Banknote Paper Deterioration Factors: Circulation Simulator Method

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The processes of banknote deterioration in circulation and the factors causing this wear have been analyzed to determine the main factors in the process of banknote deterioration in real life circulation and to ascertain which of these factors could be simulated in the process of simulated circulation. The factors that should be taken into consideration during simulated circulation are systematic mechanical and chemical influences on a banknote. The developed Circulation Simulator Method was used to evaluate Ukrainian hryvnia banknotes to obtain artificially deteriorated banknote samples whose optical properties, weight change, air permeability, bursting strength, and stiffness were within the range of corresponding parameter changes for bank notes in actual circulation. The designed method consisted of multiple mechanical damages to tested banknotes by means of centrifugally rotating them within a closed container containing a wearing agent in the presence of a soiling mixture, which imitates the typical composition of soil in banknote circulation within Eastern Europe. The proposed method can be used to determine the durability of materials and to develop manufacturing processes for banknote production.

Keywords: Banknote; Wear; Banknote durability; Banknote paper; Simulated circulation; Circulation simulator method

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INTRODUCTION

The improvement of banknote durability has been attracting attention in central banks for a long time (Marincovic *et al.* 2011; Meuer and Martin 2011). Many countries carry out research aimed at identifying the causes and effects of wear (Geusebroek *et al.* 2011; Balke 2011; Buitelaar 2008). However, factors causing the deterioration of banknotes have not yet been systematized. Arguably, this makes it difficult to study banknote circulation properties. In particular, it is impossible to adequately deteriorate the banknote's characteristics during a simulated wear process without a detailed study and analysis of the banknote wear and damage factors.

Sampling of deteriorated banknotes can be done in two ways: by examining samples of banknotes that have been in real life circulation (Buitelaar 2008), or by simulated circulation (Bartz and Crane 2006; Balke 2009). The artificial soiling tests have been widely used in banknote production planning for two decades. But the poor performance of artificial deterioration as a predictive instrument was pointed out. Thus, the simulation of circulation may yield results that are contrary to the data obtained from real circulation; *e.g.*, in determining the best protective varnish (Buitelaar 2002).

In simulated circulation so-called circulation simulators are applied. These are devices that imitate mechanical and chemical influences on a banknote with a certain degree of reliability. The method was applied for research aimed to improve the durability of the Swedish 20 Kronor banknote (Bartz and Crane 2006). The simulated circulation in the presence of a soiling mixture (but without of artificial sweat) made it possible to obtain deteriorated banknotes with greatly degraded characteristics (air permeability, double folds, stiffness, change in brightness, weight pickup). Unfortunately, there was no information on correlation between the results obtained in simulators and in real life circulation. Some data were incomprehensible (*e.g.*, change in brightness about 65%).

An interesting attempt was made to simulate the deterioration of banknotes in real life circulation subject to different influences (mechanical, chemical, thermal, time); this made it possible to ascertain treatment sets and modes for simulation (crumpling, moisten, massage, mixture, heating, flatten) (Balke 2009). Unfortunately, treatments were not integrated. They were performed step by step partly manually, partly automatically by means of IGT equipment. The correlation between the results obtained in this set of treatments and in real life circulation was impressive, but, unfortunately, it was shown by reduction in reflection intensity only. There was no information provided about other important characteristics, *e.g.*, air permeability, double folds, stiffness, weight pickup, *etc*.

Another way to simulate circulation is to engage staff to make contact with the test banknotes at regular intervals (Meuer and Martin 2011). People may be considered to be the most significant factor of influence on banknotes (Geusebroek *et al.* 2011; Buitelaar 2008). However, in real circulation, banknotes contact a much larger number of people than the bank employees involved in the study (Meuer and Martin 2011).

Thus, all implemented approaches for obtaining a sample of deteriorated banknotes (Bartz and Crane 2006; Balke 2009, Meuer and Martin 2011) have had certain disadvantages. Therefore, the issue of the correlation between the simulation and real circulation conditions in this approach has not been completely settled. Thus, only a study of the changes in quality of banknotes that have been in real circulation can give reliable results for forming opinions on banknote durability, the distribution of banknotes according to their quality in cash resources, and the correlation between the processing of banknotes in circulation simulators and the real life condition of banknotes over a corresponding period (Buitelaar 2002). However, considering that a banknote's life cycle in real life circulation can be quite long, simulated circulation becomes the only possible method for making a decision about improving technological processes or the use of new materials (inks, varnishes, and other basic components of banknotes) to provide the required durability. Therefore, it is very important to develop simulation methods of banknote deterioration that are as close to the parameters of banknotes in real life circulation as possible. The evaluation of all factors of banknotes deterioration and their simulation constitute the aim of this work.

FACTORS OF BANKNOTE WEAR

Various factors affect banknotes in circulation trials and, in one way or another, cause deterioration. These factors vary in duration, area, sources of influence, and type of energy. It also matters whether or not they come into contact with a banknote (Fig. 1).

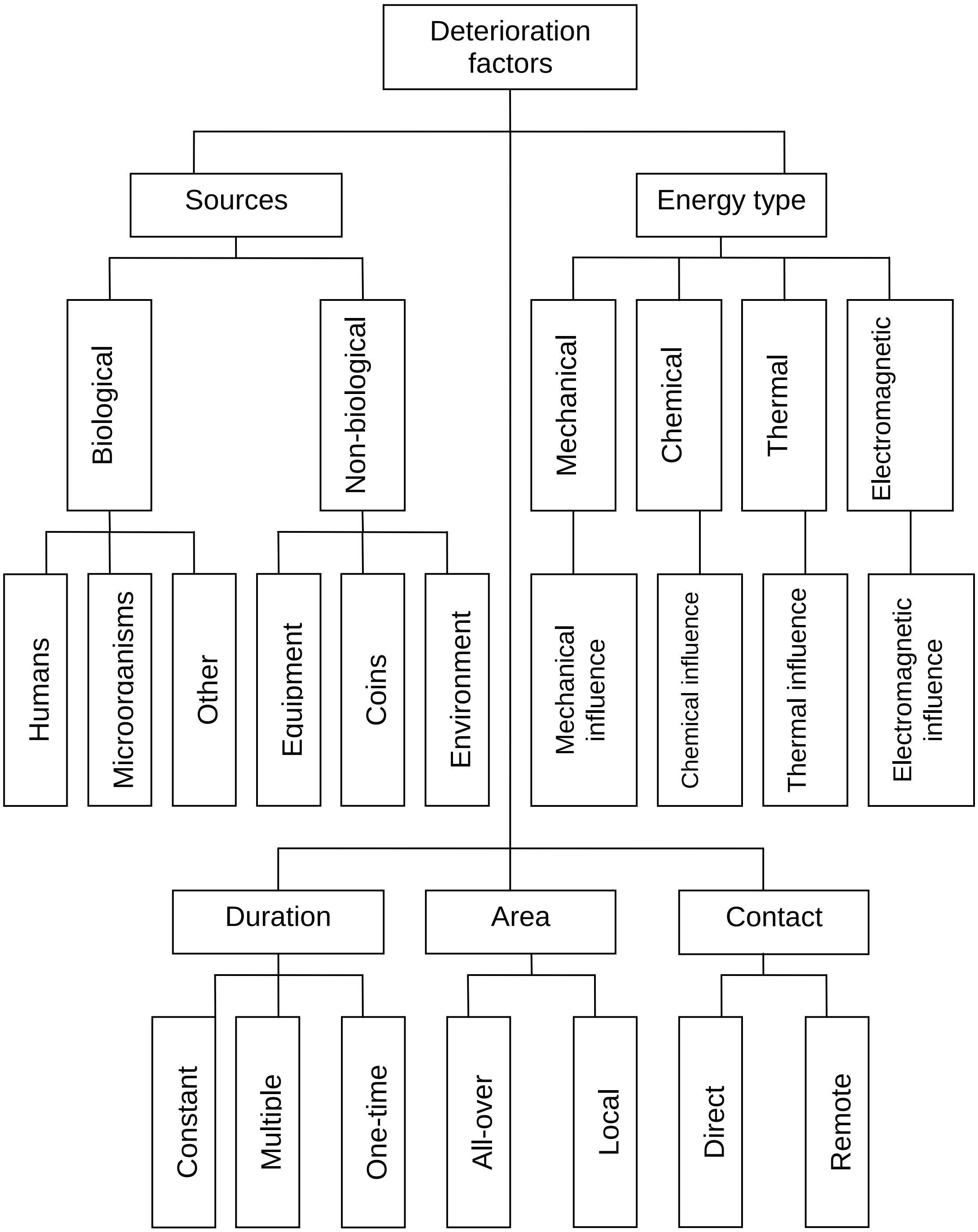

Fig. 1. Banknote wear factors

Sources of Influence on Banknotes

The sources of banknote wear are both biological and non-biological. People represent the most numerous group of biological factors. It should be noted that this source has the most significant influence on banknotes. As stated by several researchers (Geusebroek *et al.* 2011; Buitelaar 2008), the main factor in banknote soiling is finger contact, which leaves fingerprints that accumulate over time and form a yellow-brown layer of old sebum. In addition, banknotes, as well as other durable printed products, are affected by microorganisms, especially fungi, which use the paper basis of banknotes for their growth and produce various organic acids that cause banknote image fading, pigmentation, and changes in the chemical composition and structure of the paper (Buitelaar 2002; Bartz and Crane 2006).

However, given the relatively short life cycle of banknotes, which is estimated by some researchers (Marincovic *et al.* 2011; Kyrychok *et al.* 2013) not to exceed three years, which is significantly shorter than the storing period of paper editions in libraries and archives, one would assume that this factor is insignificant. The fact that during their life cycle banknotes are in heavy use, with different organic contaminants present on their surface (Balke 2009; Buitelaar 2008), along with additional microorganisms that might develop in banknotes during circulation, significantly enhances the potential impact of the biological factor.

During circulation, non-biological sources have an influence on banknotes as well. Key non-biological sources include sorting equipment, cash machines, and especially coins, which come into natural contact with banknotes during handling. In addition, banknotes are exposed to the impact of the environment in all its aspects.

Duration and Localization of Influence

While considering the duration of wear factors' influence on a banknote, it can be seen that these factors may operate either permanently throughout the whole life cycle of banknotes in circulation or temporarily, and such exposures can be one-time or multiple.

As for the area of influence, these factors can have an overall or local effect on a banknote and cause general wear and soiling, as well as local damage that is revealed in the damage to the structural integrity of a banknote and local stains.

Types of Applied Energy

Considering the type of energy applied to banknotes, the deterioration factors can be divided into mechanical, chemical, thermal, and electromagnetic. All of these mechanisms act together, reinforcing each others' effects.

Balke (2009) suggests the following mechanisms that affect the wear of banknotes: mechanical, chemical, thermal effects, and time aging. However, the inclusion of time aging to the list of mechanisms of deterioration is not necessarily entirely substantiated, as the aging of paper and prints is the result of a combined effect of several mechanisms, the foremost among which is the thermal effect combined with adsorption-desorption of water (*i.e.*, physical - chemical effect). In addition, as has been discovered in a series of studies (Fellers *et al.* 1989; Peters 2000; Area and Cheradame 2011), banknotes are affected by oxidative degradation of cellulose fibers, both generally and locally, and this impact is accelerated under the influence of light, *i.e.*, electromagnetic interference. Thus, time aging can be considered to be a secondary factor derived from chemical, thermal, and electromagnetic effects and enhanced by mechanical factors.

Mechanical influence

Banknotes in circulation experience mechanical influences with different origins (Fig. 2): bending, crumpling, twisting, friction, tearing, denting, creasing, folding, piercing, and so on. As a result of this influence, the stiffness of banknote paper decreases and its structural integrity deteriorates due to the damage done to its fibers, some of which can even detach from the surface (Balke 2009). This, in turn, causes the general deterioration of banknotes, which is revealed in the increased porosity and roughness of the paper and its reduced stiffness (Bartz and Crane 2006; Balke 2009), as well as in the violation of its structural integrity. This violation includes tears, holes, ruptures, folds, wrinkling, dog-ears, changes to the banknote perimeter, and edge tears (Table 1). The increase in the degree of general wear and tear of the paper further reduces the banknotes' resistance to mechanical and other influences.

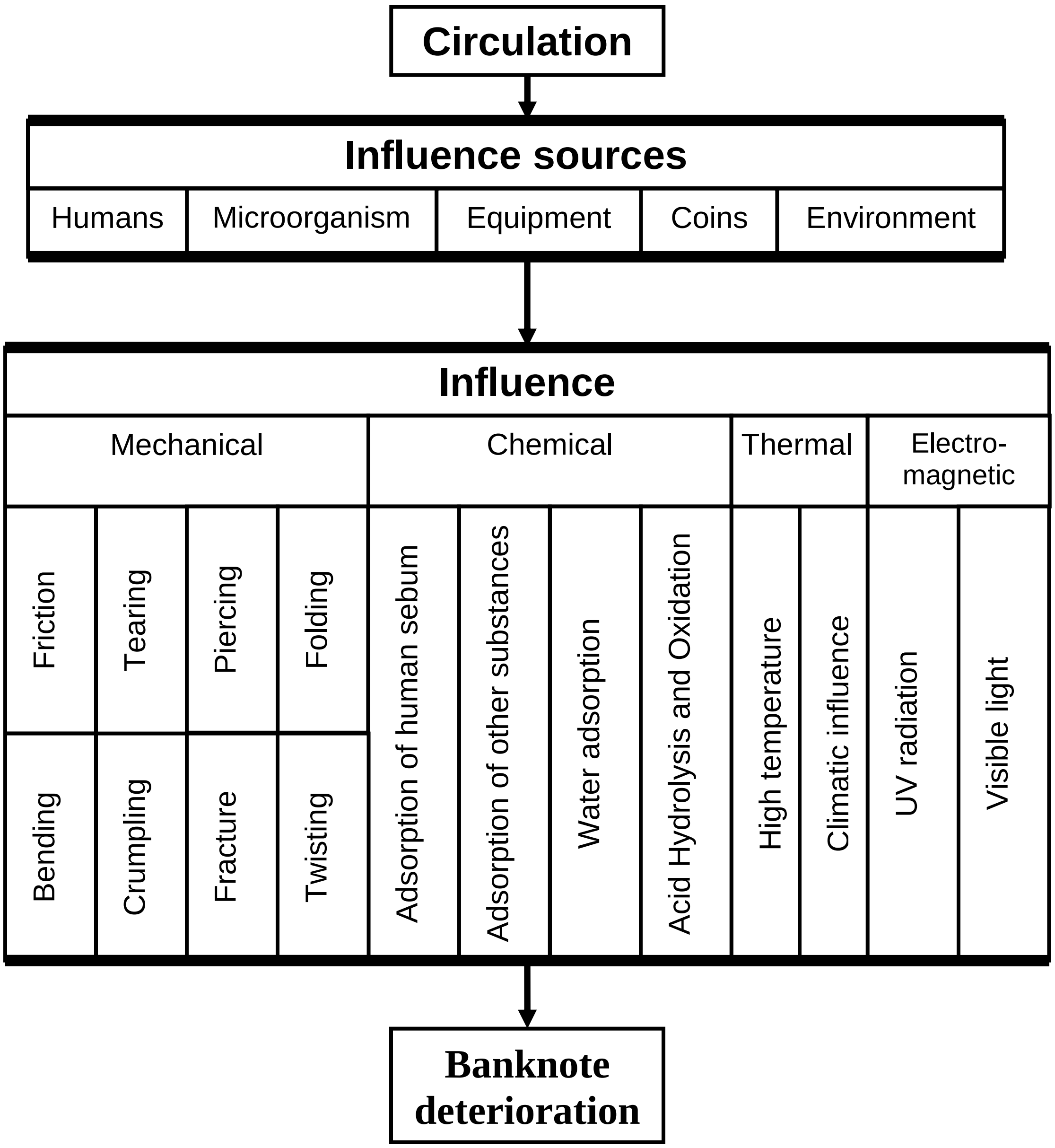

Fig. 2. The mechanism of deterioration of banknotes in circulation

Chemical influence

Another important factor resulting in banknote deterioration is the chemical effect, which for the purposes of this study will mean all processes that occur in banknotes as a result of their exposure to chemicals (organic and inorganic) and photochemical processes.

In the course of circulation, banknotes come in contact with gaseous, liquid, and solid organic and inorganic substances that can penetrate the bulk of the paper material or form a layer on its surface (Fig. 3). Fingerprints may be composed of naturally secreted materials, such as sweat (99% water and 1% solid), sebum, and foreign materials picked up on the hands. In time the sweat droplets decrease in volume as the more volatile components evaporate. After several days the fingerprints becomes more viscous and almost solid (Balke 2009). The most significant organic factor involved in banknote wear is the secretions of human sebaceous glands. Chemically, the major components of human surface fat are triglycerides (20 to 44%), waxes (23 to 25%), and free fatty acids (2 to 31%). Sebum waxes are esters of long chain fatty alcohols (average Carbon number 20) and long chain fatty acids (average carbon number 16), which comprise almost 25% of human surface skin lipids (Wootton 1989). As mentioned above, the layer of sebum that eventually covers the surface of banknotes causes changes in the color characteristics of banknotes. The natural color of sebum is yellow-brown, and these changes are especially noticeable in the blue part of the spectrum (Buitelaar 2008). Moreover, such changes of color are not uniform because of preferential accumulating of sebum on surface asperities and in wrinkles, folds, *etc.*

Water and air oxygen have the greatest impact on banknotes among the inorganic substances that influence banknotes. They cause paper aging and oxidative processes as well as hydrolytic degradation of cellulose macromolecules (Area and Cheradame 2011). In this study, water influence refers to a direct contact of water with a banknote, as well as the influence of humidity. High humidity not only causes an accelerated development of microscopic fungi (molds), but also leads to structural changes in the paper due to the elongation of cellulose fibers. As a result, a banknote becomes wavy. In contrast, very low humidity (less than 30%) leads to the irreversible loss of structurally bound water in a banknote. Consequently, paper dries out, loses elasticity, and becomes brittle and excessively crisp (Pedersoli and Ligterink 2001).

Electromagnetic influence

When it comes to such factors as the effects of electromagnetic radiation, sunlight is a primary factor, although artificial light also has a negative impact on banknotes. Both of these types of light accelerate the aging process of banknote paper, and as a result, paper becomes yellow and brittle and its strength and elasticity are reduced. In addition, the color characteristics of the print change (its brightness decreases) (Lajic *et al.* 2013), and stains (foxing) appear on banknotes due to local oxidative destruction (Choisy *et al.* 1997; Greve 2000; Rebrikova and Manturovskaya 2000). Recent findings (Skora *et al.* 2011; Zotti *et al.* 2011) suggest that most foxing stains are due to dead or alive airborne fungi. The effect of light is enhanced by the presence of light-sensitive substances on the surface and within the structure of the banknote paper. These include stains on the surface and the inclusion of certain additives in the structure of the paper during its production. It is important to note that the influence of this factor is especially profound in banknotes that have a large number of surface contaminants. Security features (security fibers, confetti, threads, *etc.*) also have their own specific optical properties (Van Renesse 2005; Perron 2010). It also matters that banknotes are periodically exposed to UV radiation while they go through authentication controls. Such radiation has the highest photochemical activity (Adcock *et al.* 1998) and consequently has the most negative impact on the banknote paper substrate.

Table 1. Types of Banknote Damage

Damage localization	Damage type	Damage feature	
Overall	General wear and tear	Security features damage	
		Intaglio printing height reduction	
		Edge micro tear	
		Abrasion	
		Ink fading and wearing off	
		Paper softness	Porosity increase
			Roughness increase
			Thickness increase
			Elasticity decrease (tensile strength decrease)
		Stiffness loss	
		Wrinkling	
	General soiling	Color change	
		Optical density change	
		Weight increase	
	Aging	Paper yellowing	
		Elasticity decrease (fragility, crispness)	
		Inks brightness decrease	
	Destruction	Total destruction	
Local		Banknote size reduction	
	Geometrical form change	Missing corner (dog-ear)	
		Missing part	
		Geometrical size change due to	Waviness
			Crumpling
			Folding
	Structural integrity violation	Mechanical	Tear
			Hole
		Thermal	Thermal edge destruction (burn)
			Thermal base destruction (perforating burn)
		Chemical	Chemical edge destruction
			Chemical base destruction
	Local soiling	Stains	
		Graffiti	Added written mark
			Added drawing
			Added seal

Thermal influence

Another factor that falls into the 'energy' category is thermal energy, which has two components: climatic thermal effects and high-temperature effects. The former refers to the changes characteristic of natural conditions, which, however, vary for different climate zones (Tam and Nazhad 2002), and the latter occurs when the temperature is near or greater than the temperature of the thermal destruction of paper (200 to 220 ^{o}C). It is clear that the influence of the latter factor is more dangerous for a banknote and leads either to its complete destruction due to burning or to local thermal damage (burnt edges, burning through, *etc.*). However, the climatic thermal effect also causes a negative change in banknotes, as it speeds up the aging process of banknote paper. It has been mentioned that a temperature increase of 10 ^{o}C doubles the speed of chemical processes (Balke 2009).

The majority of the described factors of banknote wear have a contact character, which is determined by the nature of the product. However, such factors as radiation or thermal climatic influence, unlike the effect of high temperatures, do not require contact with the object to have an effect.

Banknote Deterioration Characteristics

While distributing and processing banknotes, the following features of deterioration and damage (FRB 2008; Martinez *et al.* 2009; Cantero 2010; Kropnick 2012; Kyrychok *et al.* 2013) are monitored: security features that are visible in the infrared and ultraviolet spectrum; security features with magnetic properties; and, if technically possible, other security features; mechanical damage (tears, holes, wrinkles, dog-ears, and missing parts); general wear and tear; and local and overall soiling.

In addition to these banknote deterioration characteristics, in the course of scientific studies of the banknote deterioration process, the changes in paper porosity, paper roughness, and its durability characteristics have also been examined (Bartz and Crane 2006; Kyrychok 2013). Different methods of monitoring banknote general soiling have received a lot of attention because such soiling is a major cause of the withdrawal of banknotes from circulation. Among the characteristics that are used for such monitoring, the following changes in the optical characteristics of banknotes can be named: a change of color, which is monitored visually by personnel; changes in optical density (FRB 2008); the measurement of visible light reflected from the banknote (Bartz and Crane 2006; Martinez *et al.* 2009), spectral characteristics of banknotes in the range of 380 to 740 nm, and transmission of IR-radiation (Balke 2011).

During this research, banknotes were divided into several groups according to their quality. Usually they are divided into the five following groups (Buitelaar 2008): Class 1 - Superfit, Class 2 - Fit, Class 3 - Acceptable, Class 4 - Unfit, and Class 5 - Super unfit. The assignment of the banknote to the first four groups is grounds to make a decision for it to stay in circulation. During scientific research, this division is usually done manually.

Consideration of Factors Influencing Banknotes for Simulation of Circulation

The above analysis of banknote deterioration processes in circulation and the factors that cause it allows for the identification of the factors that are the most important in these processes and the determination of which of these factors can be simulated by means of artificial deterioration.

The factors that must be taken into consideration in the wear simulation include those having systematic effects (constant or multiple). The sources of such exposure are firstly people and coins. Simulating the impact of microorganisms is also very important, but because of biosecurity reasons, such studies should be done only for the development of banknotes with enhanced protection from microorganisms (Sabo *et al.* 2013). In addition, the simulation of circulation lasts for 1 to 2 h, which is not enough to simulate the impact of microorganisms.

During the simulation of circulation, it is necessary to ensure the simultaneous influence of different factors on banknotes, especially mechanical and chemical ones. Thermal and, in particular, climatic effects should be imitated mainly for the study of banknotes that circulate in countries with tropical climates. Because wear simulation takes a short time, various types of radiation (UV and visible light) can be taken into account in the natural course of processing and measuring of banknote characteristics.

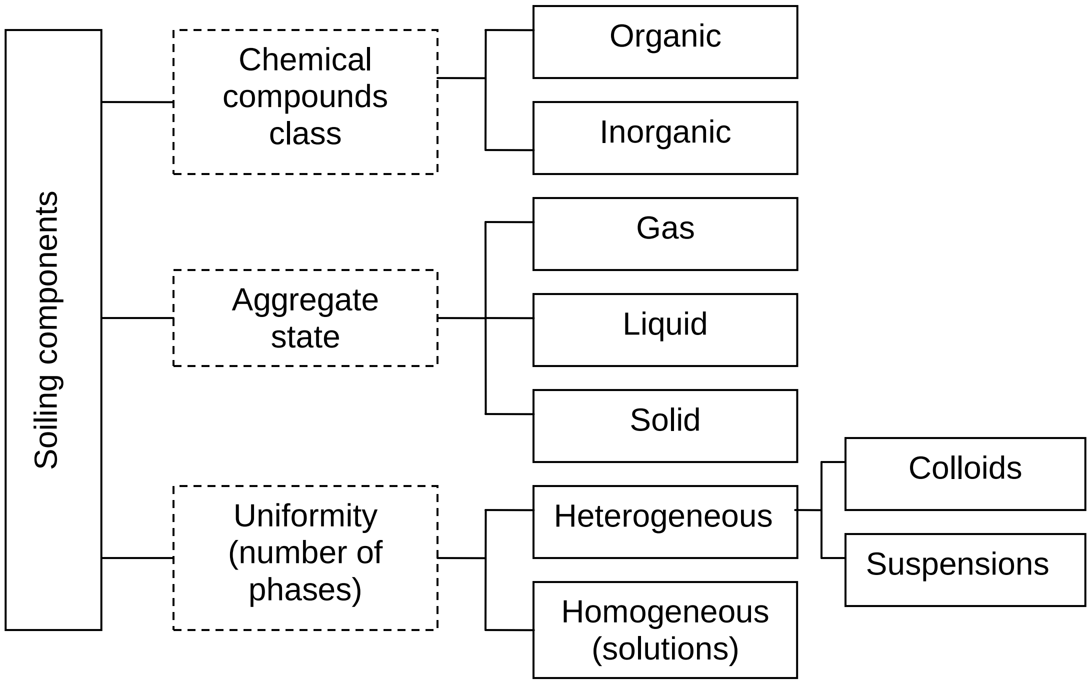

Fig. 3. Soiling component types

EXPERIMENTAL

Materials

The Ukrainian 2 hryvnia (UAH 2) banknote substrate is a 100% cotton-fiber-based structure with melamine-formaldehyde sizing. Some features of UAH 2 banknote paper are grammage: 85 g/m^2, sizing/Cobb$_{60}$: 30.0±2.0 g/m^2, double foldings (MD): 5400, tensile strength (MD): 780 mN, surface roughness (Bendsten): 350 mL/min, and ash content: 2.5%.

Method

The consideration of the factors causing deterioration of banknotes led to the development of the circulation simulator method, which allows for the production of banknote samples whose parameters are as close as possible to the parameters of banknotes in real life circulation.

The mechanical impact on banknotes was simulated by their repeated contact with a wearing agent within a closed container, while being rotated around the container axis. This kind of treatment of banknotes provided multiple types of mechanical damage, such as friction, twisting, folding, tearing, crumpling, fracture, indentation, and bending. The imitation of twisting, bending, and tearing due to the centrifugal force that occurs during rotation was enhanced by affixing stiffening strips with extra load to the shorter sides of the banknotes.

Chemical effects on banknotes were simulated by adding a soiling mixture during all cycles of the simulation. The composition of the mixture corresponds to the layer of soil on the surface of Ukrainian hryvnia banknotes and simulates organic and inorganic compounds that are found on banknotes in real circulation (Kyrychok *et al.* 2013). The soiling mixture used in the simulation was typical of banknote circulation within Eastern Europe.

1. Solid components of the soiling mixture:

- White clay as a hydrophilic analogue of dry soil with a developed surface morphology;

2. Liquid components of the soiling mixture:

- Sunflower oil and olive oil, which were used to simulate lipoid substances;
- Alcohol, 70%, which was used to increase the solubility of degradation by-products, increasing their interactions with the surface and the bulk of banknote paper.
- So-called ‘artificial sweat,’ a substance that is close in composition to human perspiration (sodium chloride (4.5 g); potassium chloride (0.3 g); ammonium chloride (0.4 g); sodium sulfate (0.3 g); lactic acid, 80% (3.0 mL); urea (0.2 g); distilled water (1000 mL)).

The following amounts of these components of soiling mixture were put into the container of the circulation simulator before the first cycle of deterioration and mixed carefully: clay: 0.24 g, sunflower oil: 0.5 mL, alcohol (70%): 0.4 mL, olive oil: 0.5 mL, and artificial sweat: 1.5 mL.

Thermal influence on banknotes were simulated by maintaining of container during all cycles of treatment at a temperature of 35±2 ^{o}C that is close to human body temperature.

Equipment

A circulation simulator is a device with an automatic rotation control mechanism for rotating a drum (container size of 280 × 220 × 220 mm with a lid, clamps, and a gasket) that can perform rotary movements within certain parameters (frequency, clockwise, and anticlockwise movement). The drum was filled with a wearing agent in the form of glass beads of two fractions 2 mm in diameter (total weight 1 kg) and 3.3 to 3.8 mm (total weight 1 kg). The drum rotation speed was 60 rpm.

The wear simulation of banknotes was performed cyclically (3 cycles of 10 min, 5 min clockwise and 5 min anticlockwise) using the soiling mixture.

To give the banknotes additional stiffness during the wear simulation process, 10-mm-wide, 0.5-mm-thick plastic stiffening strips, cut in a shape similar to a dog bone, were used. The stiffening strips had holes on each side for affixing them to pre-prepared holes on the left and right sides of the experimental banknote samples. To fix the stiffening strips, four fluoroplastic fasteners for each banknote were used: screw and nut (head diameter 16 mm, length 20 mm, thread M5, weight 9.3 ± 0.2 g).

Method of Measurement

The characteristics of banknote resistance to general soiling (brightness change, color deviations, and weight change) and matrix strength (air permeance (Bendsten) and stiffness (Taber)) were investigated.

Resistance to general soiling

Brightness change: The standard TAPPI method (TAPPI Standards 1998), which is widely used in the evaluation of banknote deterioration (Bartz and Crane 2006), was used. This describes the human perception of banknote soiling fairly well.

Color difference: ΔE^*_{ab}. This is defined in the color space CIE 1976 (L^*, a^*, b^*) by the formula $\Delta E^*_{ab} = \sqrt{(L^*_{new} - L^*_{\det})^2 + (a^*_{new} - a^*_{\det})^2 + (b^*_{new} - b^*_{\det})^2}$, where $L^*_{new}, a^*_{new}, b^*_{new}$ are the color coordinates of unworn banknotes and $L^*_{new}, a^*_{new}, b^*_{new}$ are the color coordinates after deterioration (Schanda 2007). This indicator most fully characterizes the human perception of the color change in banknotes and its shift toward a yellow-brown color as a result of wear and tear (Buitelaar 2008). It is known that humans can detect the color difference if $\Delta E^*_{ab} \geq 5$ (Schanda 2007).

Change in Weight: A standard measurement method of weighting 10 samples on a set of analytical scales was used.

The measurement of optical characteristics was performed in the non-printed area near the watermark on both the face and reverse of the banknotes.

Resistance to general wear and tear - matrix strength

Bendsten air permeability: A standardized test (ISO Standards 1992) that describes the softness and porosity of the banknote substrate and which increases as a result of the wear and tear process, was used. It also describes the surface sealing and strength of the paper fibers, as well as the bonds between them, which are reduced due to the banknote wear. The test also characterizes the relative position of the fibers.

Bursting strength: A standardized test (TAPPI Standards 2010) that characterizes the strength of paper fibers and the bonds between them, which reduce due to wear, was used.

Stiffness (Taber): A standardized test (TAPPI Standards 2013) that characterizes the bending resistance, which depends on the strength of the paper fibers and the bonds between them and becomes reduced due to wear, was used.

RESULTS AND DISCUSSION

The characteristics of samples before and after the deterioration of the banknotes by the Circulation Simulator Method were determined. A total of 100 banknote samples (in 5 series of wear simulations, 20 samples in each series) were examined. The parameters for banknotes of the same denomination - new banknotes (Class 1 - Superfit) as well as banknotes withdrawn from real circulation (Class 5 - Super unfit) – were also determined. In the latter case, a sample volume of 1000 banknotes of each grade was examined. The data are presented in Tables 3 to 5.

These data suggest that in terms of soiling and general wear and tear, the proposed Circulation Simulator Method makes it possible to rather accurately imitate the degradation of banknote characteristics in real life circulation. Almost all characteristics of artificially deteriorated banknotes were within the range of changes in the corresponding parameters of banknotes in real life circulation. There were some differences in the color coordinates of artificially worn samples and banknotes from real life circulation. A less marked shift toward a yellow-brown color during wear simulation was noticed. This discrepancy was caused by a lower degree of oxidation due to the significantly shorter time of exposure. Indeed, the average time of circulation for the corresponding banknote denomination (2 hryvnia) is 12 months (Kyrychok *et al.* 2013). However, the changes in brightness and lightness of real and artificially worn banknotes differed insignificantly. All these results suggest that the developed method of banknote wear simulation adequately models the changes that occur in banknotes in real life circulation.

Table 3. Changes in General Soiling Characteristics as a Result of Wear Simulation and Real Life Circulation

Characteristic		Brightness (%)		Color difference ΔE^*_{ab}		Weight change (g)	Weight change (%)
		Front side	Reverse side	Front side	Reverse side		
Before wear	Samples before simulation	66.33±0.17	51.33±0.21	-	-	-	-
Before wear	Grade 1 - Superfit	66.02±0.42	51.90±0.61	-	-	-	-
After wear	3 series of simulation	51.97±1.50	40.82±1.46	6.70±0.22	6.02±0.31	0.044±0.005	6.71±0.76
After wear	Real life circulation Grade 5 - Super unfit	52.56±5.06	42.26±4.34	7.55±0.40	7.05±0.45	0.046±0.009	7.01±1.37

Table 4. Changes in Color Coordinates in the Color Space CIE 1976 (L*, a*, b*) as a Result of Wear Simulation and Real Life Circulation

Characteristic		L^*		a^*		b^*		Color difference ΔE^*_{ab}	
		Front side	Reverse side	Front side	Reverse side	Front side	Reverse side	Front side	Reverse side
Before wear	Samples before simulation	86.8	80.9	2.1	8.2	4.0	8.3	-	-
Before wear	Grade 1 - Superfit	86.8	80.9	2.1	8.2	4.0	8.3	-	-
After wear	3 series of simulation	81.8	75.2	5.4	9.1	7.0	10.1	6.70	6.02
After wear	Real life circulation Grade 5 - Super unfit	81.5	75.1	5.8	10.3	7.9	11.7	7.55	7.05

Table 5. Changes in General Wear and Tear Characteristics as a Result of Wear Simulation and Real Life Circulation

Characteristic		Air permeance (Bendsten), mL / min	Bursting strength (cross-machine direction), N	Stiffness (Taber), (cross-machine direction), mN·m
Before wear	Samples before simulation	0	61.43±0.22	0.82±0.04
	Real life circulation Grade 1 - Superfit	0	62.50±1.25	0.72±0.12
After wear	3 series of simulation	20.2±2.5	51.15±0.42	0.40±0.02
	Real life circulation Grade 5 - Super unfit	39.0±19.9	45.40±6.30	0.32±0.10

CONCLUSIONS

1. The deep analysis of banknote deterioration processes in circulation and the factors that cause it allows for the identification of the factors that are the most important in these processes and the determination of which of these factors can be simulated by means of artificial deterioration. The factors that must be taken into consideration in the wear simulation include those having systematic effects. During the simulation of circulation, it is necessary to ensure the simultaneous influence of different factors on banknotes, especially mechanical and chemical ones.
2. The Circulation Simulator Method, based on analysis of the deterioration process, was designed to cause multiple mechanical damage to banknotes in simulated circulation with the use of a wearing agent (glass beads of different fractional composition) and due to the effect of centrifugal force rotation of samples within a closed container. The process of simulated deterioration occured in the presence of a soiling mixture (white clay, sunflower and olive oil, ethyl alcohol, artificial sweat), which simulates a typical composition of soil for banknote circulation within Eastern Europe.
3. This method, which was applied to Ukrainian hryvnia banknotes, yielded samples of artificially deteriorated banknotes whose general soiling characteristics (optical properties and weight change) and general wear and tear (air permeance, bursting strength, and stiffness) were within the corresponding parameters of banknotes in real life circulation.
4. The proposed method makes it possible to quite accurately simulate the degradation of the characteristics of banknotes in real life circulation. It can be used to determine the durability of materials and manufacturing processes of the Ukrainian hryvnia and other currencies.

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