

D-BN

User Manual for the ECB Circulation Model for Banknotes

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For Circulation Model Version 9

9 August 2017

Revision History of this manual

Revision	Date	Comment
1	19 May 2015	First version for Circulation Model V3
2	28 August 2015	Updated version for Circulation Model V4
3	6 June 2017	Updated version for Circulation Model V8.0.1
4	19 June 2017	Correction of errata, update for V8.0.2
5	9 August 2017	Update for V9

Version History of the circulation model

Version	Date	Comment
1	19 January 2015	First release for BSTF and PROFIT discussion
1.1	22 January 2015	Better calculation of sensor threshold → more stable steady state
2	28 January 2015	Integrate processing costs & defects in model Review of algorithm for constant quality target
3	19 May 2015	Included annual change in note volume, hoarding, negative net issuance, different ageing functions, simple and expert mode, recirculation.
4	28 August 2015	Move of all calculations to VBA → Faster calculations. New algorithm for defects taking into account soil level Batch calculation of multiple cases Fixing of a bug in the ageing function of V3
5-8	16 May 2017	Complete code review, bug fixes, removal of need for Excel Solver, introduction of model function as UDF, introduction of tools for easier modelling. Improved error handling.
8.0.1	6 June 2017	Bugfix for storing of note profiles
8.0.2	19 June 2017	Formatting fixes, fix for weekly costs on '2 Cases' sheet.
8.0.3	26 June 2017	Recirculation Threshold can now be set to any value.
9	9 August 2017	Correction of banknote inflows. Output of costs for circulation increase.

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N.B.: This manual refers to entries in the circulation model by the naming in column A of the main sheets of the model¹ and quotes these values in brackets (i.e. [F1] relates to the NCB sorting costs).

The model is available for public download at:

<http://www.ecb.europa.eu/euro/cashprof/html/index.en.html>

¹ The sheets '2Cases', 'Whatlf', 'Whatlf2' and 'Solver'

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1. Introduction

The Circulation Model has been developed by the ECB's Directorate Banknotes in close consultation and rounds of testing and improving by the NCB members of the Banknote Sorting Task Force (BSTF).

The aim of the model is to provide a better understanding on the impact of the different parameters on the euro banknote cash cycle with a special focus on the impact of NCB sorting policies on note quality and replacement rates.

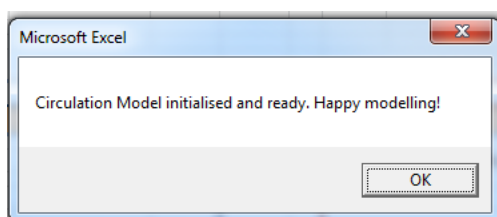
This manual explains how to operate the model (Section 2) as well as the algorithm behind (Section 3). Furthermore it describes the different input parameters (Section 4) and explains the results (Section 5). Section 6 provides a step by step example of a single calculation step of the model, whereas in Section 7 the use of the more advanced modelling functions ('*WhatIf*' and '*Solver*') is explained. Dedicated sections on known issues and tips and tricks can be found at the end.

2. How to operate the model

2.1 Opening the model

It is strongly recommended that you copy the Excel workbook containing the model to your local hard-drive before opening it. When the model is opened for the first time you will be asked by Excel to turn on the included macros, which needs to be accepted as otherwise the model will not function.

After opening the model a first initialisation will take place which should take no longer than 2-3 seconds. Afterwards you will receive the following message:



2.2 Basic principles

The model is implemented as a function in Excel VBA and can be run via different worksheets. The most simple way to run the model is via the worksheet '2Cases' which provides full access to all model functions and also displays the results in a graphical format. The function of this sheet is to directly compare two cash-cycles to each other.

Additional functions which are useful to be accessed from any worksheet of the model have been put in a dedicated ribbon called 'Circulation Model' as can be seen in figure 1 below.

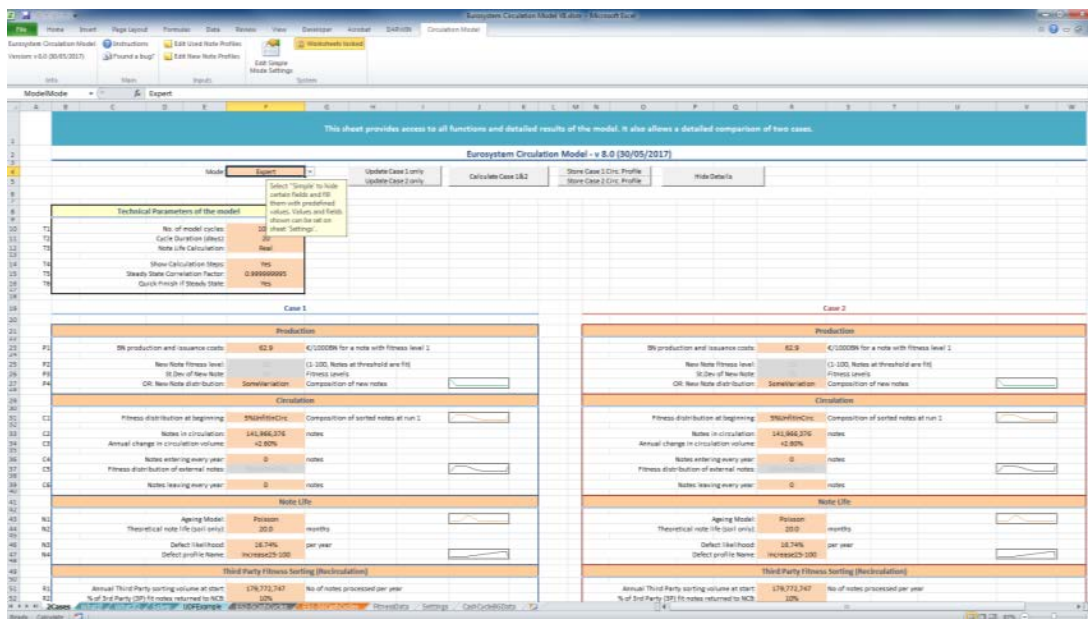
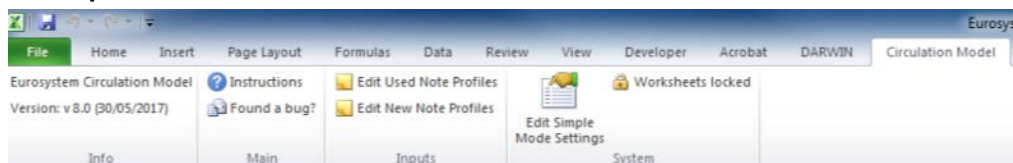


Figure 1: Main sheet '2Cases' of the circulation model with 'Circulation Model' ribbon shown

2.3 Description of the functions in the 'Circulation Model' ribbon



Instructions: Opens this document (works only if you are connected to the ESCB network and have DARWIN access).

Found a bug?: Opens an empty email to the author for providing feedback.

Edit Used Note Profile: Jumps to the sheet 'FitnessData', where you can edit the profiles of used notes which shall be available to the model as starting conditions, adding or overwriting existing ones.

Edit New Note Profile: Same as the previous command bringing you to the worksheet containing the profiles for new notes used by the model (used in [P4], if [P2] and [P3] are not specified).

Edit Simple Mode Settings: See the description for simple and expert mode in chapter 4.1. Pressing this button takes you to the sheet 'Settings', where you can define the starting values used in the simple mode of the model and also define whether or not an entry will be shown to the user when in simple mode.

Worksheets locked: Shows all hidden sheets and removes the protection. Proceed with care!

In detail, this function un-hides the following additional worksheets:

'ResultsCM': Shows detailed results and fitness profiles of each calculation cycle when the model is run from the '2Cases' worksheet.

'ResultsWI': Shows detailed results and fitness profiles of each calculation cycle when the model is run from the 'WhatIf' or 'WhatIf2' worksheet.

'Results': Shows detailed results and fitness profiles of each calculation cycle when the model is run from any other worksheet.

'Interpolation': Calculates weekly results for display in the results charts on the '2Cases' sheet via interpolation irrespective of the calculation cycle duration given in [T2].

'Options': Some settings for the ribbon and dropdown menus.

2.4 Description of the buttons in the '2Cases' sheet



Update Case1/2 only: Calculates only Case1/2, leaving the other case untouched and updates the comparison figures in the Results section of the sheet.

Calculate Case 1&2: Calculates both cases again and updates the results.

Store Case1/2 Circ. Profile: Stores the note profile in circulation after the last run (i.e. the final steady state fitness profile in circulation shown in the results section) of either Case1 or Case2 into one of the 10 available slots of the starting profile [C1]. You need to provide the slot of the profile and a new name for the profile. If no name is specified the existing one is kept.

N.B.: After storing a profile, the name in [C1] is cleared for both Case1 and Case2 and needs to be selected again.

Hide Details: Hides a major part of the detailed results showing only the final summary results of the model.

2.5 Description of the layout of the ‘2Cases’ sheet

The worksheet is set up to study the impact of various parameters to the sorting and ageing of notes by comparing two cases. The model inputs are at the top, whereas at the bottom of the sheet the results are displayed in different sections, as can be seen in the layout below.

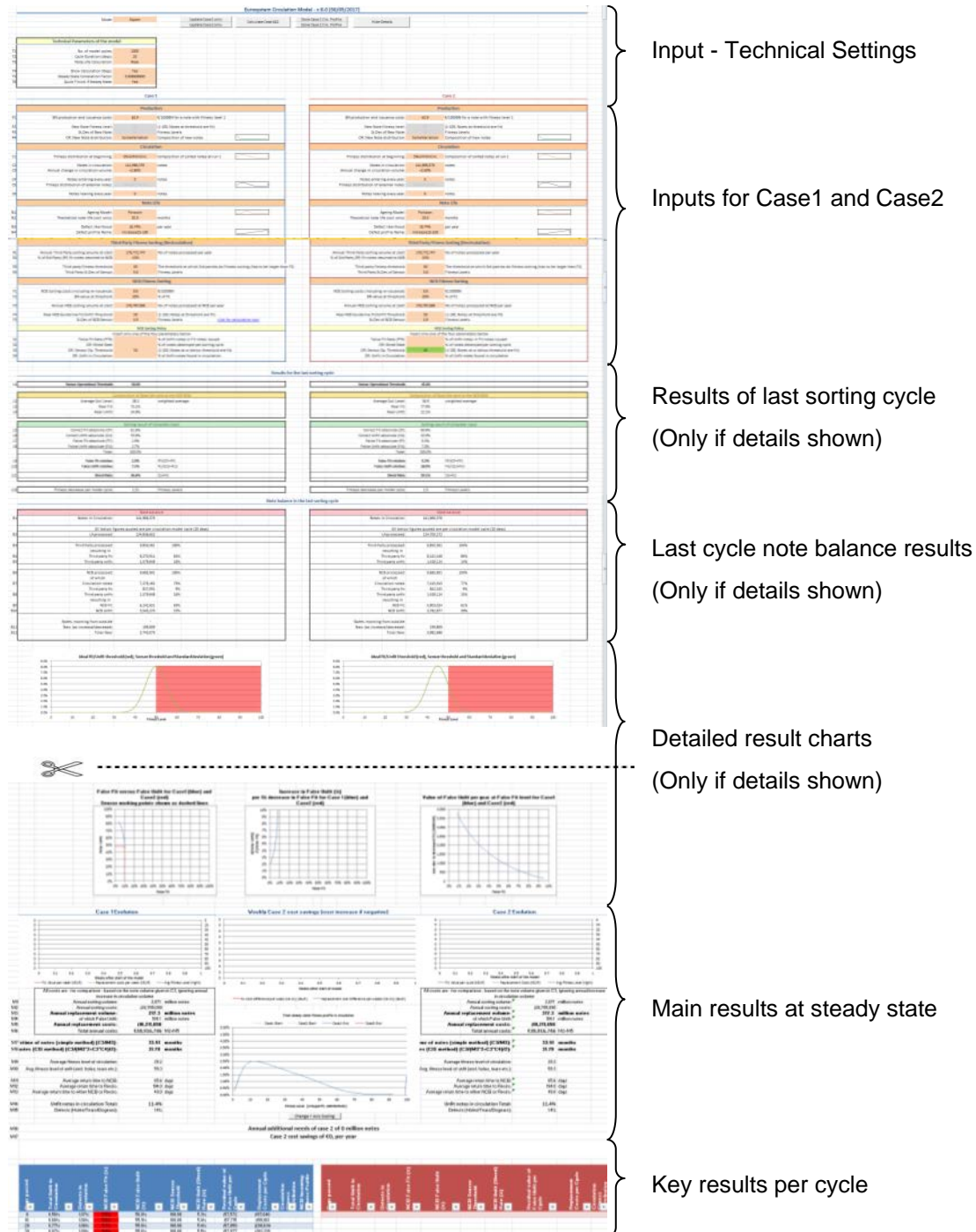


Figure 2: Overview of the various sections of the ‘2Cases’ sheet of the circulation model

3. Circulation Model Algorithm

3.1 Algorithm flowchart

The chart below shows the basic flow of the algorithm and the different sorting steps applied, as well as the naming of the various banknote flows (V). Details on the various stages are found also in chapter 4 (Inputs) and an exemplary calculation step with actual results and figures are shown in chapter 6.

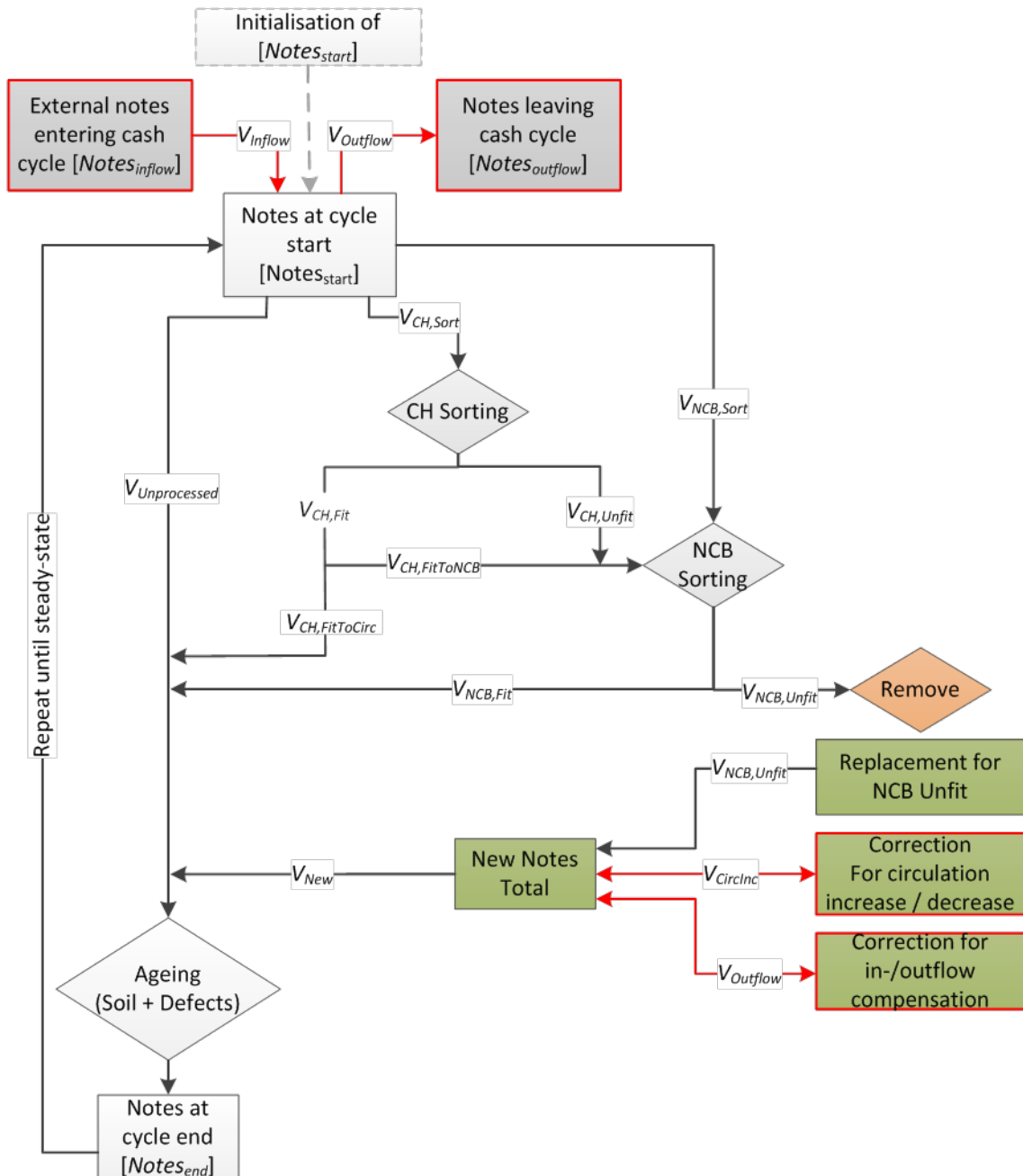


Figure 3: Algorithm flowchart of the circulation model

3.2 High-level flowchart description

- 1) The model takes as a starting point the fitness distribution of notes in circulation (*CN_Start*)
- 2) The notes are first subjected to a recirculation sorting step (*RSort*).
- 3) The notes are then sorted by the central bank (*CBSort*). The profile of notes sorted by the CB is a mix of the notes from circulation (*CN_Start*), the recirculation unfit (*R_Unfit*) and the excess recirculation fit (a definable fraction of *R_Fit*) sent back to the NCB.
- 4) Notes sorted to unfit by an NCB (*CB_Unfit*) are replaced with notes specified in the profile (*N_New*)².
- 5) Additional notes with profile (*N_New*) are added to the circulation (or the volume of new notes is reduced) for the annual growth/decrease (*N_CircInc*) and to compensate for any in- or outflows (*N_Out*).
- 6) All notes (the notes not processed in this cycle (*CN_Start*), the notes sorted to fit by third parties (*R_Fit*) and the central bank (*CB_Fit*), as well as any new notes (*N_New*)) are again mixed together to create the circulation profile at the end of the cycle (*CN_End*)
- 7) The *CN_End* profile is aged by a separate soiling and defect functions.
- 8) *CN_End_Aged* is compared to *CN_Start*. If the correlation between the two profiles is higher than the specified correlation coefficient, the steady state condition has been reached and the final results are displayed to the user. Otherwise *CN_Start* is set to *CN_End_Aged* and steps 1-7 are repeated.

² *N_New* can be any note profile and can also be e.g used notes.

3.3 Basic modelling concepts

For a detailed explanation of one model cycle please refer to chapter 6.

3.3.1 Fitness levels

- 1) Any banknote distribution (e.g. *CN_Start* being the starting distribution of the notes in circulation) is characterised as a one-dimensional array with 100 fitness levels (1 = Superfit, 100 = Superunfit/Defect).
- 2) The fitness levels are homogenously spaced with regards to sensor performance and ageing. This means that e.g. a note ages for an identical amount of levels in each calculation cycle irrespective of its current fitness level and that the NCB or recirculation sensor inaccuracy/performance in determining fit or unfit is identical across the whole fitness range³.

3.3.2 Ageing of a banknote

- 3) Within each model cycle the notes age according to a selectable distribution function [N1] for an average number of soil levels [L12]. [L12] is calculated by the theoretical note lifetime [N2], the cycle duration [T2], the quality of the new notes [P2, P3 and P4] and the Guideline fit/unfit threshold [F4].
- 4) In addition to this ageing, a banknote has a certain likelihood (expressed as percentage per year) to suffer a defect [N3] which immediately moves the note to fitness level 100 (defect), irrespective of its current fitness level.
- 5) Whereas the ageing is applied homogenously across all fitness levels, the defect likelihood [N3] is applied to the banknote distribution according to a selectable profile [N4] in relation to the notes soil level. By this approach it can e.g. be modelled that banknotes with a higher soil value have a higher likelihood of becoming defective.

3.3.3 In- and outflows of banknotes

- 6) The model allows the simulation of banknote inflows (where the volume [C4] and fitness profile [C5] needs to be specified), as well as banknote outflows (where only the volume [C6] needs to be

³ It is known from Eurosystem internal studies that the performance of a fitness sensor is not constant over the fitness range, however, usually fitness sensors operate at a certain working point at which the performance is then constant. For modelling of cash cycles the respective inaccuracy of the sensor at the set or expected working point should be used.

specified, as the fitness profile of the banknote outflows is assumed to be identical to the current circulation in the modelled cash cycle).

- 7) In- or outflows have no impact on the number of notes in circulation specified in [C2]. For outflows this is achieved by the missing notes being replaced in each modelling cycle with additional notes issued by the NCB having the (N_New) profile. For inflows the respective NCB replacement volume with new notes in each cycle is reduced accordingly.

3.3.4 Circulation volume increase

- 8) The number of new notes which need to be added to cover for the general increase of notes in circulation or the reduction in new notes due to a decrease in the note volume (specified in [C3] either as positive or negative growth) is applied in every cycle by an according increase or decrease of new notes added. However, at the end of each cycle the fitness profile and note volume is normalised to the circulation figure provided in [C2]. This is so that the model can, at fixed NCB sorting volumes [F3] and third party sorting volumes [R1] reach a steady state. Otherwise, at a constant sorting volume but changing total circulation the model would never reach a steady state⁴. As a result all modelling results are normalised to the starting conditions and different cases can also be compared more easily to each other.

N.B.: While the model takes into account the effect of note volume increase and decrease on the note profile, the costs output by the model are ALWAYS the costs of the cash cycle having the circulation and processing volume as specified at the starting point! By this approach the comparison of multiple cases is ensured irrespective of the cycles/time needed to reach steady-state.

3.3.5 Cost of replacement and false unfit banknotes

- 9) Banknotes lose value from fitness level 1 (where they have a value of [P1]) to the real fit/unfit threshold [F4]; at this threshold they have a residual value of [F2] which is expressed as a percentage of [P1], corresponding to the residual value of a note being just fit to be issued once more.

⁴ E.g. at an annual note volume increase of 10% at constant NCB sorting volume the quality in circulation constantly degrades, whereas at a constant volume decrease the quality would improve but the NCB would eventually run out of the specified note volume to sort.

- 10) When calculating the cost of false-unfit (good notes incorrectly shredded), only the residual value of each note is taken into account and not the full price of a new note.

3.3.6 Sorting of banknotes

- 11) The NCB and recirculation fitness sensors sort notes at a defined threshold (specified for recirculation in [R3] and for the NCB via one of the parameters [S1] to [S4]), but have an inaccuracy in classifying notes into fit or unfit, which results in False Fit (unfit notes being re-issued) and False Unfit (fit notes prematurely destroyed by NCB or prematurely returned to NCB by the recirculation entity) notes. This inaccuracy is modelled by a normal distribution and expressed as standard deviation with regards to the 1-100 fitness levels (parameters [R4] and [F5]).
- 12) Notes with fitness level 100 are treated as defects and are always sorted to unfit by an NCB or recirculation sensor, irrespective of sensor threshold and sensor accuracy.

3.3.7 NCB Sorting policies

- 13) NCB sorting can be done in one of four modes (policies), depending on which of the parameters ([S1]-[S4]) is provided. These modes are:
- Constant False Fit Rate [S1]: The sensor threshold at NCB sorting is in each cycle adjusted so that the notes coming from the sorting machine will contain the given amount of False Fit banknotes limit, if possible⁵. With this mode the quality of the notes issued by the NCB is tried to be kept constant irrespective of the input.
 - Constant Shred Rate [S2]: The sensor threshold is adjusted so that the shred rate (% of notes sorted to unfit by the NCB) is kept constant irrespective of the input quality. As a result the note quality reissued is directly related to the note quality sorted by the NCB.
 - Constant Sensor Threshold [S3]: The sensor threshold is left at a constant setting irrespective of the incoming quality. As a result, due to the sensor inaccuracy there will be a slight dependence on the input note quality on the notes reissued by the NCB.
 - Constant Quality in Circulation [S4]: The sensor threshold is adjusted at each cycle to issue notes of a quality that in the end will achieve a requested amount of unfit in

⁵ E.g. if the input to the sorting machine contains only 5% unfit, it is impossible to issue a note population with 8% False Fit.

circulation (This sorting mode is indirect in the sense that the result cannot be achieved within one single sorting cycle, but the final quality in circulation is reached gradually)⁶.

For this sorting mode, in case the starting conditions are far from the required quality level, the model could become unstable and start to oscillate. Use this policy only with a starting distribution close to the desired quality in circulation.

In reality most NCBs are sorting with a constant sensor threshold (some NCBs are also known to sort at a constant shred rate), especially as it is difficult to apply a sorting policy that constantly sorts based on a parameter that changes with the current note quality (e.g. false fit rate) or is difficult to determine (quality in circulation). The aim of the additional policies in the model is to show the impact on note quality and to apply in the end potentially sorting policies which are more efficient for the respective cash-cycle.

⁶ In reality this would require an NCB to constantly know the quality of banknotes in circulation which in reality is not the case.

4. Inputs on sheet '2Cases'

This section describes the various model inputs. Their description is also available on most sheets by selecting the respective field. A description is then shown as a tool-tip.

Technical Parameters of the model		
T1	No. of model cycles:	1000
T2	Cycle Duration (days):	2
T3	Note Life Calculation:	Re
T4	Show Calculation Steps:	Y
T5	Steady State Correlation Factor:	0.9999
T6	Quick Finish if Steady State:	Y

Number of cycles for the circulation model (1-1000), must be large enough for the model to reach steady state (SS), if SS conditions are relevant.

Figure 4: Example tool-tip

4.1 Mode

Options: Simple / Expert

Function: As a standard, when opening the Circulation Model it is set to 'Expert Mode', where all options are visible and can be edited. By setting the model to 'Simple Mode' certain entries of the model will be hidden and standard values are set for these hidden values, as well as starting values will be set for the other entries. The values and whether a parameter is shown to the user can be defined in the sheet 'Settings'.

Use: By switching to Simple mode, certain – less relevant – model parameters are set to standard values and hidden from view for simpler modelling.

4.2 Technical parameters of the model

4.2.1 T1 - No. of model cycles

Options: 1 – 1,000 (Integer)

Function: Number of cycles for the circulation model, must be large enough for the model to reach steady state (SS), if SS condition is relevant.

Use: This value defines how often, as a maximum, a single model cycle as described in chapter 3.2 above is carried out. One cycle has a duration (in days) specified in [T2] below.

N.B.: See also Tips and Tricks on how to quickly reach steady state conditions.

4.2.2 T2 - Cycle Duration (days)

Options: 7 - 60 (Days passed in each cycle, can also be non-integer)

Function: Defines the length of one model cycle in days, i.e. after how many days the progress is re-evaluated, the model profiles updated and checked if steady-state has been reached. Within the general accuracy of the modelling the setting only has a small impact on the final results.

Use: Suggested setting: 7-10 days

4.2.3 T3 - Note Life Calculation

Options: Ideal, Real

Function: Selects one of two methods to calculate the average note ageing per cycle based on the cycle duration [T2], theoretical note life (soil only) [N2], the Real NCB Guideline Fit / Unfit Threshold [F4] and the new note distribution [P2] - [P4].

Ideal: Note life is calculated from fitness level 1 (Superfit) to the fit/unfit threshold [F4]

Real: Note life is from the average fitness level of new notes (specified in [P2]-[P4]) to threshold [F4]

Example

Banknotes have an average life (soil only) of [N2] 12 months (i.e. 360 days), Cycle duration [T2] is set to 30 days. The new notes on average have, due to production variation, a fitness level of 10 and the NCB fit/unfit threshold [F4] is at 50:

Results: Ideal Note ageing: $(50-1) / (360/30) = 4.08$ fitness levels per cycle

Real Note ageing: $(50-10) / (360/30) = 3.33$ fitness levels per cycle

Use: If the same new note profile is selected for both cases, 'Real' shall be selected for correct results. In case the influence of different new note qualities or production variation is studied then 'Ideal' needs to be selected, as otherwise the difference in the starting quality (average fitness level) will be cancelled out by the ageing calculation.

4.2.4 T4 - Show Calculation Steps

- Options: Yes, No, Yes incl. charts
- Function: Yes: Shows the model results per cycle but does not create charts
 Yes incl. Charts: Same as above, also showing charts
 No: Hides the output of any interim results
- Use: To significantly speed up calculation.
 Example calculation times: No: 0.8 sec. - Yes: 20sec - Yes incl. charts: 40 sec.

4.2.5 T5 - Steady State Correlation Factor

- Options: 0.9 – 1 (Decimal)
- Function: After each cycle, the model compares the resulting profile of notes in circulation with the starting profile. If the correlation coefficient (using the Excel CORREL function) between the last two runs is larger than the value specified here, then steady state is assumed. If T6 below is set to 'Yes' then calculation is stopped.
- Use: To stop calculation once steady state is reached.

4.2.6 T6 - Quick Finish if Steady State

- Options: Yes, No
- Function: Once the correlation coefficient is larger than specified in T5, the calculation is stopped
- Use: To stop calculation once SS is reached as additional calculation cycles will no longer change the result.

4.3 Production parameters of the model**4.3.1 P1 - BN production and issuance costs**

- Options: 0 - 500 (EUR/1,000 BN)
- Function: Cost for new banknotes of the respective denomination in EUR/1,000BN. Shall be the total costs including costs for issuance in order to evaluate the specific case correctly.
- Use: This value is used for calculating the replacement costs for new notes and for the residual value of aged note that are sorted to unfit at the NCB (i.e. shredded) prematurely, taking into account also the value specified in [F2].

4.3.2 P2 - P4 – Specification of the new note profile

In order to simulate production variations, the fitness profile of new notes which are used in the model to replace notes going to unfit, need to be issued due to increase of the circulation volume or due to in- and outflows can be specified here. This can be done by specifying a normal distribution providing average [P2] and standard deviation [P3]. Alternatively any new note profile can be specified in the sheet 'FitnessData' from Column Q onwards and selected in [P4]. If [P4] is not empty, then the values specified in [P2] and [P3] will be ignored.

Parameter: P2 - New Note fitness level

Options: 1 – 99 (Decimal)

Function: The average fitness level of a new note.

Parameter: P3 - St. Dev of New Note

Options: 0 - 100 (Decimal)

Function: The standard deviation (in fitness levels) of new notes issued (i.e. production variation).

N.B.: In case P2 and P3 are specified, the not useable part of the distribution (i.e. entries that would have negative fitness levels or a fitness level of 0 due to the normal distribution function) will be ignored and the positive part will be normalised.

Parameter: P4: New Note distribution

Options: Any profile in sheet 'FitnessData' from column Q onwards, if left blank (by deleting any entry in the field using the 'DEL' key) then [P2] and [P3] are used. The profile provided in the sheet 'FitnessData' does not need to be normalised (will be done by the model).

4.4 Circulation parameters of the model

4.4.1 C1 - Fitness distribution at beginning

Options: Any profile specified in sheet 'FitnessData' from column C to M can be selected. The profile provided does not need to be normalised (will be done by the model).

Function: The distribution profile of the notes in circulation which is used as input in the first sorting cycle. New profiles can be added in the sheet 'FitnessData', or results of the model can

be saved as a new fitness distribution using the 'Store Case 1/2 circ. profile' buttons at the top of the '2Cases' sheet.

Use: Highly relevant on how quickly a steady state is reached or for dynamic modelling exercises. The closer this starting profile is to the steady state, the quicker the model computes the final results. In other cases where not the SS condition is relevant, but where the evolution of the circulation over time is interesting (e.g. studying the issuance of a new series), a different starting profile (e.g. New Note) can be selected and the results of each model cycle can be studied to see how the circulation changes over time.

4.4.2 C2 - Notes in circulation

Options: Larger than 0 (Integer)

Function: Amount of banknotes in circulation for the investigated cash cycle.

Use: Typical input is the number of active notes in circulation per denomination. Notes which are known to be outside of the respective cash-cycle or hoarded should be excluded.

4.4.3 C3 - Annual change in circulation volume

Options: -100% to +100%

Function: Annual increase or decrease of circulation volume due to demand changes. Will be considered for note quality and sorting parameters, BUT NOT for overall replacement costs in order to allow a neutral comparison between two cases with different note growth rates. The costs/saving due to circulation increase/decrease are output for information in result [M7]. All costs given are - for comparison - given based on the starting volume provided in [C2] (See also chapter 3.3.4).

Use: An increase in note volume has a 'cleaning effect' on circulation as more new banknotes are added to the cash cycle making overall quality better, a decrease in note volume has a contrary effect as no more new notes are issued for some of the unfit notes taken out of circulation.

4.4.4 C4 – Notes entering every year

Options: Larger than or equal to 0 (Integer)

Function: The number of notes per year entering a cash-cycle from outside having the profile specified in [C5]. As the note volume in circulation is kept constant by the model an inflow of notes is compensated by an according reduction of new notes added in each cycle.

Use: To simulate flows of notes entering a certain cash cycle (e.g. for countries having a negative net-issuance), see also section 3.3.3.

4.4.5 C5 - Fitness distribution of external notes

Options: Any profile specified in sheet 'FitnessData' from column AE to AO can be selected. The profile provided does not need to be normalised (will be done by the model).

Function: The distribution profile applied to the number of notes entering the cash cycle specified in [C4]

Use: Used to model the impact of inflows of cleaner or more soiled notes than the active circulation.

4.4.6 C6 – Notes leaving every year

Options: Larger than or equal to 0 (Integer)

Function: The number of notes per year leaving a cash-cycle. The notes leaving are assumed to have the fitness profile of the current circulation. As the note volume in circulation is kept constant by the model an outflow of notes is compensated by an according increase of new notes added in each cycle.

Use: To simulate flows of notes leaving a certain cash cycle (e.g. for countries having a positive net-issuance), see also section 3.3.3.

4.5 Note Life parameters of the model

4.5.1 N1 - Ageing Model

Options: List of pre-defined ageing functions

Function: Defines which ageing function is applied in each cycle to the notes in circulation. The following functions are available (using the built in Excel functions to generate the distributions)⁷:

Poisson: Poisson_Dist with mean = Average Ageing per cycle

⁷ The model requires discrete values for the ageing probability per increase in fitness level. The only supported function having a discrete distribution is the Poisson distribution. For all other functions the required parameter to achieve the average ageing per cycle defined as described in section 4.2.3 is determined via a linear approximation algorithm; the mentioned shape parameter of the distribution function is defined so that the resulting curve has in its discrete form the needed ageing per cycle.

Exponential: Expon_Dist with $\lambda = f(\text{Average Ageing per cycle})$

LogNormal 0.8: LogNorm_Dist with $\text{mean} = f(\text{Average Ageing per cycle})$
 $\text{standard_dev} = 0.8$

Gamma a1/a9/a10/: Gamma_Dist with $\alpha = 1, 9 \text{ or } 10$ and
 $\beta = f(\text{Average Ageing per cycle})$

Weibull k1.5: Weibull_Dist with $\alpha = 1.5$
 $\beta = f(\text{Average Ageing per cycle})$

Use: The notes age on average, per cycle according to the calculations shown in 4.2.3 (T3 - Note Life Calculation). See also the example there. This average amount of loss of fitness levels per cycle can be achieved according to various distributions as shown in the figure below⁸. The ageing model selected here defines the distribution of notes which age less or more than the average and sets the according profile which is applied in each cycle to the circulation notes.

N.B.: The exact ageing model has shown to have only a limited impact on the model results. Poisson ageing is suggested as an approximation for the average cash cycle.

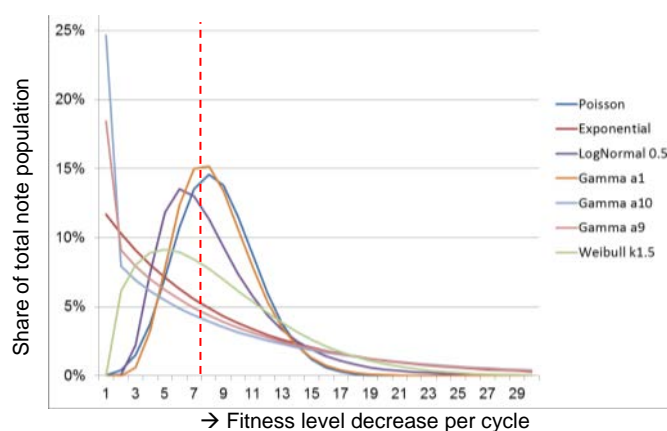


Figure 5: Various ageing distribution functions, all having an average ageing of 7.5 fitness levels per cycle.

⁸ As an extreme example, if notes on average lose 5 fitness levels per cycle, this can be 'achieved' but all notes losing exactly 5 fitness levels or e.g. 75% of the notes not ageing at all and 25% of the notes ageing by 20 levels.

4.5.2 N2 - Theoretical note life (soil only)

Options: Between 0 and 1,000 (months)

Function: Average lifetime of a note until it reaches the Fit-Unfit Threshold [F4], if it does not suffer a defect.

Use: This is the theoretical average lifetime of a note from its first issuance to the fit/unfit threshold. This figure does not take into account when it will actually be sorted out (e.g. if an NCB sorts more or less severely but also the return time to the NCB plays a role here) or whether a note has prematurely become unfit due to suffering a defect.

The actual lifetime of a note, taking also into account NCB sorting policies and defects is given as a result in [M8] and [M9]. For modelling a real cash cycle, these last two values should match a central banks actual data as a result of the model.

4.5.3 N3 –Defect likelihood / Year

Options: 0 - 100,000 %

Function: The likelihood in % per year that a note in circulation will suffer a defect (tear, tape, hole ...) that, when found either during NCB sorting or third party sorting, will result in its sorting to unfit irrespective of the fitness level. This ageing is ON TOP of the theoretical note life defined in [N2]. This factor is applied to the circulation note profile weighted across the fitness levels using the defect profile specified in [N4]. Defective notes will be assigned the fitness level 100 (super-unfit) and sorted to unfit at the next time the note is sorted by a third party or the central bank.

Use: To model defects (together with the profile [N4] below).

4.5.4 N4 – Defect profile name

Options: List of pre-defined defect profiles

Function: To model that the likelihood of a note becoming defective is related to its overall fitness level. Any profile can be specified in the sheet '*FitnessData*' from column AS onwards. The selected profile is a weighting of the total number of defects which are applied to all notes (specified by [N3] above) across the note distribution in circulation.

Use: To model defects, together with the parameter [N3] above.

On the modelling of defects

The approach implemented in the model is based on the real-life experience where usually defect notes removed from circulation are already soiled and the ageing of a note makes it more likely for them to become e.g. torn or have tapes applied to them.

Below 3 examples of applying different profiles are shown:

'Increase from 1' Profile: 

The probability of a note to become defective is increased with its soil level. *With this approach for most cash cycles good matches to real-life quality data were found.*

'Constant' Profile: 

All notes in circulation have the same probability to suffer a defect, except those already having a fitness level of 100 (i.e. are defective).

'Increase 50-75' Profile: 

In this case notes below 50 soil levels never become defect and notes above 75 have the maximum likelihood to become defective within a year. Notes between 50 and 75 fitness levels have a linearly increasing probability to become defective.

4.6 Third Party Fitness Sorting (Recirculation) parameters of the model

Sorting by third parties is modelled similar to NCB fitness sorting at a fixed threshold with the third parties using also fitness sensors that have normal distributed errors. All notes sorted as unfit by the third party (whether correct unfit or false unfit) are returned to the NCB and processed there. In addition, as is the case for some cash cycle, a certain percentage of notes sorted to fit by third parties can be selected to be returned to the NCB. This is to model excess fit stocks of third parties which are returned to the NCB.

4.6.1 R1 – Annual Third Party sorting volume at start

Options: Any non-negative integer

Function: Number of notes processed by third parties, can be 0.

Use: For the recirculation volume the figure as reported via the ECB Decision on recirculation and fitness sorting can be used, put to zero if no recirculation shall be modelled, in which case [R3] and [R4] are greyed out and not used.

4.6.2 R2 – % of Third Party Fit Notes returned to NCB

Options: 0 - 100 %

Function: The percentage of fit notes which (in each model cycle) are returned to the central bank for sorting.

Use: To model the impact of these notes when processed by an NCB.

A word on the note balance

The number of notes sorted at the NCB [F3] consists of (see also figure 3):

- 100% of Third Party Unfit notes
- + [R2]% of Third Party Fit notes
- + Notes from Circulation

In each cycle the number of notes from circulation is adjusted so that the total NCB sorting volume sums up to [F3]. In case the model should reach a stage where the number of Third Party Unfit + Third Party Fit to NCB is larger than the NCB sorting volume, the calculation is aborted and an error is displayed. In this case either:

- The NCB sorting volume needs to be increased
- [R2] needs to be reduced
- The number of third party unfit needs to be reduced (e.g. by more lenient sorting)

4.6.3 R3 – Third Party Fitness Threshold

Options: 0 - 100 (decimal)

Function: The threshold at which third parties do fitness sorting. In most cases this value is larger than the Guideline Fit/Unfit Threshold [F4] as cash-handlers usually sort less severely than central banks.

Use: To model the difference between NCB and third party sorting standards. For the Eurosystem the fitness level of the notes used for testing of third party machinery shall be used for modelling.

4.6.4 R4 – Third Party Standard Deviation of Sensor

Options: 1 – 99 (decimal)

Function: Standard deviations (inaccuracy) of the fitness sensor in fitness levels assuming a normal distribution. This parameter is similarly applied to the third party sorting as [F5] is to NCB sorting.

Use: A figure for the inaccuracy of the recirculation fitness sensor. Similar values as for NCB fitness sensors can be used.

4.7 NCB fitness sorting parameters of the model

4.7.1 F1 – NCB Sorting costs (including re-issuance)

Options: 0 – 500 (EUR/1,000 notes)

Function: Average costs for processing (i.e. receipt, sorting, packing, re-issuance or destruction) 1,000 notes at an NCB.

Use: The total cost for NCB processing. Use costs relevant for your specific cash cycle.

4.7.2 F2 - BN value at threshold:

Options: 0 – 100%

Function: The percentage of its original value [P1] a note has at the Guideline Fit/Unfit threshold [F4], i.e. the residual value of a note that can be issued just once more. For all other fitness levels between 1 (Superfit) and the threshold [F4] values are linearly interpolated (see figure below).

Use: For calculating the actual value of the false unfit notes destroyed by an NCB taking into account its residual value.

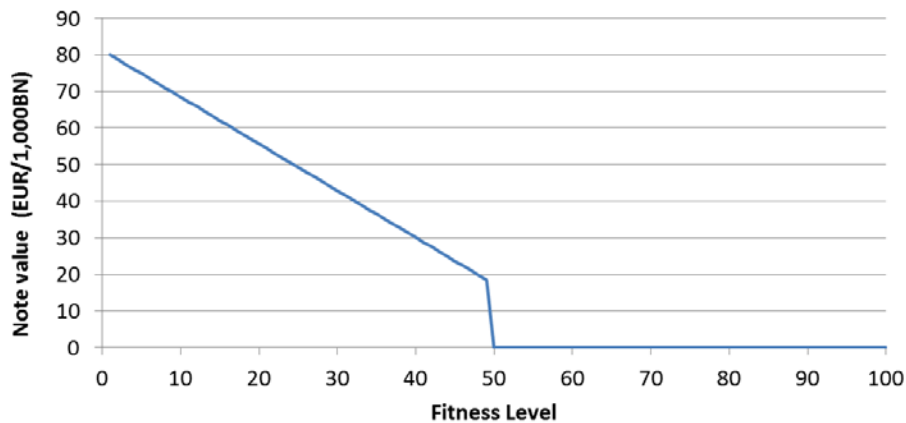


Figure 6: Value of notes at each fitness level (New note issuance costs [P1]: 80 EUR/1,000notes, Guideline Threshold [F4]: 50 Fitness Levels, Residual value [F2]: 20%)

4.7.3 F3 - Annual NCB sorting volume at start

Options: Larger than 0, integer

Function: Annual number of notes sorted at an NCB, consisting of notes coming from circulation, unfit recirculated notes and – if specified - a share of fit recirculated notes. In case the annual change in circulation volume [C3] is non-zero, the sorting volume will scale with the notes in circulation⁹, as otherwise no steady state can ever be reached (e.g. if the note volume continuously increases while the sorting volume would remain constant, the quality in circulation would continuously decrease).

Use: For modelling the NCB sorting volume in the specific cash-cycle.

4.7.4 F4 - Real NCB Guideline Fit/Unfit Threshold

Options: 1 - 100 (integer)

Function: The NCB Guideline fitness threshold. Notes above this threshold are unfit according to a defined guideline, notes at or below threshold are fit according to the guideline.

N.B.: This is the level of the 'limit banknote' and not the NCB sorting threshold. An NCB can sort either on this limit or more or less severely to adjust the circulation quality as desired. Increasing this parameter means to apply in general a more lenient fitness

⁹ If the note volume increases by e.g. 5% p.a., so will the NCB sorting volume as well as the recirculation sorting volume.

standard and has widespread impact on the model results. Normally set to 50, only adjust if necessary.

Use: To define the 'true' fit/unfit threshold of a banknote.

4.7.5 F5 - Standard Deviation of Fitness Sensor at NCB

Options: 0 - 100 fitness levels

Function: Standard deviations (inaccuracy) of the fitness sensor in fitness levels assuming a normal distribution. Can be calculated if False Fit, False Unfit and the soil distribution of the input notes at an NCB are known, using the tool linked in the circulation model. Alternatively the figure can be established by sorting a test-deck of notes with known note qualities.

Use: A value for the inaccuracy of the sorting sensor, typical values are in the range of 5 (for a very good fitness sensor) to 20 (for a below average) fitness units.

4.8 NCB Sorting policies of the model

The model supports four different NCB sorting policies. Each policy applies a different logic to setting the operational fit/unfit threshold in each model cycle. These four policies are:

4.8.1 S1 - Constant False Fit Rate (FFR)

Options: 0-100%

Function: The percentage of unfit notes (i.e. those with a threshold larger than [F4]) in the notes re-issued by an NCB.

Use: Implements a sorting policy that keeps the quality of the notes issued by an NCB at a constant level by adjusting the sensor threshold to compensate for different input qualities. *N.B.: The algorithm tries to find the closest match but in some cases may not be able to do so. E.g. if the input quality to the NCB contains only 5% unfit, it is impossible to have a sorting threshold issuing 8% false fit (i.e. unfit).*

4.8.2 S2 - Constant Shred Rate

Options: 0-100%

Function: The percentage of the notes destroyed in each cycle which are sorted at an NCB is kept constant.

Use: Implements a sorting policy that in each cycle shreds the defined percentage of the most unfit notes.

4.8.3 S3 - Constant Sensor Operational Threshold

Options: 1 - 100

Function: If selected, the sorting is carried out with this fixed setting of the fitness sensor.

Use: Implements a sorting policy that runs at a fixed sensor setting irrespective of the incoming note quality.

4.8.4 S4 – Unfit in Circulation

Options: 0-100%

Function: Specifies a quality target of the quality in circulation for the NCB sorting. If specified, the model adjusts the sorting threshold so as to keep the % of unfit notes in circulation around this level.

Use: The impact of an NCBs sorting on the quality is long-term. The algorithm is doing a forward looking 'guessing' on the quality in circulation and is UNSTABLE if the starting profile is far from the target profile. If this should happen, first try setting different shred rates [S2] to find the desired Unfit in circulation, save the resulting circulation profile and rerun the model with this profile as starting profile, now applying the quality algorithm for final results. See also the section on Tips and Tricks.

A word on the different sorting policies

In steady state conditions any of the four parameters which can be fixed for the NCB sorting policy (False Unfit Rate, Shred Rate, Sensor Threshold, Quality in Circulation) will result in identical steady stated results. I.e. if a certain cash cycle has in its steady state a FU rate of 5%, a Shred Rate of 10%, a Sensor Threshold of 45 and a quality of 15% unfit in circulation, setting either of the four sorting policies to the respective value will deliver identical results.

The main reason for the different policies is to study the impact of them on the quality in circulation over time (i.e. how quickly from a starting condition the new steady state is reached depending on the sorting policy). See also the detailed description of a sorting step in chapter 6 for further explanations.

5. Model Results

The following chapter provides an overview of the results of the model.

Detailed information on the last NCB sorting cycle at which steady state has been reached is provided below the input (results [L1]-[L12]); each item is described in chapter 5.1. The note balance (results [B1]-[B14]), are described in chapter 5.2.

Please note that the results of the last sorting cycle [L1]-[L12] and note balance [B1]-[B14] are only visible if 'Show Details' is selected on the top of the '2Cases' sheet.

Consolidated information on the overall model results are given in the tables and charts below (results called [M1]-[M21]). Each item is described in chapter 5.3.

A table at the bottom provides then for each cycle the key parameters. Each item in this result table is described in chapter 5.4.

5.1 Results of the [L]ast NCB sorting cycle

All parameters below show results of the last sorting cycle.

L1	The NCB sensor threshold according to the NCB sorting policy specified in [S1]-[S4] that was used in the last sorting cycle.
L2	The average soil level of the notes sent to the NCB sorting machine
L3/L4	The percentage of Fit/Unfit notes in the notes sent to the NCB sorting machine (share of notes in relation to [F4])
L5 – L8	Correct/False Fit and Unfit notes as outcome of the NCB sorting process at the sensor threshold [L1] as percentage of the total sorting volume.
L9	% False Fit as a share of the total notes reissued by the NCB (consisting of correct fit and false fit)
L10	% False Unfit as a share of the total notes destroyed by the NCB (consisting of correct unfit and false unfit)
L11	Total % of notes sorted by the NCB BSM which are destroyed (sum of False Unfit + Correct Unfit)
L12	The fitness decrease (note-ageing) per cycle according to the note life and the ageing method chosen (see section 4.2.3 for an example).

5.2 Note [B]alance in the last NCB sorting cycle

All parameters below show the results of the last sorting cycle.

For how these figures are calculated, please refer to the example given in chapter 6.

B1 Total number of notes in circulation ($=[C2]$)

*Values for [B3] – [B14] apply to the number of notes processed
in each sorting cycle (i.e. days specified in [T2]).*

B2 The number of notes not processed (i.e. just circulating without being seen by an NCB or third party sorting machine) within the number of days specified in [T2].

B3 Number of notes sorted by third parties

B4/B5 Notes classified as Fit/Unfit by a recirculation BHM ($[B3] = [B4] + [B5]$)

B6 Number of notes sorted by the central bank

B7/B8/B9 Composition of notes sorted at NCB of circulation, recirculated unfit and recirculation fit notes ($[B6] = [B7] + [B8] + [B9]$)

B10/B11 Notes classified as Fit/Unfit by an NCB sorting machine ($[B6] = [B10] + [B11]$)

B12 The number of notes which are coming into the cash cycle in each cycle of [T2] days (as specified per year in [C4])

B13 The number of notes which are leaving the cash cycle in each cycle of [T2] days (as specified per year in [C6])

B14 New notes entering due to change in circulation volume [C3] or due to notes leaving the cash cycle [C6]

The number of notes that need to be added or removed based on the change in circulation volume specified in [C3].

(N.B.: In case of a decrease in circulation volume or inflows, notes can only be removed from circulation by not replacing NCB unfit. I.e. the decrease can never be larger than the total amount of unfit notes. The model does not support the reduction of the note volume in circulation by not re-issuing fit notes).

B15 Total amount of new notes added in this cycle to circulation as replacement for unfit, any circulation volume increase/decrease and inflows or outflows ($[B15] = [B11]+[B14]-[B12]+[B13]$).

5.3 Detailed results of the last [M]odel sorting cycle

- M1 Annual sorting volume: The final total volume processed at NCB level per year (identical to [F3]).
- M2 Annual sorting costs ([F1] * [F3])
- M3 Annual replacement volume: The amount of new notes introduced into the cash cycle per year. (*N.B.: for any studies or cash cycle modelling this shall be crosschecked and should match real values*). *N.B.: Contains also the note volume needed to replace outflows.*
- M4 The number of notes that have been replaced with new ones despite not yet being unfit according to the Guideline Fit/Unfit threshold [F4] (i.e. False Unfit).
- M5 The residual value of [M4] according to the actual value at their fitness level (specified by [P1] and [F2])
- M6 Annual replacement costs ([M3] * [P1])
- M7 Cost/savings for increase/decrease in note volume ([C2] * [C3] * [P1])
- M8 Total annual costs for sorting and replacement excluding costs/savings for circulation volume changes ([M2] + [M6]).
- M9 Actual lifetime of notes given in months (simple method, not taking into account any annual growth):
- $$\{\text{Notes in Circulation [C2]} / \text{Annual replacement volume [M3]}\} * 12$$
- M10 Actual lifetime of notes given in months (ECB method, taking into account volume changes):
- $$LT(\text{months}) = \frac{\text{NotesInCirculation}}{\frac{\text{AnnualReplacementVolume} + \text{NotesIssuedPerYearInclIncrease}}{2}} * 12$$
- or in circulation model variables:
- $$LT(\text{months}) = \frac{[C2]}{\frac{2 * [M3] + [C2] * [C3]}{2}} * 12$$
- M11 Average fitness level of circulation: The weighted average of the fitness level of all notes in circulation (defect notes have a value of 100)
- M12 Avg. fitness level of unfit notes (excl. holes, tears etc.): The weighted average of the quality level of all unfit notes, excluding those with a level of 100 (defects).
- M13-M15 The average return time in days of a note to come back to the central bank, a third party or either of them in days.

- M16 Unfit notes in circulation Total: % of notes with a fitness value higher than [F4]
(N.B.: For modelling, this value should match the figures of the respective circulation).
- M17 Defects Holes/Tears/Dog-ears: % of total notes with defects in circulation (i.e. % of notes with a fitness level of 100)
- M18 NCB Operational sorting threshold in the last cycle (same as [L1])
- M19 Days until steady state reached (Number of cycles – in days – needed for the model to arrive at the final results) (= [M19] * [T2])
- M20 Number of cycles until model reached steady state
- M21 Annual replacement note differences: Shows the difference in notes to be replaced per year between the two cases
- M22 Annual cost difference: Outputs the total cost difference (including difference in notes shredded and processing costs) for the two cases

WARNING: In case of different annual note growth rates [C3], the comparative case 1/2 results are influenced by the different amount of new notes flowing in, with new notes having a 'cleaning function' on the overall circulation. The costs outputted DO NOT include the costs for the increased issuance, but are based on the starting volume for better comparison. See the detailed calculation steps in chapter 6 for clarification.

5.4 Descriptions of the results provided per cycle in the table

N.B.: The costs provided for the Replacement and False Unfit given in the table are PER WEEK. The values given in the main results ([M1]-[M21]) are annual figures.

No.	Item	Value (all for the respective cycle)
1	Days passed	Cycle Duration [T2] * Cycle Number
2	Total Unfit in Circulation	[M15]
3	Defects in Circulation	[M16]
4	NCB False Fit relative (%)	[L9]
5	NCB False Unfit absolute (%)	[L8]
6	NCB Sensor Threshold	[L1]
7	Shred Rate (%)	[L11]
8	Residual value of False Unfit per week	The residual value of false unfit notes destroyed per week [M5] (~[M5]/52)
9	Replacement Costs per week	[M6] per week (~[M6]/52)
10	Notes sorted by NCB (input)	The fitness profile of the notes sorted at the NCB. I.e. the weighted summary profile of circulation notes, third party unfit and a share of third party fit.
11	Notes in circulation (output)	Same profile as shown in the lower centre result chart for the respective cycle (CN_End_Aged in figure 3)

N.B.: Profiles are only shown if 'Yes, incl. charts' is selected in [T4]. In case 'Show Calculation Steps [T4]' is set to 'Yes' then no profiles are shown in the last two columns. Instead the last row shows the correlation coefficient between this cycle and the previous.

6. Example calculation step

6.1 The case

This section provides a step-by-step explanation of one calculation step of the model. For ease of understanding a fictitious case with round figures is taken, assuming that the starting note quality in circulation is homogenously distributed (all fitness levels from 1-100 have a share of 1% each in circulation, i.e. the circulation contains 50% unfit notes) and one single sorting cycle is applied with the NCB policy to achieve a false unfit rate of 8%. All starting parameters are shown in the figure below.

Technical Parameters of the model			
T1	No. of model cycles:	1	
T2	Cycle Duration (days)	30	
T3	Note Life Calculation:	Real	
T4	Show Calculation Steps:	Yes Incl. Charts	
T5	Steady State Correlation Factor:	0.999999995	
T6	Quick Finish if Steady State:	Yes	
Case 1			
Production			
P1	BN production and issuance costs:	50	€1000BN for a note with fitness level 1
P2	New Note fitness level:	50	(1-100, Notes at threshold are fit)
P3	St. Dev. of New Note:	10	Fitness Levels
P4	OR: New Note distribution:	Some Variation	Composition of new notes
Circulation			
C1	Fitness distribution at beginning:	Homogenous	Composition of sorted notes at run 1 <input type="text" value="2"/>
C2	Notes in circulation:	1,000,000,000	notes
C3	Annual change in circulation volume:	+10.00%	
C4	Notes entering every year:	250,000,000	notes
C5	Fitness distribution of external notes:	20% Unfit/Circ	
C6	Notes leaving every year:	125,000,000	notes
Note Life			
N1	Ageing Model:	Poisson	
N2	Theoretical note life (soil only):	25.0	months
N3	Defect likelihood:	10.00%	per year
N4	Defect profile Name:	IncreaseFrom1	
Third Party Fitness Sorting (Recirculation)			
R1	Annual Third Party sorting volume at start:	1,000,000,000	No of notes processed per year
R2	% of 3rd Party (3P) fit notes returned to NCB:	10%	
R3	Third party fitness threshold:	60	The threshold at which 3rd parties do fitness sorting (has to be larger than F
R4	Third Party St.Dev of Sensor:	15	Fitness Levels
NCB Fitness Sorting			
F1	NCB Sorting costs (including re-issuance):	10	€1000BN
F2	BN value at threshold:	20%	% of P1
F3	Annual NCB sorting volume at start:	3,000,000,000	No of notes processed at NCB per year
F4	Real NCB Guideline Fit/Unfit Threshold:	50	(1-100, Notes at threshold are fit)
F5	St.Dev of NCB Sensor:	10	Fitness Levels click for calculation tool
NCB Sorting Policy			
Insert only one of the four parameters below			
S1	False Fit Rate (FFR):	8.00%	% of Unfit notes in Fit notes issued
S2	OR: Shred Rate:		% of notes destroyed per sorting cycle
S3	OR: Sensor Op. Threshold:		(1-100, Notes at or below threshold are fit)
S4	OR: Unfit in Circulation:		% of Unfit notes found in circulation

Figure 7: Starting conditions for the exemplary single step model calculation.

6.2 The calculation

The calculation follows in its basic principle the flowchart in figure 3. In the following each step is described. Items in square brackets refer to model inputs. For the variable names, the same names as used in the VBA code are used for easier traceability. Variables starting with 'A_' indicate one dimensional arrays, usually from 1 to 100 containing a value per fitness level. Variables ending with 'PC' are values 'Per Cycle' of the model. The model is implemented as a VBA function called 'CalcCirculationModel' in the 'mCircModel' module of the Excel sheet with the source code being freely accessible.

1. Calculate notes sorted at NCB per cycle

$$\begin{aligned} \text{TotalNotesSortedAtNCB_PC} &= \text{NCBProcessingVolume}[F3] * \text{ModelCycleDuration}[T2] / 365 \\ &= 3 \text{ bln} * 30 / 365 = \underline{246.6 \text{ mln}} \end{aligned}$$

2. Calculate notes recirculated per cycle

$$\text{NotesRecirculatedPC} = \text{RecirculationSortingVolume} [R1] * \text{ModelCycleDuration}[T2] / 365 = 1 \text{ bln} * 30 / 365 = \underline{82.2 \text{ mln}}$$

3. Calculate note amount change per cycle (due to growth or reduction)

$$\begin{aligned} \text{NoteChangePC} &= \text{NotesInCirculation}[C2] * ((1 + \text{AnnualCirculationChange}[C3]) ^ (1 / (365 / \text{ModelCycleDuration}[T3])) - 1) = \\ &= 1 \text{ bln} * (1 + 0.1) ^ (1 / (365 / 30)) - 1 = \underline{7.9 \text{ mln}} \end{aligned}$$

4. Calculate incoming notes per cycle

$$\begin{aligned} \text{ExternalNotesIncomingPC} &= \text{ExternalNotesIn}[C4] * \text{ModelCycleDuration}[T2] / 365 \\ &= 250 \text{ mln} * 30 / 365 = \underline{20.5 \text{ mln}} \end{aligned}$$

5. Calculate notes leaving per cycle

$$\text{NotesLeavingPC} = \text{NotesLeaving}[C6] * \text{ModelCycleDuration}[T2] / 365 = 125 \text{ mln} * 30 / 365 = \underline{10.3 \text{ mln}}$$

6. Calculate defect probability per cycle

$$\text{DefectsPC} = \text{CEperYear}[N3] / 365 * \text{ModelCycleDuration} = 0.1 / 365 * 30 = \underline{0.82\%}$$

7. Do the recirculation sorting on the incoming note profile and obtain the volume of recirculation fit and unfit per cycle

The notes in circulation (A_NotesIn, as specified by profile [C1]) are subjected to a recirculation sorting step, with the recirculation sensor having a characteristic of A_RecircSensProfile, defined by the recirculation threshold [R3] of 60 and the recirculation standard deviation [R4] of 15.

A_RecircSensProfile is created using the below Excel function / code:

```
For I = 1 to 99
    A_RecircSensProfile(i) = NormDist (i, 60, 15, TRUE)
Next i
A_RecircSensProfile(100) = 1 'N.B.: notes at level 100 (i.e. defective) are always sorted to unfit
```

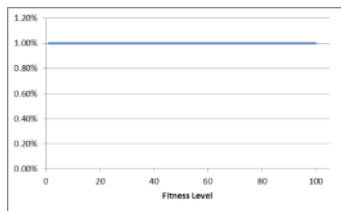
Now, for each Fitness level, A_RecircSensProfile is applied to A_NotesIn resulting in A_RecircUnfit; the same is done for (1 - A_RecircSensProfile), obtaining A_RecircFit; The below code is used for this:

```

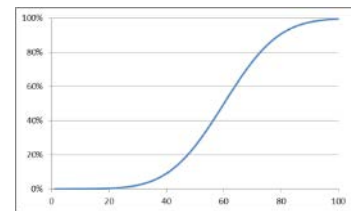
For i = 1 To 100
    A_RecircUnfit(i) = A_NotesIn(i) * A_RecircSensProfile(i)
    A_RecircFit(i) = A_NotesIn(i) * (1-A_RecircSensProfile(i))
Next i
    
```

The complete input and result profiles are shown in the charts below:

Input

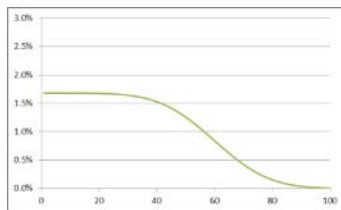


A_NotesIn (Sum = 100%), homogenous profile

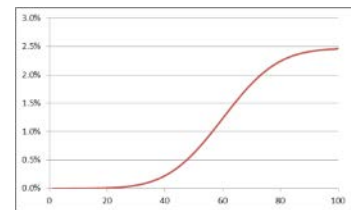


A_RecircSensProfile(Mean=60 StDev=15)

Resulting profiles (normalised)



A_RecircFit



A_RecircUnfit

The overall percentage of recirculation Fit and Unfit notes is calculated by summing up A_RecircUnfit and A_RecircFit respectively, resulting in:

RecircUnfit = 40.5%

RecircFit = 59.5%

The amount of Recirc-Fit and Recirc-Unfit per cycle is calculated as follows:

RecircUnfitPC = RecircUnfit * NotesRecirculatedPC = 40.5% * 82.2 mln = 33.3 mln

RecircFitPC = RecircFit * NotesRecirculatedPC = 59.5% * 82.2 mln = 48.9 mln

8. Calculate RecircFit sorted and not sorted by NCB per cycle

RecircFitSortedByNCB_PC = RecircFitPercBackToNCB[R2] * RecircFitPC = 10% * 48.9 mln = 4.9 mln

RecircFitNotSortedByNCB_PC = (1-RecircFitPercBackToNCB[R2]) * RecircFitPC = (100%-10%)*48.9 mln = 44.0 mln

9. Calculate circulation notes sorted at NCB per cycle

This is simply the amount of the total NCB sorting volume per cycle minus the unfit from recirculation and the fit from recirculation returned to the NCB.

$$\begin{aligned} \text{CircNotesSortedAtNCB_PC} &= \text{TotalNotesSortedAtNCB_PC} - \text{RecircUnfitPC} - \text{RecircFitSortedByNCB_PC} \\ &= 246.6 \text{ mln} - 33.3 \text{ mln} - 4.9 \text{ mln} = \underline{208.4 \text{ mln}} \end{aligned}$$

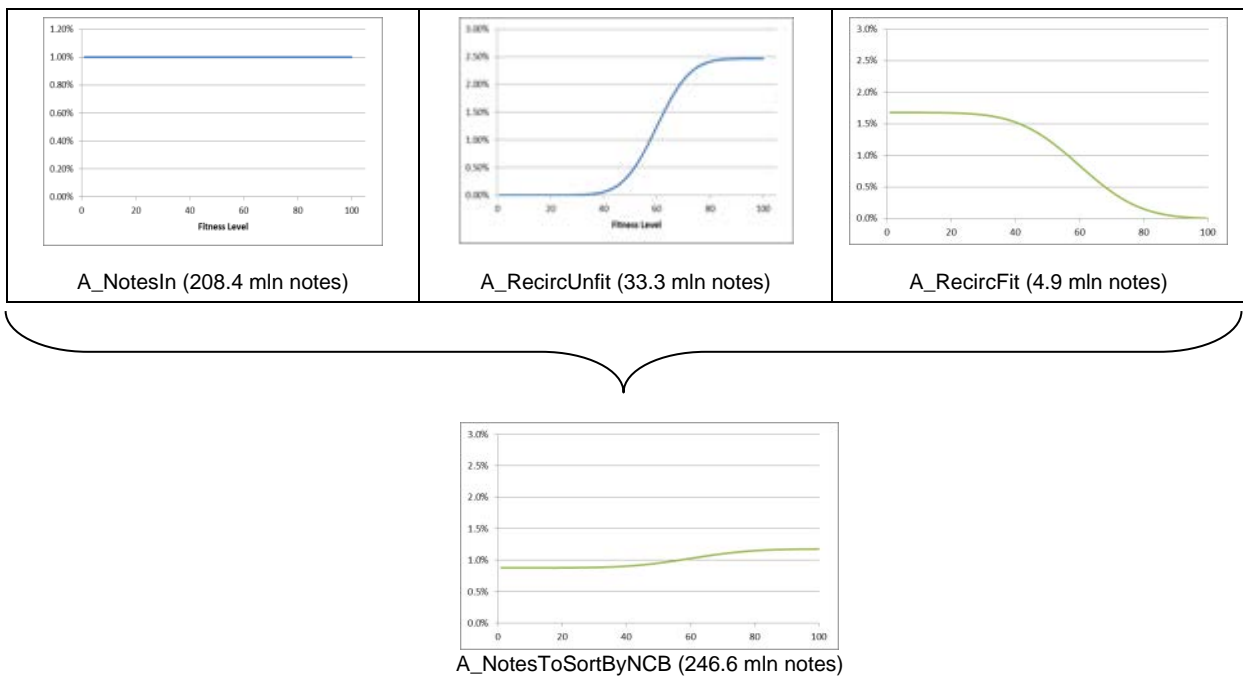
10. Calculate notes not processed per cycle

$$\begin{aligned} \text{NotesNotProcessedPC} &= \text{NotesInCirculation[C2]} - \text{CircNotesSortedAtNCB_PC} - \text{NotesRecirculatedPC} \\ &= 1 \text{ bln} - 208.4 \text{ mln} - 82.2 \text{ mln} = \underline{709.4 \text{ mln}} \end{aligned}$$

11. Create the profile of notes sorted at the NCB (mix of circulation notes, recirculation unfit and recirculation fit)

The weighted average of the arrays A_NotesIn, A_RecircUnfit and A_RecircFit is created as A_NotesToSortByNCB using the below code¹⁰ resulting in the array shown below:

```
For I = 1 To 100
  A_NotesToSortByNCB(i) = (RecircUnfitPC * A_RecircUnfit(i) + RecircFitSortedByNCB_PC * A_RecircFit(i) +
    CircNotesSortedAtNCB_PC * A_NotesIn(i)) / TotalNotesSortedAtNCB_PC
Next i
```

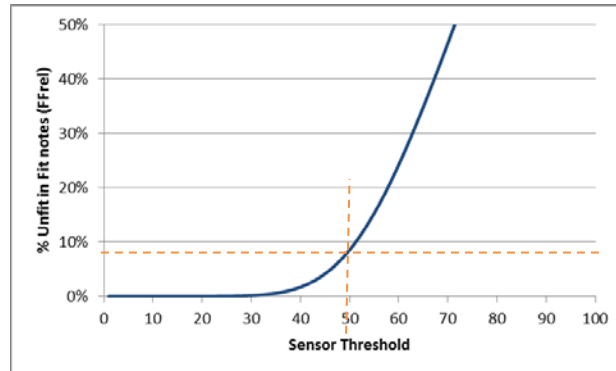


12. Determine the NCB sorting threshold to sort at the indicated sorting policy

The question to answer now is at which NCB sensor threshold the defined policy of 8% False Fit in the note re-issued by the NCB [S1] can be achieved. For this, the next step (see 13.) is carried

¹⁰ All profiles are normalised before this step.

out 100 times with the NCB sensor threshold varying from 1 to 100. The False Unfit rate is determined for each 'virtual' sorting step and the final NCB sensor threshold is determined via a linear interpolation algorithm. The figure below shows the False Fit rate when sorting A_NotesToSortByNCB at an NCB sorting threshold of 1 to 100 and highlights the NCB sorting threshold (49.50) where the relative False Fit rate of 8% is achieved.



NCBSortThreshold = 49.50

13. Carry out the sorting at the NCB

Similar to step 5, A_NotesToSortByNCB is subjected to a sorting at the NCB using a profile based on an NCBSortThreshold of 49.50 and an NCBStDev[F5] of 10):

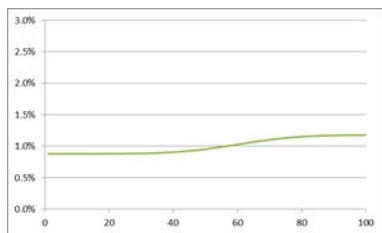
For I = 1 to 99

$$A_NCBSensProfile(i) = \text{NormDist}(i, 49.50, 10, \text{TRUE})$$

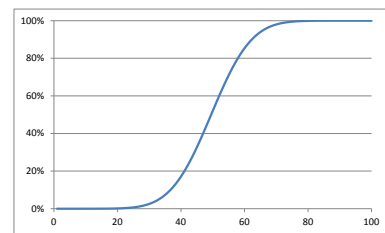
Next i

A_NCBSensProfile(100) = 1 'N.B.: notes at level 100 (i.e. defective) are always sorted to unfit

Input

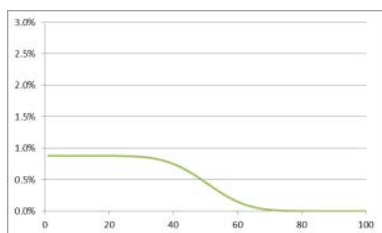


A_NotesToSortByNCB

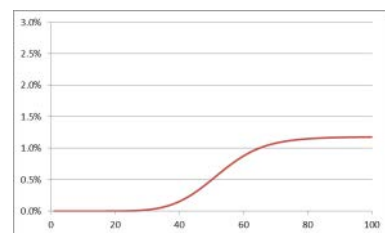


A_NCBSensProfile (Mean=49.50 StDev=10)

Result



A_NCBFit



A_NCBUnfit

The overall percentage of NCB-Fit and -Unfit notes is again calculated by summing up (integrating) A_NCBUnfit and A_NCBFit respectively, resulting in:

NCBFit = 44.0%

NCBUnfit = 56.0%

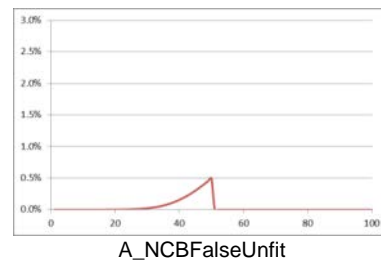
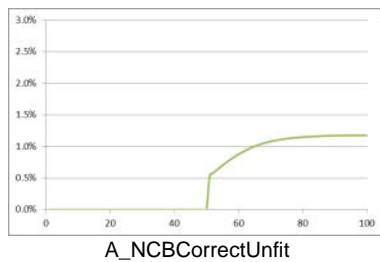
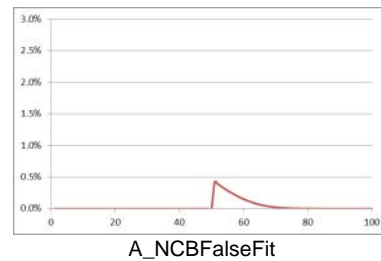
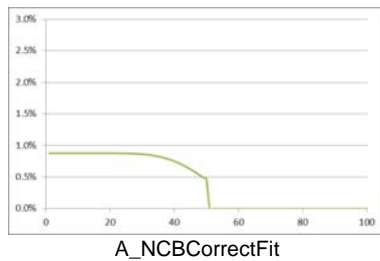
The amount of False Fit and Unfit is calculated using the two resulting profiles and checking which of the notes are actually fit/unfit against NCBFitUnfitThreshold[F4] using the following code:

```

For i = 1 to NCBFitUnfitThreshold
    A_NCBCorrectFit(i) = A_NCBFit(i)
    A_NCBFalseUnfit(i) = A_NCBUnfit(i)
Next i

For i = (NCBFitUnfitThreshold+1) to 100
    A_NCBFalseFit(i) = A_NCBFit(i)
    A_NCBCorrectUnfit(i) = A_NCBUnfit(i)
Next i
    
```

Resulting in:



The overall percentage of the four categories is again calculated by summing up the four arrays, resulting in:

NCBCorrectFit = 40.5%
 NCBCorrectUnfit = 51.8%
 NCBFalseFit = 3.5%
 NCBFalseUnfit = 4.2%

The above four note categories (totalling 100%) are the percentages in relation to the absolute NCB sorting volume. False Fit (and sometimes False Unfit) rates are within the Eurosystem also used relative to the total of the Fit and Unfit notes only. These relative figures are calculated as follows:

NCBFalseFitRel = $NCBFalseFit / NCBFit = 3.5\% / 44.0\% = 8.0\%$ (N.B.: The figure that was specified in [S1])
 NCBFalseUnfitRel = $NCBFalseUnfit / NCBUnfit = 4.2\% / 56.0\% = 7.4\%$

The amount of the six different note categories created by the NCB sorting per cycle is calculated by multiplying the above calculated percentages with the total sorting volume:

$$\begin{aligned} \text{NCBFitPC} &= \text{NCBFit} * \text{TotalNotesSortedAtNCBPC} = 44.0\% * 246.6 \text{ mln} = \underline{108.5 \text{ mln}} \\ \text{NCBUnfitPC} &= \text{NCBUnfit} * \text{TotalNotesSortedAtNCBPC} = 56.0\% * 246.6 \text{ mln} = \underline{138.1 \text{ mln}} \end{aligned}$$

$$\begin{aligned} \text{NCBCorrectFitPC} &= \text{NCBCorrectFit} * \text{TotalNotesSortedAtNCBPC} = 40.5\% * 246.6 \text{ mln} = \underline{99.8 \text{ mln}} \\ \text{NCBCorrectUnfitPC} &= \text{NCBCorrectUnfit} * \text{TotalNotesSortedAtNCBPC} = 51.8\% * 246.6 \text{ mln} = \underline{127.8 \text{ mln}} \end{aligned}$$

$$\begin{aligned} \text{NCBFalseFitPC} &= \text{NCBFalseFit} * \text{TotalNotesSortedAtNCBPC} = 3.5\% * 246.6 \text{ mln} = \underline{8.7 \text{ mln}} \\ \text{NCBFalseUnfitPC} &= \text{NCBFalseUnfit} * \text{TotalNotesSortedAtNCBPC} = 4.2\% * 246.6 \text{ mln} = \underline{10.3 \text{ mln}} \end{aligned}$$

14. Create the profile of notes in circulation after sorting one cycle

The note profile after the recirculation and NCB sorting is now generated by making the weighted average of

- notes which were not processed in this cycle,
- recirculated fit notes,
- notes entering the cash cycle specified by [C4] and [C5],
- NCB fit notes (which are returned to circulation) and
- an amount of new notes corresponding to
 - NCB Unfit notes plus
 - any changes due to a note increase/decrease as specified in [C3], plus
 - any compensations for notes leaving the cash cycle specified in [C6]

using the below formula:

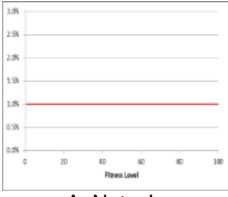
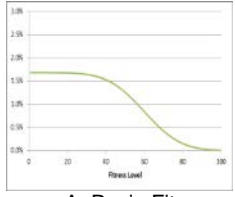
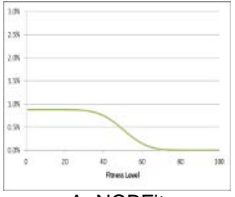
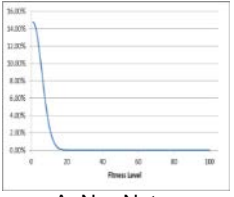
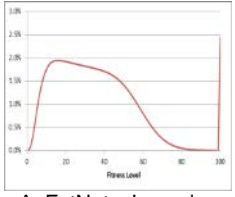
For i = 1 To 100

$$\begin{aligned} \text{A_NoteProfileAfterSorting}(i) &= ((\text{NotesNotProcessedPC} - \text{NotesLeavingPC}) * \text{A_NotesIn}(i) + \\ &\quad \text{RecircFitNotSortedByNCB_PC} * \text{A_RecircFit}(i) + \\ &\quad \text{NCBFit} * \text{A_NCBFit}(i) + \\ &\quad (\text{NCBUnfit} + \text{NoteChangePC} + \text{NotesLeavingPC} - \text{ExternalNotesIncomingPC}) * \text{A_NewNotes}(i) + \\ &\quad \text{ExternalNotesIncomingPC} * \text{A_ExternalNotesIn}(i)) / \\ &\quad (\text{NotesInCirculation} + \text{NoteChangePerCycle}) \end{aligned}$$

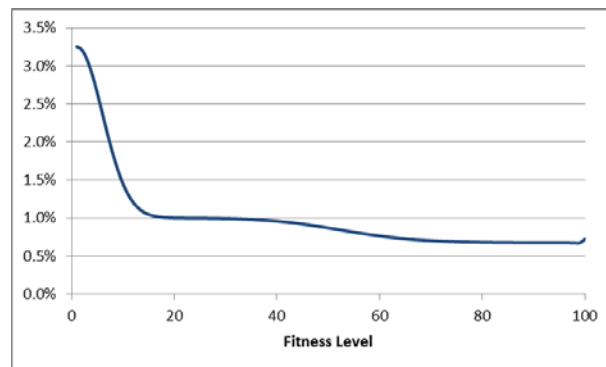
Next i

Resulting in:

Input

Note profile	 <p>A_NotesIn</p>	 <p>A_RecircFit</p>	 <p>A_NCBFit</p>	 <p>A_NewNotes</p>	 <p>A_ExtNotesIncoming</p>
Weight	<p>NotesNotProcessedPC - NotesLeavingPC (709.4mln - 10.3mln)</p>	<p>RecircFitNotSortedByNCB_PC (44.0mln)</p>	<p>NCBFitPC (108.5mln)</p>	<p>NCBUnfitPC + NoteChangePC + NotesLeavingPC - ExtNotesIncomingPC (138.1mln + 7.9mln +10.3mln -20.5mln)</p>	<p>ExtNotesIncomingPC (20.5 mln) [C5[20%UnfitInCirc]]</p>

Result



A_NotesAfterSorting

(1007.9 mln)

15. Calculate the ageing per cycle

The average amount of steps a note is ageing due to soiling is calculated, taking into account the ageing method selected in NoteLifeCalculation[T3] (see also the example on page 16). In this example 'Real' is selected, therefore the average fitness level of new notes (AvgFitLevelNewNotes) is determined first. Subsequently the amount of ageing steps is calculated based on ModelCycleDuration[T2], NoteLifeTime[N2] and the NCBFitUnfitThreshold[F4] using the below code:

```

If NoteLifeMethod = "Ideal" Then AgePerCycle = ModelCycleDuration / 30 / NoteLifeTime * (NCBFitUnfitThreshold - 1)11
If NoteLifeMethod = "Real" Then
  For i = 1 To 100
    AvgFitLevelNewNotes = AvgFitLevelNewNotes + A_NewNotes(i) * i
  Next i
  AgePerCycle = ModelCycleDuration / 30 / NoteLifeTime * (NCBFitUnfitThreshold - AvgFitLevelNewNotes)
End If

```

The calculation results in:

$$\begin{aligned}
 \text{AgePerCycle} &= \text{ModelCycleDuration} / 30 / \text{NoteLifeTime} * (\text{NCBFitUnfitThreshold} - \text{AvgFitLevelNewNotes}) \\
 &= 30 / 30 / 25 * (50 - 4.68^{12}) = \underline{1.81}
 \end{aligned}$$

16. Create the ageing distribution

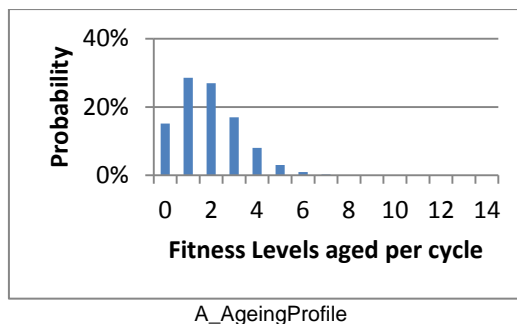
Based on AgePerCycle the ageing distribution selected in [N1] is calculated. As 'Poisson' is selected, calculation is done using the built-in Excel formula:

```

For I = 1 to 100
  A_AgeingProfile(i) = POISSON.DIST(i, 1.81, FALSE)
Next i

```

Resulting in



17. Age the resulting note profile

A_AgeingProfile is now applied to every single value in A_NotesAfterSorting, apart from those that already are at level 100 (cannot get any more soiled), using the below code:

```

For i = 1 To 99
  For j = 0 To 99
    If i + j <= 99 Then
      A_NotesAfterAgeing(i + j) = A_NotesAfterAgeing(i + j) + A_NotesAfterSorting(i) * A_AgeingProfile(j + 1)
    End If
  Next j
Next i

```

¹¹ Not used in this example.

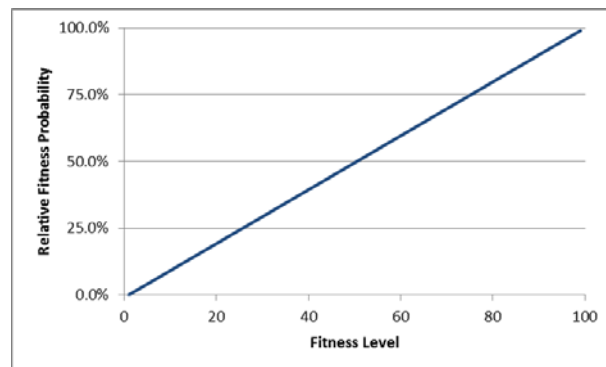
¹² The average fitness level of A_NewNotes, see earlier for the profile.

In a last step A_NotesAfterAgeing is normalised again with all notes which would have fitness levels >100 being put in the 100 bin via:

$$A_NotesAfterAgeing(100) = A_NotesAfterSorting(100) + \text{Sum_Array}(A_NotesAfterSorting, 1, 99)^{13} - \text{Sum_Array}(A_NotesAfterAgeing, 1, 99)$$

18. Apply the Defects

The probability of a defect is modelled as a function of the fitness level based on the profile defined by [N4] and is in this example set to 'Increase from 1' as shown below:



A_DefectProbability

Applying this profile to A_NotesAfterAgeing is done in a 2 step approach. In a first step the profile is applied without any factor and the number of defects added in this cycle is compared to DefectsPC (i.e. the number of defects which are specified, see step 6) in order to obtain the factor at which A_DefectProbability needs to be applied. In a second step A_DefectProbability is applied to A_NotesAfterAgeing using this factor.

```
A_ResultBackup() = A_NotesAfterAgeing()
```

```
For i = 1 To 99
  old_Result = A_ResultBackup(i)
  A_ResultBackup(i) = A_ResultBackup(i) * (1 - A_DefectProbability(i))
  NewDefectsTotal = NewDefects + old_Result - A_ResultBackup(i)
Next i
```

'Now we can determine the factor to apply to reach the desired amount of defects per cycle
DefectFactor = DefectsPC / NewDefectsTotal (0.82%/0.79%=1.034)

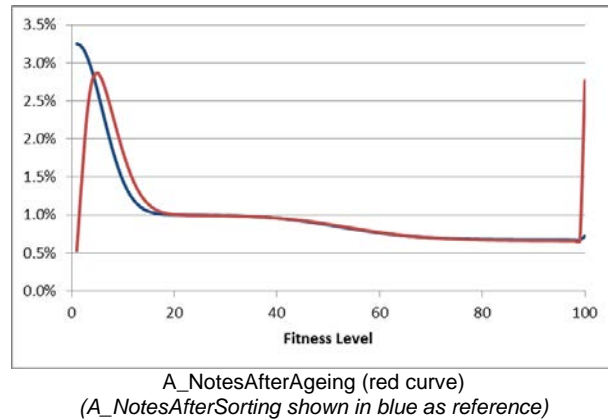
```
NewCDefects = 0
'Now we apply the changes to the actual profile
For i = 1 To 99
  old_Result = A_NotesAfterAgeing(i)
```

¹³ A function calculating the sum of a one dimensional array from entry 1 to entry 99.

$A_NotesAfterAgeing(i) = A_NotesAfterAgeing(i) * (1 - A_DefectProbability(i) * DefectFactor)$
 $NewCDefects = NewCDefects + old_Result - A_NotesAfterAgeing(i)$
 Next i

'Add the catastrophic notes to the 100 bin
 $A_NotesAfterAgeing(100) = A_NotesAfterAgeing(100) + NewCDefects$

Applying the ageing and defects results in:



19. Check steady-state and either

a. start next cycle

The correlation coefficient between A_NotesAfterAgeing and A_NotesIn is calculated using the CORREL Excel function and if no steady state is reached, the model is run again from step 1 with A_NotesAfterAgeing being used as new starting value for A_NotesIn. (In this specific example steady state is reached after 87 cycles).

b. or, output final results

In case steady state has been reached, the calculation is stopped and the result charts are created and figures outputted. Whilst some of the outputs should be self-explanatory based on the above explanations, the calculations for some others are shown below:

AnnualReplacementVolume	=	NCBUnfit / CycleDuration * 365
AnnualFalseUnfitVolume	=	NCBFalseUnfit / CycleDuration * 365
AnnualReplacementCosts	=	NCBUnfit * BNPriceNewPerNote / CycleDuration * 365
ReturnTimeNCB	=	NotesInActiveCirc / (TotalNotesSortedAtNCB_PC * CycleDuration)
ReturnTimeRecirc	=	NotesInActiveCirc / (NotesRecircPC * CycleDuration)
ReturnTimeNCBorRecirc	=	NotesInActiveCirc / (NotesRecircPC + TotalNotesSortedAtNCBPC) * CycleDuration

7. Batch functions to run multiple model cases

When modelling a cash cycle it can be useful to see how the model would react if multiple of the input parameters change. While the main '2Cases' sheet allows the comparison of two cases with one or multiple different parameters, extended functionality to carry out a sensitivity analysis of a case is possible using the sheets 'WhatIf', 'WhatIf2' or 'Solver'. None of these sheets provides the detailed graphical analysis of the '2Cases' sheet but instead provide the results of multiple cases in direct comparison.

N.B.: The algorithm is identical when run from any sheets of the circulation model. The only difference is in the different input masks and the display of the results.

7.1 Batch functions on 'Whatlf' sheet

Similar to the '2Cases' sheet the cash cycle is defined at the top of the sheet using the same input mask. In row 75 below 20 different changes of a single parameter to this base case can be defined (the parameter to be changed is in row 75 and the new value is specified in row 77). After pressing the button in row 70/71 detailed results of the 20 cases are shown in relation to the main case with bar charts indicating the relative change of each model result in comparison to the base case.

Run all "What If" cases								
What happens if I change parameter?								
Parameter to be changed:	Original val.	New val.	1		2		3	
			Value	Change to Orig	Value	Change to Orig	Value	Change to Orig
P1-BN costs	154	30.0	161	+5%	341	+121%		
N2-Note life	24.0	30.0	1590	+5%	3390	+123%		
S1-False Fit Rate	0.00%	5.00%						
Number of model cycles run:	154	1520	1520	no change				
Days until steady state reached:	50.0	50.0	50.0	no change				
NCB Operational sorting threshold:	32.4	32.4	30.5	-6%	32.6	+1%		
Average fitness level of circulation:	83.0%	83.0%	86.4%	+4%	82.9%	-0%		
fit notes in circulation Total:	17.0%	17.0%	13.6%	-20%	17.1%	+1%		
Unfit notes in circulation Total:	72%	72%	76%	+5%	72%	-0%		
Correct Fit absolute (CF):	15%	15%	12%	-20%	15%	+0%		
Correct Unfit absolute (CU):	4%	4%	3%	-19%	4%	+4%		
False Fit absolute (FF):	3%	3%	8%	+15%	8%	+1%		
False Unfit absolute (FU):	5%	5%	4%	-22%	5%	+4%		
False Fit relative:	35%	35%	41%	+15%	35%	-1%		
False Unfit relative:	24%	24%	21%	-13%	24%	+0%		
Shred Rate:	0.63	0.63	0.50	-20%	0.63	no change		
Fitness decrease per model cycle:	4,000	4,000	4,000	no change	4,000	no change		
Annual sorting volume:	40,000,000	40,000,000	40,000,000	no change	40,000,000	no change		
Annual sorting costs:	10,462,189	6,538,868	10,542,252	+1%	10,233,310	-2%		
Annual residual value of False Unfit:	959.87	959.87	831.95	-13%	955.36	-0%		
Annual replacement volume:	340.40	340.40	338.43	-1%	335.74	-1%		
of which False Unfit:	76,789,701	47,993,563	66,555,655	-13%	76,429,060	-0%		
Annual replacement costs:	116,789,701	87,993,563	106,555,655	-9%	116,429,060	-0%		
Total annual costs:	61.1	61.1	59.3	-3%	61.1	+0%		
Avg. fitness level of unfit (excl. holes, tears etc.):	4.1%	4.1%	4.0%	-2%	4.1%	+0%		
Defects (Holes/Tears/Dogears):	25.00	25.00	28.85	+15%	25.12	+0%		
Lifetime of notes (simple):	23.53	23.53	26.91	+14%	23.64	+0%		
Lifetime of notes (CIS):	#####	#####	#####	no change	#####	no change		
NotesInCirculation:	#####	#####	1,865,533,140	-0%	#####	+0%		
NotesUnprocessedPerCycle:	0	0	0	no change	0	no change		
NotesFromOutsidePerCycle:	27,397,260	27,397,260	27,397,260	no change	27,397,260	no change		
NotesRecirculatedPerCycle:	24,188,492	24,188,492	24,817,819	+3%	24,163,156	-0%		
Recirculation Fit:	3,208,768	3,208,768	2,579,442	-20%	3,234,104	+1%		
Recirculation Unfit %:	12%	12%	9%	-20%	12%	+1%		
NotesSortedAtNCBPerCycle:	109,589,041	109,589,041	109,589,041	no change	109,589,041	no change		
CirculatedNotesSortedAtNCBPerCycle(Excl. RecircUnfit):	106,380,273	106,380,273	107,009,600	+1%	106,354,937	-0%		
RecircFitNotesSortedAtNCBPerCycle:	0	0	0	no change	0	no change		
NCBFit:	83,291,198	83,291,198	86,796,009	+4%	83,414,706	+0%		
NCBUnfit:	26,297,843	26,297,843	22,793,032	-13%	26,174,336	-0%		
NoteChangeDueToGrowth/DecreasePerCycle:	3,195,367	3,195,367	3,195,367	no change	3,195,367	no change		
Return time NCB:	183	183	183	no change	183	no change		
Return time Recirc:	730	730	730	no change	730	no change		
Return time NCB or Recirc:	146	146	146	no change	146	no change		
Notes coming from outside per cycle:	0	0	0	no change	0	no change		
Steady State reached:	TRUE	TRUE	TRUE	no change	TRUE	no change		

Figure 8: Result section on the 'Whatlf' sheet'

7.2 Batch functions on 'WhatIf2' sheet

Here the main model case is defined on the left. On the right hand side the impact of changes of key model parameters to the results is displayed. In column K the relative change to each parameter can be defined and in row 15 the tolerances for the colouring of the changes (conditional-formattings) can be adjusted.

Technical Parameters of the model			Update Calculations														
No. of model cycles: 500			Tolerances of Conditional Formattings:														
Cycle Duration (days): 10			20% 20% 20% 20% 20% 20% 20% 20% 20% 20%														
Notes Life Calculation: Real			In Circulation														
Steady State Correlation Factor: 0.33333333			Sensor Threshold														
			Total Units FF Fail/FU Abs														
			Total Units per year (millions)														
			Units %														
			Replicom notes														
			False Units costs														
			Notes per year														
			Model														
Production			Notes in circulation														
BM production and issuance costs (EUR/1000): 80			Notes entering every year														
New Note fitness level: 1			Notes leaving every year														
St.Dev of New Note: 5			Fitness distribution of external notes														
Circulation			Notes in circulation														
Notes in circulation: 1,008,111,077			Notes entering every year														
Annual change in circulation volume: +3.72%			Notes leaving every year														
Notes entering every year: 0			Notes in circulation														
Fitness distribution of external notes: 0			Notes entering every year														
Notes leaving every year: 0			Notes leaving every year														
Note Life			Aging Model														
Aging Model: Poisson			Gamma a1														
Theoretical note life (coil only): 23.0			Gamma a2														
Defect likelihood: 18.00%			Gamma a3														
Defect profile Name: Coepeat			Gamma a4														
Third Party Fitness Sorting (Recirculation)			Defect likelihood														
Annual Third Party sorting volume: 1,000,000			Defect profile Name														
% of 3rd Party (3P) fit notes returned to NCB: 10%			Annual Third Party sorting volume														
Third party fitness threshold: 50			% of 3rd Party (3P) fit notes returned to NCB														
Third Party St.Dev of Sensor: 10			Third party fitness threshold														
NCB Fitness Sorting			Third Party St.Dev of Sensor														
NCB Sorting costs (including re-issuance): 10			Annual NCB sorting volume														
BM value at threshold: 20%			St.Dev of NCB Sensor														
Annual NCB sorting volume: 3,442,565,686			NCB Sensor Threshold														
Real NCB Guideline Fit/Unit Threshold: 50																	
St.Dev of NCB Sensor: 10																	
NCB Sorting Policy																	
NCB Sensor Threshold: 50																	

Figure 9: Input (left) and Result section (right) on the 'WhatIf2' sheet

This sheet, due to speed constraints, only supports modelling at a constant sensor threshold. Also, in order to allow for numeric changes the new note profile needs to be specified via the average fitness level [P2] and a standard deviation [P3], the specification via any arbitrary profile [P4] is not supported in this case. N.B.: The named new note profiles provided on the other sheets can be defined via the following values:

Profile Name	Mean [P2]	StDev [P3]
Perfect	1	0.01
Some Variation	1	5
Large Variation	5	10

7.3 Batch functions on ‘Solver’ sheet

Also here the main model case is defined on the left. For some of the key parameters ranges can be defined (columns H/I) with the step width defined in column J. Below in rows 67 to 72 you can set the expected results or any real-life results you have collected from your cash cycle which you try to match.

Technical Parameters of the model			
No. of model cycles:	500		
Cycle Duration (days):	10		
Note Life Calculation:	Real		
Steady State Correlation Factor:	0.999999995		

	Production	Total	Change			
			From	To	Step	Total Steps
P1	BN production and issuance costs (EUR/1000):	80				
P2	New Note fitness level:	1				
P3	St.Dev of New Note:	5				
Circulation						
C1	Fitness distribution at beginning:	10% UnfitInCirc				
C2	Notes in circulation:	178,717,062				
C3	Annual change in circulation volume:	+11.21%				
C4	Notes entering every year:	0				
C5	Fitness distribution of external notes:	20% UnfitInCirc				
C6	Notes leaving every year:	390,480				
Note Life						
M1	Ageing Model:	Poisson				
N2	Theoretical note life (soil only):		30	43	3	5
N3	Defect likelihood:		6%	16%	3%	4
N4	Defect profile Name:	Constant				
Third Party Fitness Sorting (Recirculation)						
R1	Annual Third Party sorting volume:	297,010,324				
R2	% of 3rd Party (3P) fit notes returned to NCB:		22%	23%	2%	1
R3	Third party fitness threshold:		50	60	5	3
R4	Third Party St.Dev of Sensor:		10	10	5	1
NCB Fitness Sorting						
F1	NCB Sorting costs (including re-issuance):	10				
F2	BN value at threshold:	20%				
F3	Annual NCB sorting volume:	117,427,552				
F4	Real NCB Guideline Fit/Unfit Threshold:	50				
F5	St.Dev of NCB Sensor:		5	15	5	3
NCB Sorting Policy						
S3	NCB Sensor Threshold:		40	50	3	4
Total cases:						720

Expected results			
Quality In Circulation	Unfit	17%	
	Defects	4%	
NCB Sorting	Shred Rate	52.16%	
	FF Rel	2%	
	FU Abs	3%	
	Recirc Unfit Rate	24%	

Find Solution with minimum deviation from expected results

Figure 10: Input (left) and Result section (right) on the ‘WhatIf2’ sheet’

After pressing the button to the right all different cases as shown in K63 are run and the best matching result is displayed below. The left part of the results table shows the best results found taking into

account only unfit in circulation, defects and destruction rate, whereas the result to the right takes into account all of the expected results.

Best solutions found				
	Minimum error on Unfit/Defects and Shred rate		Minimum error on all expected results	
Total Error (p.p.)	11.1%		20.3%	
Solution No.:	141		112	
Model settings				
Theoretical note life (soil only):	40		40	
Defect likelihood:	15.0%		15.0%	
% of 3rd Party (3P) fit notes returned to NCB:	22.0%		22.0%	
Third party fitness threshold:	60		50	
Third Party St.Dev of Sensor:	10		10	
St.Dev of NCB Sensor:	15		5	
NCB Sensor Threshold:	40		49	
Model results				
	abs.	rel. to expected	abs.	rel. to expected
Unfit	15.5%	-1.2%	17.2%	+0.4%
Defects	7.9%	+4.3%	8.3%	+4.7%
Shred Rate	46.5%	-5.6%	42.3%	-9.8%
FF Rel	2.4%	+0.2%	3.2%	+1.0%
FU Abs	13.5%	+10.0%	4.4%	+0.9%
Recirc Unfit Rate	12.3%	-11.4%	20.2%	-3.5%

This sheet, also due to speed constraints, only supports modelling at a constant sensor threshold. Also the specification of new notes via any arbitrary profile [P4] is not supported in this case (see section 7.2 on how the predefined note profiles can be used).

7.4 Modelling via the User Defined Function (UDF)

The sheet 'UDFExample' demonstrates how you can set up any number of cases using the circulation model as a standard function in Excel. The function must be entered as an Array function (see <https://support.office.com/en-us/article/Create-an-array-formula-e43e12e0-afc6-4a12-bc7f-48361075954d>). When changing any part of the Array Function DO NOT use the 'Insert Function Option' in Excel, but change the formula directly in the entry field as otherwise Excel might crash. Also take note that using too many UDFs will take time for Excel to recalculate the formulas on startup. Due to speed constraints, the UDF only supports modelling at a constant NCB sensor threshold.

A general recommendation when using UDFs to simulate cases is to always create a new file which you only use for this specific UDF modelling. Having many UDFs in a file will make it slower as Excel needs from time to time recalculate all these functions which can take a substantial amount of time and also reduce the performance of the circulation modelling using the other (batch) functions.

8. Known limitations of the model

Sorting for constant Unfit in circulation (circulation quality), sorting policy [S4]

When the starting note profile (specified in [C1]) is very different from the steady state of the model, the model might oscillate and never reach a steady state. To avoid this, apply this sorting policy only on a starting profile close to the desired one. Having a higher return frequency to the NCB (by e.g. increasing the NCB sorting volume) helps for this sorting policy to become more stable.

Severe reduction of the amount of banknotes in circulation or very large inflows

A reduction of the amount of notes in circulation is only supported by not replacing unfit notes at NCB level. The model does not support the reduction of the note volume in circulation by not re-issuing fit notes. This applies also when large inflows are modelled that would result in the NCB no longer being able to issue any new notes. In case such a condition would be reached a warning is displayed and the calculation is stopped.

9. Tips & Tricks

General

- You can abort the calculation any time by pressing 'ESC'.
- Steady State (SS) is reached quicker if your starting condition is close to the final results. Selecting a profile for [C1] which is close to your final result will reduce the number of iterations required to reach SS.
- The status bar displays the current calculation cycle and the correlation factor. Once steady state conditions are reached this is indicated by a beep.
- You can also manually unprotect all sheets and have free access to the VBA modules for background checking, studying

On the '2Cases' sheet

- Setting 'Show Calculation Steps' to 'No' on the '2Cases' sheet speeds up calculation about 20x.
- You can change the Y-Axis scale of the fitness profile (the chart called 'Final steady state fitness profile in circulation') manually by clicking the button below. This can be useful to show the whole profile in cases where you have a high number of defect notes.
- The dotted lines in the final profile chart show the starting condition.

END OF DOCUMENT