
Start season:	5
Years in simulation/ dim.	40
No. of simulations	10

Pavement

Layer	Thickness, mm	E value, MPa	Material
1	142	3522	30 SMA 40/60 + 50 GAB 0 40/60 + GAB I 40/60
2	220	300	Base course of gravel II
3	338	100	Subbase II U<=3
4		40	Frost-susceptible

Lifespan (years)

Number	IRI	Rutting	Eave	Emin
1	27.4	14.8	40	40
2	18.4	13.4	40	33.7
3	26.4	19.4	40	40
4	28.4	15.4	40	40
5	19.7	12.4	40	40
6	27.4	18.4	40	40
7	22.4	13.4	40	40
8	24.8	16.4	40	40
9	23.4	14.4	40	40
10	28.4	17.9	40	40

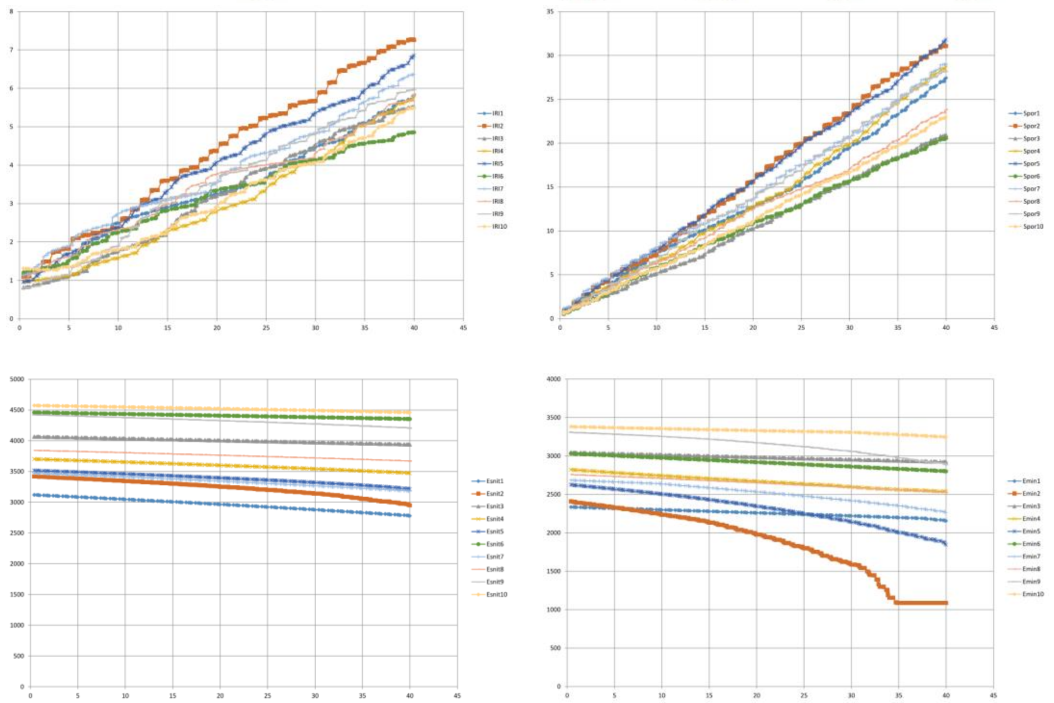


Figure 68 Documentation for design by simulation, including graphs of degradation processes - IRI, rutting (Spor), Eave (Esnit) and Emin.

5.3 Database documentation

Finally, it should be mentioned that all inputs and outputs are stored in the Access 7 database, which is defined in the MMOPP.INI file (see section 3.2). The "Section results" table, in particular, is of interest, as it contains the four lifespans (IRI, Rutting, E_{AVE} and E_{MIN}), as well as the final formation of the layers 1-4 in the columns d1 to d4.

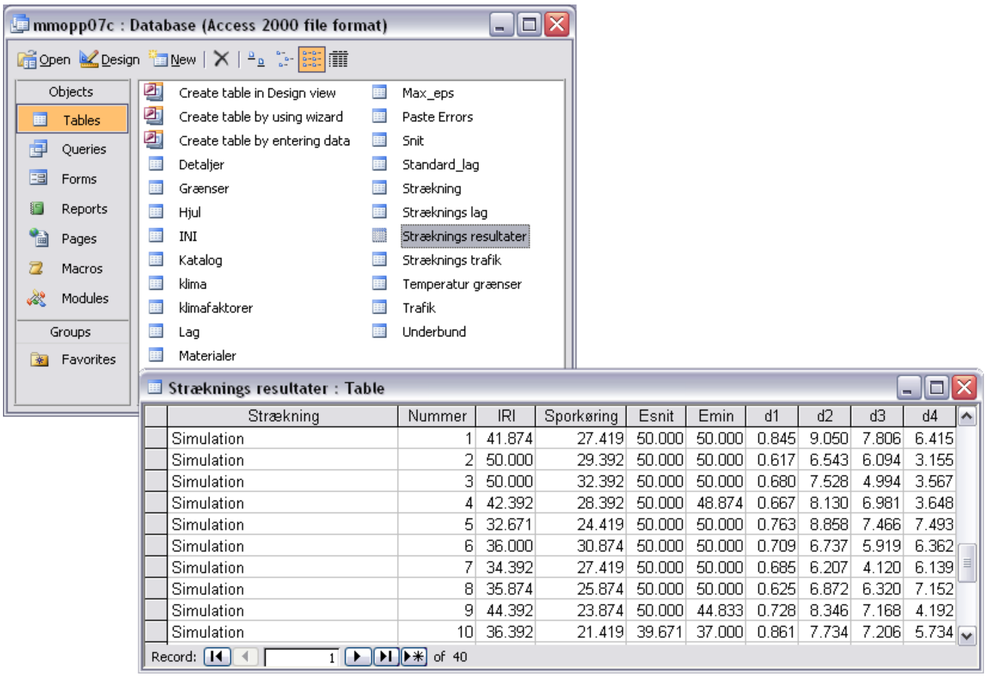


Figure 69 Section results from the Access database.

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