Article

1 Modelling euro banknote quality

Central banks are the guardians of banknote quality. In 2016 euro area national central banks (NCBs) checked 32.3 billion euro banknotes on their high-speed machines for quality and authenticity. Commercial cash handlers (CHs)[39] processed a similar number. CHs disburse banknotes of good quality to their customers and return poor-quality ones (unfit banknotes) and surplus stocks to the NCBs. These destroy all unfit banknotes after a final authenticity check. In 2016 NCBs replaced 5.4 billion unfit banknotes (around 27% of the banknotes in circulation) with new ones. Note consumption and the quality of notes in circulation differ by country. The ECB has therefore developed a computer-based model to better understand the differences in euro area cash cycles. The model simulates a cash cycle using a theoretical approach based on key figures. The simulations identify the resistance of banknotes to soil and defects, the frequency with which banknotes are returned to the NCB and the NCB sensor threshold as the three main drivers of banknote quality and cash cycle costs.

1 Introduction

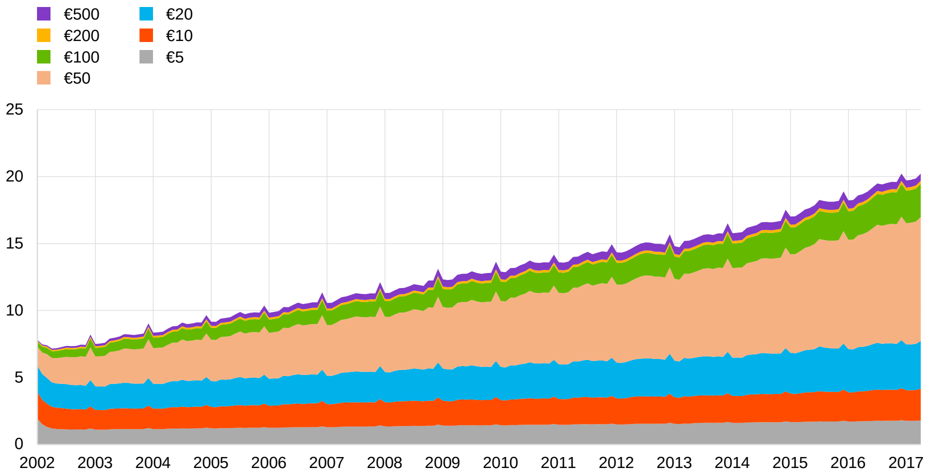
At the end of December 2016 20.2 billion euro banknotes with a nominal value of €1.12 trillion were in circulation. Compared with end-2015, this marked an increase of 7.0% in volume and 3.9% in value. These figures are in line with the average annual increase over the last five years, which was 7.8% in volume and 6.1% in value (see Chart 1). Euro banknote circulation increases if NCBs issue banknotes; it decreases if NCBs receive banknotes, usually of poor-quality or surplus stocks, from CHs.

[39] CHs are the institutions and economic agents referred to in Article 6(1) of Regulation (EC) No 1338/2001 laying down measures necessary for the protection of the euro against counterfeiting (“Credit institutions, and, within the limits of their payment activity, other payment service providers, and any other institutions engaged in the processing and distribution to the public of notes and coins […].”). In this article all parties other than NCBs processing notes for recirculation are grouped under the term CHs.

Chart 1

Cumulative number of euro banknotes in circulation

(y-axis: number of euro banknotes in billions)



Source: Eurosystem Currency Information System 2.
Note: The volumes for the €5 to €50 notes are the sum of first series and Europa series notes.

The Eurosystem has a duty to ensure public confidence in euro banknotes by maintaining their quality in circulation. Poor-quality banknotes are likely to be rejected by vending machines, and also make it less easy for the public and retailers to spot counterfeits. Two factors are mainly responsible for maintaining quality. The first is providing durable banknotes: the lifespan of the Europa series €5 and €10 banknotes has been enhanced by applying an additional protective varnish layer. The second is the involvement of NCBs in the cash cycle, replacing soiled and defective notes detected during machine processing. However, banknote quality in circulation also depends on various other factors. For example, if few ATMs dispense €5 banknotes, these will stay longer in active circulation to make up for their limited availability as change. Retailers will retain them for use rather than return them to the NCB, which is therefore unable to remove any soiled notes from circulation.

Since 2011 CHs have been able to disburse (recirculate) used banknotes, provided they observe the rules set out in ECB Decision ECB/2010/14 on the authenticity and fitness checking and recirculation of euro banknotes (the "Recirculation Framework")[40]. More specifically, any recirculated euro banknotes must have been processed on banknote sorting machines which have been tested by the Eurosystem and are listed on the ECB's website. In addition, CHs are obliged to report every six months on the number and type of machines in use, as well as on the volume of notes processed, recirculated and sorted out as unfit. The Recirculation Framework has been adopted swiftly by CHs. Since the initial reporting of machines used in accordance with the Recirculation Framework the number of compliant banknote handling machines in operation has almost doubled (from

[40] In some euro area countries the recirculation of banknotes was not allowed before that time, in others, recirculation was carried out under bilateral agreements between CHs and the NCB.

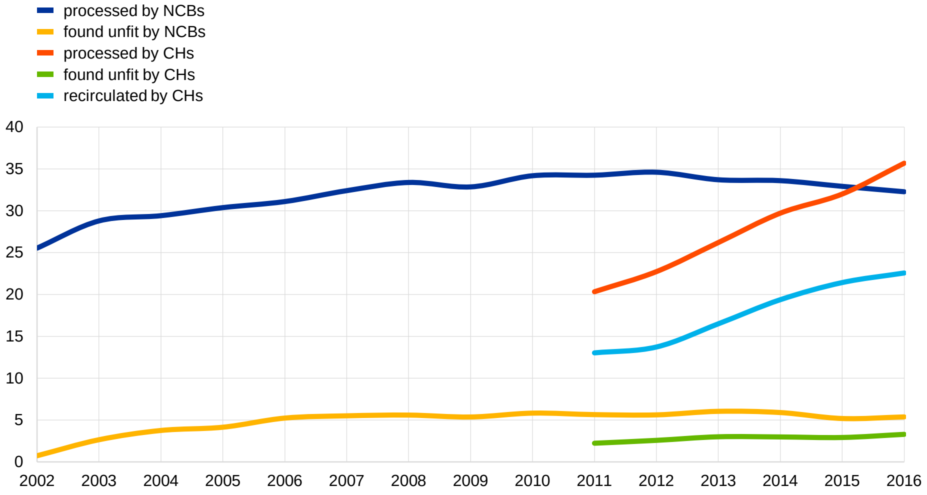
around 78,000 in 2012[41] to more than 147,000 by the end of 2016). Recirculating fit banknotes rather than returning them to an NCB allows CHs to save substantial transport and handling costs.

The number of banknotes processed by CHs in 2016 (35.7 billion) exceeded the NCB sorting volume (32.3 billion) for the first time, indicating, on a euro area level, a shift in operational involvement in the cash cycle from NCBs to CHs (see Chart 2). Of the total number of notes processed by the latter, about two-thirds (22.6 billion) were found to be fit and recirculated, with the remainder being returned to the NCBs. Only 2.3 billion of these returned notes were unfit and did not comply with the minimum quality standard stipulated in the Recirculation Framework; the remainder were fit surplus notes.

Chart 2

Number of banknotes processed/recirculated by NCBs and CHs

(y-axis: number of euro banknotes in billions)



Source: Eurosystem Currency Information System 2.

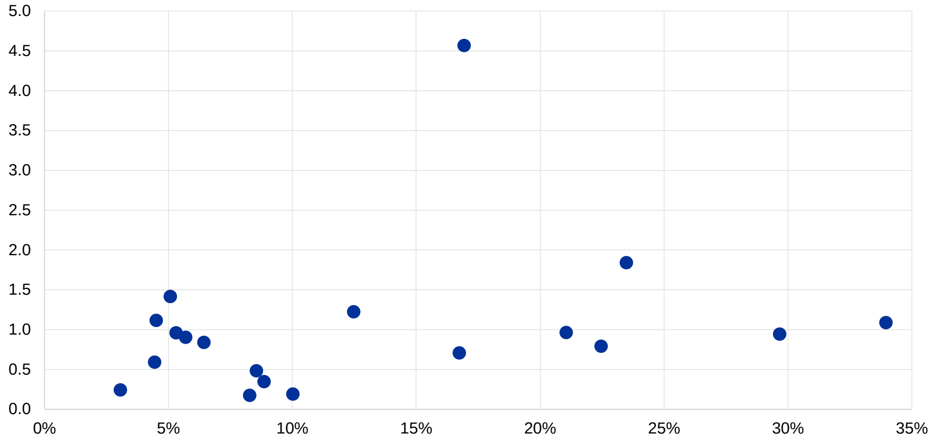
As for the quality of euro banknotes in circulation in different euro area countries, the intuitive assumption is that a higher level of destruction of poor quality banknotes – and replacement with new notes – should result in improved quality. When countries' quality in circulation is compared with the per capita rate of note destruction, however, this is not apparent (see Chart 3). The chart shows a mixed picture, with most countries having a low destruction rate of about one note per person per year, but with significant outliers. Some countries have a lower quality in circulation despite a high destruction rate; others have a very high quality in circulation even though they destroy less than half as many notes as the euro area average. This indicates that differences in national cash cycles play a significant role. These specific national influences are not yet sufficiently understood.

41 The Recirculation Framework entered into force on 1 January 2011 with a one-year transitional period for statistical reporting.

Chart 3

Quality of €5 banknotes in circulation versus note destruction in euro area countries

(x-axis: banknotes found to be unfit as a percentage of notes in circulation; y-axis: note destruction per capita from May 2014 to April 2015)



Sources: 2015 Eurosystem banknote quality survey, Eurosystem Currency Information System 2, Eurostat population figures (for smaller countries a correction for tourism and migration was introduced using national statistical data sources).
Notes: One data point per euro area country. Percentage of banknotes found to be unfit in a representative sample of a country's notes in circulation versus banknotes destroyed per inhabitant per year for the Europa series €5 banknote. See Section 2.4 for an explanation of how a representative sample of a country's banknotes in circulation was collected. The sampling for the 2015 banknote quality survey was carried out in the period from March to May 2015. Banknote destruction is the total for the period from May 2014 to April 2015.

The ECB has developed a computer-based model which includes all main parameters known to affect a cash cycle and can be applied on both a national and aggregate euro area level. The model is designed to provide a better understanding of the different euro area countries' cash cycles as well as the factors that influence note consumption and note quality.[42] Section 2 of this article looks at the main stakeholders in a cash cycle and the key parameters which influence banknote quality. Section 3 outlines the model. Section 4 shows the results obtained by applying the model to two theoretical national cash cycles.

2 The banknote lifecycle

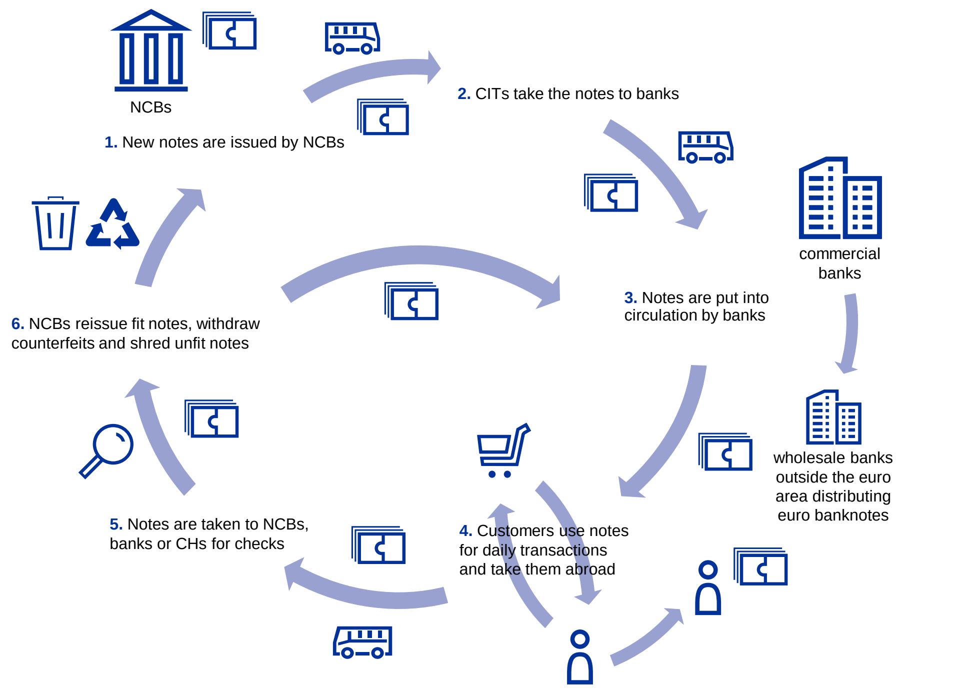
2.1 Overview of stakeholders

The cash cycle involves several interacting processes and stakeholders. An overview of a typical euro area cash cycle is shown in Figure 1. NCBs issue euro banknotes (printed by multiple accredited printing works). From here they are picked up by CHs, usually using cash-in-transit companies (CITs), which deliver them to commercial banks or retailers, or directly to ATMs. The public receive banknotes primarily from ATMs or as change from retailers, and to a lesser extent over the counter at banks. Retailers' excess banknotes are deposited at a bank branch or

42 The model will be available for download on the ECB's website and can also be applied to non-euro area cash cycles. The simulation of local cash cycles is also of relevance for other (larger) countries where different regions show a similarly mixed picture.

picked up by CITs. They are then either returned to the NCB for quality and authenticity checks or recirculated by a CH. Depending on the denomination of the note and the country, a note may be processed and returned to the cash cycle multiple times before becoming unfit and sorted out for destruction.

Figure 1
The banknote lifecycle



Euro banknotes are also exported to and imported from countries outside the euro area by both specialised CHs (e.g. banknote wholesale banks supplying bureaux de change) and the public, for tourism or commercial purposes. Cumulative net exports to non-euro area countries in the form of bulk shipments of euro banknotes by banknote wholesale banks by the end of 2016 amounted to €172.8 billion. As there are also large unregistered flows, other sources[43] estimate that more than 30% of euro banknotes issued in Germany by value circulate outside the euro area. Estimates of a denominational breakdown are not yet available.

These inflows and outflows from/to outside the euro area, or between the different countries within it, have a substantial impact on national cash cycles. Some euro area countries experience negative net issuance of certain denominations, i.e. an NCB receives more banknotes from CHs than it issues. This occurs when notes migrate into the country from abroad, either from another euro area country or from regions outside the euro area. Banknote migration is caused primarily by tourism and cross-border commuting. To balance these "natural" flows,

[43] See *The international role of the euro, Interim report*, ECB, June 2016 or Bartzsch, N., Rösl, G. and Seitz, F., "Foreign demand for euro banknotes issued in Germany: estimation using indirect approaches", *Discussion Paper*, Series 1, No 21, Deutsche Bundesbank, 2011.

the Eurosystem regularly transports large volumes of euro banknotes across borders. These ensure that countries with a positive net issuance are able to meet the demand for banknotes at any time.

While the general cash cycle holds true for all NCBs, the share processed by NCBs and CHs and their respective roles vary considerably from country to country. This is due to national specificities. In 2016 the aggregate ratio of processing by CHs to processing by NCBs was close to 1.1 (see Chart 2), but national figures range from 0 (i.e. no recirculation by CHs at all) to CHs processing more than five times the NCB note volume.

2.2 Banknote fitness as judged by humans and machines

Over their life banknotes deteriorate and their quality, i.e. fitness, decreases. The fitness of a banknote is defined by its soil level and whether it carries any defects. Recent research into the ageing of banknotes has identified soiling as one of the main reasons circulating notes become unfit. Soil consists primarily of human sebum (a waxy substance produced by skin glands) transferred onto notes by handling, and dirt particles.[44] The second unfit category comprises defects such as stains, graffiti markings, tape, dog-ears and tears. While soiling is typically a gradual process, a banknote usually becomes defective at a particular moment in time (e.g. when it is torn or stained).

The difficulty for all automated fitness measurements is to ensure that the machine judgement correlates well with the human perception of the condition of a banknote. Fitness is usually measured by sorting machines that process up to 33 banknotes per second, capture an image of a banknote, apply different algorithms to the image and finally decide whether or not it is fit for circulation. However, the fitness assessment by sorting machine can be influenced by different factors. The most prominent are: (1) imperfections in the note transport and camera system; (2) dust from the processed banknotes (such as residues of paper fibres or ink) affecting the image quality; (3) the gloss on new banknotes, which has been shown to significantly affect soiling assessment; (4) potential production variations, despite strict quality controls, resulting in slight differences in new batches of notes.

To ensure NCBs apply standards that match human perception, the ECB has created a standardised batch or "test deck" of euro notes from circulation for evaluating sorting machines. The test deck contains banknotes of all fitness levels. On the basis of a visual assessment by Eurosystem experts (i.e. human perception), a "true" fitness value has been allocated to each banknote in the test deck. Naturally, no judgement by an automated fitness sensor will exactly match the fitness value derived from human expert judgement, so there will be some cases of misclassification. Either fit banknotes are incorrectly prematurely destroyed (false unfit notes) or unfit banknotes are judged fit and reissued (false fit notes). Eurosystem research has confirmed, by applying the test deck, that different high-

[44] See Balke, P., "From Fit to Unfit: How banknotes become soiled," Watermark 2011, Rostov-on-Don.

speed sorting machines have substantially different classification accuracy,[45] primarily owing to the different technologies and algorithms used.[46]

2.3 Eurosystem standards for measuring banknote fitness

The Eurosystem has defined minimum thresholds at which an NCB must classify a banknote as unfit for circulation (the "Eurosystem threshold[47]"). These thresholds include limits for soiling and all defect categories. All NCBs must adhere to these minimum requirements, and only a small percentage of the notes they reissue are allowed to not fulfil these criteria. This tolerance margin (8% of notes reissued) takes into account the uncertainties of machine note classification. NCBs can apply a stricter sorting policy to counteract low quality of banknotes in the national cash cycle.

The minimum fitness standards for CHs ("CH threshold") are defined in the Recirculation Framework and are lower than those for NCBs. This to ensure that, even including the measuring tolerances, the banknotes reissued by an NCB are fit for the CHs and can be recirculated a number of times before reaching the end of their life.

2.4 How the Eurosystem measures quality in circulation

Every year the Eurosystem collects a representative sample of the "transactional" denominations (€5 – €100) and determines the percentage of unfit banknotes in this sample according to the Eurosystem threshold. Samples taken from circulation in each euro area country are processed on the high-speed sorting machines of two NCBs and the average percentage of unfit notes in each sample, whether due to soil or to defects, is calculated. The results of this annual quality survey among other things help the NCBs decide whether banknote quality in circulation is adequate and if necessary adjust their sorting policy.

The Eurosystem also carries out a survey of public perceptions of note quality (every two years) and an online poll[48] (since 2012), both of which correlate well with the quality survey. Both polls focus on the quality of the €5 and €50 notes. The €5 note usually has a lower quality because it remains in circulation as change, returning to NCBs less often. Taking the euro area average, the quality of the €5 note is considered good, with 75% of participants ranking quality as acceptable or higher (see Chart 4). For the €50 note almost all respondents (99%) consider the note to be of at least acceptable quality. Comparing the national results of the quality survey

---

45 Alternative methods have also shown that the accuracy of a sensor is dependent on the denomination and is not consistent along a normalised fitness range.

46 See e.g. Buitelaar, T., "The Colour of Soil", DNB Cash Seminar 2008, Amsterdam, 28-29 February 2008.

47 When presenting percentages of unfit notes in circulation, this article refers to notes unfit according to the Eurosystem threshold.

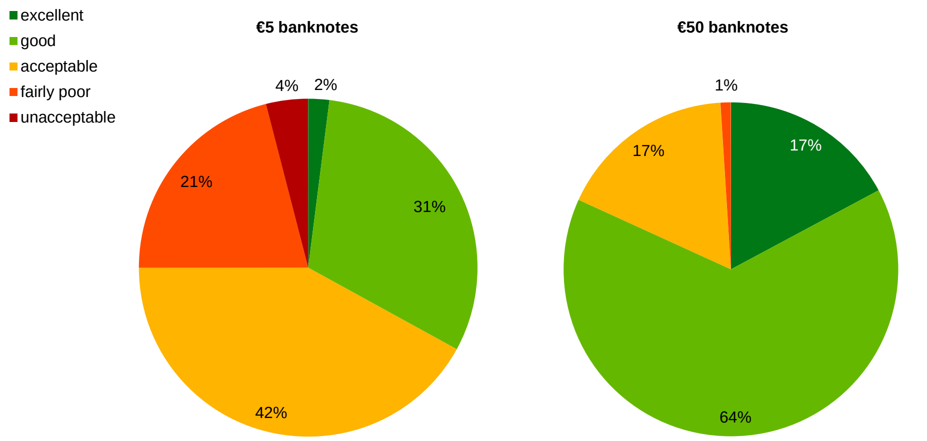
48 See online survey on the quality of euro banknotes.

with the national responses in the online poll reveals a good correlation between the percentage of unfit notes found in a country's sample and public opinion of the €5 note (see Chart 5). However, this pattern is not observed for the €50 note; as this is generally of good quality, there is no data in the unfit/negative responses area (top right) of the graph.

Chart 4

Physical condition of euro banknotes as found in the 2012 public opinion survey

(Eurosystem averages)

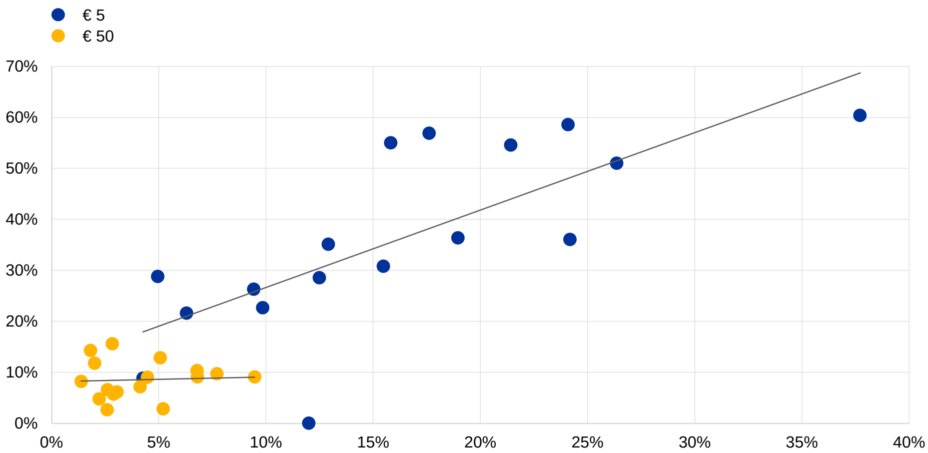


Source: 2012 ECB public opinion survey on euro banknotes.
Notes: Answers to the survey question "How would you generally describe the physical condition of the €5/€50 banknotes in circulation?" Results shown are for 2012, as the latest figures (2014) were affected by the introduction of the Europa series €5 note.

Chart 5

Correlation of unfit banknotes found in circulation with public feedback received per country for €5 and €50 notes

(x-axis: banknotes found to be unfit as a percentage of notes in circulation; y-axis: percentage of negative responses (fairly poor/unacceptable) in the online poll)



Sources: 2012 Eurosystem online survey on the quality of euro banknotes and 2012 Eurosystem quality survey.
Note: One data point per euro area country.

2.5 The lifespan of a banknote

All euro banknotes within a single denomination have the same substrate and print specifications; however, the life of a note from first issuance to destruction at an NCB depends on both its physical durability and national cash cycle characteristics. How banknotes are used by the public (e.g. whether they are stored in wallets or in trouser pockets) and even environmental factors such as humidity play a significant role in the time it takes for a note to become unfit. The frequency with which notes are returned to either CHs or NCBs then has an impact on how soon the unfit ones can be removed from circulation.

The lifespan of a banknote is commonly defined as the total number of notes in circulation divided by the notes destroyed per year. However, this approach does not take into account banknotes that are not actually circulating at all because they are being used as a store of value, have been lost, or have migrated out of the national cash cycle or even out of the euro area entirely.[49] More accurately, the life of a banknote can be stated as:

$$Lifespan[years] = \frac{Notes\ in\ active\ circulation}{Notes\ destroyed\ per\ year}$$

However, the data available does not allow the active circulation for each country and denomination to be determined accurately. The Eurosystem therefore has to rely on estimates which take into account national data on NCB and CH processing and NCB destruction volumes. Known banknote flows due to commuting, tourism or CH shipments are also included in these estimates.

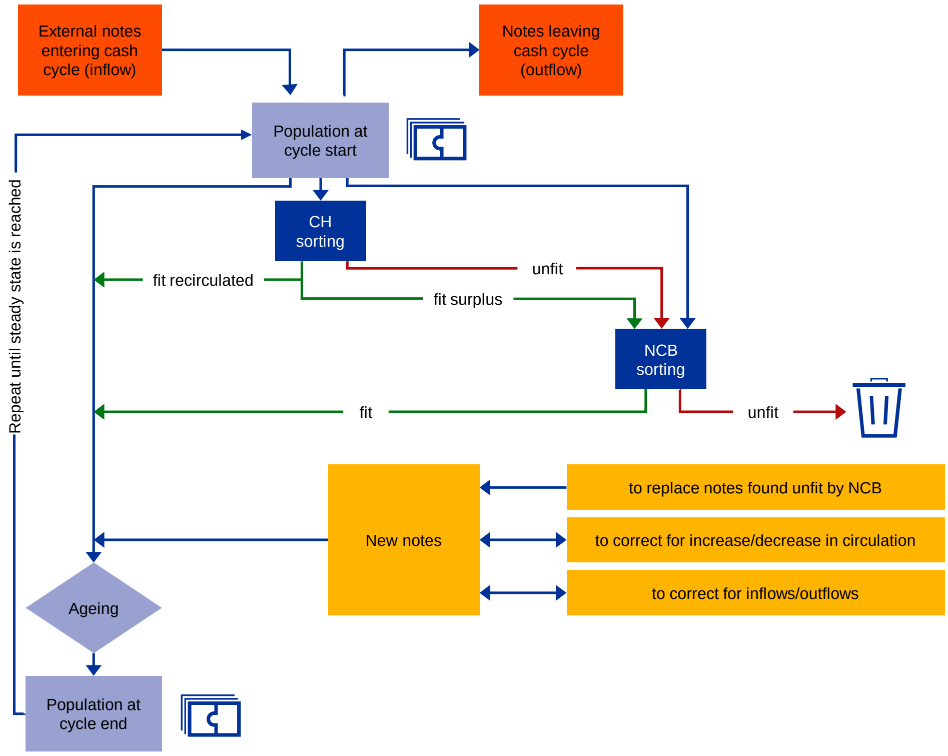
3 The model – definitions and methodology

The ECB's model simulates a cash cycle. The most important results generated are the NCB shred rate, the quality in circulation (the percentage of unfit banknotes in circulation), the replacement cost and the actual banknote life in circulation. The model starts with a population of banknotes which can be defined by the operator. After the model is started, the population evolves over a number of iterations until a steady state is reached. Each iteration in the model simulates the sorting and ageing within the cash cycle over one week. Steady state in the cycle is reached at the equilibrium where the sorting activities of CHs and the NCB counteract the ageing of notes in circulation due to soiling and defects, increases or decreases in circulation volume and inflows and outflows.[50] The cash cycle as implemented in the model is shown in Figure 2 and explained in more depth below.

49 Although the Europa series €5 note has been in issue since May 2013, at the end of 2016 342 million notes of the first series €5 had not yet been returned to the NCBs.

50 The results presented are based on steady-state cash cycles. The model also allows dynamic step changes in a cash cycle to be simulated and the evolution of parameters to be monitored over time.

Figure 2
The note circulation model



The model defines banknote fitness on a scale of 1 to 100, with the Eurosystem threshold set at 50. A fitness level of 1 is the cleanest new note, and 100 is any note which is more than twice as soiled as the threshold. Defects are binary and assigned a fitness level of 100, which ensures that they are consistently sorted out as unfit by CHs and NCBs.[51] Any population of banknotes in the model has a fitness profile, which shows the frequency of fitness levels within it. The model starts with a note population which represents the banknotes in active circulation. In every iteration the following steps are carried out:

1. Part of the note population is sorted into fit and unfit notes by CHs.

2. A further portion of the notes is then sorted by the NCB. These notes are a mix of notes from circulation, the notes found by CHs to be unfit and notes found by CHs to be fit but sent back to the NCB as surplus. The banknotes processed by the NCB are sorted into fit and unfit, with all unfit banknotes being removed from circulation.

51 This is the predominant case in reality, as camera systems usually have no problem detecting defects such as dog-ears.

3. New notes are added,[52] equivalent to the number of notes sorted out as unfit by the NCB plus an additional correction for general circulation growth or decrease and compensation for any inflows and outflows.

4. All notes in circulation (i.e. notes not processed in the cycle, notes sorted as fit by CHs and the NCB and any new notes) are aged. Ageing entails applying algorithms to simulate how banknotes gradually become soiled and suffer defects.

5. Lastly, the fitness profile of the population at the end of the cycle is compared with what it was at the beginning. If the two are sufficiently similar, steady state has been reached and the final results are displayed. Otherwise steps 1-5 are repeated as long as necessary.

The ageing of a banknote is simulated in two steps, representing soiling and defects. The average soiling per cycle is determined by the "theoretical note life" and applied to each note via a definable distribution function.[53] The theoretical note life is the time it takes for a new banknote to become unfit, i.e. to go from fitness level 1 to 50. It is an input parameter for the model and dependent on banknote durability but also on environmental factors, such as how intensively banknotes are used by the public in the simulated cash cycle.

In the next step, defects are simulated by the likelihood (expressed as a percentage per year) of each banknote suffering a defect (i.e. being moved instantly from its current fitness level to 100). The defect likelihood is applied to the banknote distribution according to a selectable profile in relation to the notes' fitness levels. With this approach, it can be modelled, for example, that banknotes with a higher soil value have a higher likelihood of becoming defective.[54]

The NCB and CH sorting steps are both simulated by applying a model sensor with inaccuracies following a Gaussian distribution[55] to the fitness profile of incoming notes. The inaccuracy of the model sensor is expressed as standard deviation (SD) in relation to the fitness scale. Chart 6 shows how a fitness sensor, operating at a threshold of a fitness level of 45 and having an inaccuracy modelled by an SD of 5 fitness levels, separates a typical note circulation profile (with 20% unfit notes) into fit and unfit notes. In the example, sensor inaccuracies mean that a small number of the notes sorted as fit are more soiled than the Eurosystem threshold (false fit 0.4%[56]), but also that a substantial number of notes sorted as unfit are well below the Eurosystem threshold (false unfit 9%).

---

[52] The model allows any fitness profile for new banknotes to be specified. Typically, a Gaussian distribution reflecting some production variations is used.

[53] A Poisson distribution is used as a standard, with other distribution functions also supported.

[54] Studies have shown that the closest correlation to real-life quality data can be achieved by applying, in each cycle, a defect probability which increases linearly with the fitness level.

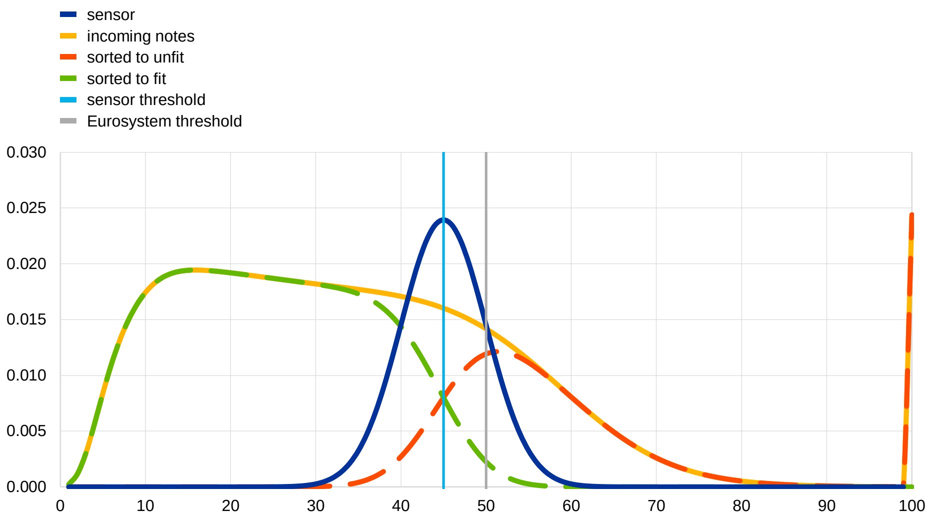
[55] The Gaussian behaviour was identified during earlier large-scale studies on sorting machines.

[56] False fit and false unfit figures are the share of total sorted notes.

Chart 6

Schematic depiction of the circulation model sorting step

(x-axis: note fitness level (1: new, 50: Eurosystem threshold, 100: very soiled); y-axis: frequency)



Source: ECB Banknote Circulation Model.
Notes: The spike at the 100 fitness level denotes defective and very unfit notes.

Modelled banknote inflows can have any fitness profile. The fitness profile of outflows is assumed to be the same as that of the current note circulation in the cash cycle. Both inflows and outflows are modelled to be neutral to the circulation volume. For outflows this is achieved by replacing the missing notes in each model cycle with additional new notes issued by the NCB. For inflows the volume of new notes added by the NCB as a replacement in each cycle is reduced accordingly.

Total cash cycle costs are modelled as the sum of NCB sorting costs and the note replacement costs. Model inputs for the two cost components are the NCB's sorting costs (per 1,000 notes sorted)[57] and the issuance costs for new notes.[58] As shown in Figure 2 the new notes which have to be issued are equivalent to unfit notes destroyed by the NCB, outflows and any circulation increases.[59] A third component is the processing costs for CHs; this is not modelled as no consolidated data exists.

4 Application of the model to two theoretical cash cycles

The section presents an analysis of two theoretical cash cycles, both of which resemble typical national cash cycles for different NCBs and/or denominations. Following a sensitivity analysis conducted on the two base cases,

57 Including all NCB costs for lodging, unpacking, processing, destruction of unfit notes, repackaging of fit notes, storing and reissuing.

58 Including production, transport, storage and handling costs.

59 For more in-depth studies the model also outputs the residual value of false unfit notes using a linear depreciation from fitness level 1 to a definable residual value at the Eurosystem threshold (50). This aspect is not covered in this article.

the two strongest factors (NCB sorting threshold and theoretical banknote life) are discussed in more detail.

4.1 Definition of two cash cycles

The two cash cycles used, representing the cash cycles of two theoretical countries, are identical in all aspects (e.g. theoretical life of a banknote, accuracy of sorting sensors used) except for the involvement of the CHs and the NCB. In Cash Cycle 1, the NCB is actively involved and recirculation by CHs is limited. Cash Cycle 2 represents a country where CHs recirculate a large share of the volume of banknotes in circulation. The values of the input parameters for the two cycles are shown in Table 1.

Table 1

Overview of the input parameters for the two base cash cycles

Input parameter	Cash Cycle 1	Cash Cycle 2
New note issuance costs	€50 per 1,000 notes	
New note fitness level	1	
New note fitness variation (SD in fitness levels)	5	
Notes in active circulation	1 billion	
Annual change in circulation volume	+5%	
Note inflows/outflows	none	
Ageing model	Poisson	
Theoretical note life (due to soiling)	24 months	
Defect likelihood per year	10% (increasing linearly with the fitness level)	
CH sorting volume per year	2 billion	5 billion
CH share of fit notes sent to NCB (as surplus)	25%	
CH sorting threshold	70	
NCB sorting threshold	50 (i.e. at Eurosystem threshold)	
CH and NCB sensor inaccuracy (SD in fitness levels)	10	
NCB sorting costs	€10 per 1,000 notes	
NCB sorting volume per year	5 billion	2 billion
Eurosystem fit/unfit threshold	50	

Notes: Rounded Eurosystem averages and estimates were used for all input parameters. In this example, the estimates for new note issuance costs and NCB sorting costs are the same for both theoretical cash cycles and do not include any economies of scale due to different NCB sorting volumes or different annual note replacement volumes (see Table 2 below).

The model results for the two theoretical cash cycles are shown in Table 2.

Table 2

Results for the two base cash cycles

Model results	Cash Cycle 1	Cash Cycle 2
Technical		
Percentage of unfit notes in circulation	6.8%	14.7%
NCB destruction (shred) rate	11.5%	23.8%
Annual note replacement volume*	574.6 million	476.5 million
Average note life in circulation	20.9 months	25.2 months
Financial		
Annual note replacement costs	€28.7 million	€23.8 million
Annual NCB sorting costs	€50 million	€20 million
Total costs**	**€78.7 million**	**€43.8 million**

Source: ECB Banknote Circulation Model.
* The note replacement volume and costs quoted here do not include notes needed to increase the circulation volume (as they are not replacing unfit notes). The additional cost due to new notes needed to increase circulation volume is, in this case, €2.5 million in the first year for both cash cycles ([1billion notes in circulation] increased by [5%], at [€50 per 1,000 new notes]).
** Excluding CH processing costs.

The two cycles studied, despite using notes with the same theoretical note life, result in a different note life in circulation. In Cash Cycle 2 fewer banknotes are returned to the NCB (2 billion against 5 billion in Cash Cycle 1), but these are more soiled. This can be seen by the NCB destruction (shred) rate, which is much higher in Cash Cycle 2. Even though a higher percentage of NCB-sorted notes are destroyed in Cash Cycle 2, the absolute volume of shredded banknotes is lower, resulting in a lower annual replacement of about 100 million notes. As a result notes are about 4.5 months longer in circulation, resulting in a substantially lower quality in circulation (14.7% unfit compared with 6.8% for Cash Cycle 1). This is expected, as the CH threshold is more lenient (70) than the NCB threshold (50) and the proportion of notes recirculated is substantially higher in Cash Cycle 2. Cost-wise, Cash Cycle 1 has almost twice the annual costs of Cash Cycle 2. This is due primarily to the substantially higher NCB sorting volume/costs and only to a small extent to the increased replacement costs.

4.2 A sensitivity analysis of the model based on the two cycles

All the model input parameters affect the final note quality in circulation and total costs; this section examines the sensitivity of the results to the input parameters, identifies key drivers and examines whether changing the input parameters affects the two theoretical cash cycles in the same way. The analysis is based on a scenario approach. The base values of the input parameters for the two cash cycles (as defined in Table 1) are modified to give new scenario values. The scenario values are set within ranges considered to be either within the inaccuracy of the respective parameter or within the expected range in which they can be adjusted by the Eurosystem. Parameters which are either fixed (e.g. the NCB or CH sorting volume) or have no impact on quality (e.g. banknote replacement or sorting costs) are not included in the analysis. Table 3 presents an overview of the modification of each model input for each scenario. For most input parameters both an increase and a decrease from the base value are simulated. For every scenario the results for note quality (expressed as the percentage of unfit notes in circulation) and total cash cycle costs are presented as change in relation to the base case results.

Table 3

Sensitivity analysis of key model parameters for the two cash cycles

(Changes in percentage points for unfit notes in circulation and EUR millions for total costs)

			Results			
			Cash Cycle 1		Cash Cycle 2	
			Unfit notes in circulation	Total costs	Unfit notes in circulation	Total costs
Base case results			**6.8%**	**78.73**	**14.7%**	**43.82**
Scenario input	**Base cash cycle value**	**Scenario value**				
Note production parameter						
New note fitness variation (SD in fitness levels)	5	1	-0.5	-1.96	-0.6	-1.04
		15	+1.2	+5.60	+3.5	+4.43
Note circulation parameters						
Notes in active circulation	1 billion	0.9 billion	-0.9	-2.33	-1.3	-1.86
		1.1 billion	+0.9	+2.27	+1.2	+1.82
Annual change in circulation volume*	+5%	0%	+0.3	+1.02	+0.8	+1.01
		+15%	-0.5	-1.90	-0.9	-1.37
Note inflow (5% unfit)	0	0.25 billion	+1.5	-7.31	+3.4	-8.10
Note inflow (20% unfit)	0	0.25 billion	+2.3	-5.87	+4.7	-6.67
Note outflow	0	0.25 billion	-1.4	+7.44	-3.2	+8.17
Note lifespan parameters						
Theoretical note life (due to soiling) in months	24	18	+2.8	+6.66	+4.6	+5.96
		30	-1.7	-4.57	-2.5	-3.27
Defect likelihood per year	10%	5%	-0.5	-1.09	+0.2	-0.84
		15%	+0.3	+0.86	+0.1	+1.14
CH parameters						
CH share of fit notes sent to NCB (as surplus)	25%	15%	-0.1	+0.02	-0.3	+0.08
		35%	+0.1	-0.02	+0.4	-0.09
CH sorting threshold	70	60	-0.3	+0.12	-2.3	+0.71
		80	+0.1	-0.04	+1.7	-0.24
CH sensor inaccuracy (SD in fitness levels)	10	5	+0.1	-0.03	+0.8	-0.21
		15	-0.1	+0.05	-0.7	+0.27
NCB parameters						
NCB sorting threshold	50	45	-2.6	+2.88	-2.6	+2.54
		55	+3.5	-3.38	+4.0	-1.35
NCB sensor inaccuracy (SD in fitness levels)	10	5	+1.0	-2.87	+1.0	-0.41
		15	-1.0	+3.60	-0.1	+1.86

Source: ECB Banknote Circulation Model.
* The note replacement volume and costs quoted here do not include notes needed to increase the circulation volume (as they are not replacing unfit notes). Additional costs for new notes due to a circulation increase for the two scenarios would be zero (for the no growth scenario) and €7.5 million (for the +15% scenario).

The table above shows that the parameters which have the largest impact on the final quality of notes in circulation are – for both cycles – the NCB sorting

threshold and theoretical banknote life. These parameters are studied in more detail in Sections 4.3.1 and 4.3.2. Other parameters such as banknote outflows have a comparable impact, but they are outside the control of a central bank.

The new note fitness variations, which in the model are expressed as SD in fitness levels, also significantly affect quality and costs. For Cash Cycle 1, changing the SD between 1 (highly uniform production) and 15 (substantial variations which affect soil detection[60]) fitness levels can result in either savings of €1.96 million or additional costs of €5.60 million compared with the base case. The overall range covers about 10% of the total cash cycle costs. In addition, the simulated increase compared with the base case has a negative impact on quality, adding an additional 1.2 percentage points to the proportion of unfit notes in circulation. The same trend is visible for Cash Cycle 2, with, however, a slightly different magnitude regarding quality and costs.

The – difficult to determine – number of notes in active circulation has a substantial impact on the model results. As a larger note circulation volume results in notes being returned less frequently to the NCB or CHs,[61] this leads to more unfit notes in circulation. Subsequently the NCB note destruction volume increases, resulting in additional replacement costs. The behaviour is similar for both cycles. For an accurate modelling of any specific national cash cycle a good knowledge of the active circulation is required.

Changes to the NCB sensor accuracy and CH sorting threshold or sensor accuracy affect the two cash cycles very differently. Cash Cycle 2 reacts about ten times more strongly to changes in the CH sensor performance (expressed as SD in fitness levels) or sorting threshold than Cash Cycle 1. This was expected, but to a lesser extent, considering that the CH sorting volume in Cash Cycle 2 is only 2.5 times the CH sorting volume in Cash Cycle 1. Yet it is a clear indication that in cash cycles with substantial recirculation, the performance of the machines used by CHs needs to be carefully monitored. NCB sensor accuracy has an impact on cash cycle costs which is about 3-7 times higher for Cash Cycle 1, indicating that efforts to improve the NCB sensor performance are most cost-effective where the NCB accounts for the largest share of note sorting. The result that better CH or NCB sensors lead to a slightly lower note quality in circulation is counter-intuitive. The reason is that “bad” sensors sort out a substantial amount of fit notes which are close to the threshold (e.g. notes with 40 – 50 fitness levels), which are in turn replaced with brand new notes. This has the side-effect of cleaning the circulation, at the expense of destroying still fit notes.

The model confirms that inflows and outflows of notes play a substantial role in the national cash cycles of the euro area. In the sensitivity analysis annual inflows and outflows of one-quarter of the total note circulation volume are

60 Such as, for example, differences in the watermark or paper tint. The estimations of the SD for production variations are based on internal ECB studies and in the past are estimated to have occurred. The Eurosystem is constantly trying to reduce such production variations.

61 At constant sorting volumes, which is the case in this simulation.

simulated.[62] As outflows are replaced in the model with new banknotes, an increase in the quality in circulation, together with an increase in the replacement costs, is observed. For incoming notes, the sensitivity analysis studies inflows of two note quality levels (5% and 20% unfit in the note population). Even when banknotes of good quality (with 5% unfit) enter a cash cycle, such an inflow has a negative impact on the circulation quality as it restricts the NCB's possibility to issue new notes. This effect becomes more pronounced the lower the incoming note quality becomes. In both inflow cases the NCB has a substantially lower need for new notes as a result of the inflows and accordingly lower replacement costs. The impact is very similar for both cash cycles.

The impact of other parameters, such as the ageing model or the defect likelihood in relation to note fitness (increasing or constant), is small and therefore not included in Table 3.

4.3 Detailed analysis of key cash cycle parameters

The sensitivity analysis above changed individual model parameters, but kept the NCB sorting threshold at the Eurosystem threshold (50). In reality, however, an NCB can modify the sorting threshold on its machines. This section looks at the possibility of adjustments of the NCB sorting threshold, to steer the note quality (4.3.1) or benefit from an extended note life (4.3.2).

4.3.1 NCB sorting threshold

An adjustment of the sorting threshold by an NCB has an impact both on the quality in circulation and replacement costs. In real life NCBs select a sorting threshold which meets the requirements of the cash cycle in their country. Cash cycles can be different owing to geographical, cultural and societal differences. Chart 7 shows the effect of adjusting the NCB sorting threshold on the two cash cycles. The dotted parts of the lines indicate sensor thresholds where the notes reissued by the NCB would include too many unfit notes (false fit > 8%) and no longer conform to the minimum note quality allowed within the Eurosystem.[63]

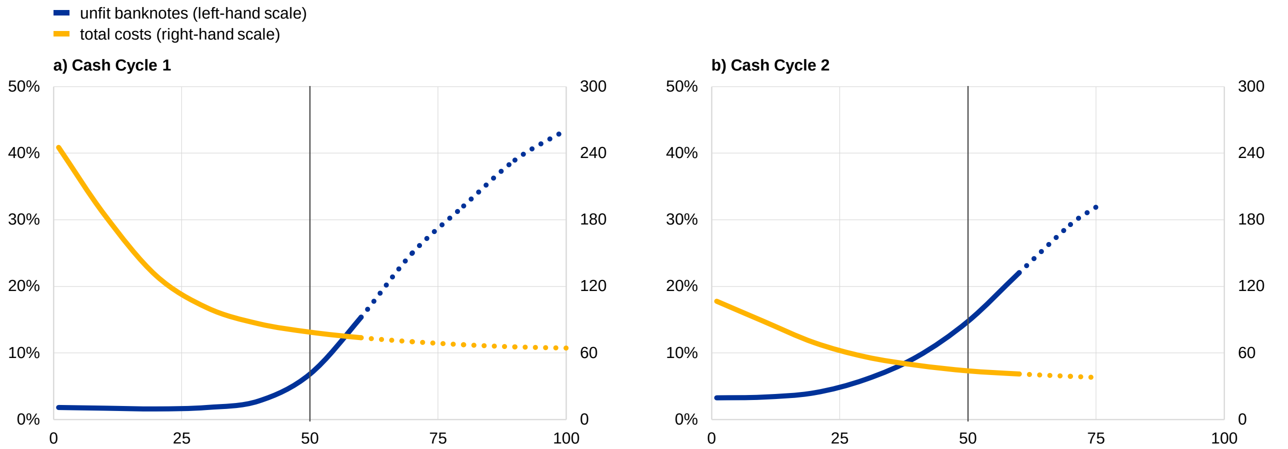
[62] On the basis of Eurosystem estimates, such inflows and outflows commonly occur in national cash cycles.

[63] Additionally, for Cash Cycle 2, no steady-state condition could be derived at NCB sensor settings higher than 75 as the resulting quality in circulation would be too low and the number of notes returned by CHs as unfit would be larger than the total annual NCB sorting capacity of 2 billion notes.

Chart 7

Quality in circulation and total cash cycle costs as a function of the NCB sorting threshold

(x-axis: NCB sorting threshold; left y-axis: percentage of unfit notes in circulation; right y-axis: total cash cycle costs in EUR millions)



Source: ECB Banknote Circulation Model.
Note: The vertical lines at 50 refer to the base cases as defined in Section 4.1. The dotted parts of the lines correspond to NCB sensor thresholds where the notes reissued by the NCB would contain too many unfit notes (false fit > 8%).

As expected, for more severe (lower) sorting thresholds, the total cash cycle costs increase and note quality improves in both cash cycles. However, the magnitude is very different in the two cycles. In Cash Cycle 1, with more severe sorting, the quality can be improved to about 2% unfit notes in circulation. In Cash Cycle 2, even with all notes received destroyed and replaced with new notes,[64] the best quality that can be reached is about 4% unfit notes in circulation. The total costs for Cash Cycle 1 remain in all cases higher than for Cash Cycle 2 owing to the constant difference of €30 million p.a. for the additional NCB processing in Cash Cycle 1 (5 billion notes compared with 2 billion for Cash Cycle 2).

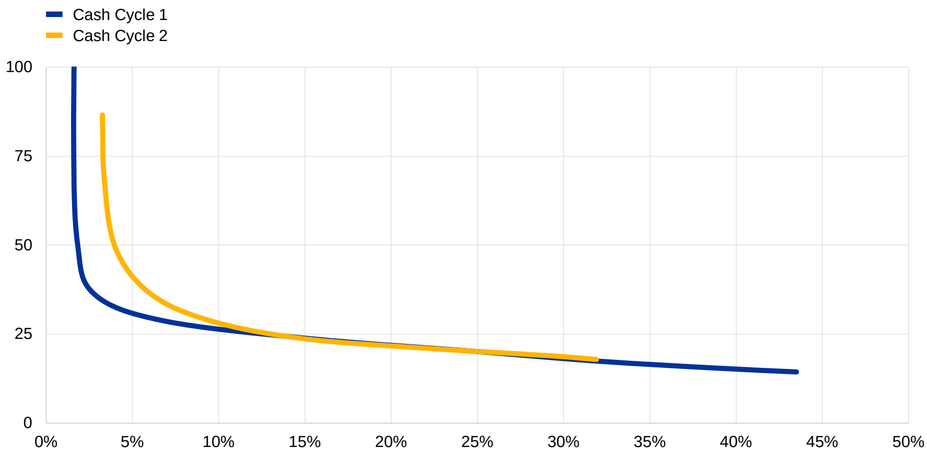
The question arises of whether a higher NCB sorting volume is beneficial. This is not immediately evident from Cash Cycles 1 and 2, as a substantial difference in the cash cycle costs is due to a different quality in circulation but also to the different annual NCB processing costs. To answer this question we therefore need to look at note replacement costs for the two cash cycles in relation to the percentage of unfit notes in circulation (see Chart 8).

[64] By sorting at an NCB fitness threshold of 1.

Chart 8

Annual replacement costs as a function of note quality

(x-axis: percentage of unfit notes in circulation; y-axis: annual note replacement costs in EUR millions)



Source: ECB Banknote Circulation Model.
Note: The chart reflects the change in circulation note quality produced by adjustment of the NCB sorting threshold.

Chart 8 shows that as long as there are more than about 10% unfit notes in circulation, the replacement costs are identical in both cycles. However, with a higher frequency of notes being returned to the NCB (as in Cash Cycle 1), the quality of notes in circulation can be raised to about 5% with only a linear increase in replacement costs. If NCB processing volumes are lower (Cash Cycle 2), the point where any further improvement in note quality comes at exponentially higher replacement costs is already at about 10% unfit in circulation.

Understanding the relationship between the extent of NCB note processing, the note replacement volume and the achievable note quality in circulation is especially relevant for the Eurosystem. The replacement costs for banknotes are shared by an allocation of the total note production volume according to each NCB's share in the ECB's capital.[65] The NCB note processing costs are, on the other hand, covered by the NCB in question. Each NCB must therefore ensure that its involvement in the cash cycle is sufficient to achieve the required national note quality without an overproportionate note consumption. The level of the NCB's involvement also needs to take into account the other factors influencing the national cash cycle, such as national differences in note life, inflows/outflows or the role of CHs.

4.3.2 Increasing banknote life

As already mentioned, one input in the model is the theoretical note life, which is the average time a note takes to become gradually soiled from new (fitness level 1) to the Eurosystem threshold (50). An increase in this parameter corresponds either to

65 Using a key which is linked to the countries' shares in the total population and gross domestic product of the EU.

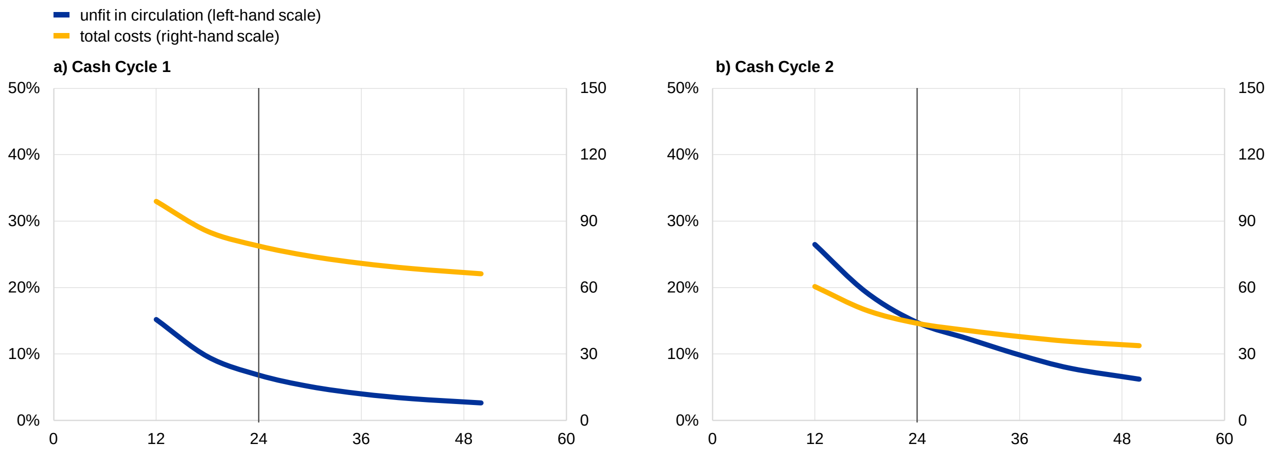
an increase in soil resistance or people treating banknotes more carefully. The actual average life of a note until destruction is then dependent on the frequency at which notes are returned to the NCB and the NCB's sorting threshold.

Chart 9 shows the – unsurprisingly – very positive effect of an increased theoretical note life on total cash cycle costs owing to reduced note replacement needs, as well as a significant increase in the note quality in circulation. If the theoretical life increases from 24 to 36 months, the note replacement costs drop for Cash Cycle 1 from €28.7m to €20.9m and for Cash Cycle 2 from €23.8m to €17.8m, and quality improves by 2.8 and 4.9 percentage points respectively.[66]

Chart 9

Impact of an increase in theoretical note life on quality and total cash cycle costs

(x-axis: theoretical note life in months; left y-axis: percentage of unfit notes in circulation; right y-axis: total annual cash cycle costs (NCB processing and replacement costs) in EUR millions)



Source: ECB Banknote Circulation Model.
Note: The vertical lines at 24 months refer to the base cash cycles as defined in Section 4.1.

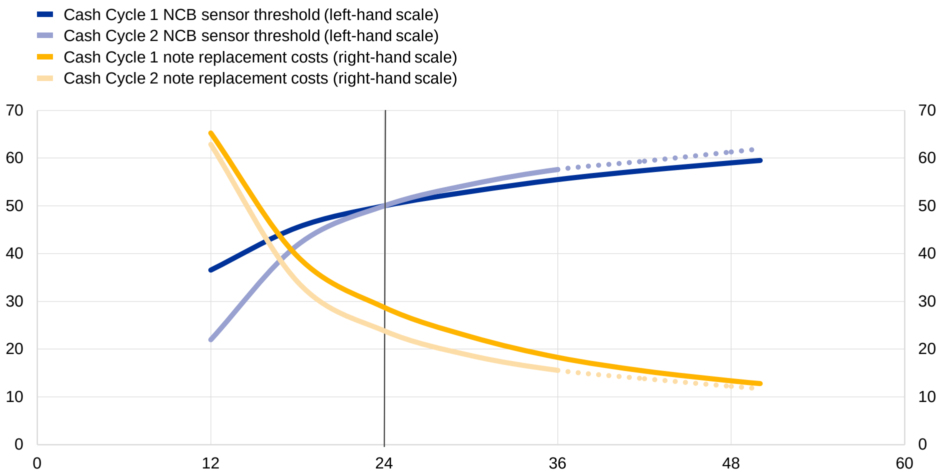
The total cost savings due to an extended note life could become even larger if the NCB decides to maintain its existing level of quality in circulation despite issuing notes with a longer life. An NCB can achieve this by adjusting its sorting threshold to settings which are more lenient than the Eurosystem threshold. This change in sorting policy is of course only possible within the limit of 8% false fit notes which can be reissued by the NCB. Chart 10 shows that if such a policy is implemented, the same increase in note life (from 24 to 36 months) further reduces replacement costs for Cash Cycle 1 to €18.3m (-€2.6m) and for Cash Cycle 2 to €15.6m (-€2.2m).

[66] The improvement in quality is larger in Cash Cycle 2 owing to the lower note quality of the base case.

Chart 10

Increasing theoretical note life while keeping constant note quality

(x-axis: theoretical note life in months; left y-axis: NCB sensor threshold; right y-axis: replacement costs in EUR millions)



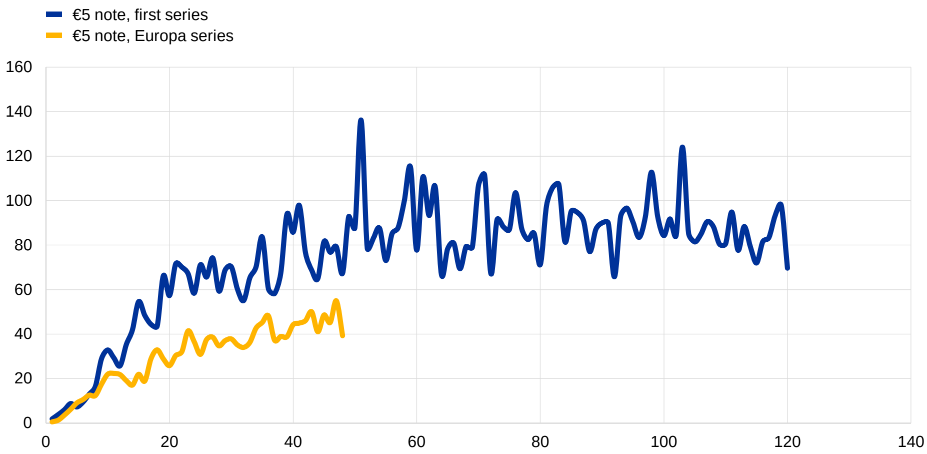
Source: ECB Banknote Circulation Model.
Notes: The chart shows the impact of an increase in the theoretical note life on replacement costs at constant quality in circulation. The blue lines indicate the required adjustment to the NCB sorting threshold to keep the constant quality in circulation. For Cash Cycle 2, unfeasible scenarios (more than 8% unfit in notes reissued by the NCB) are indicated by dotted curves.

These model results are very much in line with the Eurosystem experience with the Europa series €5 (introduced in May 2013) and €10 (September 2014) banknotes, which have been protected against soiling by an additional varnish layer. Varnishing has resulted in a substantial decrease of about 50% in the note replacement volume, resulting for the €5 note in annual savings of about 500 million new banknotes at a stable quality in circulation as found by the quality survey. The 2012 annual destruction of the first series €5 notes amounted to 1.1 billion notes, whereas from May 2016 to April 2017 only 0.57 billion Europa series €5 notes had to be replaced at a similar note volume in circulation. Chart 11 shows this reduction very clearly by comparing the monthly note replacement in the months after first issuance. For the €10 note a similar reduction in the replacement rate is currently emerging.

Chart 11

Monthly destruction of the first series €5 and the Europa series €5 notes

(x-axis: months after first issuance of the series; y-axis: monthly note destruction in millions)



Sources: Eurosystem Currency Information System 2.
Notes: For the first series, data are from January 2002 onwards, for the Europa series, data are from May 2013 onwards.

The savings for the Eurosystem from the varnishing of the Europa series have and will continue to substantially outweigh the additional production costs.

Box 1

Modelling country-specific cash cycles based on real data

The circulation model developed can be a valuable tool for decision-making. In the case of well-defined cash cycles, such as those presented in the sensitivity analysis, the impact of various policy-related factors can be comprehensively studied and better informed decisions can be made.

When, however, more detailed quantitative results are needed for a specific country, the success of such an analysis depends heavily on how well the cash cycle can be defined, in other words on the calibration of the model. Some of the parameters are known for every country: for example, the NCB sorting threshold or the NCB and CH processing volumes. Other parameters of the model, however, might not be well defined, or even not obtainable from the data currently available. Such parameters are the active circulation, the theoretical note life, the likelihood of defects, or the inflows/outflows. In this case, the inputs for the model are calibrated on the basis of expert estimation, which carries the danger of inaccuracy or error.

With an increasing volume of real-life data becoming available and increasing possibilities for processing incoming data streams, it becomes less and less necessary to rely on expert estimation to model a cash cycle. There is currently a clear trend towards new sorting machines collecting and storing detailed fitness data per banknote. This in principle allows banknotes to be monitored individually and the model parameters that govern the main steps of the cash cycle to be extracted.

With this outlook in mind, the possibility of building an alternative circulation model based on available data from sorting centres was explored. Data were taken from an external circulation trial (ECT) that took place in three countries. An ECT is an exercise, designed to accurately simulate country-specific cash cycles, where one or more NCBs issue within a very short period (1-2 weeks) a statistically relevant number of banknotes, which are then monitored, typically by serial number reading in NCB cash centres. The alternative model treats each banknote as an independent agent, which has a number of attributes: soil value, age (since issuance) and time since last sorting. This allows more complex relationships to be modelled. The work carried out focused on extracting statistical estimates of the ageing rate, the return frequency and the defect likelihood.

The alternative model's results were validated for the three countries participating in the ECT against known figures on a number of aspects, covering the quality in circulation and the unfit rates at NCB and CH sorting. The overall results were considered to be relatively promising. In most of the cases the quality in circulation was predicted with reasonable accuracy, taking into account the uncertainty of the real-life figures on note quality in circulation. However, there were some non-negligible discrepancies between the model results and the real-life figures. These were attributed mainly to inaccuracies in the data (due for instance to technical limitations of fitness sensors or the difficulty of accounting for effects of CH sorting on the note quality at the NCB) or unknown/not included parameters (e.g. migration was not modelled because of the absence of information on the fitness profiles of inflowing notes).

Lessons were learnt from this modelling approach. The data collection used was not specifically designed for the purposes of modelling banknotes in circulation. It is clear that the quality of the data has a significant impact on the quality of the data-based model itself. Moreover, simulating all the relevant aspects of a cash cycle can be challenging owing to the lack of accurate data, for instance data on the CH sorting. The success of such a modelling approach, therefore, lies in the existence of a well-designed and controlled data collection, reflecting the actual circulation and mitigating technological limitations.

5 Conclusions

Applying the ECB's computer-based circulation model to two theoretical cash cycles enabled significant parameters governing banknote quality and overall cash cycle costs to be identified. The model showed that the quality of notes in circulation increases when (1) notes are returned more frequently to the central bank, (2) sorting at the central bank becomes more severe and (3) banknotes have an increased resistance to soil and defects. The first two factors imply additional costs, however; the former for note processing and transport, and the latter for replacement notes. A balance between the ideal return frequency and severity of central bank sorting must be struck for each individual cash cycle. Increasing banknotes' resistance to soil increases the note quality in circulation and reduces the annual replacement costs. Further savings can be achieved if a central bank applies a more lenient sorting policy, so that the increase in quality is traded for additional savings in the replacement note volume.

The model also quantified the impact of additional factors. Increasing the accuracy of NCBs' fitness sensors yields savings primarily in cash cycles with a higher NCB involvement in the sorting of notes directly from circulation. Changes to the variations in the production of new banknotes or the severity of note sorting by

CHs play a substantial but comparatively smaller role in quality and cash cycle costs. Model assumptions for note ageing were shown to have an even smaller impact on note quality.

The studies showed that the note quality in a cash cycle is also heavily influenced by factors outside the control of the Eurosystem such as the active circulation volume and inflows and outflows of banknotes due to migration and tourism. While data on such factors are difficult to obtain, a consistent individual data recording of the fitness properties of each single banknote processed at NCB level would, while ensuring an anonymous use of banknotes, substantially improve figures compared with current estimates.

The Eurosystem is currently working to evaluate and improve its fitness sensors and algorithms in order to deliver consistent and linear fitness values which are linked to human perception. This will allow NCBs to better monitor and adjust their circulation quality as well as provide more reliable data to be used in future modelling.