Toilet Paper Perforation Efficiency

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Today, the toilet paper market offers product types with varying number of plies, providing better mechanical strength and liquid absorption. Several tissue paper perforation systems exist, and the best commonly applied is a top-cutting mechanism that includes an oblique blade, a combined oblique blade, or a simple spiral blade. The perforation efficiency must be high to have an easy sheet separation from the roll of the toilet paper, which does not always occur. Hence, consumer satisfaction can depend on the perforation performance. To study this, a laboratory perforation system was used to perforate different commercial toilet papers (in brands and number of plies) and evaluate their perforation efficiency. A finite element method (FEM) was used to simulate the curve of the progression of perforation efficiency as a function of the cut distance. The main findings were a stabilization of the perforation efficiency from a cut distance of 6 mm and a 15% increase in the cut distance for the laboratory blade to match the industrial perforation efficiency. The FEM analysis confirmed the behavior of the evolution of perforation efficiency with the increase of the cut distance.

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INTRODUCTION

The use of toilet paper was first recorded in China in 851 AD (Bennett 2009). The perforated roll toilet paper known today originated in the 19th century, with the patent of Seth Wheeler in 1894 (Wheeler 1894). The toilet paper market presents this product with a diverse number of plies (1 to 6 plies). A greater number of plies increases the thickness, which provides greater strength and liquid absorption. Globally, tissue paper, with toilet paper is included, is the fastest growing sector of the paper industry, where each person in the world consumes an average of 4.4 kg per year (Haggith and Martin 2018). From the specifications of a 3-ply toilet paper roll with 150 sheets, it weighs about 78 g. This means that each person in the world consumes about 56.5 rolls per year (more than 1 roll per week per person). Between 2010 and 2015, tissue paper production increased 3.5% annually, and it is expected to grow almost 6% per year between 2018 and 2022. The environmental benefit that has been seen, despite this rapid evolution of the tissue market, especially in developing countries, is to compensate the increase of digitization and the decline in the use of printing and writing paper (Skene and Vinyard 2019).

Today, the use of disposable products is high, but many consumers are concerned with the level of resources needed to produce these products. Thus, the development of environmentally friendly disposable products remains an important work (Olson *et al.* 2016). Tissue paper products, such as kitchen, toilet, and facial papers, are similar and usually perforated to facilitate portioning (Ogg and Habel 1992; Schulz and Gracyalny 1998; Baggot *et al.* 2006). In a roll of perforated toilet paper, the holes with a certain cut distance along a line are called perforation lines. These lines of weakness are parallel to the axis on which the toilet paper is rolled and aim to divide the roll of toilet paper into portions with a predefined length. This predefined length between two perforation lines is known as a "sheet" (Ogg and Habel 1992; Chih 2018). Figure 1 shows a scheme that presents these concepts.

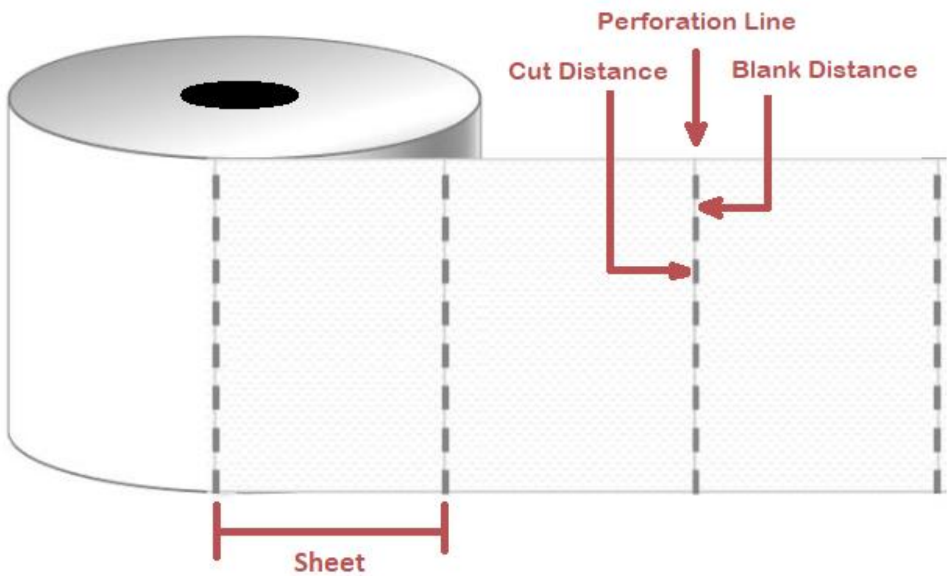

Fig. 1. Diagram of the concepts associated with toilet paper perforation

In the existing tissue paper perforation techniques, an upper cutting blade and a lower roll are generally used. Currently, the most widely used top-cutting mechanism includes an oblique blade, a combined oblique blade, or a simple spiral blade (Shiang 2012). Because the perforation blade operates in a rotating spiral, the contact between the blade and the paper sheet is theoretically at one point, which reduces the impact of this on the sheet. The soft contact (low impact) between the perforation blade and the paper sheet increases its lifetime and decreases the failure phenomena, such as the break of the blade (Chih 2018). There are disadvantages in the methods currently known for perforating tissue paper sheets. The forces generated in this operation cause vibrations that are harmful to the general processing of the sheet. In addition, there must be well-defined speed limitations, because high processing speeds cause high levels of vibration, causing imperfections in sheet cuts, sheet breaks, and/or machine malfunction (Baggot *et al.* 2006).

When the tensile strength of the perforated toilet paper is strong, the paper sheet is split off the perforation line. In contrast, when the tensile strength is weak, the sheet when pulled out from the toilet paper roll is not well controlled, leaving more than a predetermined number of sheets (Schulz and Gracyalny 1998; Mukai and Shimizu 2003). This low tensile strength can also impair the runnability of the converting machine, causing successive breaks of the sheet after the perforation process. Therefore, for all of this to be avoided, the tensile strength in the machine direction (MD) of the perforation must be controlled so that it falls within a predetermined range. In contrast, the tensile strength of perforated toilet paper is greatly influenced by the tensile strength of the base paper itself in MD (fibrous composition, formation, and orientation of the paper sheet) (Mukai and Shimizu 2003). These problems, which are associated with the separation of the sheets by the consumer, can have a negative impact on the customer's loyalty and satisfaction with the brand of the product in question (Schulz and Gracyalny 1998). Thus, the study of the perforation efficiency, by definition "the difference between the tensile strengths of non-perforated and perforated material from the same sample divided by the tensile strength of non-perforated material," of a toilet paper is extremely important for the producers of this type of product (ISO 12625-1:2019). To have an easy sheet detachment from the toilet paper roll, the perforation efficiency must be high. Equation 1 is used to evaluate the perforation efficiency according to the standard ISO 12625-12 (2010),

$$E_p = 100 \times [1 - (\bar{S}_p / \bar{S}_{np})] \tag{1}$$

where E_p is the perforation efficiency (%); $\bar{S}_p$ is the average tensile strength of perforated papers (N/m); and $\bar{S}_{np}$ is the average tensile strength of unperforated papers (N/m).

In this context, the objective of the present work is to evaluate the perforation efficiency for different cut distances in commercial papers of 2, 3, 4, and 5 plies, using a laboratory perforation system and comparing them with the industrial perforation of each one of these.

EXPERIMENTAL

Materials

Eight commercial toilet papers with a minimum service length of 125 mm were selected. This set is composed by two samples of each 2-ply, 3-ply, 4-ply, and 5-ply papers. These toilet papers were identified according to the following legend: XP_i, where X is the commercial toilet paper sample brand, P_i is the number of plies, and XP_iC_j where C_j is the cut distance (mm) of the perforation. The values of i = 2, 3, 4, and 5 represents the number of plies, and j = 2, 3, 4, 5, 6, 7, and 8 mm represents the cut distances performed.

Methods

To start this work, samples of commercial toilet paper with sheet length of 125 mm minimum were selected, meeting the ISO 12625-12 (2010) standard requirement of the 100 mm gauge length. Then, the samples were prepared to perform the tensile tests according to the above referred standard (width of 50 mm and a length of a minimum of 125 mm up to 150 mm). These samples were then perforated in the laboratory with the repeated cutting distances of 2, 3, 4, 5, 6, 7, and 8 mm. All the perforations were performed in the center of each sample along the cross direction (CD).

All samples were subjected to tensile tests along the MD on a Thwing-Albert® VantageNX universal testing machine (Thwing-Albert Instrument Company, West Berlin, NJ, USA) at a rate of elongation of 50 mm/min, in accordance with the standard mentioned above. Samples tensile tests were performed with and without perforation as illustrated in Fig. 2.

A customized optical system (Mendes *et al.* 2013, 2014, and 2015) was used to record the measurements of the cut distance of the toilet paper samples. The image acquisition of the performed cut distances was carried out with precise requirements of lighting and magnification. After it was properly configured for the application in hand, the optical system allowed the observation of the elements to be measured using processing tools for this task. In this work, four different measurements were considered of each sample, which were used for the calculation of the corresponding mean and standard deviation for all the studied paper samples.

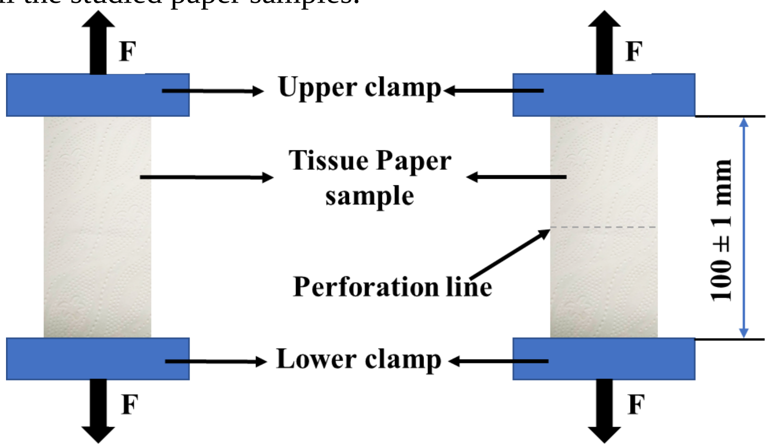

Fig. 2. Set-up of the tensile tests without and with perforation (Vieira *et al.* 2021)

All toilet paper samples were stored and tested at a temperature of 23 ± 1 °C and a relative humidity of 50 ± 2% according to ISO 187 (1990).

Numerical Model

In this work for the 2-ply toilet paper (BP_2) the influence of the cut distance was studied using mechanical simulation tools. The aim was to evaluate how the tensile strength decreases with the cut distance and how it affects the perforation efficiency. A simpler model was used to verify the stabilization of the perforation efficiency from a cut distance of 6 mm.

A finite element model (FEM) was executed in the software Abaqus/Standard finite element (Dassault Systèmes®, version 14.1, Vélizy-Villacoublay, France), using a linear elastic constitutive model to replicate the tensile tests on the 2-ply toilet paper BP_2 with 2, 3, 4, 5, 6, 7, and 8 mm of cut distances. The Young's modulus used, 1.38 MPa, was obtained by the tensile test performed in the sample without perforation and calculated as the slope between two specific points in the initial linear part of the load-elongation curve. An estimated value of 0.3 was used for the Poisson coefficient assuming that volume does not change. The sample geometry was a single shell with a width of 50.0 mm, a length of 100.0 mm, and a thickness of 0.3 mm. An axial load was employed by controlling a uniform elongation of 10.0 mm of the top surface. The lower surface was constrained to move and rotate in all directions. The CPS4R elements used in these models were 23503, 16043, 15252, 13222, 13165, 12158, and 12139 for the cut distances of 2, 3, 4, 5, 6, 7, and 8 mm, respectively. An ellipse was used for the cut's geometry with 0.01 mm to the smaller diameter and the longer diameter was matched to each cut distance. Perforation efficiency was calculated based on the tensile strength of the toilet paper sample without perforation. Load was increased iteratively, in several simulations, until this tensile strength value ($\overline{S}_{np}$ = 265.89 MPa in accordance with Table 1 for BP_2) was reached in the most critical element. The procedure was the same for each cut distance.

RESULTS AND DISCUSSION

From the previous work by Vieira *et al.* (2021), these toilet papers (with the same notation) were morphologically characterized. The fiber composition of the samples is mostly composed by hardwood short fibers. However, small differences were found in softwood long fibers content.

Tables 1 and 2 show the results for determining the perforation efficiency, as well as the measurements of the cut and blank distances laboratory performed for the 2-, 3-, 4-, and 5-ply toilet papers.

In Fig. 3, the cut distance measurements made on all toilet paper samples by cut blade size are shown. All the effective cuts were inferior to the target cuts. Comparing all the cuts for the same cut blade, they had an average coefficient of variation of 2.1% which indicates that this is a good mechanical method of laboratory perforation for this kind of tissue paper sample.

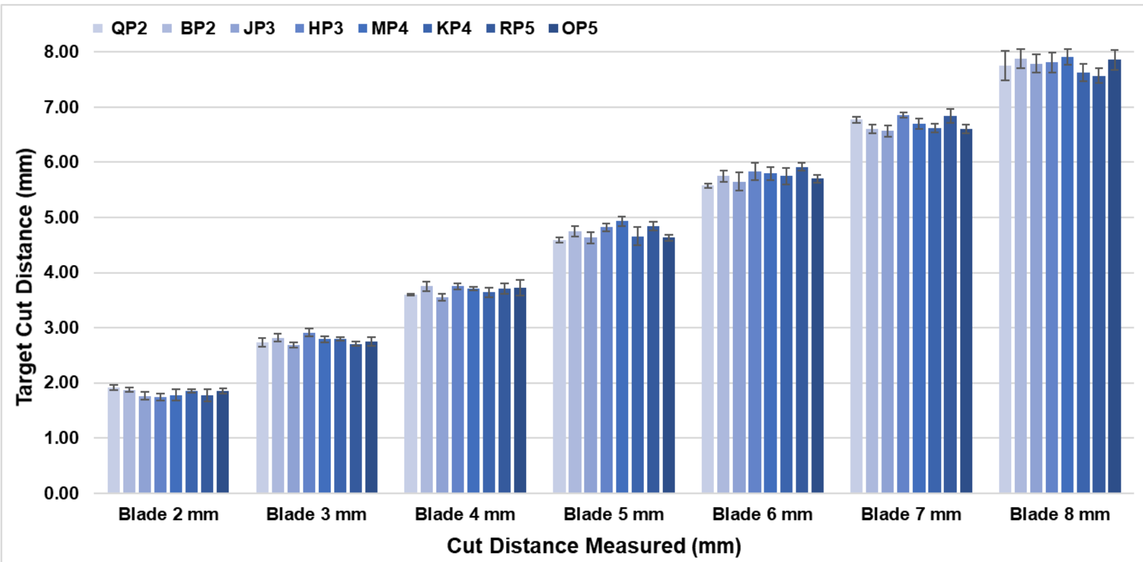

Fig. 3. Evaluation of the cut distances for all study samples

The evolution of perforation efficiency with the variation of the cut distances is presented in Fig. 4, by number of plies of toilet paper. It can be confirmed that for all samples there was a stabilization of the perforation efficiency above a cut distance of 6 mm. Therefore, for cutting distances higher than this value, perforation efficiency is not gained, which may impair the runnability of the paper sheet in the converting machine. In the previous work Vieira *et al.* (2021), the authors concluded that with the increase of the cut distance, stress concentration factor tends to increase asymptotically, physically meaning that the stress gets more homogenously distributed. Because the samples are from commercial papers of different brands, they have different fibrous compositions, which justifies the gap between the curves for the toilet papers with the same number of plies. Images obtained by the customized optical system are shown in Fig. 5, which represents the 6 mm cut distance of the 2-, 3-, 4-, and 5-ply toilet papers. The figure verifies that samples had uniform and clean cuts, and that with the increase of the number of plies the cut was not affected.

Table 1. Perforation Efficiency and Cut Distance for 2-ply and 3-ply Toilet Papers

Toilet Paper ID	Tensile Index (Nm/g)		Tensile Strength (N/m)	Perforation Efficiency (%)	Target Cut Distance (mm)	Cut Distance Measured (mm)		Blank Distance Measured (mm)	
	$\bar{x}$	± σ				$\bar{x}$	± σ	$\bar{x}$	± σ
QP_2	**5.87**	0.19	**175.38**						
QP_2C_2	**3.49**	0.24	**104.34**	**40.5**	**2**	**1.92**	0.05	**1.15**	0.03
QP_2C_3	**2.58**	0.20	**77.26**	**55.9**	**3**	**2.73**	0.08	**1.21**	0.06
QP_2C_4	**2.13**	0.16	**63.65**	**63.7**	**4**	**3.60**	0.02	**1.27**	0.04
QP_2C_5	**1.73**	0.19	**51.80**	**70.5**	**5**	**4.59**	0.05	**1.22**	0.03
QP_2C_6	**1.37**	0.10	**41.09**	**76.6**	**6**	**5.58**	0.04	**1.18**	0.05
QP_2C_7	**1.34**	0.15	**40.08**	**77.1**	**7**	**6.77**	0.05	**1.19**	0.03
QP_2C_8	**1.00**	0.10	**39.85**	**77.3**	**8**	**7.75**	0.27	**1.21**	0.03
BP_2	**7.13**	0.44	**265.89**						
BP_2C_2	**3.65**	0.28	**136.05**	**48.8**	**2**	**1.87**	0.04	**1.11**	0.02
BP_2C_3	**2.83**	0.26	**105.72**	**60.2**	**3**	**2.82**	0.07	**1.20**	0.05
BP_2C_4	**2.14**	0.31	**79.67**	**70.0**	**4**	**3.75**	0.09	**1.19**	0.06
BP_2C_5	**1.78**	0.19	**66.33**	**75.1**	**5**	**4.75**	0.10	**1.17**	0.07
BP_2C_6	**1.23**	0.13	**46.82**	**82.4**	**6**	**5.75**	0.10	**1.12**	0.05
BP_2C_7	**1.22**	0.12	**45.51**	**82.9**	**7**	**6.60**	0.08	**1.20**	0.03
BP_2C_8	**1.12**	0.13	**41.82**	**84.3**	**8**	**7.88**	0.17	**1.14**	0.07
HP_3	**7.00**	0.22	**305.25**						
HP_3C_2	**3.35**	0.35	**146.01**	**52.2**	**2**	**1.76**	0.06	**1.15**	0.09
HP_3C_3	**2.78**	0.14	**121.19**	**60.3**	**3**	**2.69**	0.07	**1.22**	0.06
HP_3C_4	**2.12**	0.09	**92.53**	**69.7**	**4**	**3.55**	0.06	**1.22**	0.04
HP_3C_5	**1.85**	0.23	**80.65**	**73.6**	**5**	**4.63**	0.07	**1.21**	0.07
HP_3C_6	**1.32**	0.10	**57.39**	**81.2**	**6**	**5.65**	0.16	**1.09**	0.07
HP_3C_7	**1.20**	0.14	**52.54**	**82.8**	**7**	**6.57**	0.05	**1.22**	0.01
HP_3C_8	**1.13**	0.15	**50.06**	**83.6**	**8**	**7.79**	0.18	**1.19**	0.07
JP_3	**6.86**	0.21	**360.10**						
JP_3C_2	**3.38**	0.16	**177.61**	**50.7**	**2**	**1.74**	0.07	**1.18**	0.07
JP_3C_3	**2.69**	0.26	**141.22**	**60.8**	**3**	**2.91**	0.05	**1.21**	0.04
JP_3C_4	**2.15**	0.21	**113.04**	**68.6**	**4**	**3.75**	0.06	**1.19**	0.05
JP_3C_5	**1.69**	0.13	**88.53**	**75.4**	**5**	**4.82**	0.11	**1.15**	0.06
JP_3C_6	**1.19**	0.13	**62.46**	**82.7**	**6**	**5.83**	0.17	**1.11**	0.06
JP_3C_7	**1.21**	0.16	**63.63**	**82.3**	**7**	**6.86**	0.10	**1.13**	0.06
JP_3C_8	**1.29**	0.18	**63.60**	**82.3**	**8**	**7.81**	0.17	**1.15**	0.06

Table 2. Perforation Efficiency and Cut Distance for 4-ply and 5-ply Toilet Papers

Toilet Paper ID	Tensile Index (Nm/g)		Tensile Strength (N/m)	Perforation Efficiency (%)	Target Cut Distance (mm)	Cut Distance Measured (mm)		Blank Distance Measured (mm)	
	x̄	± σ				x̄	± σ	x̄	± σ
KP_4	**6.78**	0.29	**410.05**						
KP_4C_2	**3.71**	0.22	**224.70**	**45.2**	**2**	**1.85**	0.03	**1.17**	0.04
KP_4C_3	**2.88**	0.19	**174.33**	**57.5**	**3**	**2.80**	0.03	**1.10**	0.06
KP_4C_4	**2.29**	0.10	**138.44**	**66.2**	**4**	**3.64**	0.08	**1.25**	0.07
KP_4C_5	**1.85**	0.21	**111.97**	**72.7**	**5**	**4.66**	0.17	**1.16**	0.05
KP_4C_6	**1.48**	0.18	**89.47**	**78.2**	**6**	**5.75**	0.15	**1.12**	0.04
KP_4C_7	**1.29**	0.08	**78.30**	**80.9**	**7**	**6.62**	0.08	**1.14**	0.04
KP_4C_8	**1.20**	0.18	**74.81**	**81.8**	**8**	**7.63**	0.16	**1.17**	0.04
MP_4	**8.89**	0.40	**611.07**						
MP_4C_2	**4.44**	0.33	**305.24**	**50.0**	**2**	**1.78**	0.10	**1.18**	0.07
MP_4C_3	**3.55**	0.10	**243.75**	**60.1**	**3**	**2.79**	0.06	**1.13**	0.04
MP_4C_4	**2.97**	0.09	**204.28**	**66.6**	**4**	**3.71**	0.03	**1.18**	0.02
MP_4C_5	**2.26**	0.24	**155.20**	**74.6**	**5**	**4.93**	0.09	**1.11**	0.06
MP_4C_6	**1.71**	0.15	**117.25**	**80.8**	**6**	**5.80**	0.12	**1.10**	0.08
MP_4C_7	**1.64**	0.12	**112.73**	**81.6**	**7**	**6.70**	0.09	**1.16**	0.06
MP_4C_8	**1.52**	0.21	**108.33**	**82.3**	**8**	**7.91**	0.14	**1.11**	0.08
OP_5	**7.53**	0.27	**572.06**						
OP_5C_2	**3.60**	0.31	**273.28**	**52.2**	**2**	**1.85**	0.05	**1.13**	0.08
OP_5C_3	**2.63**	0.20	**200.22**	**65.0**	**3**	**2.75**	0.08	**1.10**	0.05
OP_5C_4	**1.92**	0.19	**146.03**	**74.5**	**4**	**3.72**	0.14	**1.21**	0.03
OP_5C_5	**1.73**	0.16	**131.60**	**77.0**	**5**	**4.63**	0.06	**1.13**	0.03
OP_5C_6	**1.32**	0.11	**100.28**	**82.5**	**6**	**5.70**	0.07	**1.05**	0.01
OP_5C_7	**1.21**	0.10	**91.79**	**84.0**	**7**	**6.60**	0.08	**1.24**	0.07
OP_5C_8	**1.08**	0.16	**87.97**	**84.6**	**8**	**7.86**	0.18	**1.15**	0.05
RP_5	**5.54**	0.35	**423.59**						
RP_5C_2	**3.39**	0.24	**258.71**	**38.9**	**2**	**1.78**	0.11	**1.12**	0.06
RP_5C_3	**2.60**	0.22	**198.85**	**53.1**	**3**	**2.71**	0.04	**1.18**	0.04
RP_5C_4	**2.06**	0.21	**157.46**	**62.8**	**4**	**3.71**	0.09	**1.20**	0.03
RP_5C_5	**1.53**	0.16	**116.95**	**72.4**	**5**	**4.84**	0.08	**1.14**	0.07
RP_5C_6	**1.31**	0.10	**100.43**	**76.3**	**6**	**5.92**	0.07	**1.14**	0.06
RP_5C_7	**1.30**	0.06	**99.09**	**76.6**	**7**	**6.84**	0.12	**1.13**	0.09
RP_5C_8	**1.12**	0.12	**95.90**	**77.4**	**8**	**7.57**	0.13	**1.13**	0.07

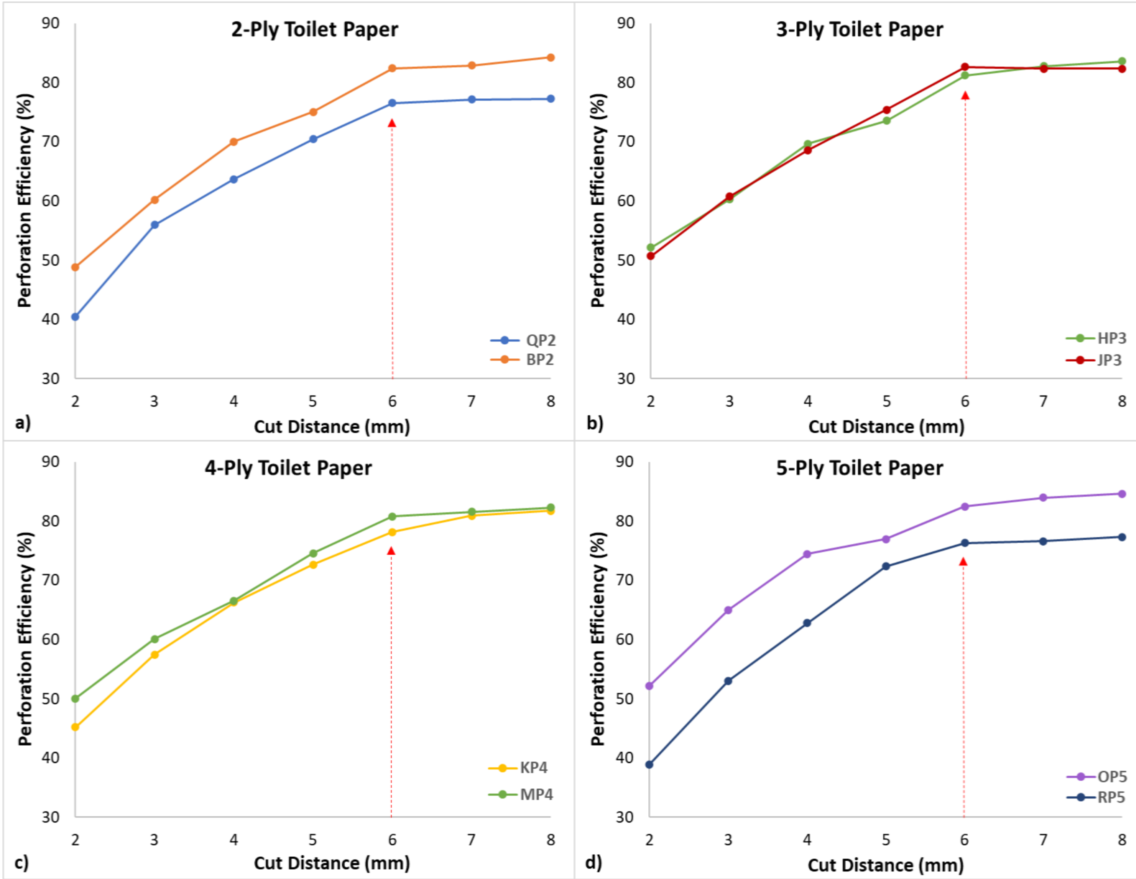

Fig. 4. Evolution of perforation efficiency with the variation of the cut distances: a) 2-ply toilet paper; b) 3-ply toilet paper; c) 4-ply toilet paper, and d) 5-ply toilet paper

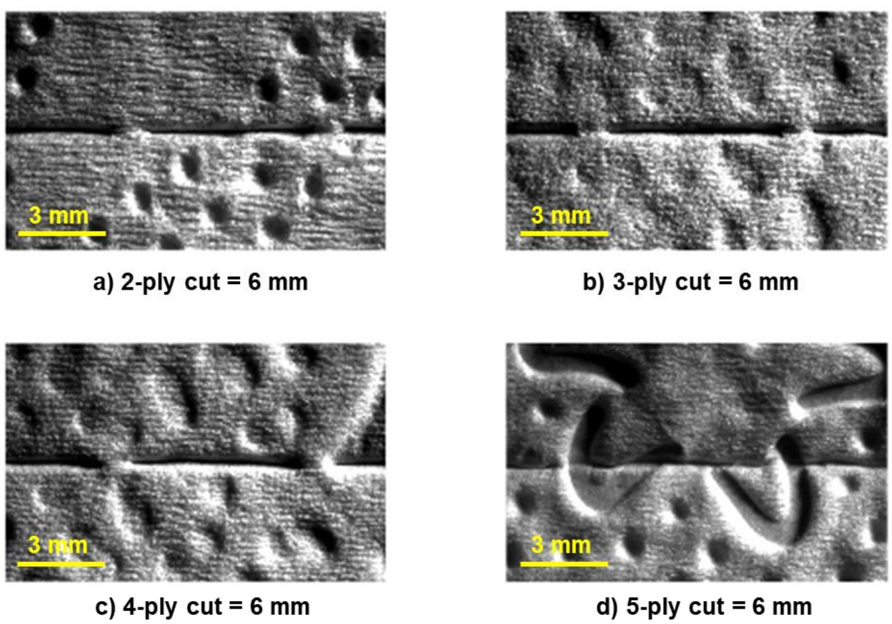

Fig. 5. Optical images of the 6 mm cut distance from: a) 2-ply toilet paper; b) 3-ply toilet paper; c) 4-ply toilet paper; and d) 5-ply toilet paper

Figure 6 presents the confirmation of the perforation efficiency stabilization to a cut distance of 6 mm by the FEM simulation. This curve shows the same behavior as the curves related to experimental data. The gap between the curves of simulation and experimental data is due to the parameters assumed for the simulation, *i.e.*, despite the Young's modulus and the sample dimensions being the same, it was considered to be one homogeneous and isotropic shell (although 2-plies in toilet paper), not considering the fibrous orientation, friction between plies, volume changes due to creping, and embossing. Another justification is the fact that the FEM simulation is performed for an exact cut distance (target dimension) and the cut distance performed in the laboratory is always smaller than the target dimension (according to the values presented in Tables 1 and 2).

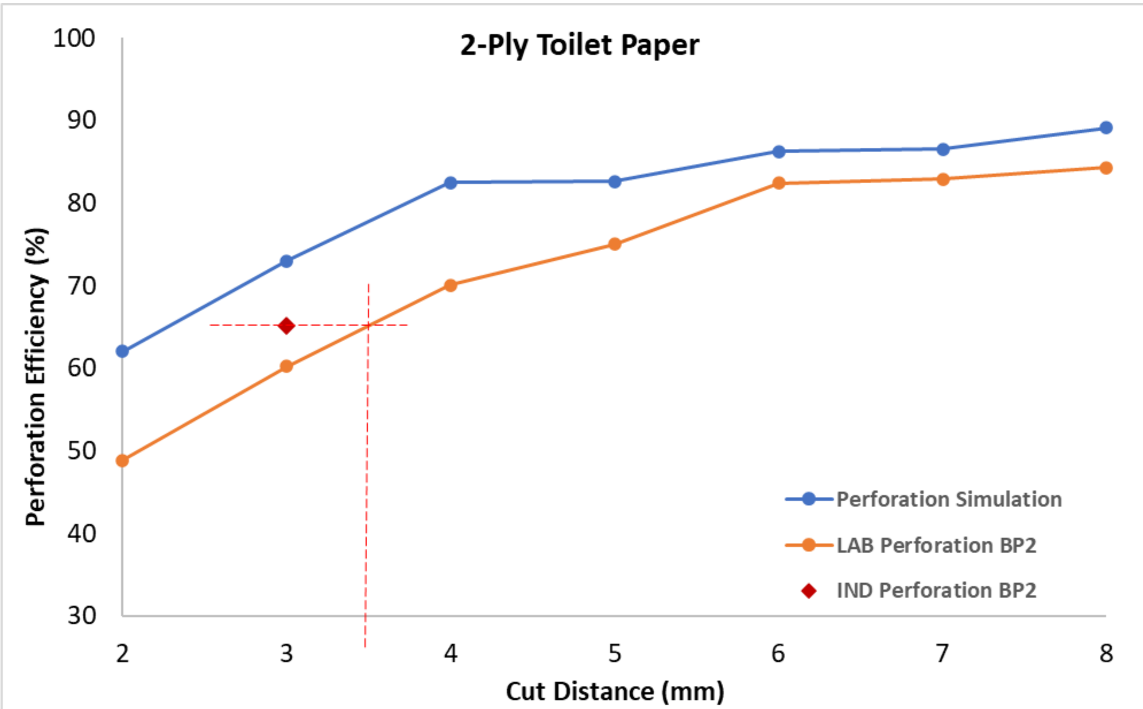

Fig. 6. Comparison of the evolution of perforation efficiency with the variation of the cut distances of the FEM simulation, laboratory (LAB) perforation, and industrial (IND) perforation results for a 2-ply toilet paper (BP_2)

Figure 6 shows the industrial perforation of the same commercial toilet paper. Comparing laboratory perforation with the same industrial perforation, the first achieves a higher perforation efficiency; this can be justified by looking at Figs. 7(b) and 7(c), respectively. Figure 7(c) shows a thinner and less marked cut, without affecting the fibrous structure adjacent to the cut. In contrast, Fig. 7(b) shows a thicker and more marked cut, weakening the structure nearby the cut. To achieve the same perforation efficiency of the industrial 3 mm cut, a 3.5 mm cutting blade would need to be used. Therefore, to equalize the efficiency of industrial perforation with laboratory perforation the cut distance of the laboratory blade must be increased 15% when compared to the industrial cut distance.

In addition to the qualitative comparison of industrial and laboratory cuts, Fig. 7 illustrates the sequence of all cut distances (2 mm to 8 mm) that were laboratory performed in this work, keeping the blank distance constant (1 mm).

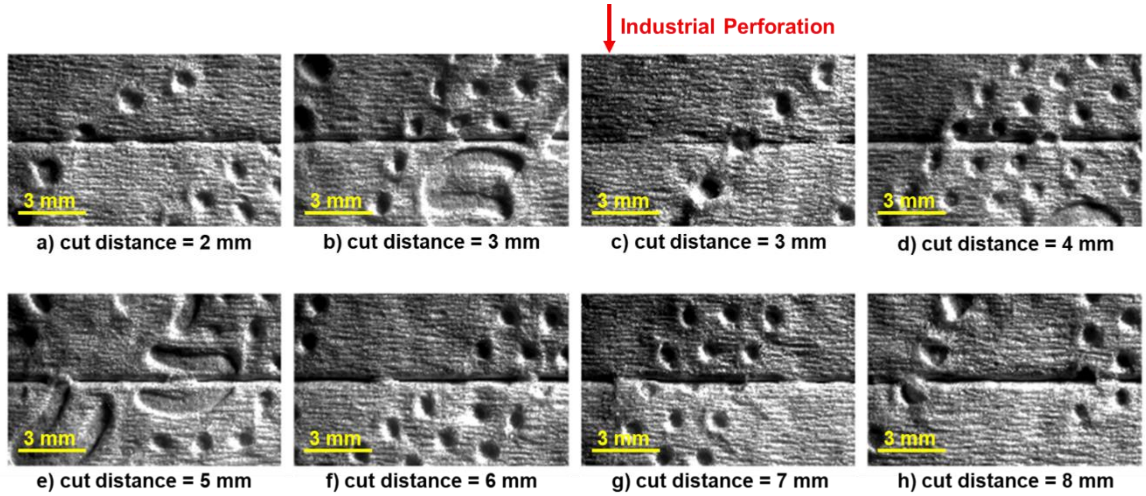

Fig. 7. Optical images of the different laboratory cut distances for the BP_2 toilet paper and the industrial perforation for the same toilet paper

Figure 8 compares the industrial and laboratory perforations in different commercial toilet papers from the measurements of the cuts by the optical system. Analyzing this figure, it is confirmed that the dimensions of the laboratory cuts are always smaller than the industrial ones. In addition, both types of cut are inferior to the target measure.

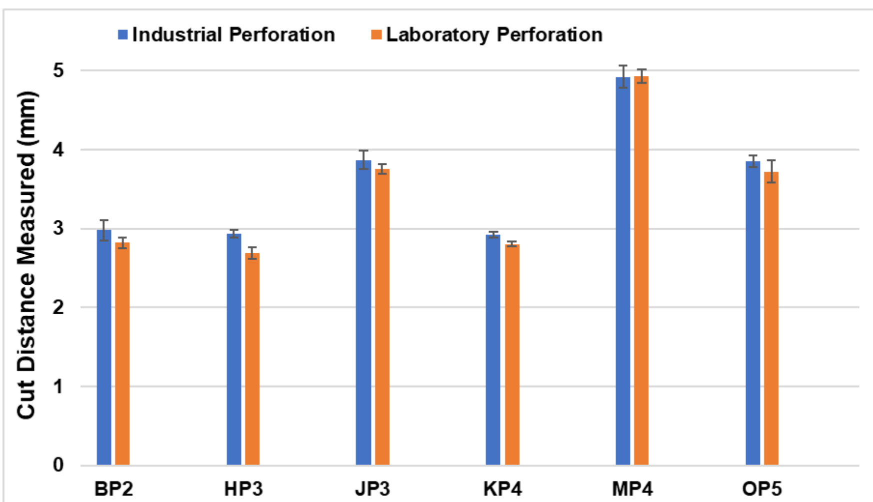

Fig. 8. Comparison of industrial *vs* laboratory cut distances for different toilet papers

In agreement with what was previously presented in Fig. 4, the stabilization for a 6 mm laboratory cut, and because this cut was inferior to the industrial one, it can be assumed that industrially this stabilization will occur for a 5 mm industrial cut. In brief, industrially, the maximum cut to obtain an optimized perforation efficiency without impairing the runnability of the converting machine is 5 mm. Of the analyzed papers, the one with the best perforation efficiency was a 4-ply paper with a cut distance of 5 mm (MP_4). The findings of this study suggest that the fibrous composition and the number of plies had a small contribution in the perforation efficiency results. The cut distance had the biggest impact in the results of the perforation efficiency.

CONCLUSIONS

1. The optimization of the perforation efficiency was obtained for a 6 mm laboratory cut distance, corresponding to an industrial cut distance of 5 mm.
2. The evidence from this study suggests that the major impact on perforation efficiency is related to the dimensions of the perforation cuts and not the fibrous composition and number of plies of the toilet paper samples.
3. In general, the results of the finite element method (FEM) simulation analysis support the idea that the value of perforation efficiency tends towards an establishment from a specific cut distance of 6 mm.
4. The described laboratory approach applied to this set of samples, has the potential to explain the perforation behavior on the converting machine, although for that a blade with a cut distance 15% higher than the industrial cut distance must be used.

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