16. RAILWAY WHEEL WEAR PREDICTION MODULE 2

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16. Railway wheel wear prediction module

16.1. Generalities

The prediction of wheel and rail profile wear in the program package “Universal Mechanism” is organized on the base of the scanning tool (UM Optimization) supplemented by the *evolution* concept. The evolution is series of multivariant calculations (MVC) of identical structure (iterations) which differ in external conditions. In case of prediction of wheel profile wear the external conditions are wheel profile curves which are changed at the end of every MVC (iteration) in compliance with the tribological wear model.

Let us consider the mathematical model of the wheel profile evolution after single MVC. Let $F = \{F_i\},\ i = 1,\ldots,N_F$ be a set of families in MVC. Every family is a simulation of railway dynamics on given external conditions and a set of speed values, $F_i = \{V_{ij}\},\ j = 1,\ldots,N_{vi}$. Here V_{ij} is a single simulation with the given speed. In the context of a single MVC, the external conditions are:

- track irregularities,
- track type (tangent, curve, switch),
- rail profiles,
- curve or switch parameters.

Consider an example. Let MVC contain three families $F = \{F_1, F_2, F_3\}$, where F_1 is the movement in a tangent section, F_2, F_3 – movement in curves $R = 300, 600$ m, so $N_F = 3$. The sets of speeds for each of the families are the following:

$$F_1 = \{15, 20, 25\},\ F_2 = \{13\},\ F_3 = \{15,18,21\}$$

speeds in m/s.

Dimensionless weight coefficients are introduced for every family. These coefficients determine the ratios of external conditions on the track for which the wear of wheels is computed

$$\alpha_i, i = 1,\ldots,N_F .$$

The α_i coefficient corresponds to the family F_i according to the formula

$$\alpha_i = \frac{s_i}{s},\ \sum_{i=1}^{N_F} \alpha_i = 1,$$

where s is the total track length; s_i is the total length of sections corresponding to the external conditions of the family F_i, e.g. the total length of curves R = 600 m including transition lengths.

Simplified computations are foreseen when it is supposed that the total lengths of left and right curves are equal so that the left and the right wheels of a wheelset are equally worn. In this case only left curves can be taken into account. Otherwise, families for both left and right curves should be included in MVC.

Weight coefficients should be set for speeds within a family

$$\beta_{ij}, \sum_{j=1}^{N_{vi}} \beta_{ij} = 1$$

which define a speed distribution diagram for the family.

The forward/backward symmetry takes into account a possible forward and backward motion without 180^o turn of the vehicle. In this case the wear of wheels symmetric relative to the vehicle centre is equal.

Let $e_{ijk,l}, e_{ijk,r}$ be wear diagrams across the tread for the left and right wheels of wheelset k measured in mm and computed according to a tribological model for the family F_i at the speed V_{ij}. A B-spline is used for smoothing of the diagrams. Step size for the unsmoothed diagrams can be set by the user. The default step size is 1mm.

The resultant diagrams $e_{k,l}, e_{k,r}$ corresponding to the wear reduced to one conditional meter of the track (wear intensity) are computed according to the following algorithm

- in the case of the left/right symmetry, the averaging

  $$e_{ijk,r} := (e_{ijk,r} + e_{ijk,l}) / 2,$$
  $$e_{ijk,l} := e_{ijk,r},$$

  takes place;
- in the case of the forward/backward symmetry, the averaging of diagrams for wheels symmetric relative to the vehicle centre takes place

  $$e_{ijk,w} := (e_{ijk,w} + e_{ij(N-k+1),w}) / 2, \ \ w = l, r,$$

  where N is the number of wheelsets in the vehicle.
- The averaged diagram of the wear intensity is computed by the formula

  $$e_{k,w} = \sum_{i=1}^{N_F} \alpha_i \sum_{j=1}^{N_{vi}} \beta_{ij} \frac{e_{ijk,w}}{s_i}, \ \ w = l, r.$$

After that the material removal is executed according to the following algorithm

- The maximal value of the wear intensity is computed for all the wheels

  $$e_m = \max_k \{\max\{e_{k,l}\}, \max\{e_{k,r}\}\}.$$
- The path S corresponding to the maximal wear depth δ of material removal on one iteration is computed

$$S = \frac{\delta}{e_m},$$

the default value is $\delta = 0.1\text{mm}$

- The material removal for each of the wheels is computed as

$$e_{k,w}S,\ w = l,r,$$

the step size of the material removal function can be set by the user, the default value is 2 mm

- new profiles are generated with the second smoothing.

After that the new iteration of the evolution process starts.

Note that the algorithm uses double smoothing of profiles: smoothing wear diagrams and smoothing profiles after removal the material. The smoothing of wear diagrams is optional.

16.2. Models of wear intensity

The following models of the wheel wear intensity are used in UM

1. Archard model

The model is based on the hypothesis of the linear dependence between the volume wear I and the work of creep forces A:

$$I = k_V A,$$

where I is the volume wear, m^3;

k_V is the factor of the volume wear, m^3/J;

A is the work of friction, J.

2. Specht model

This model also uses the linear dependence between the volume wear and the work, but it is assumed that there exist two areas within the contact patch: the areas of moderate and intense wear with different values of wear coefficients:

$$\begin{cases} I = k_V A, & w < w_{cr}, \\ I = k_V \alpha A, & w \geq w_{cr}, \end{cases}$$

where I is the volume wear, m^3;

k_V is the factor of the volume wear, m^3/J;

A is the work of friction, J; w is the friction power, W/m^2;

w_{cr} is the critical power, W/m^2, α is the jump coefficient.

3. VNIIZHT-1 model is:

$$I = k\xi^2 p,$$

where p is the pressure in the contact patch,

ξ is the full creepage.

4. Plasticity model takes into account the plasticity:

$$I = k \cdot \xi^2 \cdot p^* \cdot \min\left(tg(p/p^*), 1.5\right),$$

where p^* is the critical pressure.

This model tends to the VNIIZHT-1 model for small p.

Choice of wear coefficient

In the first and second models (Archard and Specht), the volume (mass) wear is proportional to the work of friction. Choice of the wear factor is a difficult problem depending on material properties, contact conditions etc. Experiments show that the mass wear factor lies in the interval $10^{-4}..10^{-2}$ mg/J [1].

According to [2], the values of the mass wear factor is $k_m = (1.8..2.4)\cdot 10^{-3}$ mg/J for stiff wear conditions like that for the Gottard line.

In [3] a good coincidence with results obtained on a test rig was achieved by $k_m = 1.7\cdot 10^{-3}$ mg/J.

For the Specht model [4] the author supposes $k_m = 7.8\cdot 10^{-4}$ mg/J for the moderate area, i.e. $k_V = 1\cdot 10^{-13}$ m^3/J for the steel with 7800 kg/m^3 density. In the intense wear area $k_m = 7.8\cdot 10^{-3}$ mg/J. Critical friction power $w_{cr} = 4$ W/mm^2.

Remark

UM uses the volume wear factor (not the mass one!) [m^3/J], $k_V = \frac{k_m}{\rho}\cdot 10^{-6}$, where ρ is the material density.

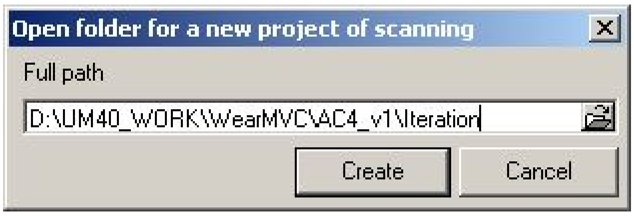
16.3. Example: creation of wheel profile evolution project and analysis of results

16.3.1. Evolution project

In this section we consider the process of creation of a wheel profile evolution project for the rail car AC4 model.

16.3.2. Creation of new project

1. Run the **UM Simulation** program.
2. Select the **Advances analysis | Scanning: new project…** menu command.

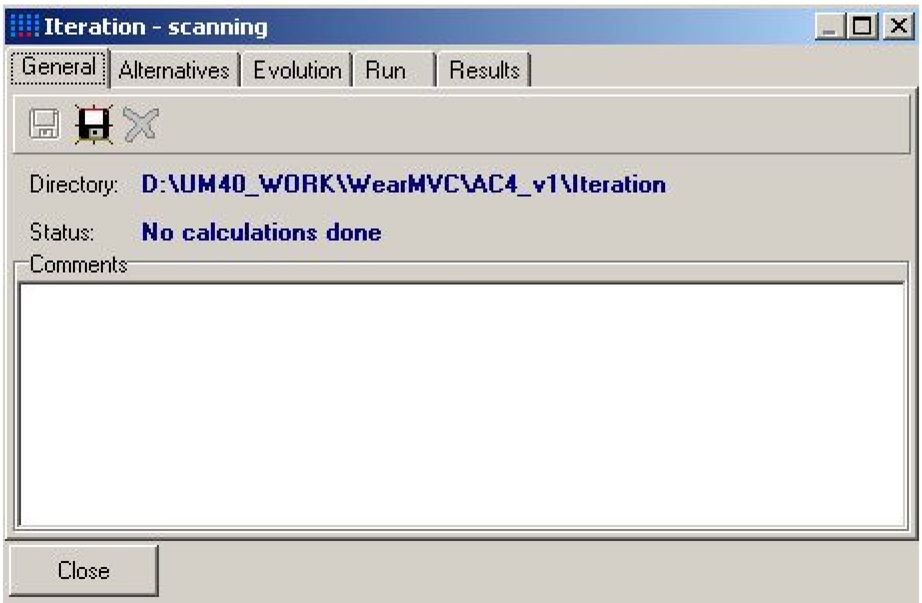


D:\UM40_WORK\WearMVC\AC4_v1\Iteration

Fig.16.1. Dialog for selection of project directory

3. Set a path for the new project directory in the dialog box, Fig. 16.1 and click the **Create** button. The project window appears.
   Note that in the above example the iterations will be stored in the directories
   d:\um50\WearMVC\AC4_v1\iteration_1 (the first iteration),
   d:\um50\WearMVC\AC4_v1\iteration_2 (the second iteration),
   ………………………
   d:\um50\WearMVC\AC4_v1\iteration_i (the i-th iteration),
   ……………………….

Thus, the root directory for the project is *d:\um50\WearMVC\AC4_v1*.



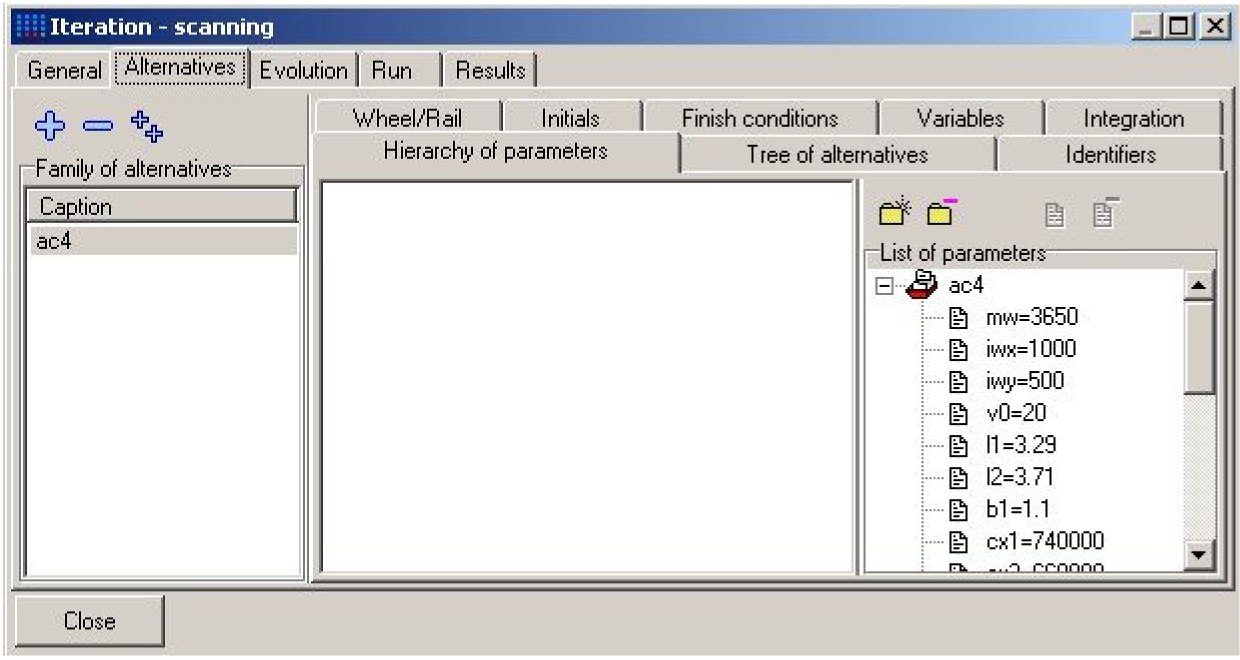
Directory: D:\UM40_WORK\WearMVC\AC4_v1\Iteration

Status: No calculations done

Fig.16.2. Scanning project window

16.3.3. Add a new family to the project

1. Open the **Alternatives** tab of the window.



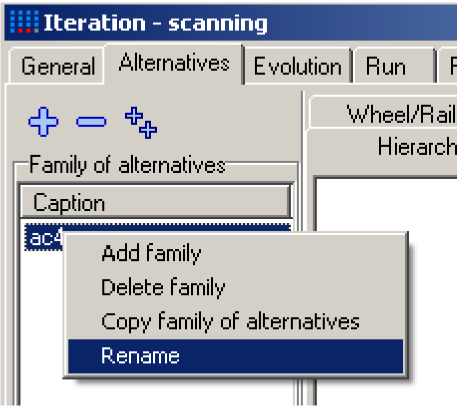
ac4
mw=3650
iwx=1000
iwy=500
v0=20
l1=3.29
l2=3.71
b1=1.1
cx1=740000

Fig.16.3. Adding a family to the project

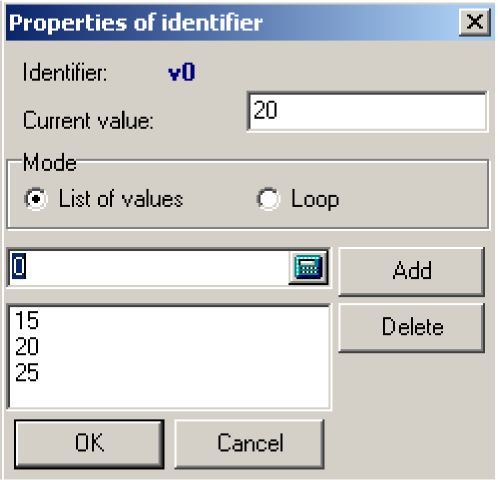
2. Click the ✚ button and select the {UM50}\Samples\Rail vehicles\AC4 model. The selected model is copied to the directory of the project, and the name of the model is added to the list of the families of alternatives, Fig. 16.3.

16.3.4. Hierarchy of parameters

Our project will include three families: motion of the railcar in a tangent section, and in curves R = 300 m, R = 600 m. Rename the family in the list as *ac4_tangent* by the **Rename** command of the popup menu.



Only one parameter should be used for scanning in the evolution projects: the vehicle speed **v0**.



Identifier: v0

Current value: 20

Mode

● List of values ○ Loop

0

15
20
25

Fig.16.4. Window for creating a list of parameter values

1. Click on the v0 parameters in the **List of parameters,** Fig. 16.3.
2. Add 15, 20 and 25 m/s as a set of vehicle speed, Fig. 16.4. Close the window.
3. A new **Group 1** has been added to the **Hierarchy of parameters**, Fig. 16.5. Rename it as **Speed** using the **Rename** group of parameters command of the popup menu. Thus, 3 numeric experiments are planned for the family in the tangent section.

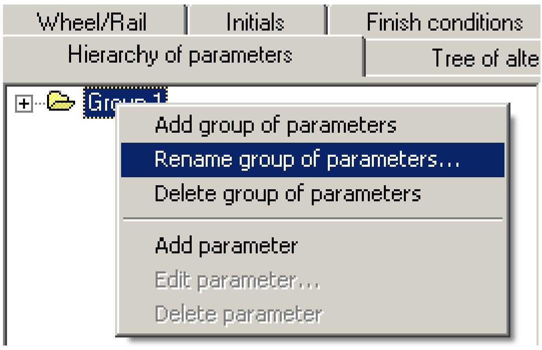
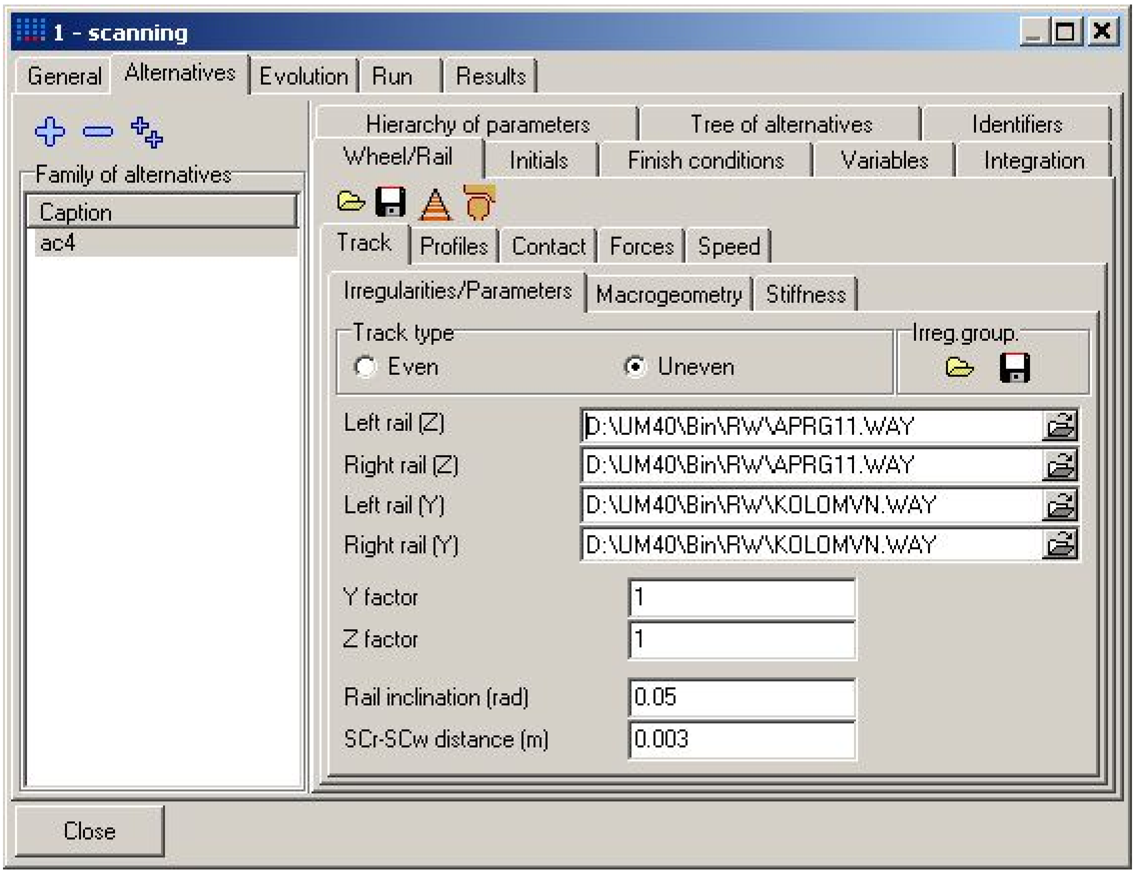


Fig.16.5. Hierarchy of parameters

16.3.5. Railway parameters

Setting railway parameters is a necessary step of the development of the evolution project.



Track type
○ Even ● Uneven

Left rail (Z) D:\UM40\Bin\RW\APRG11.WAY

Right rail (Z) D:\UM40\Bin\RW\APRG11.WAY

Left rail (Y) D:\UM40\Bin\RW\KOLOMVN.WAY

Right rail (Y) D:\UM40\Bin\RW\KOLOMVN.WAY

Y factor 1

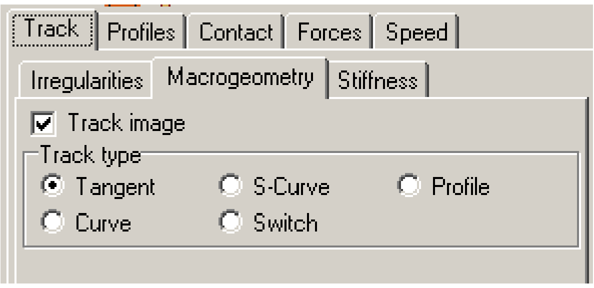
Z factor 1

Rail inclination (rad) 0.05

SCr-SCw distance (m) 0.003

Fig.16.6. Track irregularities

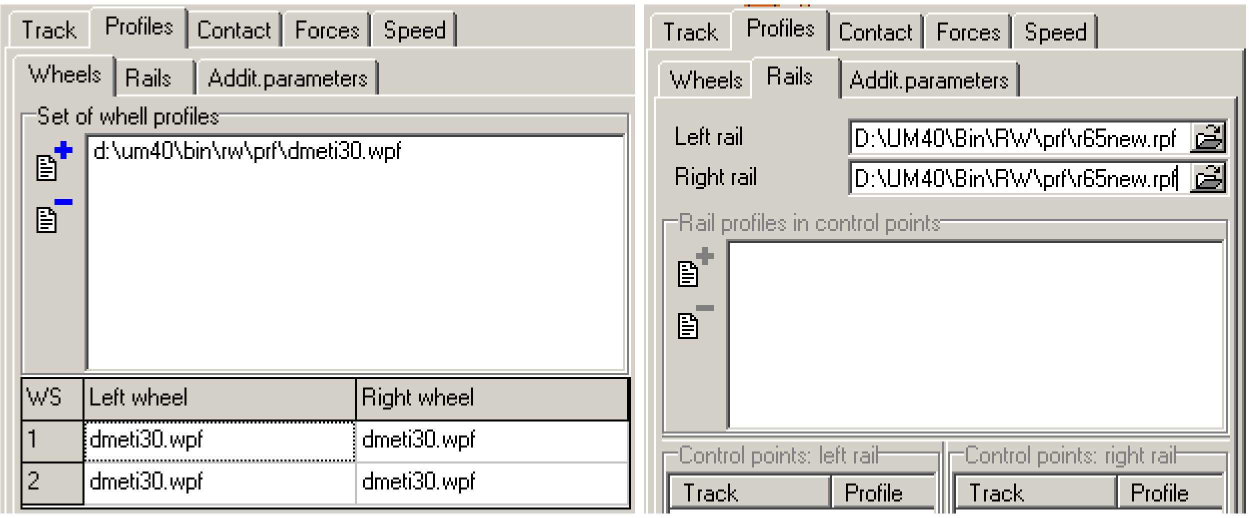
1. Track irregularities. Open the **Wheel/Rail | Track | Irregularities** tab, select the **Uneven** type and assign irregularity files like in Fig. 16.6.



☑ Track image

Track type
● Tangent ○ S-Curve ○ Profile
○ Curve ○ Switch

2. Open the **Wheel/Rail | Track | Macrogeometry** tab to set the **Tangent** type for the track section.



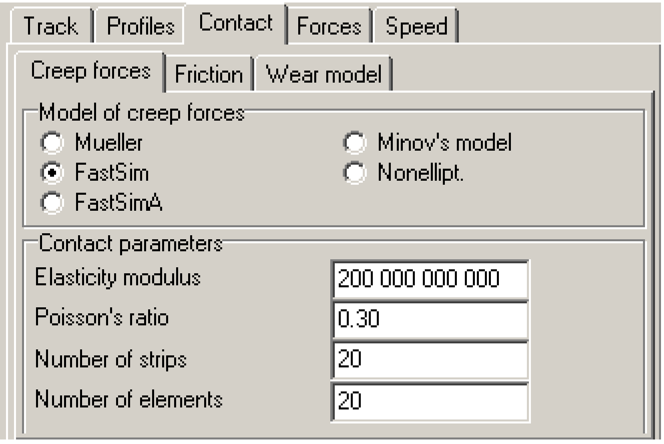
d:\um40\bin\rw\prf\dmeti30.wpf

WS	Left wheel	Right wheel
1	dmeti30.wpf	dmeti30.wpf
2	dmeti30.wpf	dmeti30.wpf

Left rail D:\UM40\Bin\RW\prf\r65new.rpf
Right rail D:\UM40\Bin\RW\prf\r65new.rpf

Fig.16.7. Wheel and rail profiles

3. Use the **Wheel/Rail | Profiles | Wheels** and **Wheel/Rail | Profiles | Rails** tabs to assign the **r65new.rpf (**rail**)** and **dmeti30.wpf** (wheel) files for the start profiles, Fig. 16.7.



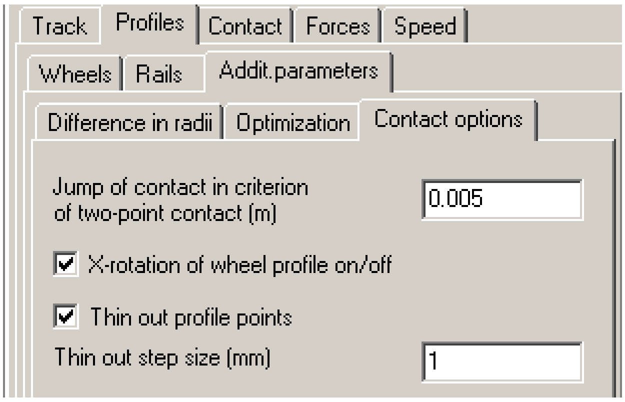
○ Mueller
● FastSim
○ FastSimA
○ Minov's model
○ Nonellipt.

Elasticity modulus 200 000 000 000
Poisson's ratio 0.30
Number of strips 20
Number of elements 20

Fig.16.8. Model of creep forces

4. Creep forces. Open the **Wheel/Rail | Contact | Creep forces** tab, and set the **FastSim** forces model as well as its parameters as in Fig. 16.8.

Remark. Note that **FastSim** or **Nonelliptic** creep force models only can be used in the profile evolution projects.



Jump of contact in criterion of two-point contact (m) 0.005

☑ X-rotation of wheel profile on/off

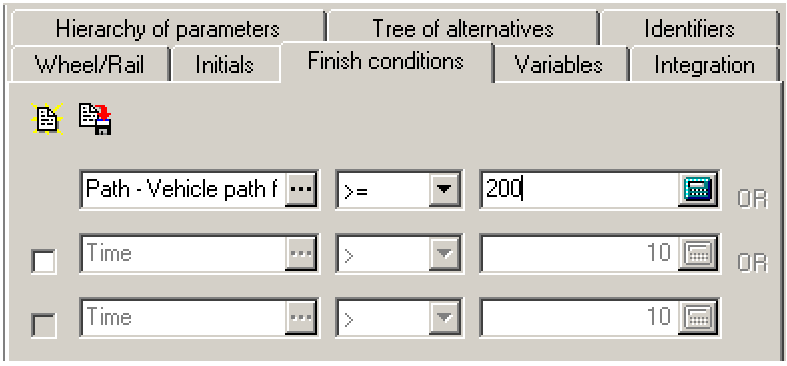
☑ Thin out profile points

Thin out step size (mm) 1

Fig.16.9. Additional contact model options

5. Follow Fig. 16.9 to set additional parameters of the contact model. Note that the **“Jump of contact… ”** parameter value should be set within the interval 0.01..0.015 m *if the non-elliptic contact model is used*.

16.3.6. Finish conditions



Path - Vehicle path f | >= | 200 | OR

☐ Time | > | 10 | OR

☐ Time | > | 10

Fig.16.10. Finish conditions

During the scanning the simulation process can be terminated by special conditions like

Variable [condition] Numeric value.

Here any variable may be used. For rail vehicles the default condition is the following:

Path >= 300 m.

Thus, the simulation process ends when the vehicle has run 300 m. In our short example we decrease this value to 200 m, Fig. 16.10. Required variable for finish conditions can be formed in the **Master of variables** and dragged into the field with a variable name.

Now the first family has been described. Save the project by the 💾 button on the **General** tab. We continue with other families.

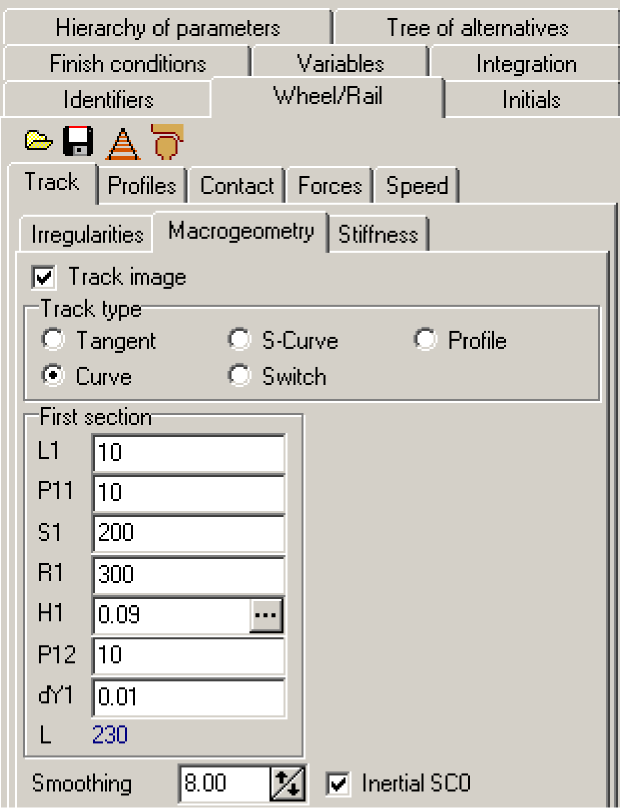
16.3.7. Copying families

Other two families corresponding to motion in curves are created by the copying of the first family.

1. Open the **Alternatives** tab and click the button. A new family with the name *ac4_tangent(1)*, which is an exact copy of the *ac4_tangent* family.
2. Rename into *ac4_r300.*

Now let us change parameters of the new family to set its motion in the curve R = 300 m with the 13 m/s speed – speed with zero uncompensated acceleration.

Open the **Wheel/Rail | Track | Macrogeometry** tab and set the **Curve** track type with the parameters like in the Fig. 16.11.



☑ Track image

Track type
○ Tangent ○ S-Curve ○ Profile
● Curve ○ Switch

First section
L1 10
P11 10
S1 200
R1 300
H1 0.09
P12 10
dY1 0.01
L 230

Smoothing 8.00 ☑ Inertial SC0

Fig.16.11. Curve parameters

3. To set the speed,
   - open the **Hierarchy of parameters** tab,
   - expand the **Speed** node,
   - select the **v0** parameter by the mouse and choose the **Edit parameter**… in the popup menu, Fig. 16.12,

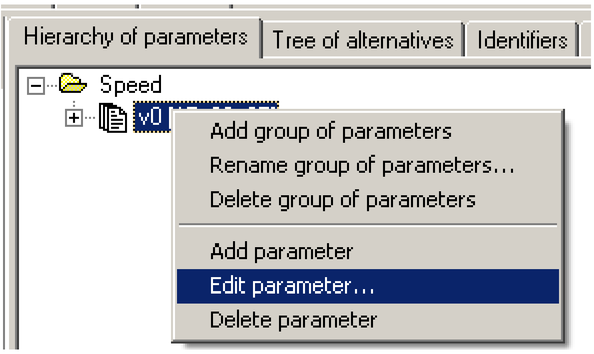


Fig.16.12. Setting of hierarchy parameters

- delete all elements in the list of velocities in the appeared dialog box,
- add one value of speed – 13 m/s.

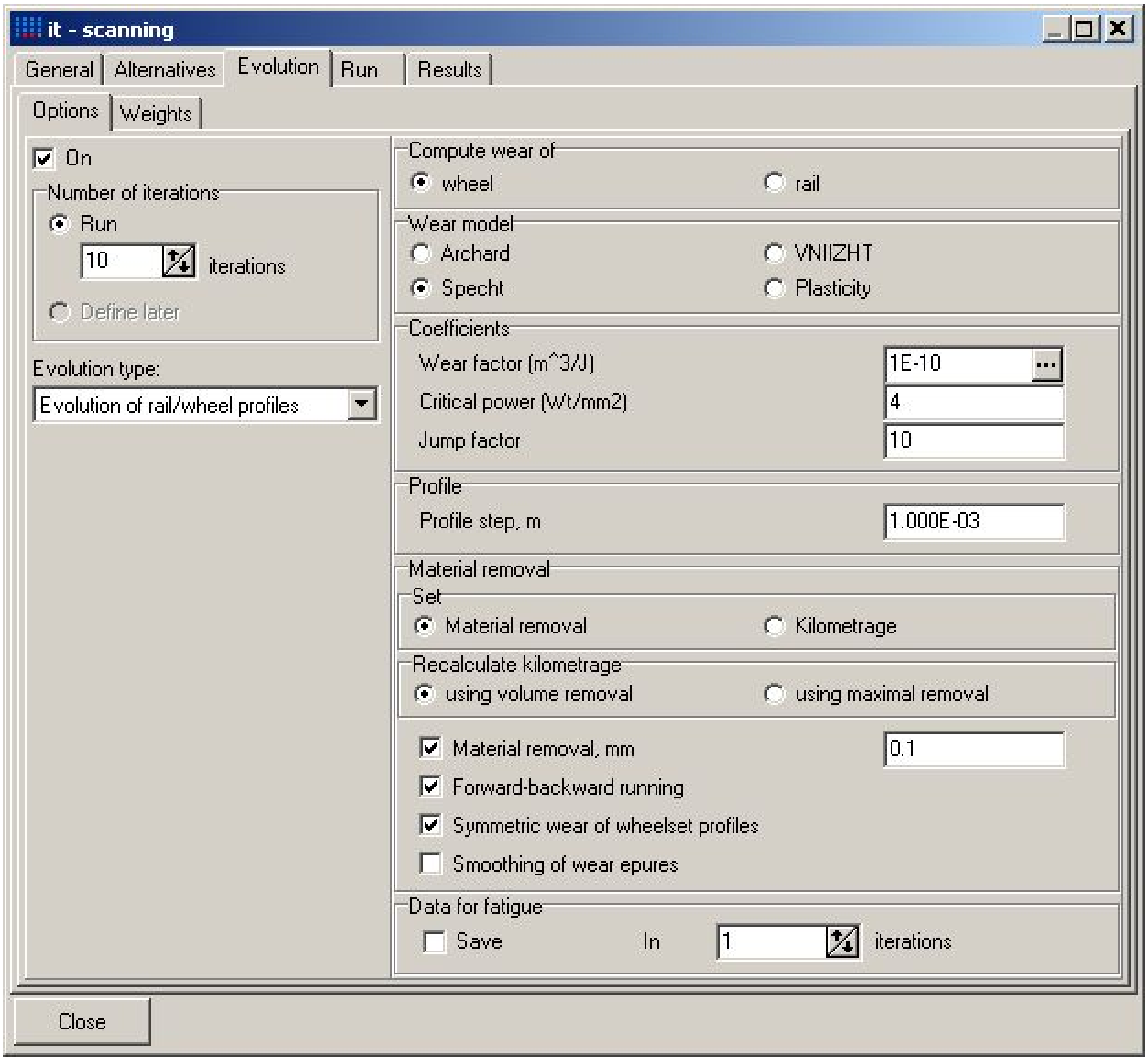
4. Change the path to 240 m on the Finish condition tab. This distance is equal to the length of the curve.
5. The family for the evaluation of wheel profile wear in the curve 300 m is ready. Save the project.

Copy the second family, rename it to *ac4_r600*. Set the curve radius **R1** = 600. Open the **Hierarchy of parameters** tab, delete the value of speed 13 m/s and set the list of speed values: 15, 18, 21 m/s in the above manner.

All necessary families have been created. Save the project.

16.3.8. Parameters of profile evolution

Open the **Evolution | Options** tab. Select the **On** switch. Set other parameters like in Fig. 16.13.



☑ On

Number of iterations
● Run
10 iterations
○ Define later

Evolution type: Evolution of rail/wheel profiles

Compute wear of
● wheel ○ rail

Wear model
○ Archard ○ VNIIZHT
● Specht ○ Plasticity

Coefficients
Wear factor (m^3/J) 1E-10
Critical power (Wt/mm2) 4
Jump factor 10

Profile
Profile step, m 1.000E-03

Material removal
Set
● Material removal ○ Kilometrage
Recalculate kilometrage
● using volume removal ○ using maximal removal

☑ Material removal, mm 0.1
☑ Forward-backward running
☑ Symmetric wear of wheelset profiles
☐ Smoothing of wear epures

Data for fatigue
☐ Save In 1 iterations

Fig.16.13. Profile evolution parameters

Let us consider parameters in the form in more detail.

The group **Compute wear of** – choice of profiles for wear: **wheel** or **rail**.

The group **Wear models**: **Archard, Specht, VNIIZHT** and **Plasticity** are described in Sect. 16.2.

Coefficients – numeric values of constants for the corresponding wear models.

Profile step, m – discretization step along the profile for the accumulation of friction work.

The group **Material removal** contains options for setting of material removal parameters.

The group **Set** (**Material removal** or **Kilometrage**): choice of parameter which value will determine the maximal removal for an iteration. The value is set in the field **Material removal, mm** or **Kilometrage, km** correspondingly. For example, if material removal is set equal to 0.1 mm then the maximal removal for an iteration will be approximately 0.1 mm (it could be deviations because of profile smoothing) and kilometrage will be recalculated according to the data obtained for the current iteration. If kilometrage for an iteration is set then the removal material will corresponds to the kilometrage value. When the kilometrage is set it is necessary to pay attention that the material removal for this value is not too high. It may lead to incorrect simulation results. The recommended maximal value of material removal is 0.1 mm (linear removal).

The group **Recalculate kilometrage**: choice of parameter which will be used for the recalculation of kilometrage after an iteration completed. If the recalculation by **using volume removal** is set then kilometrage will be recalculated in proportion to the volume of removal material; **using maximal removal** – the recalculation will be done in proportion to the maximal value of removal material (linear removal).

Material removal, mm (or **Kilometrage, km**) – the maximal depth of material removal after each of iterations (the kilometrage is recomputed correspondingly) or kilometrage value for an iteration. See Sect. 16.1 for more details.

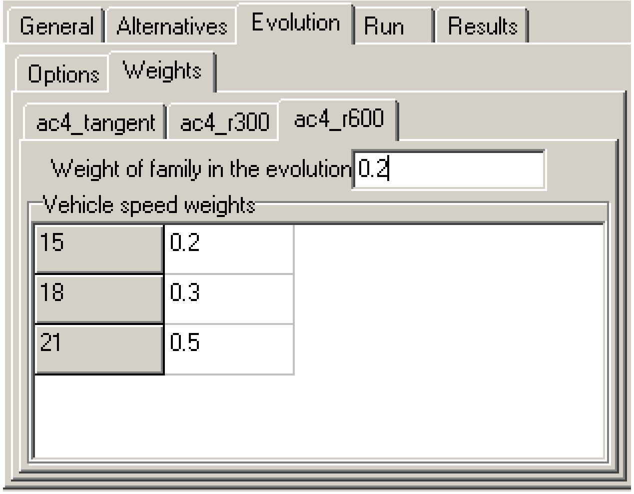
Forward/Backward run – backward motion of a vehicle without 180 degrees turn is taken into account, see Sect. 16.1 for more details.

Symmetric wear for wheelset – a simplified variant of the profile wear computation when it is supposed that the wear of the left and right wheels are equal, Sect. 16.1.

Smoothing of wear epures – turn on/off the smoothing of wear epures before the removal of material from wheel or rail profile will be made by using these epures (turned off by default).

Now let us set weight coefficients on the **Evolution | Weights** tab, Fig. 16.14. Firstly, set **weights of the families in the evolution**: *ac4_tangent* – 0.7; *ac4_r300* – 0.1, *ac4_r600* – 0.2.

If the scanning for a family includes several values of speed, weight coefficients for these values must be set as well. For the first family it will be 0.4; 0.3; 0.3, for the third one 0.2; 0.3; 0.5, Fig. 16.14.



Weight of family in the evolution 0.2

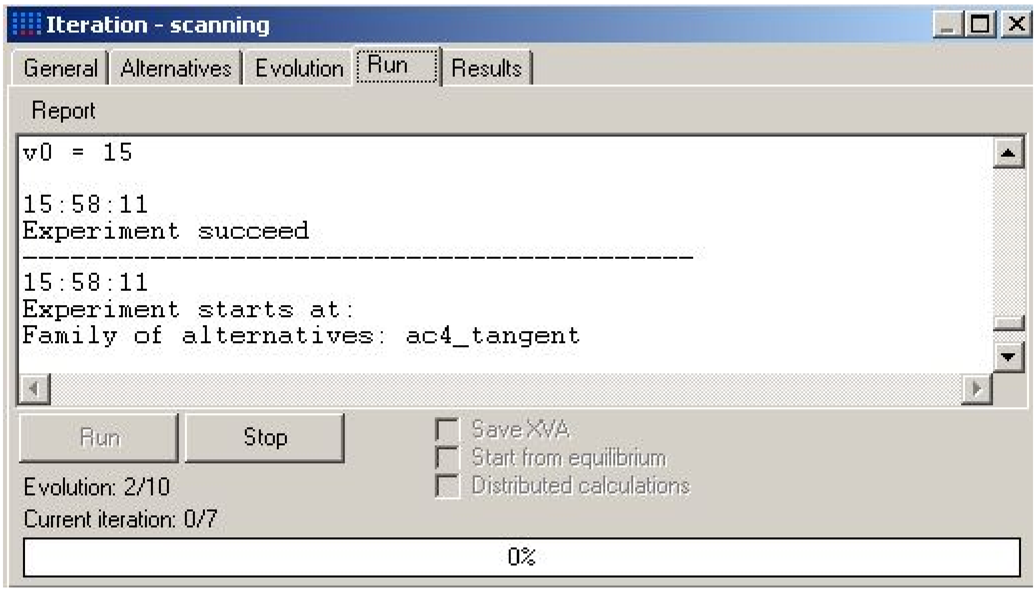
Vehicle speed weights

15	0.2
18	0.3
21	0.5

Fig.16.14. Weight coefficients

Remark. Normalization of weight coefficients according to Eqs. (1), (2) is done automatically. The user can input their values in percents, kilometers etc.

The project is ready. Use the **Run** button on the **Run** tab, Fig. 16.15.



```
v0 = 15

15:58:11
Experiment succeed
-------------------------------------------
15:58:11
Experiment starts at:
Family of alternatives: ac4_tangent
```

☐ Save XVA
☐ Start from equilibrium
☐ Distributed calculations

Evolution: 2/10
Current iteration: 0/7
0%

Fig.16.15. Report tab of the computation process

16.3.9. Breaking and continuing computations

The **Stop** button can be used any time to break the process of computations. The user can estimate or delete (the ✖ button on the **General** tab) the results or close the program.

To continue the computations, the user should start the program, open the project by the **Advanced analysis | Scanning: reload** (or **Scanning: open project…)** menu command and start the project continuation on the **Run** tab.

The fully computed projects can be continued if the user increases the number of evolution iterations, Fig. 16.13.

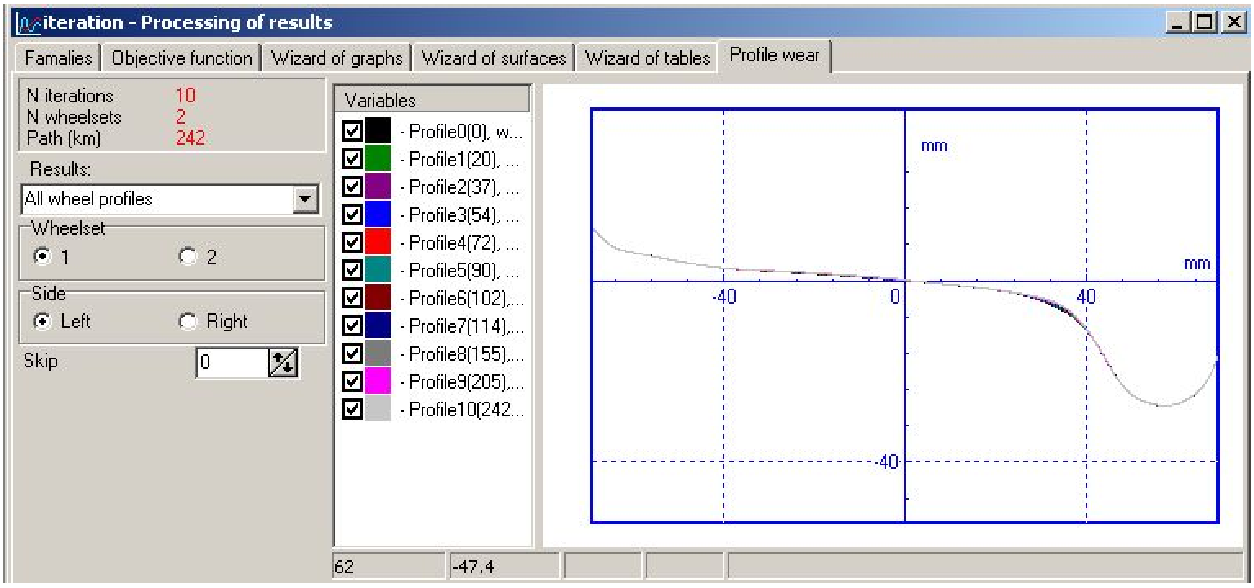
16.3.10. Processing results

Estimation of the wear computation results is available

- After breaking the process
- After end of the process

Results are available as well with a special tool by the **Advanced analysis | Scanning: load results…** menu command. In this case results of several projects can be opened simultaneously.

If the window of scanning is open, the results are available of the **Results | Profile wear** tab.



N iterations 10
N wheelsets 2
Path (km) 242

Results: All wheel profiles

Wheelset ● 1 ○ 2

Side ● Left ○ Right

Skip 0

☑ - Profile0(0), w...
☑ - Profile1(20), ...
☑ - Profile2(37), ...
☑ - Profile3(54), ...
☑ - Profile4(72), ...
☑ - Profile5(90), ...
☑ - Profile6(102),...
☑ - Profile7(114),...
☑ - Profile8(155),...
☑ - Profile9(205),...
☑ - Profile10(242...

62 -47.4

Fig.16.16. Tab with results

Note that the railcar is a two-axle vehicle with a long base. It has big angles of attack in curves, and large wear.

The following results are available:

- **All profiles**: profiles for the selected wheel or rail for all the iterations. The first plot in this case corresponds to the start profile. In parentheses, the traversed path is shown in case of wheel wear simulation or the quantity of passages of investigated vehicles in case of rail wear simulation.
- **All epures:** averaged smoothed diagrams of wear density $e_{k,w}$ for all the iterations. In parentheses, the traversed path is shown in case of wheel wear simulation or the quantity of passages of investigated vehicles in case of rail wear simulation.

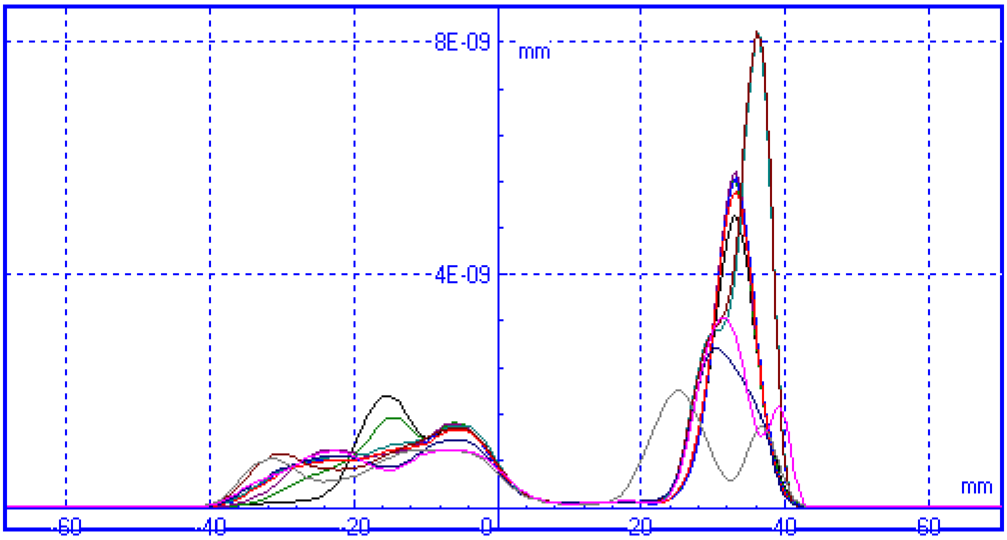


Fig.16.17. All wear diagrams for a wheel

- **All non-smoothed epures:** averaged non-smoothed diagrams of wear density $e_{k,w}$ for all the iterations. If the **Smoothing of wear epures** check-box (par. 16.3.8) is turned off then smoothed and non-smoothed epures are the same. In parentheses, the traversed path is shown in case of wheel wear simulation or the quantity of passages of investigated vehicles in case of rail wear simulation.
- **Last profile:** a start and resultant profiles are shown for selected wheel.

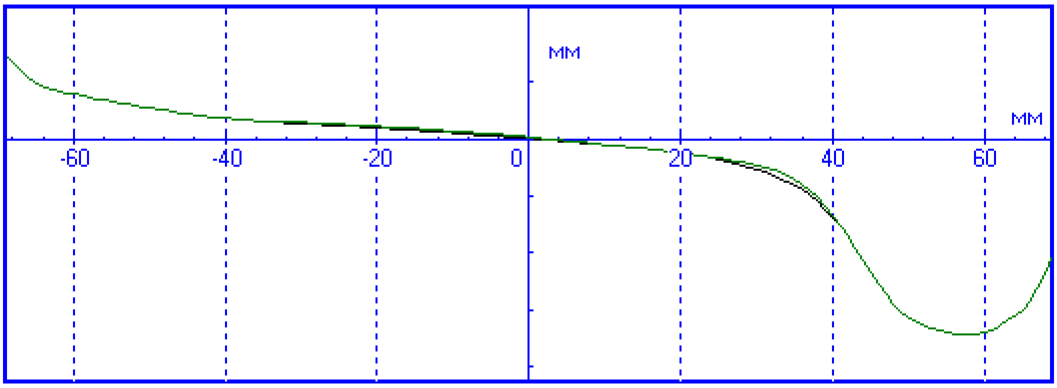


Fig.16.18. Start and resultant profiles

- **All last profiles:** the resultant profiles for all the wheels are shown.
- **Wear rate:** the plot of wear rate is shown. The abscissa of the plot is the number of iteration; the ordinate is the square of removal material in the section of wheel profile for 1 meter of traversed path or in the section of rail profile for 1 passage of investigated vehicles.

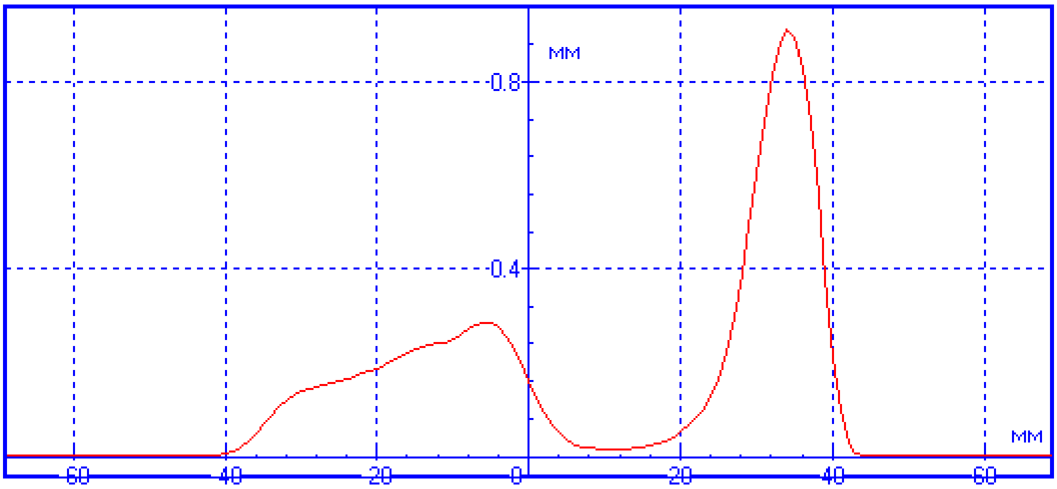


Fig.16.19. Depth of wear versus the wheel tread

Any plot can be dragged to another graphic window and compared with results of other computations.

Plots can be saved as text files or exported to MS Excel by popup menu commands.

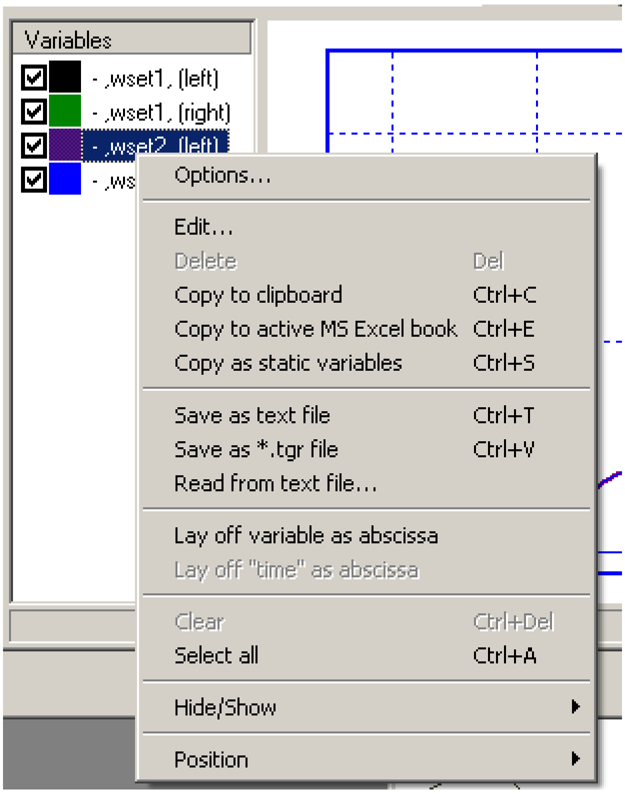
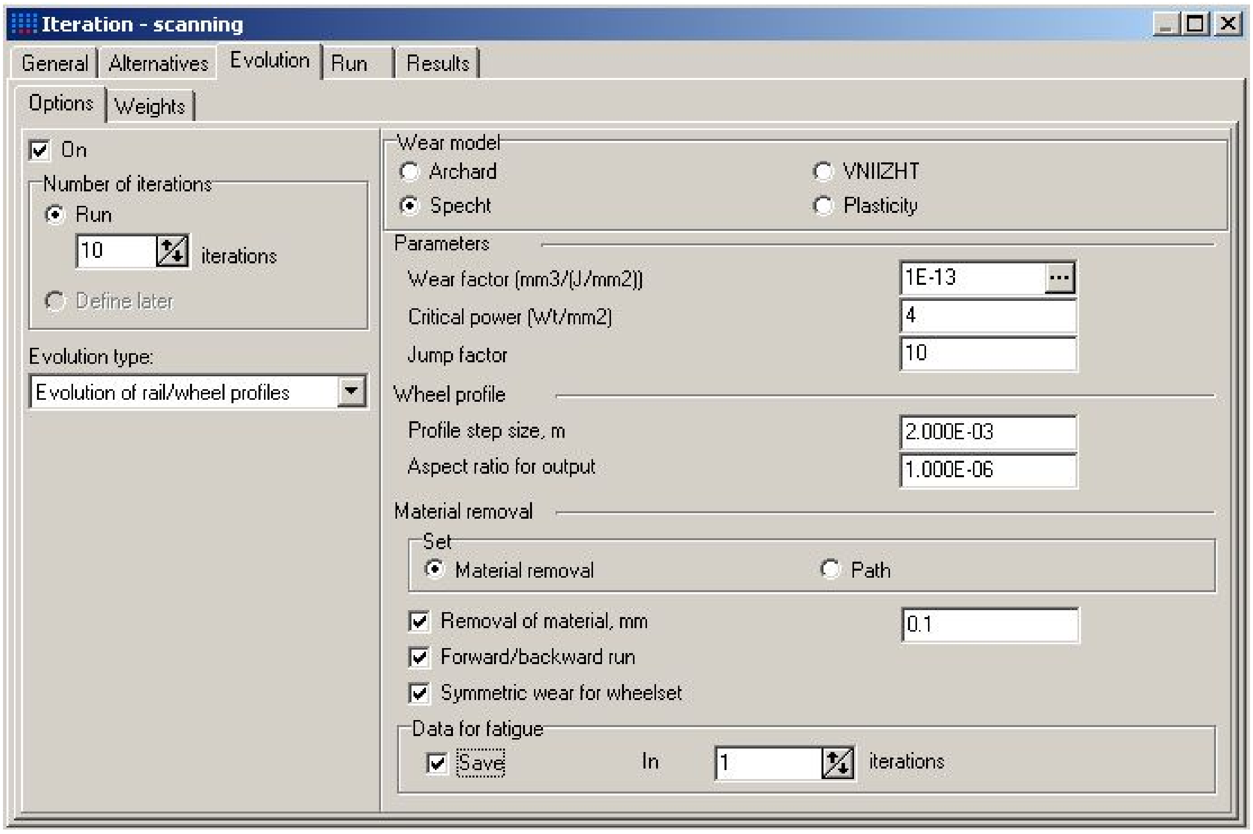


Fig.16.20. Popup menu of a graphic window

16.4. Wheel loading

Wheel loading computation is implemented in UM for fatigue analysis with external software. The loading estimation is executed simultaneously with wear computation.

Use the **Save** key of the **Data for fatigue** group to switch on/off estimation of loading. Data can be saved in several iterations.



☑ On

Number of iterations
● Run
10 iterations
○ Define later

Evolution type: Evolution of rail/wheel profiles

Wear model
○ Archard
● Specht
○ VNIIZHT
○ Plasticity

Parameters
Wear factor (mm3/(J/mm2)) 1E-13
Critical power (Wt/mm2) 4
Jump factor 10

Wheel profile
Profile step size, m 2.000E-03
Aspect ratio for output 1.000E-06

Material removal
Set
● Material removal
○ Path
☑ Removal of material, mm 0.1
☑ Forward/backward run
☑ Symmetric wear for wheelset

Data for fatigue
☑ Save In 1 iterations

Fig.16.21. Profile evolution parameters

The loading results are stored in the *WheelLoadData.txt* text file and include

- Arrays of contact coordinates, normal and contact forces in one section of each of the wheels, the period of data is one revolution of the wheel;
- Current wheel profiles.

The results are stored taking into account symmetries of the project:

- If the forward/backward key is on, data on the rear wheels are joined with the corresponding front wheels;
- If symmetric wear for wheelset is foreseen, data for the right wheels are joined to those for the left ones.

The file includes comments describing the output format. The *WheelLoadDataShort.txt* is the same data file, but it does not include comments.

16.5. References

1. Chudzikiewicz A., Kalker J.J. Wheel-rail wear calculation with the FASTSIM routine // The Archives of Transport, Vol. 1, No 1-2, Warsaw, 1989.
2. Krettek O., Szabó A., Békefi E., Zobory. I. On Identification of Wear Coefficient Used in the Dissipated Energy Based Wear Hypothesis // Proc. of the 2nd Mini Conference on Contact Mechanics and Wear of Rail/Wheel Systems, Budapest: 29–31 July. Budapest: 1996. P. 260–265.
3. Braghin F., Bruni S., Resta F. Wear of railway wheel profiles: a comparison between experimental and a mathematical model // 17th IAVSD Symposium Dynamics of Vehicles on Road and Tracks (IAVSD 2001), P. 43–45.
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