MINISTRY OF EDUCATION AND RESEARCH
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DOCTORAL THESIS

ABSTRACT

Contributions to the improvement of the die-cutting process in flexographic technology with complex geometry die-cuts

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DOCTORAL THESIS

ABSTRACT

Contribuții privind îmbunătățirea procesului de ștanțare în tehnologia flexografică cu ștanțe cu geometrie complexă /

Contributions to the improvement of the die-cutting process in flexographic technology with complex geometry die-cuts

DOCTORAL COMMITTEE

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Contents

Chapter 1.
Current state of the research in flexographic technology

This chapter presents the products produced and the materials used in flexographic technology. **There is a category of products obtained by flexographic technology which are indispensable for marking and identifying products or obtaining services covering the most varied fields, such as:** labels used for on-shelf signage/information of products or attaching to the product for product identification, tickets for cultural/sporting events/fairs/exhibitions, for land, air, sea transportation. These products are supplied to customers in folded form, in rolls or in pieces.

Such products involving die-cutting with special shapes, in which the cutting of the finished shape is combined with transverse and longitudinal die-cuts, are obtained by flexographic printing. They may fall into the category of **complex products in flexography** when they include, in addition to contour cuts for total or partial separation from the strip of material, elements which may be arranged in close, tangential or intersecting positions, grouped symmetrically or asymmetrically in relation to the whole surface of the finished product thus produced:

- a sequence of perforations of constant or variable size and spacing, with a functional breaking or folding function;
- perforated holes of various shapes and sizes starting from Ø 2 mm circles. These can sometimes be combined with notches by partial cutting in the thickness of the material or straight lines imprinted in the texture of the material, obtained by pressing the fibers, to promote bending.

Plastics, paper and cardboard are used in the production of labels and packaging (particularly in the food, pharmaceutical and cosmetics sectors), requiring selective collection by the end consumer.

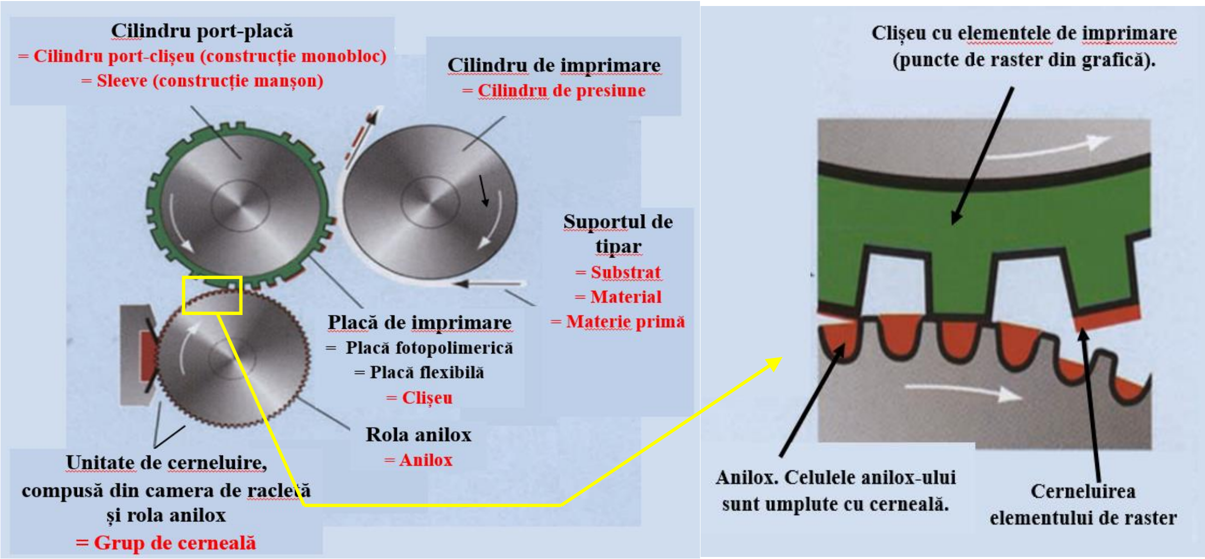
At the present stage, Forest Stewardship Council® (FSC) certified materials are used for printing paperboard and self-adhesive substrates made of semi-glossy, thermal-sensitive paper, an example being BPA-free thermal paper [3, 4]. Major thermal paper and cardboard manufacturers have developed solutions to increase the processability of thermal materials by cutting, slitting and die-cutting.

Obtaining the finished product in flexographic printing involves the following processes:

a) the **printing process** (fig.1.6);

b) **finishing process in line with the printing**, it is carried out immediately after printing, and the most common operations are: varnishing (varnish is applied similar to an ink); lamination, (adhesive is applied similar to an ink on the foil with which the printed material is laminated); die-cutting in the case of labels, tags, thin cardboard products; side cutting of the printed roll to remove excess waste.

c) **finishing process outside the printing machine**, by cutting the printed rolls to the finished roll format imposed by the customer’s requirements, using specialized machines for longitudinal slitting rolls of material.



a) b)

Fig. 1.6. Presentation of the flexographic printing technique in a printing unit: a) schematic diagram; b) active printing elements: the printing plate and the anilox [2, 12].

The variable elements that intervene in the printing process are: human factors, defects in the materials used, non-conformities in the operation of the machine and external factors independent of the printing process.

Chapter 2.
Study on the role of die-cutting in flexographic technology

Die-cutting is a technological process of finishing printed products by which a certain shape of finished or semi-finished products is obtained. Different types of self-adhesive, cardboards, folding products made of cardboard or paper of different thicknesses can be obtained [24].

The flexographic die-cutting process is characterized by the use of flexible material die-cuts or one-piece die-cuts used in specific cases.

Flexible die-cuts have a plane shape [6,7], while one-piece die-cuts have the shape of rotating cylinders [30] made of special materials on which the cutting knives are engraved. Engraved cylinders are rarely used, flexible die-cuts are commonly used, which have the advantages of low cost and versatility [24]. **The doctoral thesis studied flexible die-cuts.**

The flexible die-cuts are made of sheet metal with specific properties required for the processing of the desired product, having on one side the knives with which the geometry of the finished product will be cut to shape (Fig. 2.1).

Fig. 2.1. Geometry of a die-cut for rectangular self-adhesive labels [31].

Fig. 2.2. Mounting the die-cut on the magnetic cylinder by rotating it [31].

a) The **technical characteristics of flexible die-cuts** are represented by: the thickness of the sheet, the angle at the tip of the cutting knives, the shape of the die-cut nests, the number of repetitions of the nests per die-cut, the die-cut repetition (this is essential in calculating the product's fit on the die-cut) and the height of the cutting knives [28].

b) The **material characteristics of flexible die-cuts** are given by non-adhesive properties, durability, shock resistance, being chosen according to the material to be die-cut and the product run / repeatability of the order.

Choosing the quality of the die-cut and knife geometry

When choosing the quality of a die-cut and the geometry of the knives, the size of the expected print run over one year, the type and thickness of the material to be die-cut are taken into account.

Based on these considerations, there are die-cuts that require chrome plating to increase die-cut hardness and run production. From this perspective, some manufacturers classify die-cuts by quality types which include chrome plating.

Other die-cut manufacturers classify die-cuts according to the angle of the cutting knives, indicating additional options that may be required when making the die-cut such as additional surface quality of the die-cut (e.g.: depositing of a non-adhesive coating) or of the cutting knife (laser hardening) [28].

Features of flexographic die-cutting

Flexographic printing machines may have one or two die-cutting units [32]. Depending on the type of machine, these die-cutting units may be an integral part of the printing line construction, or they may be independent, movable structures that can be mounted within the technological line when die-cutting is required. The die-cutting units are positioned after the printing units.

After die-cutting the product is wound on a reel when the product is delivered in reels, or it is taken on a conveyor when the product is delivered by piece.

The construction of a die-cutting unit essentially involves two vertically angled cylinders, at least one of which is magnetic, on which the flexible die-cut is mounted, and the other of which is designed to generate counter-pressure.

In this chapter we have addressed a number of issues that arise in the flexographic die-cutting process such as:

Defects manifested in the die-cutting of successive runs by mechanical destruction of the die-cut

In the die-cutting of successive runs, the human factor plays a decisive role in the handling of the parts that are mounted in the die-cutting unit, and there are cases where poor handling means that the die-cuts are the first in the die-cutting unit to be prone to mechanical destruction.

a) b)

Fig. 2.14. Examples of mechanically damaged die-cuts: a) the surface of the plate is punctured; b) the bent corner does not adhere to the magnetic cylinder [37].

Defects resulting from the collection of impurities between the die-cut and the magnetic cylinder.

a) b)

Fig. 2.17. Example of a complex die-cut: a) the knife was destroyed on the contour; b) the waste was not cut completely and destroyed some wraps of material on the roll [31].

Defects identified by static testing, when mounting the die-cut on the magnetic cylinder

Fig. 2.20. Example of a die-cut whose length is longer than the magnetic cylinder repeat: the ends overlap [31].

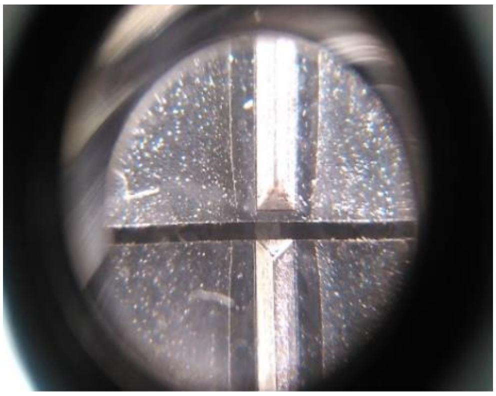


Fig. 2.21. Example of a die-cut with longitudinal knives that have not been cut complementarily to ensure continuity of cut [31].

Defects identified by dynamic testing: exfoliated knife edge, destroyed nests.

Fig. 2.22. In order to identify the defect, waste was not removed from the die-cut material [37].

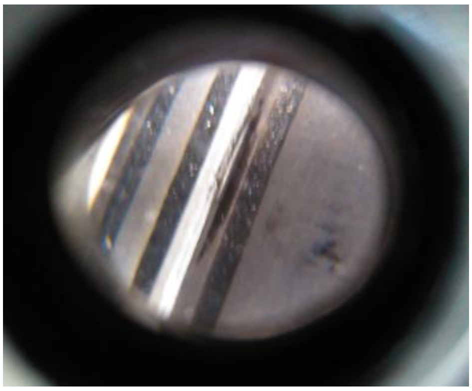


Fig. 2.23. The cutting edge of the die-cut knife exhibited fine exfoliation [37].

Non-conformities encountered in longitudinally perforated die-cuts

The case of **die-cuts that rotated on the magnetic cylinder** during the order print run was studied. The analysis was generated by the occurrence of this effect when obtaining self-adhesive labels, in the case of a die-cut with a large number of knives on the active face.

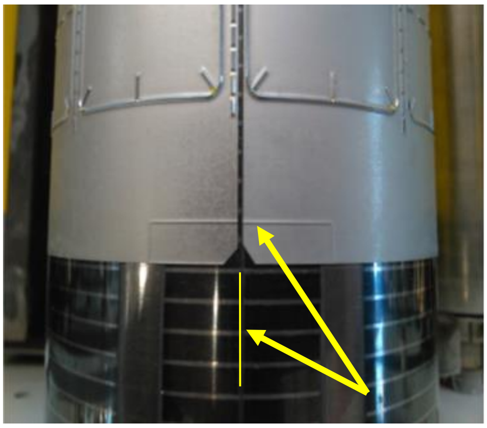


Fig. 2.28. Correct mounting of the die-cut before entering the print run [37].

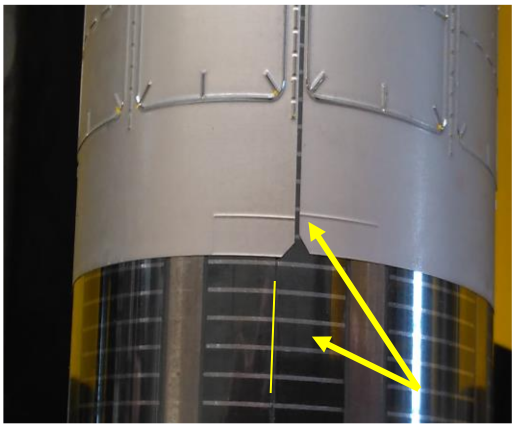


Fig. 2.29. After a short run the die-cut was rotated on the magnetic cylinder [37].

Solutions to solve the problem are still being researched.

Defects in die-cutting caused by the material being die-cut

In addition to the die-cut defects and non-conformities described above, flexographic production processes also have problems with the material from which the finished products are die-cut, which may have quality deviations.

Uneven thickness of die-cut material

The appearance in an order run of portions of material strip with a thickness greater or less than that indicated in the material data sheet leads to non-conforming die-cutting, with negative effects on the die-cuts.

Fig. 2.32. The knives do not cut the self-adhesive label correctly [31].

Fig. 2.33. Knives penetrate the material [31].

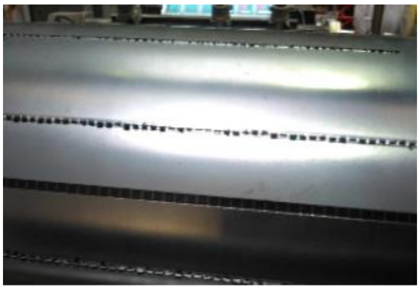


Fig. 2.34. Knives destroyed on the perforated line [31].

A synthesis of the production information concerning such cases encountered in the print runs indicated premature and uneven wear of the knives on all the die-cuts analyzed, leading to a decrease in the expected durability of each die-cut model (Fig. 2.34), and premature replacement of the die-cut.

Chapter 3.
Conclusions on the current state of research on the die-cutting process in flexographic technology

The following conclusions have been drawn from the analysis of the current state of the art in flexographic printing and die-cutting research and development.

- Although the printing industry has had to reinvent itself in the last 15-20 years due to the expansion of internet facilities, virtual libraries, flexographic technology continues to dominate the market for flexible labels and packaging (see § 1.1):

- In the case of the complex cardboard products studied in the doctoral thesis, it is decisive to check the tensioning of the rolls of material when feeding the machine as well as the correct choice of the process programming data. (see § 1.4).

- In the absence of detailed die-cutting procedures, there has often been an increase in the moment of the clamping force of the die-cut, resulting in premature wear of the knives, increased consumption of die-cuts and shorter lengths of material die-cut with the same die-cut (see § 1.4).

- Depending on the size of the print runs, the knife surface of the die-cut can be subjected to anti-adhesive or chrome plating treatments for wear resistance. The knives can also be laser-hardened at the tip, and their geometry depends on the material to be die-cut (see § 2.2).

- In specialized studies, no references were found on how die-cuts knife treatments influence the die-cutting process, such a study could influence the economic choice of die-cuts quality depending on the print runs (see § 2.2).

- The main technical characteristics of the die-cuts are: ● the thickness of the sheet; ● the height of the knives and the cutting angle; ● the shape of the die-cut nests (rectangle, circle, ellipse, special shape, particular shapes of transverse/longitudinal knife/perforation type); ● the number of nests per die-cut; ● the repetition of the die-cut (see § 2.2).

- Product finishing in flexography is achieved by the following processes as follows: ● **die-cutting with die-cutting unit**; ● **cutting with cutting units**. **In the doctoral thesis, the classical unit with rotating disk knives was used for side cutting of the material** (see § 2.4).

- Irrespective of the form of the product to be obtained, the following groups of defects have been frequently encountered in flexographic die-cutting (see § 2.5): ● **Defects occurring after die-cutting of successive runs, by mechanical destruction of the die-cut; ● Die-cut execution non-conformities; ● Die-cut design non-conformities reflected in the die-cut product; ● Non-conformities and defects produced by the material being die-cut**

- From the analysis of the history of die-cutting activity in the printing house, it was found that there is a lack of production procedures required for the die-cutting regimes in case of adjusting the process parameters, namely the moment of the die-cutting clamping force and the die-cutting speed, which can be easily applied by the printers in order to reduce premature wear of the knives and to obtain large lengths of die-cut material.

Chapter 4.
Research and development directions, main objective and methodology to improve the die-cutting process in flexographic technology with complex geometry die-cuts

4.1. Research and development directions

● Increasing the efficiency of the flexographic production workflow;

● Determination of the main elements affecting the quality of preformed products obtained using complex die-cuts; premature and uneven wear of knives, die-cut quality;

● Mathematical modeling of the problem of minimizing the wear of die-cutting knives;

● Experimental research and personal contributions on knife wear in flexographic die-cutting and mathematical model validation;

● Personal contributions to improving the die-cutting process.

4.2. Main objective of the research and development activity

Development and implementation in the production of print runs, of a flexographic die-cutting methodology that involves increasing the quality of preformed products with a high degree of complexity, based on controlled modification of the technological parameters of production and applicable on any type of machines and complexity of die-cutting, thus to:

(1) Develop a comparative analysis of the flexographic workflow, identifying opportunities to reduce auxiliary times.

(2) Improve the process of flexographic die-cutting of complex preformed products by analyzing two quality models exemplified with the *Preformed Box* product, namely the Quality Model by Conceptualization Levels and the Product Model called “Optimal Quality”.

(3) Design of the methodology for the construction of a mathematical model describing the problem of knife wear in the flexographic die-cutting process, applicable to any type of printing machine, regardless of the degree of complexity of the die-cut.

(4) Personal contributions on knife wear in flexographic die-cutting, through studies on: ● the cutting phases of the cardboard (abrasive material that wears the knives); ● the causes leading to premature withdrawal of the die-cuts from the production of the print runs, without reaching the maximum knife wear; ● identification of the line with the maximum number of knife lengths that simultaneously perforate the material, and calculation of the active forces in the area.

(5) Formulation of a flexographic die-cutting process control algorithm, with proposed solutions directly applicable in production.

(6) Personal contributions to the improvement of the die-cutting process: testing of the proposed solutions on a number of 3 new die-cuts, executed with the same requirements as the previous die-cuts and operated in runs under identical conditions. Scheduling the experiments using the factorial experiments method, where tests were carried out for two technological parameters (moment of clamping force of the die-cut and die-cutting speed) with 5 and 3 levels respectively, in total 45 experiments.

(7) Validation of results on each of the identified critical intervals.

(8) Verification of the behavioral pattern in runs of the three new die-cuts, i.e. the fulfillment of the restrictive conditions formulated in the mathematical model construction and presentation of the obtained results.

Chapter 5.
Contributions on increasing the efficiency of the technological production workflow

Some of the contributions presented in this chapter have been disseminated in the author's work [23, 48].

5.1. Introduction

In this chapter a comparative analysis of the production workflow in a flexographic printing house is presented by investigating the possibilities of reducing the auxiliary time consumed in order to increase the efficiency of the flexographic production workflow [46, 47].

Due to the complexity of flexographic printing, due to the multitude of elements that intervene during the production flow, the prioritization of the products that enter the printing press was carried out, so that there is an optimal run execution time by reducing auxiliary times. FIFO (first input, first output) and MinSetup modeling strategies were applied.

5.2. Case study

We studied the general structure of a flexographic printing process, which can be divided into 3 technological processes: Printing - Finishing - Delivery.

Describing the process in this way allows a simple graphical representation of the complex flexographic printing process (Fig. 5.1), with three types of data being transmitted in the system [48, 55]:

- **verifiable input data**;
- **uncontrollable input data;**
- **output data.**

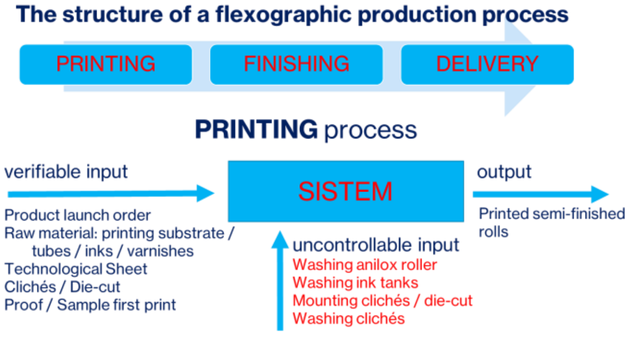


Fig. 5.1. Input and output data in a flexographic printing process [48].

For the case study, the first four products noted P1, P2, P3, P4, belonging to a single type of flexographic printing machine symbolically noted Machine 1, were chosen in the order of incoming repeat orders in the reception.

The distinctive features of the four products are:

- P1 is printed on foil and does not require die-cutting; it is used as flexible packaging;

- P2 is a TAG - a non-adhesive label with a signaling or marking function, containing perforated cross lines with a fold/tear function;

- P3 is a self-adhesive label, intended for application on container packaging;

- P4 is a double-sided ticket printed on cardboard for cultural activities.

Process structure

In Fig. 5.2 presented the research approach for increasing the efficiency of the flexographic production technology flow, through the FIFO (first in, first out) strategy, applied to the case study, where the input and output quantities of the system are represented by horizontal arrows and the vertical arrows represent the mechanisms supporting the system functions.

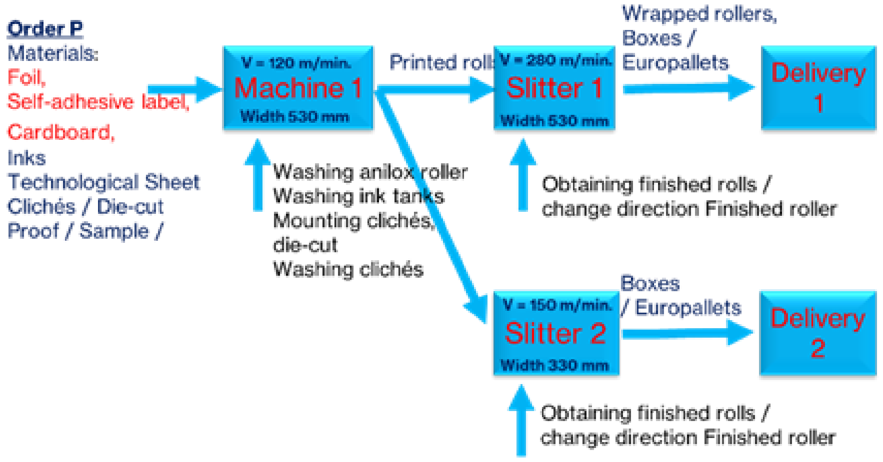


Fig. 5.2. Production flow diagram for an existing physical system [48].

Fig. 5.3 shows the components of the production flow, numbered in the order of the sequence of the work phases, according to the machines involved and the stationary and delivery stations.

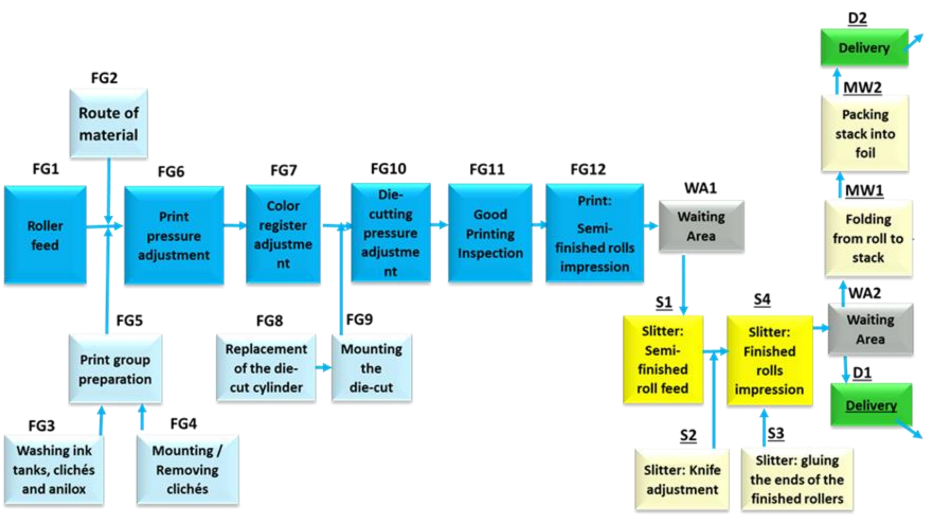


Fig. 5.3. The active components in the production flow and the sequencing of work steps [48].

In flexography, products printed on both sides involve a special path of the material in the machine in order to be printed on the reverse side, so the next time the next product enters the press, the path must be rerouted. In the case study, products P1, P2 and P3, do not require rerouting after printing product P4 printed both sides, regardless of the order in which they enter the press, instead it increases the preparation time of the material path for printing product P4.

For running the printing process, auxiliary time analysis and comparative study, two working scenarios were chosen as follows [48, 56]:

- Scenario 1 in which each product is printed independently one after the other, in order of arrival (FIFO). Thus, for each printed product, all ink groups are prepared and for each die-cutted product, the appropriate die-cutting cylinder is installed.

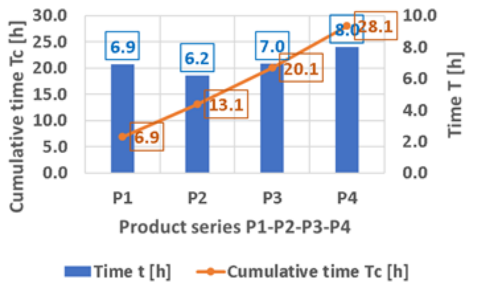


Fig. 5.4. Scenario 1. Machine loading time $T_{1\_P1P2P3P4} =$ 28,1 h for independently printed products P1, P2, P3 and P4.

- Scenario 2 in which the products successively enter the press forming series according to the MinSetup strategy. To obtain the series, different combinations of the four types of products were applied, obtaining, by permutations, 24 series with the order of entry of the products into the press.

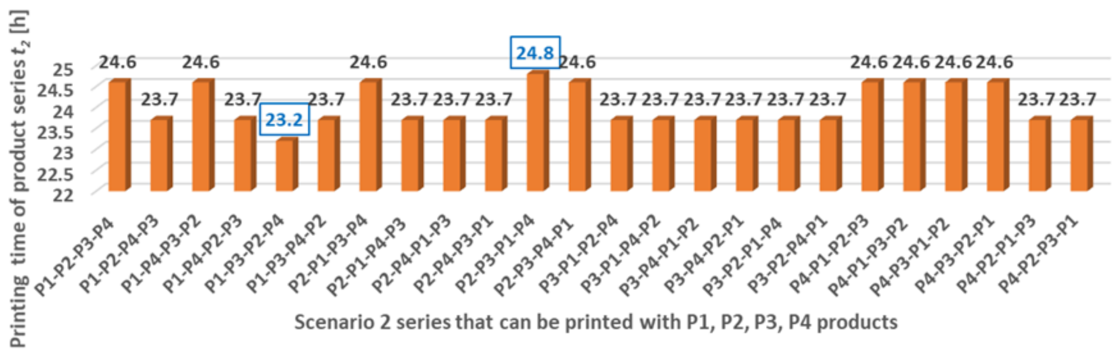


Fig. 5.9. Time $T2\_series$ of machine loading for the production runs of each of the 24 series obtained by permutation of products P1, P2, P3 and P4 [48].

The following conclusions can be drawn from the analysis of the efficiency gains in the flexographic production workflow:

- Scenario 1 is the one in which the products were executed independently, one after the other, the maximum preparation and execution time being: for P1 - 6,9 h, for P2 - 6,2 h, for P3 - 7,0 h, for P4 - 8,0 h. The total machine loading time to complete all four products is 28,1 h.

- Scenario 1 corresponds to cases where unscheduled products are introduced into the production flow from the requirement to deliver the product urgently. This is a maximum time consumer.

- Scenario 2 is the scenario in which the MinSetup strategy is applied, by which a comparison is made between the scenarios obtained by permuting P1, P2, P3, P4 products, choosing the best variant.

Chapter 6.
Contributions on the determination of the main characteristics influencing the quality of preformed products obtained with complex geometry die-cuts

Research on the determination of the main elements influencing the quality of preformed products obtained with complex die-cuts also includes elements disseminated in the author's works [23, 24, 31, 59].

The quality features of complex products produced by flexographic printing are presented.

6.1.1. Defining quality requirements for the products studied

The first product quality model, established on conceptualization levels

The first quality model (Fig. 6.1) of box-type products was realized according to the product model proposed by Philip Kotler [58], known as the founder of „marketing management". Starting from the analysis of the functions of a packaging box, its conceptualization levels were established.

The second product quality model, also called optimal quality

The second product model is called „optimal quality", i.e. the concrete, objective quality of the product obtained, whereby it satisfies both the conditions laid down in the technical documentation and the customer's requirements. This product model takes into account both the infrastructure of the printing organization and the human resources, making it possible to determine the specific activities to ensure the quality of the product under analysis.

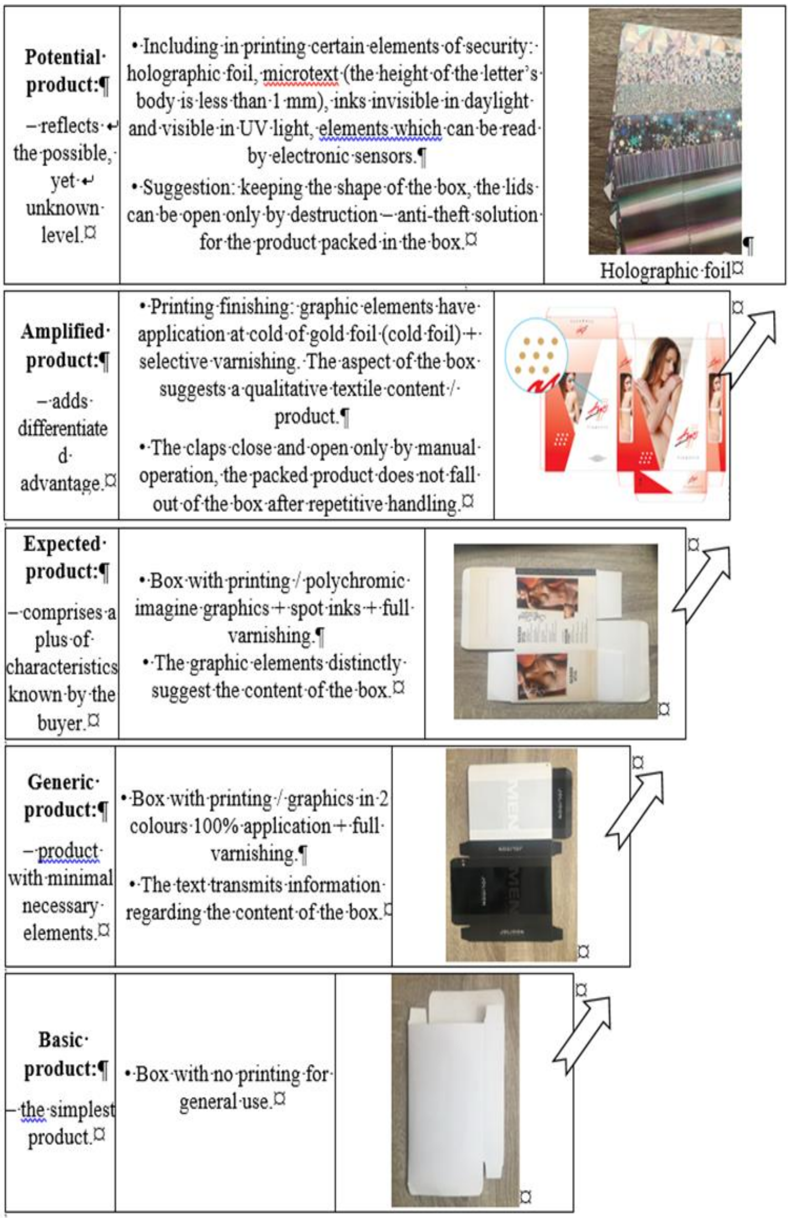


Fig. 6.1. *Pre-formed box* product quality model, by conceptualization levels.

The analyzed quality model is shown in Fig. 6.2: the **characteristics provided in the data sheet**, are included in circle A, **the characteristics realized by the printing process**, are summed in circle B, the **characteristics requested by the customer** are those included in circle C.

For the printing industry in Romania, these two product models form the basis for realistic contracts between producers and recipients. Unfortunately, very often the requirements addressed to flexographic printers reveal a lack of knowledge of the technological processes and their specific limitations.

Using the Pareto chart, in Figure 6.5 on the horizontal axis, the large groups of problems identified between June 2016 and March 2017 have been highlighted; on the vertical axis on the left, the frequency of their occurrence has been represented, on the right, the cumulative frequency of the total number of problems identified has been represented in percentages. The blue bars represents the frequency with which the problem groups occurred; the red line indicates the frequency with which the cumulative defects occurred, and the green line represents the 80/20 threshold.

It was found that production processes were disrupted 55 times due to problems in the die-cutting unit, with the Pareto chart (Fig. 6.5) revealing that 80% of these were caused by the die-cuts not cutting deep enough into the material, with the labels being caught in the waste matrix.

The Pareto chart was also performed for the period September 2017 - March 2018, (Fig 6.6) resulting in the due problems.

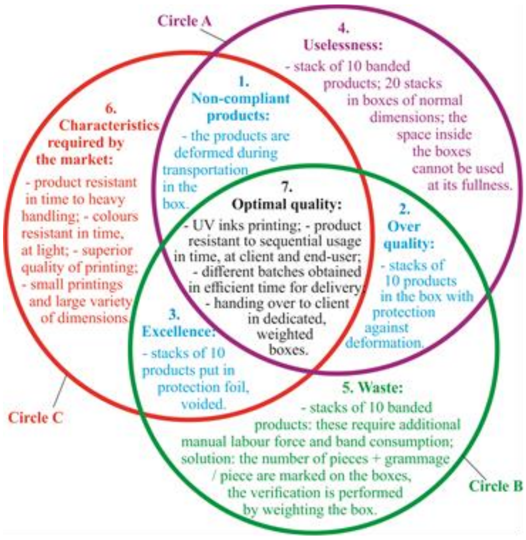
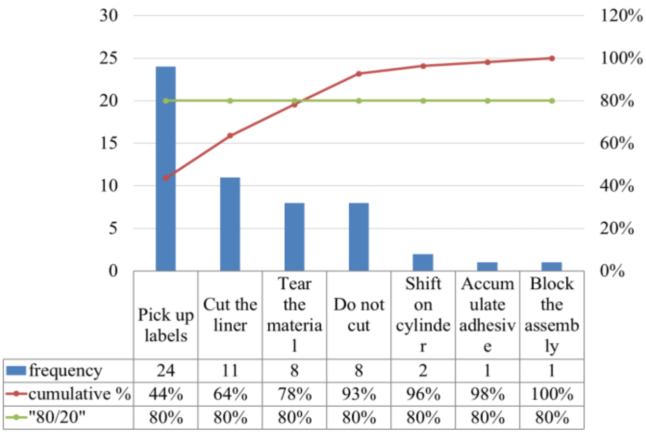
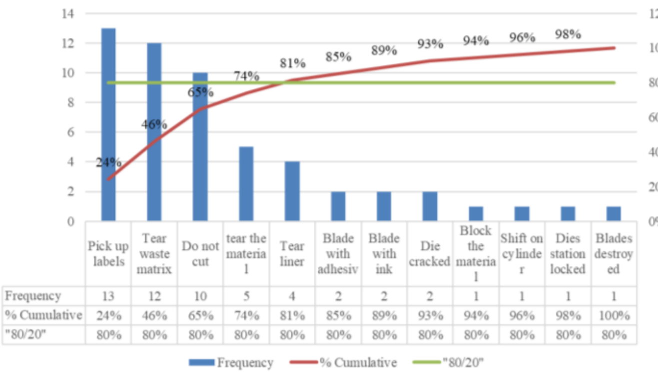


Fig. 6.2. The model of optimal product quality *Pre-formed box* results from the intersection of circles A, B and C.



	Pick up labels	Cut the liner	Tear the material	Do not cut	Shift on cylinder	Accumulate adhesive	Block the assembly
frequency	24	11	8	8	2	1	1
cumulative %	44%	64%	78%	93%	96%	98%	100%
"80/20"	80%	80%	80%	80%	80%	80%	80%

Fig. 6.5. Pareto diagram with the problems identified in die-cutting between June 2016 and March 2017 [59].



	Pick up labels	Tear waste matrix	Do not cut	tear the material	Tear liner	Blade with adhesiv	Blade with ink	Die cracked	Block the material	Shift on cylinder	Dies station locked	Blades destroyed
Frequency	13	12	10	5	4	2	2	2	1	1	1	1
% Cumulative	24%	46%	65%	74%	81%	85%	89%	93%	94%	96%	98%	100%
"80/20"	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%

Fig. 6.6. Pareto diagram with the problems identified in die-cutting between September 2017 and March 2018 [31].

6.1.2. Contributions on improving the die-cutting process with complex geometry die-cuts

On the basis of the information collected from the statistical worksheets of the production archive registered in the period 2015 - 2020, as well as the drawings of complex product die-cuts **that were made by the author of the thesis**, all types of complex die-cuts intended for preformed products were selected.

Seven types of complex product models were identified which required a total of 45 die-cuts for order runs during the analyzed period. The dimensions, the complexity of the knife geometry on the die-cut and the number of worn/destroyed die-cuts in the runs were analyzed.

For the research in the doctoral thesis, the Model 3 die-cut was chosen because it had the highest die-cut consumption, with the most complex geometry and positioning of the knives on the surface of the table.

For the die-cuts entered into work on the order runs since the period of research interest of the author of the thesis (doctoral studies started in 2019), it was possible to implement procedures in the worksheets of the die-cuts, the die-cutting parameters in correlation with the events in the process of printing and die-cutting production, an activity initiated and supervised by the author of the doctoral thesis.

6.1.3. Presentation of the complex finished product

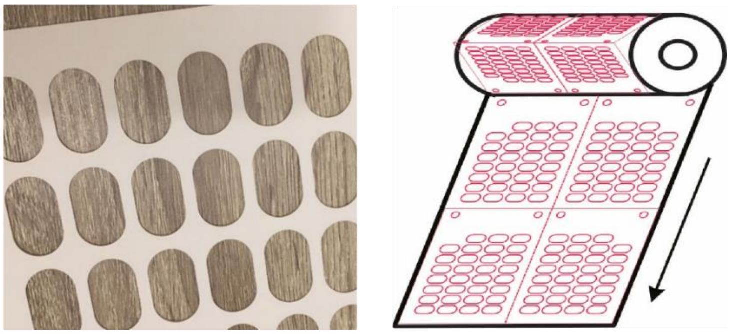
The researched printed product was **one of the most demanded and complex products used in any industry. The graphics associated with the shape, imposes in die-cutting, the need to obtain identical holes and dimensions for the two parts that overlap by folding.**

In the production archive, the 24 Model 3 die-cuts were identified. For the research it was chosen to study all the complex die-cuts for which the dimensions of the finished product were constant, without any change in the positions/shapes of the holes or the perforation line, thus allowing relevant analysis and comparisons to extract accurate results. A total of 15 Model 3 die-cuts were studied.

In 2019, upon entering the doctoral research program, the undersigned directly participated in recording additional production data (the moment of die-cut clamping force correlated with die-cutting speed and length of die-cut material). I also closely followed undesirable events occurring in the die-cutting unit as well as in the die-cutting process itself.

Feature, Unit of measurement	Standard	Tolerance	Value
Thickness μm	ISO 534	± 3%	450
Weight g/m²	ISO 536	± 2%	280
Moisture content %	ISO 287	± 1.0%	8.5
Roughness of the face of material μm	ISO 8791-4	max 1.3	0.8
Roughness of the back of material μm	ISO 8791-4	max 6	4

Fig. 6.17. Technical data of laminated cardboard.



a) b)

Fig. 6.18**.** Final product: a) cardboard sample with laminated composition and b) sketch of a finished roll.

6.3. Contributions on increasing the quality of complex geometry die-cuts

In developing research on improving the die-cutting process in flexographic technology, the influence of die-cutting quality (unchromed, chrome plated and chromed with laser hardening at the knife tip) was studied.

The experimental studies were carried out on 3 types of die-cuts: unchromed, chrome plated, chrome plated and laser hardened at the tip of the knives (noted M4, M3, M6) for processing the same product.

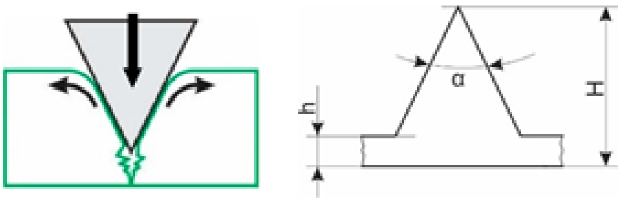
6.3.1. Materials used and knife geometry

The quality of a flexible die-cut is defined by the geometry of the cutting knife and the material characteristics. The steel from which the die is made must be shock resistant and at the same time have high durability [69]. In addition, it must allow multiple cycles of mounting and dismounting the die on the magnetic cylinder. The type of workflow and process parameters influence the choice of a specific material for die-cut fabrication. 50CrMo4 tool steel has very good abrasion resistance and thermal conductivity. It is calibrated and has high temperature stability.

Table 6.1. Chemical composition of 50CrMo4 (1.7228) steel: EN 10083-3-2006.

C	Yes	Mn	P	S	Cr	Mo
0,46-0,54	max 0,4	0,5-0,8	max 0.025	max 0.035	0,9-1,2	0,15-0,3

The die-cutting was carried out for an abrasive material, i.e. 0.450 mm thick cardboard weighing 280 g/m^2 for the complex product analyzed.



a) b)

Fig. 6.29. The die-cutting knives: a) die-cutting process; b) geometry of the die-cutting knives: H - height of the knives; h - thickness of the die-cutting table; α - cutting angle recommended by the manufacturer.

6.3.2. Types of parameters analyzed for the construction and adjustment of complex geometry die-cuts

The following parameters have been defined:

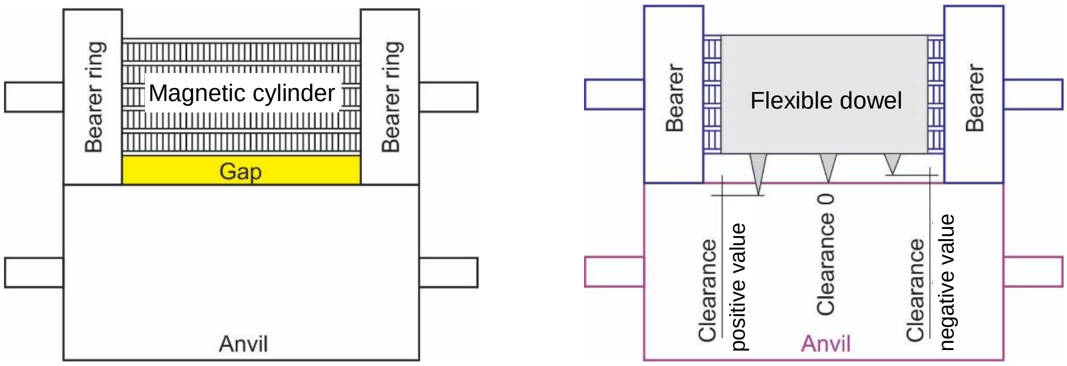
- Gap - the space between the body of the magnetic cylinder and the counter-cylinder (Fig. 6.30.a), which is calculated as follows [24]

$$Gap = (\Phi\ Rolling\ rings - \Phi\ Magnetic\ cylinder)/2 \quad (6.7)$$

For the magnetic cylinder used in the die-cutting of the finished product studied, the gap value was:

$$Gap = 145{,}586\ mm - 143{,}806\ mm = 0{,}890\ mm \quad (6.8)$$

- Clearance - the empty space between the knife tip and the pressure counter-cylinder; in the case of punching through the material it has a positive or zero value, and in the case of self-adhesive it has a negative value (cut the face of the material to the liner) (Fig. 6.30.b).



a) b)

Fig. 6.30. Die-cutting unit parameters: a) gap definition; b) clearance definition.

The die-cuts have been designed in such a way that for each complete die-cutting obtained by a rotation of the magnetic cylinder on which the die-cut has been mounted, 2 pieces of product with the following characteristics are produced: 8 circular holes $\Phi = 11\,mm$, 124 rectangular holes with two semicircular sides of dimensions $27\,mm \cdot 11\,mm$ and repetition of the die-cut $= 2 \cdot 228{,}6\,mm = 457{,}2\,mm$.

All 3 dies M4, M3 and M6 had the same flat contour dimensions of $500\,mm \cdot 457{,}2\,mm$ and were executed with the same knife geometry, height and angle at the tip, each having the same total number of knife lengths per die-cut that were machined.

6.3.3. Scheduling experiments

The experiments were programmed by applying the factorial experiments method. Thus, both small values such as $M_{(f)} = 50;\ 70\,Nm$, as well as usual values of the die-cut's clamping, $M_{(f)} = 90;\ 110$ Nm, and for the die-cutting speed were chosen values accepted for printing in the printing process of products in this range, namely $v = 50;\ 60\ m/min$.

For all three types of die-cuts analyzed - M4, M3 and M6, the periods of time during which they worked under identical operating conditions were taken into account, i.e. until the first waste not completely ejected from the nests appeared, in which case the worn knives could no longer ensure full penetration of the material thickness.

Results obtained for knives without chrome plating (M4 die-cut)

In order to evaluate the in-service behavior of the three types of die-cuts, knife wear was analyzed by measuring the height H of the knives and the length of die-cut material.

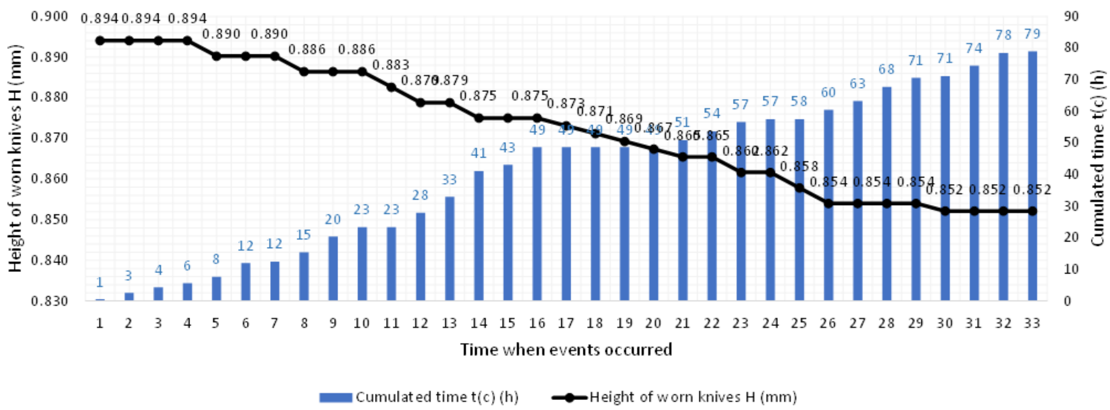


Fig. 6.35. M4 die-cut M4 knife wear as a function of knife height variation at each event.

The durability of the unchromed M4 was:

$$D_{dM4} = 239.253\, m/0{,}4572\ \ m/rotation = \ 523.300\, rotations \quad (6.17)$$

Results obtained for chrome plated knives (M3 die-cut)

The M3 die-cut had the same knife geometry as the M4 die-cut, in this case the active part was chrome plated.

The M3 die-cut was withdrawn when the first waste not fully ejected from the nests appeared, i.e. when the used knives were no longer able to punch through the full thickness of the material, the maximum moment of clamping force being 120 Nm.

$$D_{dM3} = 271.157\, m/0{,}4572\ \ m/rotation = \ 593.081\, rotations \quad (6.18)$$

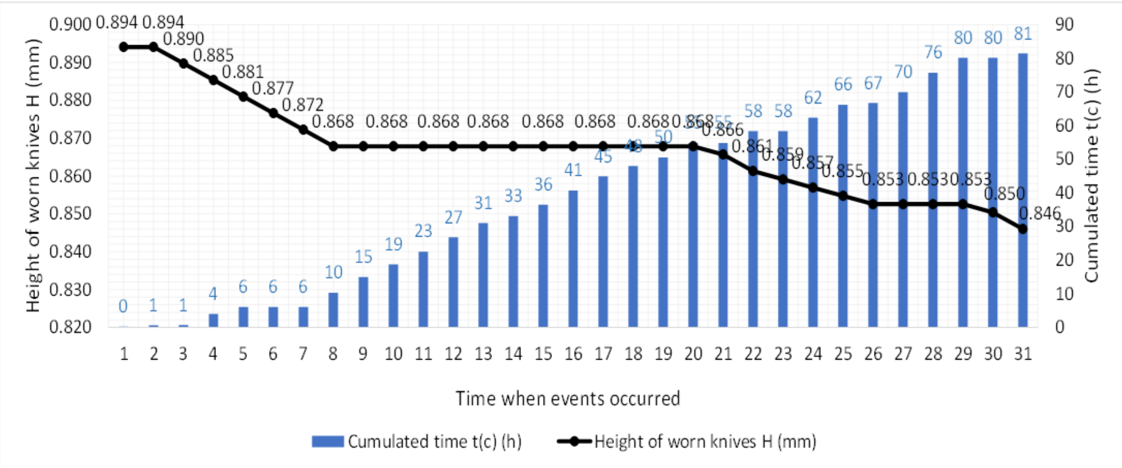


Fig. 6.39. Wear of the M3 die-cut knives as a function of the variation in knife height at each event.

Results obtained for chrome-plated and laser-hardened knives (M6 cutter)

The M6 die-cut had the same structure as the M4 and M3 die-cuts respectively, but its knives were chrome plated and laser hardened at the tip.

The die-cut worked for a maximum time of 89 h with the moment of clamping force and velocity kept constant, the die-cut remained in production.

$$D_{dM6} = 312.120\, m/0{,}4572\ \ m/rotation = \ 682.677\, rotations \quad (6.19)$$

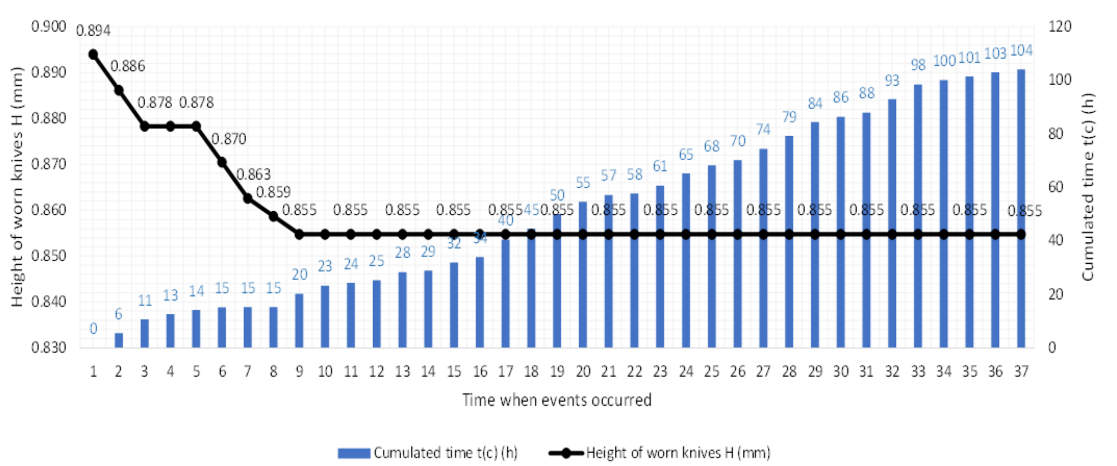
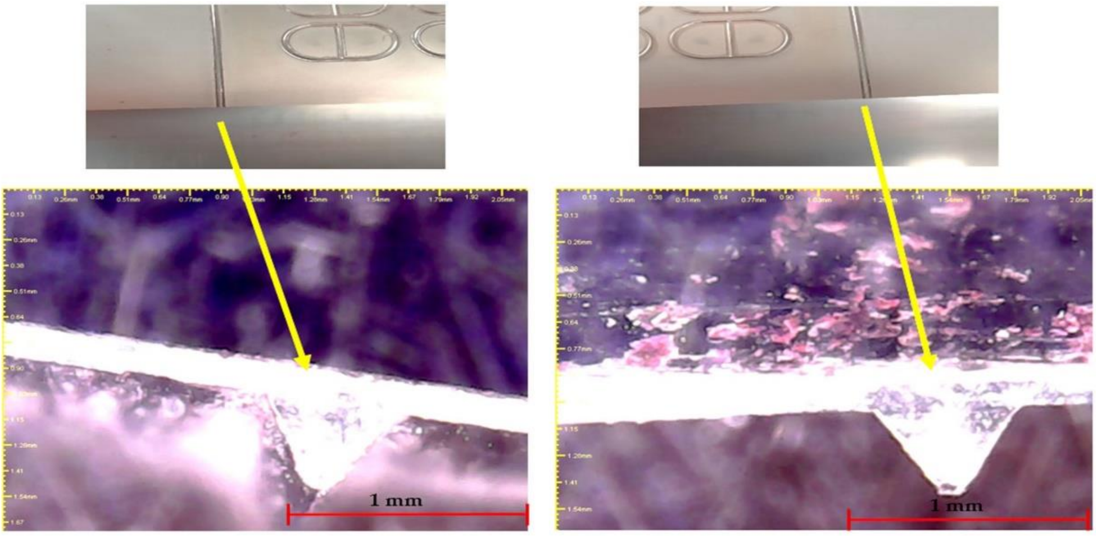


Fig. 6.43. Wear of the M6 die-cut knives as a function of the variation in knife height at each event.

The heights of the knives on the die-cuts were measured before the first printing and after their withdrawal from production. A total of 80 measurements were carried out and the arithmetic mean values of the homogeneous intervals of the measurements were calculated to establish the maximum and minimum values.

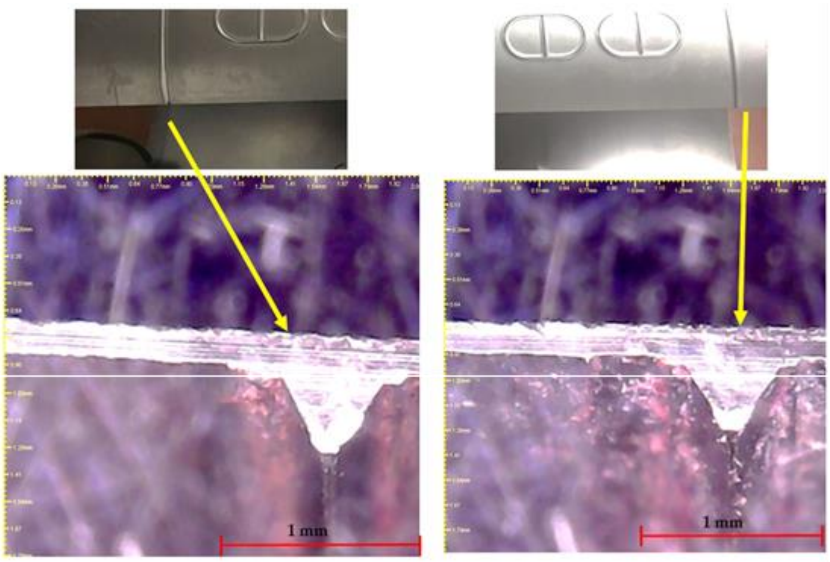
The macrostructure analysis was performed using a Basic VIS metallographic optical microscope produced by KERN. The 50x microscope analysis of two adjacent knives on the unchromed, worn M4 die-cut (Fig. 6.44) showed two different profiles, characterized as follows: one was sharply rounded and the other flattened, which highlights their uneven wear in the context of both knives entering simultaneously into the die-cut of the abrasive material, which was thin cardboard. The images were taken at the physical removal of the die-cut from production, when the minimum height of the worn knives measured $0{,}846\ mm$.



(a) (b)

Fig. 6.44. M4 die-cut: (a) left side knife wear and (b) right side knife wear.

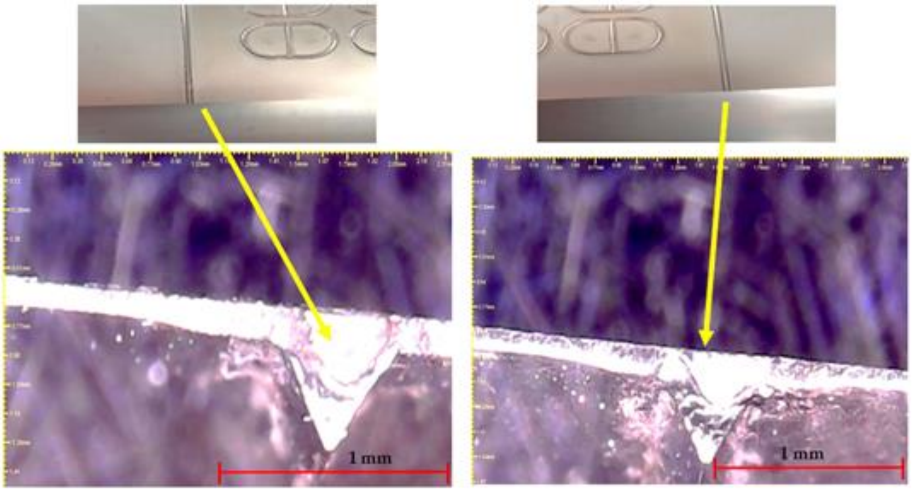
The wear of the M3 chrome-plated die-cut knives was highlighted with a 50x microscope. Fig. 6.45 shows how the tip area is sharply flattened in the case of two knives which, being side by side, enter the die-cut at the same time, so that the shape of the worn tips is similar. The images were taken when the M3 was taken out of production when the first waste not fully ejected appeared, with the minimum height of the spent tips of $0{,}846\ mm$.



a) b)

Fig. 6.45. M3 die-cut: a) left side knife wear; b) right side knife wear.

After a maximum die-cut length of $312.120\ m$ obtained with M6 chrome-plated and laser-hardened cutters, a small degree of wear was observed at the tips of the cutters seen under the 50x microscope, which appeared slightly dull compared to the other cutters (Fig. 6.46).



a) b)

Fig. 6.46. M6 die-cut: a) left side knife wear; b) right side knife wear.

The identification of the highest knife heights on the unchromed M4 die-cut concurrent with the existence of frequent changes in the moments of the clamping force and die-cutting speed, resulted from the fact that at least one knife appeared on the active surface of the unchromed die-cut, worn enough to not completely punch through the material and the resulting waste to remain hanging from the nest. The random wear of the knives is due to the varying thickness of the die-cut cardboard and the fact that paper/cardboard are highly abrasive materials, which affects the shape integrity of the die-cut knives.

In all three die-cuts, the occurrence of a nested nested waste immediately causes the application of an additional squeezing force moment or a change in die-cutting speed; these moments were marked by small amounts of die-cut material at the squeezing force moments.

6.4. Conclusions

● The case study was carried out for the preformed thin cardboard *folding box* product, as the product is commonly made by this technological process. (v. § 6.1).

● A total of 7 types of complex preformed product designs (Fig. 6.11) were identified in the production archives, produced by flexographic technology between 2015 and 2020, which required a total of 45 similar die-cuts consumed in order runs (see § 6.1.2).

● There were 11 die-cuts available for the survey, but out of the total of 15 die-cuts, only quantitative and qualitative information was available for 4 die-cuts (see § 6.2).

Extrapolation analysis of the data on the durability of die-cuts revealed the following:

- The durability of the M6 die-cut was higher than the other two because it had chrome plated and laser hardened knives, and the fact that it remained in production for a longer time indicates a further increase in durability above the $682.677\ rotations$, the wear on the knives being constant across the surface of the die-cut at all points on the knives.

- The durability of the chromed M3 die-cut was higher than that of the unchromed M4 die-cut with $69.781{,}27\ rotations$, die-cutting by $31{,}900\ m$ more than the unchromated die-cut; thus, the chromization of the M3 die-cut improved the resistance of the knives when cutting cardboard, which is an abrasive material.

- The durability of the unchromed M4 compared to the chrome-plated M3 indicates low resistance to cutting an abrasive material (cardboard) with thickness variations of $+/-3\%$ from $0{,}463\ mm$ to $0{,}436\ mm$, resulting from manufacturing.

- It has been demonstrated that chrome plating and laser hardening at the tip of the knives maximized the length of die-cut material, while at the same time uniform wear of the knives and a decrease in the number of setting times.

Chapter 7.
Mathematical modeling to determine the wear of die-cut knives

The realization of the mathematical model for the determination of the wear of the die-cutting knives also includes elements disseminated in the author's works [23, 24, 87].

In this chapter the possibility of choosing and realizing a model of the flexographic die-cutting process for determining knife wear in complex dies die-cutting, where production practice has shown a high number of die-cuts consumed for small print runs, was studied.

There are very few details about the flexographic die-cutting process in the specialized literature, as there is currently no methodology to help the best use of die-cuts to obtain maximum lengths of die-cut material in optimal conditions of quality of the finished product.

The height of the die-cut knives *H*, the wear of the knives *W*, the die-cutting speed *v*, the moment of the clamping force M_f and the length of the die-cut material *L* [24] were taken into account.

The construction of the mathematical model, based on the identification of some laws of variation of the parameters and the formulation of a performance criterion, aimed at designing a program to modify the moment of the die-cut clamping force - M_f and the die-cutting speed - *v*, which in the production of runs would lead to a decrease in the wear *W of* the knives and implicitly to an increase in the length *L* of the die-cut material.

The stage transformations, led to the linear program (7.32) for which the **Simplex algorithm** was applied (Table 7.2).

$$(\min) f = 0x_1 + Ex_2 + 0x_3 + 0x_4 + x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12}$$

$$\begin{cases} x_1 - Ax_2 + 0x_3 + 0x_4 + 0x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} = 40 \\ x_1 + 0x_2 + 0x_3 + 0x_4 + 0x_5 + x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} = a_1 \\ x_1 + 0x_2 + 0x_3 + 0x_4 + 0x_5 + 0x_6 - x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} = a_2 \\ 0x_1 + 0x_2 + x_3 - Bx_4 + 0x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} = v_0 \\ 0x_1 + 0x_2 + x_3 + 0x_4 + 0x_5 + 0x_6 + 0x_7 + x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} = b_1 \\ 0x_1 + 0x_2 + x_3 + 0x_4 + 0x_5 + 0x_6 + 0x_7 + 0x_8 - x_9 + 0x_{10} + 0x_{11} + 0x_{12} = b_2 \\ 0x_1 + 0x_2 + 0x_3 + 0x_4 + x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + x_{10} + 0x_{11} + 0x_{12} = 0 \\ 0x_1 - Cx_2 + 0x_3 + 0x_4 + x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} - x_{11} + 0x_{12} = W_0 - 0{,}001 \\ 0x_1 - Dx_2 + 0x_3 + 0x_4 + x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} - x_{12} = W_0 - 0{,}001 \\ x_1,\ x_2, x_3, x_4, x_5 \geq 0;\ x_r \geq 0\ where\ r = 6 - 12;\ x_s \geq 0\ where\ s = 13 - 18\ \text{și}\ A, B, C, D, E \geq 0 \end{cases} \tag{7.32}$$

Table 7.2. Application of the Simplex algorithm for the first iteration.

			0	E	0	0	1	0	0	0	0	0	0	0	M	M	M	M	M	M	Iteration 1
CB	VB	VVB	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	Column coming out of the base
M	x_{13}	40	1	-10	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	$40:1=$ **40**
0	x_6	a_1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	$a_1:1=a_1$
M	x_{14}	a_2	1	0	0	0	0	0	-1	0	0	0	0	0	0	1	0	0	0	0	$a_2:1=a_2$
M	x_{15}	v_0	0	0	1	$-A$	0	0	0	0	0	0	0	0	0	0	1	0	0	0	–
0	x_8	b_1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	–
M	x_{16}	v_b	0	0	1	0	0	0	0	0	-1	0	0	0	0	0	0	1	0	0	–
0	x_{10}	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	–
M	x_{17}	$W_0-0{,}001$	0	$-B$	0	0	1	0	0	0	0	0	-1	0	0	0	0	0	1	0	–
0	x_{12}	$W_0-0{,}001$	0	$-D$	0	0	1	0	0	0	0	0	0	-1	0	0	0	0	0	1	–
	f	$(39{,}009+a_2+v_0+v_b+W_0)\cdot M$	$2M$	$(-A-C)\cdot M-E$	$2M$	$-B\cdot M$	M	*	$-M$	*	$-M$	*	$-M$	*	*	*	*	*	*	*	

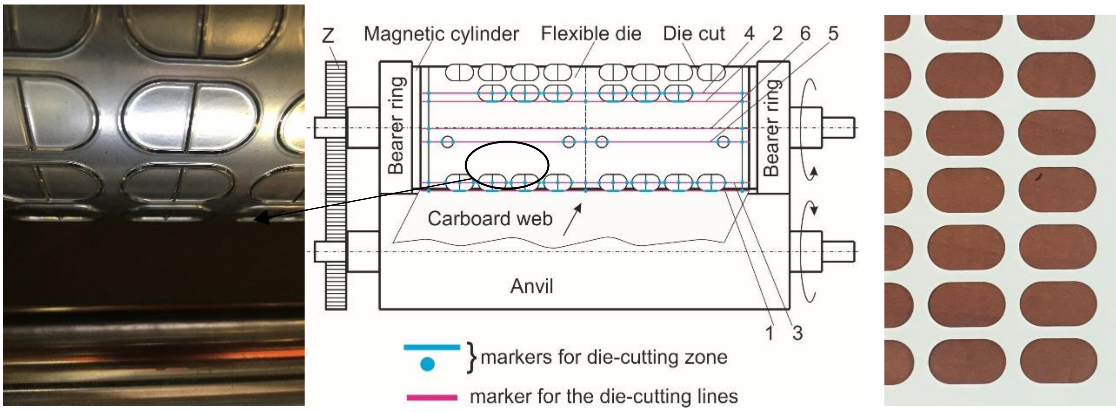
The methodology can be used in any printing house, in cases where there is a large (e.g. double) number of rejected die-cuts after small runs of orders (compared to the expected runs), although the complex product would require a small annual consumption of die-cuts.

Chapter 8.
Experimental investigations and personal contributions on the wear of complex geometry die-cuts

Some of the experimental research and personal contributions on knife wear in flexographic die-cutting have been disseminated in the author's papers [24, 59, 87].

In order to increase the durability of die-cuts (increasing the length of the die-cut material and reducing the wear of the die-cut knives), the evolution of the wear of the die-cuts of a group of flexible production die-cuts was analyzed.

The experimental investigations were performed with the die-cutting unit shown in Fig. 8.3. a. Longitudinally the knives are parallel to the die-cutting surface, and transversely they gradually penetrate the cardboard material during rotation (Fig. 8.3. b). Thus, in the tangency zone of the two cylinders of the die-cutting unit, we can distinguish: knives that enter the cut through linear segments, knives that enter the cut following the curvilinear contour, and knives that cut parallel to the direction of the web travel in the machine [87]. Thus during a complete rotation of the die, six types of simultaneous cuts are distinguished (Fig. 8.3. b).



a) b) c)

Fig. 8.3. Die-cutting unit: a) the die-cut mounted in the group; b) sketch of the die-cutting unit with cutting areas marked; c) final product.

For all the cuts made with each of the die-cuts, the same magnetic die-cut-holder gear cylinder was used (Fig 8.3), and the machine setting parameters for each run were the same: thin cardboard with a thickness of $0{,}450\ mm$; the adjustment of the cutting depth of the die-cuts was done by bringing the magnetic cylinder close to the pressure counter-cylinder by means of a screw device, where tightening was done with a torque wrench with a graduation between $40-200\ Nm$ [87].

8.3. Choice of representative die-cuts for the study of maximum die-cut length and knife wear

Starting in 2019, over 4 years, the dynamic behavior of a total number of 40 die-cuts (the number of all complex die-cuts used on the seven product models executed in the printing house between 2019-2023) was studied in parallel.

In the last 10 years the demands of the customers have increased, with most of them demanding the best possible quality of the die-cut material. Thus, customers often ask manufacturers to harden the surface of the die-cut for higher durability, such as laser hardening of the knives at the tip. For these reasons, the 8 laser tip-hardened dies were chosen.

The 8 die-cuts on which experimental investigations were carried out had the following common characteristics:

- were used exclusively for die-cutting the same material, i.e. thin cardboard with a grammage of 280 g/m^2 (± 2%) ISO 536 and a thickness of 450 µm (± 3%) ISO 534;
- were made for very large print-run requirements in the order of hundreds of thousands of meters and abrasion resistance, since cardboard is an abrasive material;
- had the same knife geometry, i.e. triangular in profile, with a 70-degree angle at the tip;
- were used for die-cutting the same complex product (Fig. 8.3.c);
- were made with a chrome-plated surface and laser-hardened knife tips.

8.3.2. Determination of maximum die-cut length and knife wear

The knife wear and die-cut length are shown in Table 8.2.

The experimental research was carried out over 4 years in the production of real runs. As the figures are large, a multiple [·1000 m] was chosen for the unit of measurement rounding the result to 2 decimal places.

The four boundary behaviors of the die-cuts in Table 8.3 were analyzed in turn, with the following characteristics [87]:

- minimum machined length, minimum die-cut wear: D1 ;
- minimum machined length, maximum die-cut wear: M1 ;
- maximum machined length, maximum die-cut wear: M0 and D4 ;
- maximum machined length, minimum die-cut wear: this is the optimal option.

Table 8.2. Knife wear and die-cut length [87]

Die-cut	W_{max} [mm]	L_{max} [·1000 m]
M0	0,060	261,6
M1	0,053	36,1
M2	0,055	117,3
M5	0,040	3,4
D4	0,053	227,9
D1	0,005	41,5
D2	0,042	45,9
D3	0,033	28,0

Table 8.3. Two-dimensional distribution table of the eight die-cuts: M0, M1, M2, M5, D1, D2, D3 and D4 [87]

W_{max} [mm] / L_{max} [-1000 m]	0,005 - 0,023	0,023 - 0,042	0,042 - 0,060	Number of values W_{max} in range
3,4 - 89,5	D1	M5, D2, D3	M1	5
89,5 - 175,6			M2	1
175,6 - 261,6			M0, D4	2
Number of values L_{max} in range	1	3	4	8

The random causes that can lead to a die-cut being withdrawn from production before the knives are completely worn out have been determined. Defects commonly found in complex die-cuttings have been presented in subchapter 8.1.1.

Such situations have also been encountered in some of the analyzed die-cuts. Thus:

D1 die-cut - was REMOVED after 41.500 m because it was hit mechanically at the last adjustment, the torque wrench fell on the knives of the die-cut destroying them.

D2 die-cut - because it was made longer than the circumference of the cylinder, the edges of the die-cut overlapped when mounted on the magnetic cylinder, so the raised edge was impressed in the material and REMOVED after 45.900 m.

D3 die-cut - after execution the die-cut was left flat, unpreformed, and with a burr on one of the edges; when mounted on the magnetic cylinder the edges overlapped and the raised edge was printed in the material being REMOVED after 28.000 m.

D4 die-cut - this die-cut had DEFECTIVE workmanship for an area of knives not cutting deep enough, but was kept in production out of necessity to fill up delivery batches until a new die-cut arrived. It experienced high material losses on setting: from 227.900 m die-cut, 14.000 m there were losses, and it had high knife wear of 0,053 mm.

M0 die-cut - on this die-cut we recorded the die-cutting parameters M_f , v only from about half the lifetime of the die-cut, when $M_f = 110\ Nm$, i.e. since the start of the doctoral research program.

Following these events and the analysis of Table 8.2, the following 3 die-cuts were chosen for analysis: M5, M1, M2 executed at the same quality, chromed and laser hardened at the tip of the knives because they represent the extreme cases that can occur in die-cuting.

8.4. Personal contributions on improving the die-cutting technology process

The following modifications of the die-cutting technological process have been proposed and implemented in order to improve it:

Adjustment of the clamping moment M_f of the die-cut has been carried out in increments of **10 units, starting from $\boldsymbol{M_{f0} = 40\ Nm}$.**

The die-cutting conditions were identical for all die-cuts, with blade-stopper to remove debris escaping from the die-cutting unit and with blowers to avoid trapping debris in the roll winding. These conditions were taken into account when determining the reduction of the knife height from the maximum nominal value of new knives to the minimum measured value of worn knives.

The mathematical model presented in the previous chapter has been applied to three representative die-cuts M5, M1 and M2.

8.5.3. Solving the mathematical model using the Simplex algorithm

$$\begin{cases}
(min)f = 0x_1 + 0{,}003x_2 + 0x_3 + 0x_4 + 0x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} + Mx_{13} + Mx_{14} + Mx_{15} + M_4x_{16} + Mx_{17} \\
x_1 - 10x_2 + 0x_3 + 0x_4 + 0x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} + x_{13} + 0x_{14} + 0x_{15} + 0x_{16} + 0x_{17} = 40 \\
x_1 + 0x_2 + 0x_3 + 0x_4 + 0x_5 + x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} + 0x_{13} + 0x_{14} + 0x_{15} + 0x_{16} + 0x_{17} = 80 \\
x_1 + 0x_2 + 0x_3 + 0x_4 + 0x_5 + 0x_6 - x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} + 0x_{13} + x_{14} + 0x_{15} + 0x_{16} + 0x_{17} = 70 \\
0x_1 + 0x_2 + x_3 - 10x_4 + 0x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} + 0x_{13} + 0x_{14} + x_{15} + 0x_{16} + 0x_{17} = 30 \\
0x_1 + 0x_2 + x_3 + 0x_4 + 0x_5 + 0x_6 + 0x_7 + x_8 + 0x_9 + 0x_{10} + 0x_{11} + 0x_{12} + 0x_{13} + 0x_{14} + 0x_{15} + 0x_{16} + 0x_{17} = 40 \\
0x_1 + 0x_2 + x_3 + 0x_4 + 0x_5 + 0x_6 + 0x_7 + 0x_8 - x_9 + 0x_{10} + 0x_{11} + 0x_{12} + 0x_{13} + 0x_{14} + 0x_{15} + x_{16} + 0x_{17} = 30 \\
0x_1 - 0{,}003x_2 + 0x_3 + 0x_4 + x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + x_{10} + 0x_{11} + 0x_{12} + 0x_{13} + 0x_{14} + 0x_{15} + 0x_{16} + 0x_{17} = 0{,}003 \\
0x_1 + 0x_2 + 0x_3 + 0x_4 + x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} - x_{11} + 0x_{12} + 0x_{13} + 0x_{14} + 0x_{15} + 0x_{16} + x_{17} = 0 \\
0x_1 - 0{,}003x_2 + 0x_3 + 0x_4 + x_5 + 0x_6 + 0x_7 + 0x_8 + 0x_9 + 0x_{10} + 0x_{11} + x_{12} + 0x_{13} + 0x_{14} + 0x_{15} + 0x_{16} + 0x_{17} = 0{,}008 \\
x_1 \geq 0, x_2 \geq 0, x_3 \geq 0, x_4 \geq 0, x_5 \geq 0, x_r \geq 0 \text{ where } r = 6 - 12, x_s \geq 0 \text{ where } s = 13 - 17
\end{cases} \quad (8.46)$$

Table 8.8. Application of the Simplex algorithm for the first iteration.

			0	0.003	0	0	0	0	0	0	0	0	0	0	M	M	M	M	M	Iteration 1
CB	VB	VVB	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	Column coming out of the base
M	x_{13}	40	1	−10	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	40: 1 = **40**
0	x_6	80	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	80: 1 = 80
M	x_{14}	70	1	0	0	0	0	0	−1	0	0	0	0	0	0	1	0	0	0	70: 1 = 70
M	x_{15}	30	0	0	1	−10	0	0	0	0	0	0	0	0	0	0	1	0	0	–
0	x_8	40	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	–
M	x_{16}	30	0	0	1	0	0	0	0	0	−1	0	0	0	0	0	0	1	0	–
0	x_{10}	0.003	0	−0.003	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	–
M	x_{17}	0	0	0	0	0	1	0	0	0	0	0	−1	0	0	0	0	0	1	–
0	x_{12}	0.008	0	−0.003	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	–
	f	$170M$	$2M$	$-10M - 0.003$	$2M$	$-10M$	M	*	$-M$	*	$-M$	*	$-M$	*	*	*	*	*	*	

8.6. Formulation of an algorithm for adjustment the die-cutting process parameters

One of the solutions applicable to the existing conditions in the print shop where the tests were carried out, was to halve the values of the successive increments of the process parameters $M'_{fi} = 40 - 110\ Nm$ and $v'_k = 30 - 50\ m/min$.

8.7. Conclusions

The successive cardboard cutting phases in the flexographic die-cutting process were identified.

The main reasons why complex die-cuts are frequently withdrawn early from production (without reaching maximum knife wear) and which lead to significant losses in production were highlighted.

The degree of compexity of the die-cut, and the degree of compexity related to the die-cutting process was analyzed, with the result that in the tangency zone of the active cylinders in the die-cutting unit, six types of concurrent cuts are made during a complete rotation of the die-cut, in which combinations of linear, curvilinear and point sections are die-cut, depending on the length and position of the knives entering the cut

The total number of die-cuts studied over 4 years, starting in 2019 (the beginning of the doctoral research work) covered 7 complex die-cut patterns and 40 die-cuts consumed in production.

Three representative die-cuts, M5, M1 and M2, were identified by analyzing the wear of the knives and the length of die-cut material for each die-cut, as well as the results of the random causes study that led to the premature withdrawal from production of some of them.

Taking into account the possibility of applying adjustments from 5 to 5 units, both for the moment of the die-cut clamping force and for the die-cutting speed (the fine variation of the speed is realized from the control panel of the machine), the algorithm for the adjustment of the flexographic die-cutting process was formulated.

Chapter 9.
Personal contributions to improving the die-cutting process

Research on die-cutting process improvement also includes elements disseminated in the author's work [23, 24, 87].

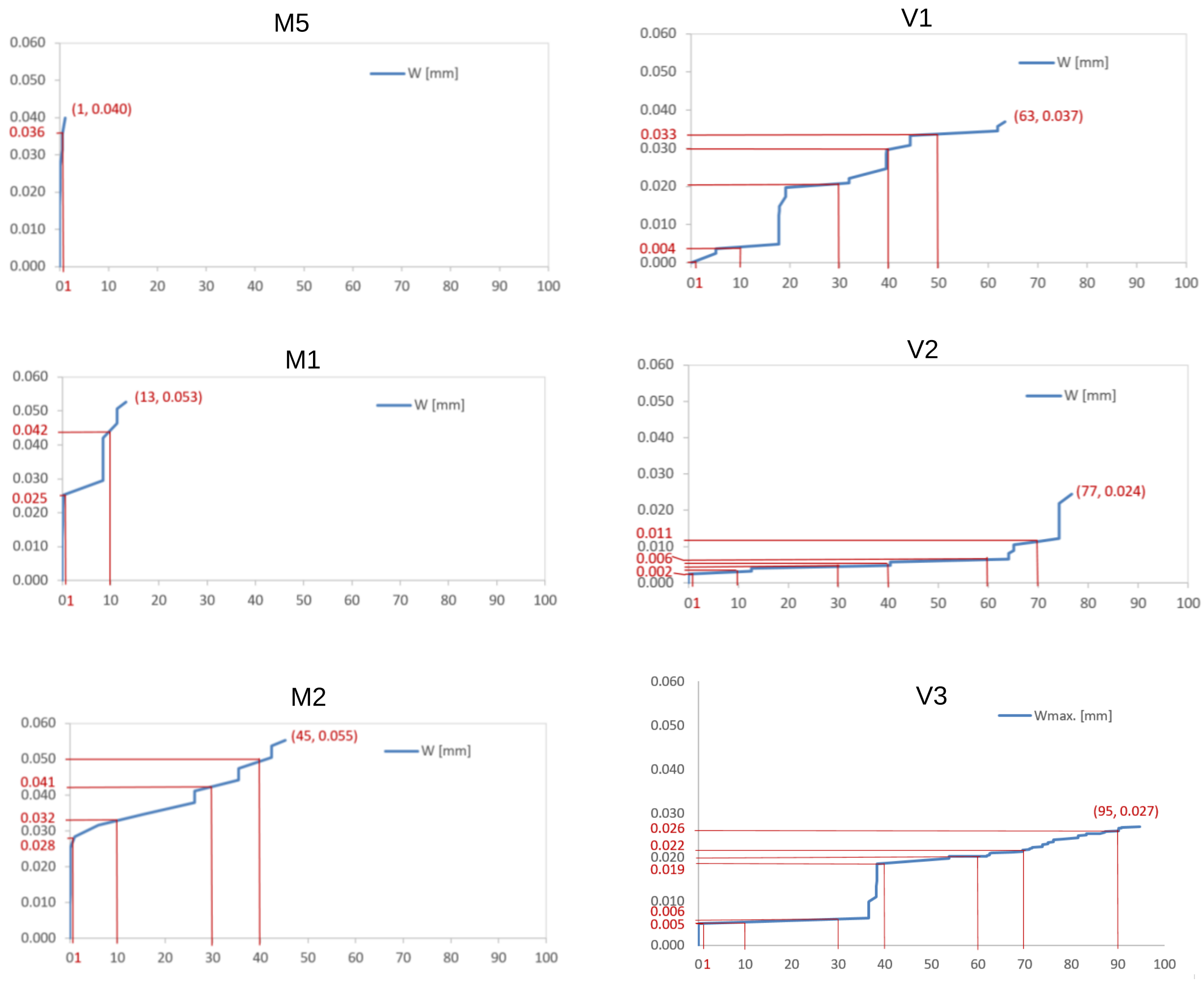
9.1. Testing of the proposed solutions on new die-cuts introduced in production

To test the proposed solutions, 3 new die-cuts, noted V1, V2, V3, chrome-plated, intended for very large print runs (in the order of hundreds of thousands of meters) [24], were used, and the knives were laser-hardened at the tip, triangular profile with 70 degree angle at the tip.

The die-cuts were used exclusively for die-cutting of the complex product studied for the thin paperboard material 280 (± 2%) g/m^2 ISO 536 and 450 (± 3%) µm ISO 534.

Testing of the three new die-cuts took place over the course of a year, during which time they were tracked in the production process.

With the results obtained from the experiments, the variation of knives wear as a function of the time of use of the die-cuts for the two groups of die-cuts: the M5, M1, M2 die-cuts used in the old conditions of production and the new V1, V2, V3 die-cuts were represented with the help of chronograms with the results of the experiments proposed as a result of the research (Fig. 9.1. a and b) [87].



a) b)

Fig. 9.1. Variation in time [h] of the wear of the die-cuts:
a) M5, M1, M2 - the group of new die-cuts used in the old production conditions;
b) V1, V2, V3 - the group of new die-cuts after the implementation
of the solution proposed in the doctoral thesis [87]

From Fig. 9.1.a, for the M5 chronogram, the evolution with poor performance of the die-cut was observed. It was necessary to increase the clamping force, which caused a rapid wear of the knives so that after one hour, the wear of the knives reached 0,033 mm. At 0,040 mm the die-cut was withdrawn as it no longer ensured waste ejection and the spinning effect could not be stopped [87].

Compared to M5, for one hour use of the die-cut, the M1 chronogram indicates a knife wear of 0,025 mm and although this is a high value, the die-cutting proceeded normally and the quality of the product was adequate. After 10 hours of operation the knife wear reached 0,042 mm at which point the M5 was already withdrawn. Above this value, the die-cut worked for another 3 hours and the wear of the knives at the time of withrawal was 0,053 mm .

Of the group of test die-cuts, M2 had the best evolution over the interval $M_f = 40 - 120\ Nm$, this was the benchmark die-cut in the study. The M2 chronogram shows a wear of 0,028 mm after one hour of die-cutting, and after 30 hours of die-cutting the wear reached the value of 0,041 mm in a time three times longer than the ten hours of use corresponding to the M1 die-cut knives.

In parallel (Fig. 9.1.b), the group of the experimental stamps V1, V2, V3 was analyzed. The solutions developed by means of the mathematical model were applied to them as follows: in the working procedures, the successively increasing values applied with the torque wrench were modified, respectively, the increases in the M_f values were decreased from 10 units to 5 units. At the same time, the variation of the velocity at the die-cutting conditions was also adjusted in steps of 5 units. At the same time, the procedure of repeating the range of values $M_f = 70 - 90\ Nm$ applied after the value $M_f = 100\ Nm$.

Compared to the die-cuts in the experimental group, of the three, V1 had the lowest performance. Compared to any of the die-cuts in the group of new die-cuts used under the old production conditions, the V1 chronogram showed significantly better values. Thus, after one hour of operation the wear of the knives was $0{,}004\ mm$ and after 60 hours the wear was $0{,}033\ mm$, for a period of time six times greater than the wear of the knives of die-cut M2 after ten hours of die-cutting (M2 being the best of the group M5, M1, M2).

V2 chronogram showed better results than V1, due to the earlier application of the value range $M_f = 70 - 90\ Nm$ respectively after $25.780\ m$ compared with the V1 sample, where the same range of M_f was applied after $49.440\ m$. Thus the wear of the knives did not increase rapidly and after 60 hours of die-cutting reached the value of $0{,}006\ mm$. After 77 hours of use the die-cut was taken out of the tests and had a knife wear of $0{,}024\ mm$, basically the knife wear value of the M1 die-cut after one hour of die-cutting.

ChronogramV3 demonstrates the effects due to successive application of the range of values eight times $M_f = 70 - 90\ Nm$ but without exceeding the value of $90\ Nm$. These repetitions were applied after 54 hours of operation and resulted in a moderate increase in knife wear with no further jumps.

After 70 hours of operation the knife wear was $0{,}022\ mm$, the V2 was removed from the tests at a knife wear of $0{,}024\ mm$ at 77 hours of use. The V3 die-cut had been in operation for 95 hours and had reached a wear of $0{,}027\ mm$.

Table 9.19 shows the comparative analysis carried out after the introduction of the new die-cuts in production and compliance with the new rules imposed by the results of the research carried out in the doctoral thesis.

Table 9.19. Comparative analysis of the behavior of the studied die-cuts

Die cut	Maximum knife wear W_{max} $[mm]$	Time of use T $[h]$	Maximum die cut length L_{max} $[\cdot 1000\ m]$
M5	0.040	0.52	3.4
M1	0.053	1.91	36.1
M2	0.055	2.90	117.3
V1	0.037	63.45	178.1
V2	0.024	76.70	225.9
V3	0.027	94.70	263.6

9.5. Conclusions

Until these studies and researches were carried out, no positive results were obtained in the printing industry when die-cutting complex products with holes and perforated lines, so that the die-cuts were prematurely withdrawn from production, due to reasons that affected the quality of the finished product.

The experiments presented in the thesis, the partial and final results obtained, were applied in parallel to the other complex die-cut models as they entered print run production, resulting in all cases in an increase in the length of die-cut material. These activities were coordinated directly by the thesis author.

Chapter 10. Overall conclusions, main contributions and directions for further research

10.1. General conclusions

(1) The doctoral thesis develops a number of issues related to the improvement of the die-cutting process in flexographic technology with complex geometry die-cuts, such as: increasing the efficiency of the flexographic production workflow and proposing a mathematical model that allows finding optimal solutions for decreasing the wear of the flexible die-cuts knives.

(2) The scientific importance of the doctoral thesis is supported by the contributions made to the development and implementation of a methodology for the exploitation of complex geometry die-cuts used in flexographic technology, in the production of print runs in accordance with the orders received and realized in a printing house, based on the controlled modification of the technological production parameters, namely the moment of the die-cut clamping force and the die-cutting speed.

(3) From the state-of-the-art analysis of flexographic technology and the role of die-cutting in flexography, a number of conclusions have been drawn, which are presented in Chapter 3.

(4) In view of the data and conclusions from the state-of-the-art review of flexographic technology and the role of die-cutting in flexography, the research directions outlined in Chapter 4 were considered to be topical.

(5) In relation to the current status and research directions for the improvement of the die-cutting process in flexographic technology with complex geometry die-cuts, the main objective of the doctoral research activity (see also § 4) was determined as the development and implementation in the production of print runs according to orders, of a flexographic die-cutting methodology involving the increase of the quality of preformed products with high degree of complexity, based on the controlled modification of the technological production parameters and applicable for any type of machines and complex geometry die-cuts. The relevant conclusions on the research work to achieve the main objective, in relation to the methodological benchmarks (see § 4), are the following:

○ Improved the way of scheduling the use of the die-cuts, by identifying and implementing conditions that can lead to a reduction in auxiliary times, increasing the efficiency of the maximum use of the machines (see § 5).

○ The source of the maximum auxiliary time consumed in production was identified by applying Scenario 1 (FIFO) compared to Scenario 2 (MinSetup). It was proved that, in the production of print runs made in the company where the research was conducted, Scenario 1 also reflects the cases when the requirement arises for urgent delivery of a product unforeseen in the current production schedule. These are very time consuming by disrupting the production flow: changing magnetic cylinder, preparing new inks, washing vats for different color groups, and losses increase substantially if it is also necessary to change the material route through the machine (see § 5).

○ A mathematical model has been proposed, taking into account: - the constraints imposed by the flexographic printing process parameters - the moment of clamping force of the die-cuts, the die-cutting speed, the knife wear (measurement of worn knives) and the length of the die-cut material; - the performance criterion - minimization of knife wear (see § 7).

○ Simplex method was applied to solve the mathematical model (see § 7).

○ Of the 11 die-cuts, 3 of them (M4, M3 and M6 die-cuts) were experimentally investigated (see § 6.3) in order to determine the influence of the quality of the die-cut material (unchromed, chrome plated and chrome plated with tip hardening of the knives) on the aim of the thesis, to improve the flexographic die-cutting process by obtaining minimum wear of the die-cut knives (see § 8.2). Thus, the following aspects were highlighted:

- for the M4 unchromed die-cut was confirmed the poor resistance to flexographic die-cutting of a highly abrasive material, such as the one used in all experiments (cardboard of thickness $0{,}450\ mm$). The knives wore out unevenly very quickly and the waste was not completely ejected from the nests, making it necessary to increase the moment of the die-cut clamping force at short intervals;
- The M3 chrome-plated die-cut allowed an increase in the length of die-cut material of 31,900 *m* more than the unchromed die, by improving the resistance of the knives to cutting abrasive material, but insufficient for the variations in cardboard thickness of +/- 3 % indicated by the manufacturer;
- The M6 chrome-plated and laser hardened at the tip of the knives had the highest durability of the three die-cuts, with the knives wearing evenly over the entire surface of the die, as confirmed by macrostructure analysis using a metallographic optical microscope, Basic VIS produced by KERN. The 50x images taken when the M6 die-cut was taken out of production showed the appearance of the knives uniformly worn at the tip.

○ The die-cutting process was found to be improved by applying the proposed algorithm for adjusting the die-cutting parameters: 3 new die-cuts were made (noted V1, V2, V3), which comply with the same quality requirements as the M5, M1, M2 die-cuts, respectively for die-cutting the same type of thin cardboard, 0.450 *mm* thick, and intended for working in very large runs, in the order of hundreds of thousands of linear meters (chrome and laser hardened die-cuts), with 70 degrees at the tip of the knives. The production conditions were the same: the same magnetic cylinder was used for installation in the die-cutting unit and the same input data were set on the machine control panel (see § 9).

10.2. Main contributions

For the realization of the main objective of the doctoral research activity, the following contributions were made in the study:

- Specific procedures were developed and implemented to ensure the quality of the flexographic printing process in which the author participated directly: - printing preparation procedure; - first printing sample printing procedure; - intermediate samples printing procedure; - die-cut boxes finishing procedure.

- Two quality models have been constructed in order to define quality requirements for complex flexographic preformed products: a quality model by conceptualization levels and an optimal quality model for the same product. The quality models obtained in the thesis were subsequently used in collaborations with various beneficiaries (see § 6).

- The construction of a mathematical model has been realized, which can be applied by data customization to any model of flexible die-cuts dedicated to any type of flexographic presses, in conditions where the production of runs ordered by customers shows rapid wear with premature withdrawals from production, and the number of die-cuts consumed exceeds the consumption forecast for the order.

- Before the start of the research, the adjustment of the torque of the die-cut clamping force was done every 10 units with a starting value of 40 *Nm* (values allowed by the torque wrench). The results of the algorithm for programming the parameters of the die-cuting process by increasing the moment of the clamping force of the die-cut with constant values from 5 to 5 units were implemented on the technological flow.

- A methodology for flexographic die-cutting with complex geometry die-cuts was designed and implemented.

10.3. Research development directions

1. The problem of the wear of flexible die-cut knives used in flexographic technology requires continuous research into the materials from which the die-cuts are made and how their properties are compensated by chrome plating, both of which influence the size of the print runs.
2. Study the use of die-cuts made of new materials, different from those used until now. It is necessary to use high quality, resistant and durable materials, which are necessary to obtain the precise details and complex patterns in the flexographic die-cutting process.
3. Using die-cutting process simulation programs to optimize the process.
4. Research on the development of flexographic technology in Industry 4.0 and further adaptation to Industry 5.0. Possibilities of connecting equipment, creating an intelligent supply chain, the convergence of physical and cybernetic means through IoT (Internet of Things), as well as digitization, automation, with a special focus on the shift to industrial digital transformation, cloud computing, artificial intelligence and Big Data technologies will be studied.

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