

Wrong Design of Cipher Keys: *Analysis of Historical Cipher Keys From the Hessisches Staatsarchiv Marburg Used in the Thirty Years' War*

Eugen Antal
Slovak University of
Technology in Bratislava
Slovakia
eugen.antal@stuba.sk

Jakub Mírka
The State Regional Archives
in Pilsen
Czech Republic
mirka@soaplzen.cz

Abstract

Nomenclator is a complex encryption system consisting of several different simpler encryption systems used together during the encryption. It is one of the main encryption systems used before the twentieth century. In some cases, there are large collections of historical ciphers preserved in archives. Those from a particular time period or geographic location are very valuable and can bring insights to the cipher design from a specific time/location. This paper provides the first detailed empirical analysis of historical cipher keys from the Thirty Years' War deposited in Hessisches Staatsarchiv Marburg. We describe a large variety of analyzed keys with a focus on those properties (poorly designed keys) that can decrease the security of the cipher. We further show that these properties alone do not imply a bad design, sometimes a combination of several properties is needed and at the same time a bad use of the encryption key.

1 Introduction

The study of historical ciphers is essential for understanding how ciphering evolved in the past. In this paper, we examine a special encryption system called *Nomenclator*. It is one of the main encryption systems used before the twentieth century and used extensively in European warfare and diplomacy. Many encrypted documents and cipher keys have survived¹ in archives around the world. In some cases, also as large collections from a particular time period or geographic location (Láng, 2020; Antal et al., 2021). Studying such a collection of ciphers can help to better understand some aspects of historical cryptography.

¹There are thousands of ciphers preserved in archives. Many of the encrypted documents are still unsolved.

Research in this field is progressing in recent years. Projects, like the *DECRYPT*² (Megyesi et al., 2020) and the *HCPortal*³ (Antal and Zajac, 2020; Antal and Zajac, 2021), are mainly focusing on the digitization and processing of encrypted documents and cipher keys, and developing new methods to solve these ciphers. Gaining new knowledge about how these ciphers were designed and used is necessary for a better understanding of these ciphers and for developing effective and sophisticated solving methods. It is therefore necessary to investigate the design and structure of historical cipher keys (Tudor et al., 2020; Megyesi et al., 2021).

If a nomenclator system is correctly constructed and used, it is very hard (or impossible) to crack. On the other hand, many of them were designed and used incorrectly (Dunin and Schmech, 2020; Antal et al., 2021). In the available literature, to the knowledge of the authors, there is no comprehensive study of the poor design of encryption keys. This paper provides the first detailed empirical analysis of the weak cipher key design from a specific time period. We investigated a collection of cipher keys from the Thirty Years' War deposited in Hessisches Staatsarchiv Marburg.

2 Nomenclator Encryption System and Cipher Key Design

Nomenclator is a special encryption system consisting of several different simpler encryption systems used together during the encryption. This type of encryption was very popular and was used for a long time period. It was used from the fourteenth to the nineteenth century (Dunin and Schmech, 2020; Meister, 1906; Lasry et al., 2020). The design of these systems was very variable. It is possible to find examples from small (very sim-

²<https://de-crypt.org/>

³<https://hcportal.eu>

ple) instances to very complex ones. We recall the main characteristics of this type of encryption system summarised from Antal et al. (2021):

A *nomenclator* mostly contains a substitution of *letters* (monoalphabetic or homophonic substitution) in a combination with substitution of *n – grams* (bigram and/or trigram substitution),⁴ *codes* and *nulls*. It is not widespread, but some nomenclators contain a polyalphabetic substitution, too.

The sub-encryption systems (encryption rules) are described by a cipher key, which is very characteristic:

- Cipher key is mostly drawn on a large paper sheet.
- The individual sub-encryption systems are mostly graphically separated.
- Codes used in a nomenclator can grow its size to several pages. In that case, it is often organized as a small book.
- The cipher text alphabet is often represented by (combinations of) letters, numbers, and special symbols/glyphs.⁵
- Cipher key sometimes contains a part not only for encryption but also for decryption (where the elements are ordered by the cipher text units).

An example of a good cipher key design is visible in figure 1. This nomenclator contains a large homophonic substitution, bigram substitution, and many nulls and codes (codes are not visible on this image). If the text encrypted with this key is not too long, and the key is correctly used,⁶ it is almost impossible to solve such a cipher without additional information or without finding the correct key (Dunin and Schmech, 2020; Antal et al., 2021).

However, many cipher keys were also poorly designed (Mírka and Vondruška, 2013; Antal and Mírka, 2018; Dunin and Schmech, 2020; Antal et al., 2021).

⁴There are often section for substitution of syllables, but from the structural point of view the *n*-grams category is more suited.

⁵In many cases, a special separator is required such as a dot or comma. This is necessary to clearly distinguish/split the cipher text units.

⁶In fact, incorrect usage of a strong cipher key (e.g. not using nulls/using a small number of nulls, or not using all possible homophones from the table) can lead to the depreciation of the strength of the key.

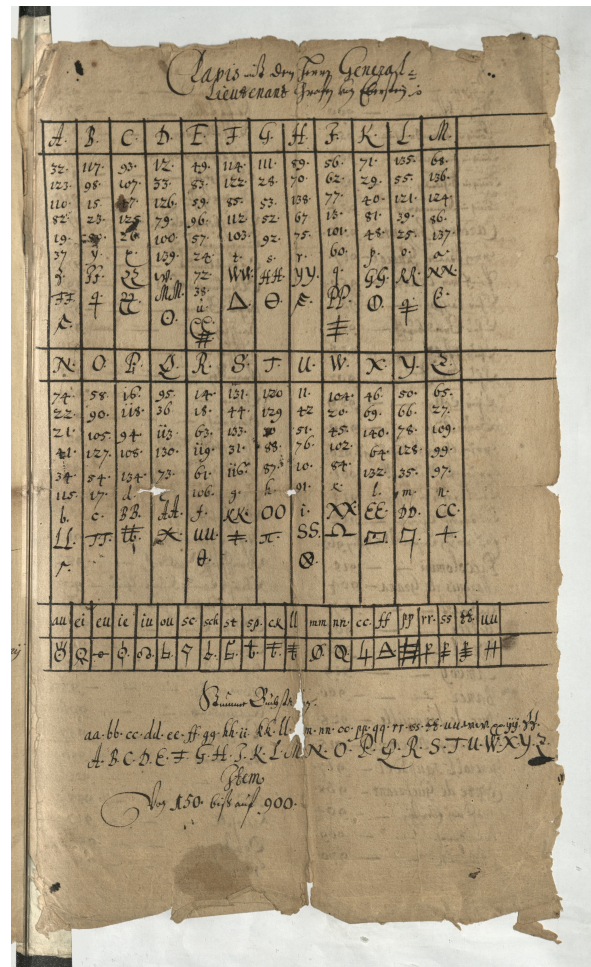


Figure 1: Cipher key example (part of the key). HLA-HStAM Best. 4d Nr. 1218.

We introduce a less formal definition of the weak (wrong/poor) cipher key:

A *cipher key is weak if it contains one or more properties, that decrease the security of the cipher.*

The security of a cipher (nomenclator) is decreased, when:

- at least one sub-encryption part of the cipher can be distinguished from other sub-encryption parts, and as a consequence, it is significantly easier to (partially) solve at least one sub-encryption part; or
- the symbols of the cipher alphabet are assigned according to some regular patterns, and as a consequence, it is significantly easier to (partially) solve at least one sub-encryption part.

In the next section, we will describe some properties of poorly designed keys that can decrease the security of the cipher. We further show that these properties alone do not imply a bad design. Sometimes a combination of several properties

and/or a bad use of the encryption key are necessary for successful cryptanalysis.

3 Empirical Analysis of Wrong Key Designs

Complex encryption systems are problematic in many ways. The design of a nomenclator cipher key and writing it on a paper requires a lot of effort and patience. From the preserved archival documents (mainly from cipher keys), it is obvious that often not enough attention was paid to the design of the key. After a more detailed examination of the preserved keys, it is possible to identify various properties in the encryption keys which in some cases significantly reduce the security.

We investigated a collection of cipher keys deposited in Hessisches Staatsarchiv Marburg (HLA-HStAM Best. 4d Nr. 1218). The collection contains 126 keys from the Thirty Years' War. Because we focus mainly on nomenclator encryption systems, some keys do not fit our requirements. We excluded⁷ all cipher keys which were:

- consisting of only a monoalphabetic substitution,
- consisting of only a polyalphabetic substitution,
- drafts/incomplete key reconstructions,

but kept cipher keys consisting of only codes or homophonic substitution.⁸ Please note that some keys were repeated (or were very similar),⁹ in that case, we kept/counted all instances. The remaining 93 cipher keys have the following structure:

- 78 are nomenclator¹⁰ systems (83.87%),
- 82 contain a homophonic substitution part (88.17%),
- 13 are only homophonic substitutions (13.98%),

⁷We excluded 33 cipher keys.

⁸Despite the fact that in this case there are no multiple sub-ciphers used, we evaluated these keys too. Codes and homophonic substitutions are the most common part of a classic nomenclator. It is also hard to determine the exact boundary between e.g. a code and a nomenclator (Dunin and Schmech, 2020).

⁹In some cases there are different key users written on similar/equal keys.

¹⁰Based on section 2, we define a nomenclator as a cipher consisting of at least two different simple encryption systems.

- 74 contain a code part (79.57%),
- 2 are only codes (2.15%).

Because our collection mainly consists of cipher keys only (encrypted documents were not preserved for all keys), we directly focus on the analysis of the structure of these keys, trying to identify some specific properties. We divide the investigated cipher key properties into two main categories: properties that can *distinguish* the sub-encryption parts, and properties that describe some regularities in the key that can help to *crack* (at least partially) the cipher.

3.1 Distinguishing the Nomenclator Parts

In this section, we focus on the 78 cipher keys, which consist of at least two sub-cipher parts. The most commonly used symbol set in the cipher keys were numbers (with an increasing tendency through the centuries) (Megyesi et al., 2021). This also corresponds with our case, we identify 66 cipher keys from the 78 (84.615%), where numbers were used in at least two sub-cipher parts. Our goal is to figure out if it is possible to distinguish¹¹ these sub-cipher parts - separate the numbers into intervals.

In figure 2 there is an example of a cipher key where numbers were used in the homophonic table and in the code part. In this case, the used numbers can be easily divided into three groups: numbers from 2 to 121, numbers from 300 to 2600 (increasing by 100), and numbers 8000+ (increasing by 1000). Assigning numbers in a special format (e.g. large numbers increasing with a constant step) is one of the worst strategies in the cipher key design. If there is a sufficient number of occurrences of the numbers in a cipher text, it is clearly visible from a statistical analysis. This example is a bit special. Since three different intervals appeared, one would assume that they were used in the case of three different sub-cipher parts. But in our case, these three parts belong only to two sub-cipher parts. With a little luck, we can assume that such a trick and can try to assign the 300-2600 interval to the letters (or to codes). Sometimes this is obvious after applying frequency analysis.

Similar example is on figure 3 where the homophonic part (numbers 10-85) is clearly distinguish-

¹¹In Dunin and Schmech (2020) there is present a nice example where the numbers used in the homophonic substitution part of the nomenclator can be easily separated from those numbers used for code groups.

Ciphre mit leicht unterscheidbaren Zahlenintervallen
Wegen des 2ten 11. Junij 1690.

#	B	C	D	E	F	G	H	I	K	L	N
1300	1000	1700	1800	1900	2000	2100	2200	2300	2400	2500	2600
62	63	72	77	82	87	92	97	102	107	112	117
64	65	73	78	83	88	93	98	103	108	113	118
64	65	74	79	84	89	94	99	104	109	114	119
65	70	75	80	85	90	95	100	105	110	115	120
68	71	76	81	86	91	96	101	106	111	116	121

N	O	L	E	R	S	T	U	W	X	Y	Z
1400	1300	1200	1100	1000	900	800	700	600	500	400	300
57	52	47	42	37	32	27	22	17	12	7	2
58	53	48	43	38	33	28	23	18	13	8	3
59	54	49	44	39	34	29	24	19	14	9	4
60	55	50	45	40	35	30	25	20	15	10	5
61	56	51	46	41	36	31	26	21	16	11	6

Mitra
a. b. c. d. e. f. g. h. i. k. l. m. n. o. p. q. r. s. t. u. v. x. y. z.

aa. bb. cc. dd. ee. ff. gg. hh. ii. kk. ll. mm. nn. oo. pp. qq. rr. ss. tt. uu. vv. ww. xx. yy. zz.

Bayler	8000	Heilbrunn	25000
Bayler in Bayern	9000	Landshut	26000
Bayler in Brandenburg	10000	Leipzig	27000
Bayler in Preussen	11000	Magdeburg	28000
Bayler in Sachsen	12000	Milau	31000
Bayler in Hannover	13000	Piedemont	32000
Bayler in England	14000	Hatfeld	35000
Bayler in Frankreich	15000	Lapins	34000
Bayler in Italien	16000	Paris	37000
Bayler in Spanien	17000	Rom	38000
Bayler in Portugal	18000	Venedig	39000
Bayler in Russland	19000	Wien	40000
Bayler in Schweden	20000	Stockholm	41000
Bayler in Dänemark	21000	Kopenhagen	42000
Bayler in Norwegen	22000	Oslo	43000
Bayler in Island	23000	Reykjavik	44000
Bayler in Amerika	24000	New York	45000

Figure 2: Cipher key with easily distinguishable number intervals. HLA-HStAM Best. 4d Nr. 1218.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	
86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	

Bayler	8000	Heilbrunn	25000
Bayler in Bayern	9000	Landshut	26000
Bayler in Brandenburg	10000	Leipzig	27000
Bayler in Preussen	11000	Magdeburg	28000
Bayler in Sachsen	12000	Milau	31000
Bayler in Hannover	13000	Piedemont	32000
Bayler in England	14000	Hatfeld	35000
Bayler in Frankreich	15000	Lapins	34000
Bayler in Italien	16000	Paris	37000
Bayler in Spanien	17000	Rom	38000
Bayler in Portugal	18000	Venedig	39000
Bayler in Russland	19000	Wien	40000
Bayler in Schweden	20000	Stockholm	41000
Bayler in Dänemark	21000	Kopenhagen	42000
Bayler in Norwegen	22000	Oslo	43000
Bayler in Island	23000	Reykjavik	44000
Bayler in Amerika	24000	New York	45000

Figure 3: Cipher key with easily distinguishable number intervals. HLA-HStAM Best. 4d Nr. 1218.

able from codes (numbers 100+).

If the numbers for each sub-cipher part were as-

signed in clear intervals (e.g. two-digit numbers for homophones, three-digit numbers for bigrams, and four-digit numbers as code groups or in a similar way) we can easily separate them, as it was shown in the previous examples. It is also possible to do it if there are no large gaps between these intervals, however, this does not have to be trivial. On figure 4 the used numbers are divided into four groups: numbers 1-11 are nulls, numbers 12-90 are homophones, numbers 91-100 are common bigrams, and numbers above 100 are code groups. Separating the sub-cipher parts is not impossible in that case, but in general, we do not know the exact number of used sub-cipher parts before/during the analysis.¹²

A	B	C	D	E	F	G	H	I	K	L	M	N	O	P	Q	R	S	T
20	82	59	36	13	28	25	21	20	28	24	24	19	15	55	50	23	18	14
46	89	68	42	22	68	63	48	51	62	54	59	43	27	44	47	58	38	22
61	75	86	40	29	85	76	65	70	65	73	70	60	52	56	72	52	57	37
78	87	69	49	29	85	76	65	70	65	73	70	60	52	56	72	52	57	37

U	W	X	Y	Z	aa	bb	cc	dd	ee	ff	gg	hh	ii	jj	kk	ll
12	17	21	39	16	89	90	91	92	93	94	95	96	97	98	99	100
25	27	55	67	45												
49	41	81	71													
84																

Notes: 1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11.

Resolutive Clavis.

12	11	24	1	26	d	43	k	60	n	72	r	84	u	96	mm
13	10	25	11	27	o	49	v	67	a	79	l	85	g	97	aa
14	9	26	22	28	s	50	m	62	r	74	o	86	d	98	pp
15	0	27	77	29	y	51	l	63	g	75	c	87	c	99	ss
16	z	28	f	30	c	52	j	64	s	76	k	88	b	100	tt
17	w	29	i	31	h	41	w	53	o	65	t	77	t	89	aa
18	j	30	g	32	d	34	l	66	f	78	u	90	cl	91	ch
19	n	31	k	33	n	35	x	67	y	79	s	91	ch	92	ch
20	a	32	t	34	p	36	f	68	c	80	i	92	ch	93	ch
21	x	33	p	35	e	37	t	69	e	81	n	93	ch	94	ch
22	c	34	m	36	a	38	r	70	m	82	b	94	ch	95	ch
23	r	35	g	37	g	39	c	71	e	83	a	95	ch	96	ch

Bayler	8000	Bayler General	115	Bayler armee	129
Bayler in Bayern	9000	Bayler in Brandenburg	116	Bayler armee	130
Bayler in Preussen	10000	Bayler in Sachsen	117	Bayler armee	131
Bayler in Hannover	11000	Bayler in England	118	Bayler armee	132
Bayler in Frankreich	12000	Bayler in Italien	119	Bayler armee	133
Bayler in Spanien	13000	Bayler in Portugal	120	Bayler armee	134
Bayler in Russland	14000	Bayler in Schweden	121	Bayler armee	135
Bayler in Dänemark	15000	Bayler in Norwegen	122	Bayler armee	136
Bayler in Island	16000	Bayler in Amerika	123	Bayler armee	137
Bayler in Schweden	17000	Bayler in Dänemark	124	Bayler armee	138
Bayler in Norwegen	18000	Bayler in Island	125	Bayler armee	139
Bayler in Amerika	19000	Bayler in Schweden	126	Bayler armee	140
Bayler in Dänemark	20000	Bayler in Norwegen	127	Bayler armee	141
Bayler in Island	21000	Bayler in Amerika	128	Bayler armee	142

Figure 4: Cipher key with distinguishable number intervals. HLA-HStAM Best. 4d Nr. 1218.

It is recommended, as the first step of the analysis, to calculate the frequency of each number in the ciphertext as provided in an example in Dunin and Schmech (2020) on page 143. However, the

¹²Many cipher keys were constructed in such a way that increasing number intervals were assigned in a specific order (e.g. (nulls), homophonic substitution, bigrams, codes, (nulls)).

frequency analysis does not necessarily lead us to the right assumptions. It highly depends on the key structure (e.g. the number of used homophones, number of entries in the code part, number of nulls used) and if the key was used correctly.¹³ It also depends on the length of the analyzed encrypted text.

Totally, in 75.76% of the investigated cipher keys (from the 66 cipher keys where numbers were used in multiple sub-cipher parts) can be the numbers in the sub-cipher part separated into clear intervals. Moreover, in 91.53% of cases (from the 59 cipher keys where substitution and code parts were present), the interval used in the substitution part contained smaller numbers than in the code's part. Thus, we can expect that the substitution tables would almost always contain smaller numbers than the codes.

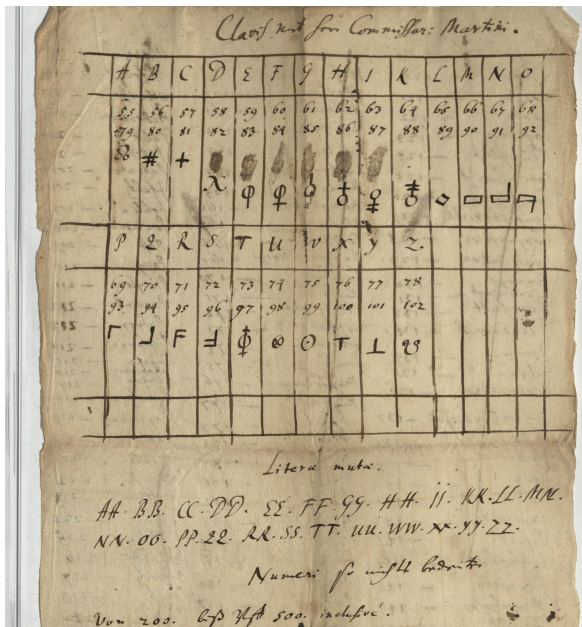


Figure 5: Cipher key with special rows. HLA-HStAM Best. 4d Nr. 1218.

We can summarize our findings in the chart visible on figure 7.

In many cases, there are sub-cipher parts where multiple symbol sets were used (not only numbers). These parts can contain a special row of letters (*a-z/A-Z*), or double letters (*aa-zz/AA-ZZ*) or numbers/symbols¹⁴. On figures 1 and 6 there is

¹³An example of incorrect key usage is choosing the same homophone when others are available (Dunin and Schmech, 2020).

¹⁴This property can be used only when the mentioned rows (or symbols/numbers) are used only in one sub-cipher part.

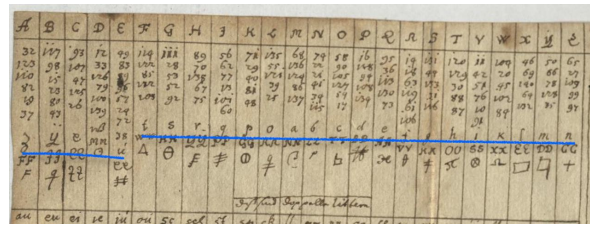


Figure 6: Homophonic substitution containing a row of letters. HLA-HStAM Best. 4d Nr. 1218.

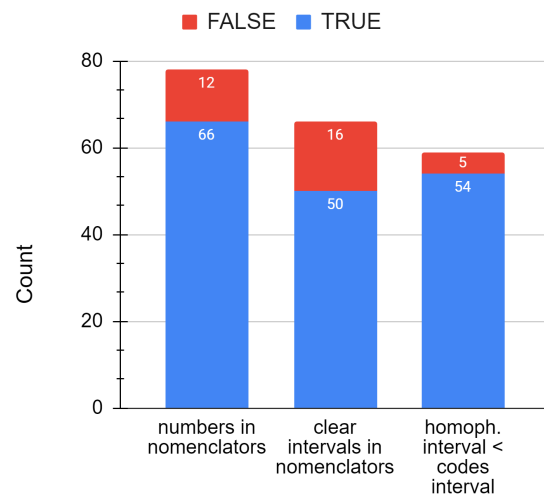


Figure 7: Statistics of selected cipher key properties

one row of lower case letters in the homophonic substitution. In figure 2 the nulls consist of a row of letters and double letters. In figure 5 the homophonic substitution contains a row of symbols, and the symbols are used only in that part; nulls also contain double upper case letters. This property can be also available in codes. In such a case we can deal with these rows separately (assigned to one specific sub-cipher part). It will not necessarily solve the whole sub-cipher part but can help in the cryptanalysis. If a special row is present in the homophonic substitution (as in figure 6) and there is sufficient occurrence of these symbols in the ciphertext, we can solve this part as a simple substitution. In Antal and Zajac (2013) and Antal et al. (2021) the authors were able to correctly assign¹⁵ the row of numbers to the homophonic part based on statistical analysis, however, the length of the analyzed text was too short to break the ci-

¹⁵In that example the key from figure 1 was used. The lower case letters occur 72 times in the cipher text and have a large *index of coincidence* producing the properties of simple substitution.

pher.

In 36.56% of the all investigated cipher keys (from the total 93) there is a special row in at least one of the sub-cipher parts.¹⁶

These explained properties can be used to help to separate/distinguish the sub-cipher parts in the nomenclator cipher key. These properties can be mostly used only to simplify the solving process, and are not necessarily enough to solve the whole cipher. However, this kind of simplification can increase the chance of successfully solving many times.

3.2 Solving the Nomenclator Parts

After separating the sub-cipher parts (see section 3.1) we can try to solve each of the sub-part of the cipher separately. If we are not dealing with a nomenclator system (e.g. only with a homophonic substitution), and there is enough information in the text, we can use well-known automated/statistical approaches to solve the cipher. However, if several different ciphers were used together, and gradually swapped - even, identifying and separating a sub-cipher part is not enough to break the cipher. In many cases, as described in Dunin and Schmech (2020), the key may contain a sorted part in an easy-to-determine alphabetical or numerical order. In this section, we will investigate these kinds of properties in the homophonic and code parts of the cipher keys.

Poorly designed homophonic substitutions

The major part (88%) of the investigated cipher keys contain a homophonic substitution. There are available well-designed ones, consisting of a large number of homophones that can be assigned to each letter and without any visible drawbacks in the design. A lot of keys contain some very specific properties that can significantly reduce the security of the cipher. We identify four properties:

1. the rows of the homophonic table contain continuous numbers,
2. the columns of the homophonic table contain continuous numbers,
3. there is a specific pattern how were the numbers filled in the homophonic table,

¹⁶This kind of row in the homophonic substitution part was probably intended by the authors to strengthen substitution, but paradoxically it could often weaken it as a result.

4. each column consists of a fixed/same number of elements.

The image shows a handwritten table titled "Clavis in Substitutionibus seu" and "Liber 1. Cap. 1. de Substitutionibus". The table has 26 columns labeled with letters A through Z. The first row contains numbers from 10 to 81 in increments of 10. The second row contains numbers from 34 to 81 in increments of 1. The third row contains symbols: a, b, c, d, e, f, g, h, i, k, l, m, n, o, p, q, r, s, t, u, v, x, y, z. The fourth row contains numbers from 58 to 81 in increments of 1.

Figure 8: Continuous numbers in the rows of a homophonic substitution. HLA-HStAM Best. 4d Nr. 1218.

A very weak design of a homophonic substitution is shown in figure 8. The rows are filled with increasing numbers (interval 10-81) starting in the first row from the left. This key also contains the fourth property - all columns consist of exactly 3 elements. During the cryptanalysis, if we can guess these properties, or can estimate (based on a frequency analysis of the cipher text), we can easily fill the table (or we can use a simple helper computer program if we need to check some combinations). Similar example is visible on figure 5. There are two rows of numbers filled in the same way as before (starting from the number 55), but the third row consists of symbols. In this case, the symbols are not used in any other sub-cipher part of the nomenclator, so we can solve it separately as a simple substitution. After solving the numeric rows, it is highly probable that the symbol row can be easily determined.

Some keys contain an ordered sequence in the rows of the homophonic table only partially. In figure 3 we can see continuous number sequences of different lengths altered in the rows. In this example, there are mainly sequences of length 5 and 10 numbers. In such a case, we can write a helper computer program and check some predefined sequences/lengths. Another example of partially ordered sequences in the rows is in figure 9. In addition, there are nulls (marked as *Literae mutae*) inserted to break the sequences. However, there is a fixed pattern of how it was done (sequence of four numbers, two nulls, sequence of four numbers, ...). We can try several variations as before. Even if we hit only partially the correct structure, it can help a lot in the solving process.

Another very weak design of a homophonic substitution is shown in figure 10. In that case,

A	B	C	D	E	F	G	H
100	99	98	97	96	95	94	93
90	80	81	82	83	84	85	86
89	72	73	74	75	76	77	78
17	110	109	108	107	106	105	104
121	135	136	137	138	139	130	131

I	K	L	M	N	O	P	Q
70	65	68	67	69	64	66	63
50	48	49	47	46	45	44	43
38	27	29	26	28	25	23	22
101	111	119	118	117	116	115	114
137	147	148	149	146	145	144	143

R	S	T	U	V	X	Y	Z
64	57	58	59	51	52	53	54
40	30	32	31	33	35	34	37
10	20	15	16	17	18	19	11
112	120	129	126	127	128	127	123
140	151	152	153	154	155	156	157

Figure 9: Continuous numbers in the rows of a homophonic substitution. HLA-HStAM Best. 4d Nr. 1218.

a	b	c	d	e	f	g	h	i	k	l	m	n	o	p	q	r	s	t	u	v	x	y	z
12	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61
18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64

Nota

77. 29. K. 2. m. n. o. 30. 75. 87. 92. R. 9. 77. 76. 77. 192. 95. 70. n. P. L. 29.
 7. a. s. 97. 63. 78. p. 7. f. 209. 9. 97. 50. 63. 2. R. 10. 8. 5. 70. 9. 13. 14.

Figure 10: Continuous numbers in the columns of a homophonic substitution. HLA-HStAM Best. 4d Nr. 1218.

the columns are filled with increasing numbers (interval 15-62) starting in the first column from the top. This is the same situation as in the first example. We can easily try to fill the table. In some cases, like the key in figure 11 the columns contain ordered sequences, however, the length of the columns differs and the column does not continue from the number ended in the previous column. This key design is also weak, but it requires more effort during the solving process.

Some cipher keys may contain a combination of the first, second, and fourth weakness, as visible on figure 2 and highlighted on figure 12. There

A	B	C	D	E	F	G	H	I	K	L	M	N	O	P	Q	R	S	T	V	W	X	Y	Z
12	10	8	5	1	10	10	22	23	35	33	28	27	45	46	61	61	52	54	62	66	68	71	71
13	11	9	6	2	17	20	22	24	35	34	29	30	44	49	62	62	53	55	63	67	69	72	72
14			7	3	18			25	36	35	30	31	45	50	63	63	54	56	64	68	70	73	73
15				4	19			26	37	36	31	32	46	51	64	64	55	57	65	69	71	74	74

Figure 11: Continuous numbers in the columns of a homophonic substitution. HLA-HStAM Best. 4d Nr. 1218.

are continuous numbers in the columns starting in the last column and continuing to the left. Each of these columns consists of five elements (continuous numbers) except for the column Y. In addition, there is a row that consists of increasing elements (fixed-step 100). On figure 13 there is even worse design present. The first column starts with a low number and the column numbering continues to the right without skipping any number. There is one row in addition with increasing elements (fixed-step 100). It is highly probable that we can separate the first row in both cases. We can try to fill the rows and columns of fixed length with continuous numbers using a computer program.

A	B	C	D	E	F	G	H	I	K	L	M
1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	2500	2600
62	67	72	77	82	87	92	97	102	107	112	117
63	68	73	78	83	88	93	98	103	108	113	118
64	69	74	79	84	89	94	99	104	109	114	119
65	70	75	80	85	90	95	100	105	110	115	120
66	71	76	81	86	91	96	101	106	111	116	121

N	O	P	Q	R	S	T	U	V	X	Y	Z
1700	1800	1900	2000	2100	2200	2300	2400	2500	2600	2700	2800
57	52	47	42	37	32	27	22	17	12	7	2
58	53	48	43	38	33	28	23	18	13	8	3
59	54	49	44	39	34	29	24	19	14	9	4
60	55	50	45	40	35	30	25	20	15	10	5
61	56	51	46	41	36	31	26	21	16	11	6

Figure 12: Continuous numbers in the rows and columns of a homophonic substitution. HLA-HStAM Best. 4d Nr. 1218.

There were also used other - less simple and harder to detect - ways of filling the table with numbers. In general, there is a huge variety of patterns how we can fill/construct the homophonic table. We will show a few of them. On figure 14 there is a simple pattern. The homophonic table consists of two rows consisting of odd numbers only. If we look at the first two columns, we can see that there are numbers 3, 5, 7, 9 (fixed dif-

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	
2	7	12	17	22	27	32	37	42	47	52	57	62	67	72	77	82
3	8	13	18	23	28	33	38	43	48	53	58	63	68	73	78	83
4	9	14	19	24	29	34	39	44	49	54	59	64	69	74	79	84
5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85
6	11	16	21	26	31	36	41	46	51	56	61	66	71	76	81	

Figure 13: Continuous numbers in the rows and columns of a homophonic substitution. HLA-HStAM Best. 4d Nr. 1218.

ference 2). And the pattern of the filling is: first row/first column, first row/second column, second row/first column, and second row/second column. This pattern continues on the next two neighboring columns and so on. Similar example is on figure 15 with the same constant step. In this case, the table is divided into two parts (for letters A-M and for letters N-Z) and the pattern is applied in the same row but between the first and the second part of the table (instead of the first/second rows). This specific pattern can be also seen as follows: some of the neighboring columns in the same row have a different offset of four. Finding these patterns may be complicated.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	X	Y	Z
2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	53	56	59	62	65	68	71	74
7	10	13	16	19	22	25	28	31	34	37	40	43	46	49	52	55	58	61	64	67	70	73	76	79
12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	63	66	69	72	75	78	81	84

- Admiral - 100.
- Admiral - 101.
- Admiral - 102.
- Admiral - 103.
- Admiral - 104.
- Admiral - 105.
- Admiral - 106.
- Admiral - 107.
- Admiral - 108.
- Admiral - 109.
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- Admiral - 194.
- Admiral - 195.
- Admiral - 196.
- Admiral - 197.
- Admiral - 198.
- Admiral - 199.
- Admiral - 200.

Figure 14: Specific pattern in a homophonic substitution. HLA-HStAM Best. 4d Nr. 1218.

We can summarize our findings in the chart visible on figure 16. Totally, 82 cipher keys were analyzed where a homophonic substitution was present.

In this subsection, we focused on some flaws in the design of a homophonic substitution which is most commonly used also in nomenclators in the

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80
70	74	78	82	86	90	94	98	102	106	110	114	118	122	126	130	134
69	68	72	76	80	84	88	92	96	100	104	108	112	116	120	124	128
88																
92																

Figure 15: Specific pattern in a homophonic substitution. HLA-HStAM Best. 4d Nr. 1218.

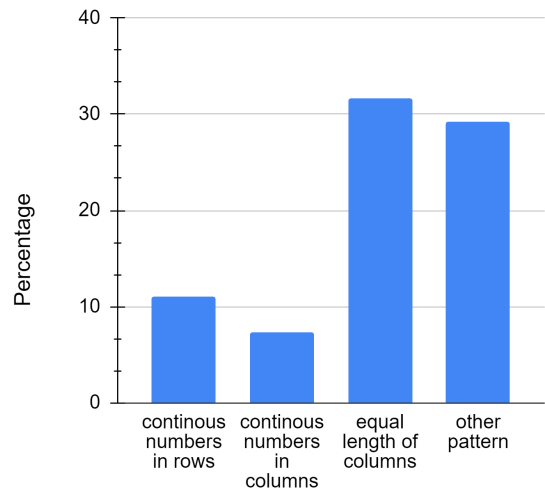


Figure 16: Statistics of selected cipher key properties

analyzed cipher keys. It is clear that there are regularities and easy to detect patterns in many cases. Some of the shown patterns can be used directly to break the cipher. In some cases, it is needed to be present more properties (like the combination of the first/second property with the fourth one) to be able to successfully solve the cipher. During the cryptanalysis of a given cipher text, it is recommended to first perform a statistical analysis and in addition, we recommend trying to separate the sub-cipher parts (if we are dealing with nomenclators) and start the solving process with a special

analysis of the homophonic parts. Several different and commonly used patterns/regularities with different parameters can be checked using a computer program within a few minutes.

Poorly designed codes

The second most frequent part of the available sub-cipher type is a code.¹⁷ The length and the structure of codes vary. Some keys contain only a few code words, some may contain thousands. In some cases also multiple code groups are assigned to each plain text word/phrase forming a homophonic code system. The code groups may contain only numbers, sometimes a combination of letters, double letters, numbers, and symbols. If only numbers were used and these numbers are assigned in a specific order to words (also sorted alphabetically), we have got a one-part code. In many cases, if a one-part code is used, it is easier to solve (Dunin and Schmech, 2020) than the two-part (shuffled order) ones. Nice examples of easily distinguishable one-part codes are on figures 3 and 13. On figure 17 we can see a special construction of a one-part code. The words are grouped based on the first letter of the word, ordered alphabetically, the code groups are generated with a specific prefix (upper case letter) for each group, and increasing numbers are assigned starting from 10. Similar example is on figure 3. The code is a one-part code divided into sub-groups based on the starting letter in the word. For each code word, a three-digit number was used. It is also visible that the sub-groups are based on a two-digit prefix (all words starting with letter *a* starts with a fixed prefix 10, all starting with letter *b* starts with a fixed prefix 12, starting with letter *c* starts with a fixed prefix 15). This prefix is different for each group (starting letter).

On figure 18 we can see a one-part homophonic code, however there are exactly two adjacent numbers assigned to each word/phrase.

4 Conclusions

In this paper, we have shown that many of the analyzed cipher keys were poorly designed. We identified several specific properties of the cipher keys (key parts) which represent a possible security flaw. We divide these properties into two large categories. One that can help to separate the

¹⁷Please note that for codes a qualitative analysis is given only.

E.		J.		M.
Ent	R. 10	paradithor	S. 10	May
Enno	L. 11	parament	S. 11	manag
Eilendly	L. 12	par ditia	S. 12	mag
E. J. J. J. J.	L. 15	pa	S. 15	maltes
E. J. J. J.	R. 17	pa	S. 17	malting
		pa	S. 18	mal
		pa	S. 19	mal
		pa	S. 20	mal
		pa	S. 21	mal
		pa	S. 22	mal
		pa	S. 23	mal
		pa	S. 24	mal
		pa	S. 25	mal
		pa	S. 26	mal
		pa	S. 27	mal
		pa	S. 28	mal
		pa	S. 29	mal
		pa	S. 30	mal
		pa	S. 31	mal
		pa	S. 32	mal
		pa	S. 33	mal
		pa	S. 34	mal
		pa	S. 35	mal
		pa	S. 36	mal
		pa	S. 37	mal
		pa	S. 38	mal
		pa	S. 39	mal
		pa	S. 40	mal
		pa	S. 41	mal
		pa	S. 42	mal
		pa	S. 43	mal
		pa	S. 44	mal
		pa	S. 45	mal
		pa	S. 46	mal
		pa	S. 47	mal
		pa	S. 48	mal
		pa	S. 49	mal
		pa	S. 50	mal

Figure 17: One-part code with a prefix. HLA-HStAM Best. 4d Nr. 1218.

Word	Code 1	Code 2
Administrateur	102	103
Amulation	104	105
Action	106	107
Aler	108	109
Aliance	110	111
Ambassadeur	112	113
Ammunition	114	115
Amrobiren	116	117
Amree	118	119
Artillerie	120	121
Assurance	122	123
Assistent	124	125
Ataque	126	127
Austria	128	129
Exilium Oxenstirn	130	131

Figure 18: One-part homophonic code. HLA-HStAM Best. 4d Nr. 1218.

nomenclator sub-parts, and one that is more suited to cryptanalysis. However, in many cases, these properties can be successfully used in a combination. Finding such a property alone does not imply a bad design. There could be well-designed cipher keys where some of the properties are present but cannot be exploited (see the example on figure 1). If we are solving a nomenclator (and have a long enough cipher text available), we can simply

check if there is any of the described properties present. If the cipher key was designed (also used) correctly, we have still a chance¹⁸ that the used cipher key is preserved somewhere.

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¹⁸A complex nomenclator can be solved also in such a way as described in Antal et al. (2021).

Appendices

A Additional information about cipher key examples

- Figure 1 – Nomenclator used for the correspondence of the chancellery of Landgravine of Hesse-Kassel with Kaspar von Eberstein, Joachim de Wiquefort, Adolph Wilhelm von Krosigk, Hans Adam von und zu Karpf and Johann von Geysso in the 1640s.
- Figure 2 - Nomenclator used for the correspondence of the chancellery of Landgravine of Hesse-Kassel with Karel Rabenhaupt ze Suché, created in June 1640.
- Figure 3 - Nomenclator used for the correspondence of unspecified persons probably in the 1630s.
- Figure 4 – Nomenclator used for the correspondence of the chancellery of Landgravine of Hesse-Kassel with the commander of Ziegenhain Justinus Ungefug probably in the 1640s.
- Figure 5 – Nomenclator used for the correspondence of the chancellery of Landgravine of Hesse-Kassel with not otherwise specified commissioner Martini in 1640s.
- Figure 6 – Nomenclator used for the correspondence of the chancellery of Landgravine of Hesse-Kassel and Kaspar von Eberstein, created in April 1641.
- Figure 8 – Cipher key used for the correspondence of unidentified persons.
- Figure 9 – Nomenclator used since May 1639 for the correspondence of the chancellery of Landgravine of Hesse-Kassel probably with James King of Birness and Dudwick and since December 1639 also with Peter Melander von Holzappel.
- Figure 10 – Nomenclator used for the correspondence of the Electorate of Cologne with Gottfried Huyn von Geelen, intercepted in 1640 in Lippstadt.
- Figure 11 – Nomenclator used for the correspondence of the chancellery of Landgravine of Hesse-Kassel with English resident William Curtius probably in 1639.
- Figure 12 – Nomenclator used for the correspondence of the chancellery of Landgravine of Hesse-Kassel and Karel Rabenhaupt ze Suché, created in June 1640.
- Figure 13 - Nomenclator used for the correspondence of the chancellery of Landgrave of Hesse-Kassel with (Franz Ulrich?) Wasserhuhn, created for his mission to Alexander Leslie probably in 1636.
- Figure 14 – Nomenclator used for the correspondence of the chancellor Christoph Deichmann with Johannes Vultejus and (Moritz Otto?) von Günterode probably at the turn of the 1630s and 1640s.
- Figure 15 – Nomenclator used for the correspondence of the chancellery of Landgraves of Hesse-Kassel and Kaspar von Eberstein probably in the 1630s.
- Figure 17 - Nomenclator used for the correspondence of Duke Maximilian I of Bavaria with Gottfried Huyn von Geelen and the commander of the fortress Wolfenbüttel, intercepted in 1636 by Daniel Rollin de Saint-André.
- Figure 18 – Nomenclator used for the correspondence of the chancellery of Landgraves of Hesse-Kassel probably with Reinhard Scheffer and with the commander of Dorsten in the 1630s/1640s.