Converting Operations Impact on Tissue Paper Product Properties – A Review

Joana C. Vieira,* Paulo T. Fiadeiro, and Ana P. Costa

Tissue paper is deep-rooted in our daily life because of its different types of products that allow various applications. Tissue paper is a low grammage paper that is mainly characterized by softness, tensile strength, liquid absorption, and elasticity. These characteristics are essential when producing products such as toilet paper, kitchen rolls, hand towels, napkins, and facials. The tissue paper production involves two stages: formation of the tissue paper sheet itself and its converting into different finished products. Converting is characterized by several operations, namely: unwinding, winding, embossing, lamination, perforation, cutting, packaging, and palletizing. The most impacting operation is the embossing, which consists of marking a pattern on the paper sheet by applying pressure, with the intent to produce papers more aesthetically pleasing to the final consumer and/or a way to identify a particular brand. Also, it affects final properties, increasing the liquid absorption capacity and bulk but reducing softness and tensile strength. Converting is complex and has a huge impact on the finished products properties. In this review, the authors explored the different steps of converting and how they impact the different properties of finished tissue products.

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INTRODUCTION

The tissue paper market has been expanding worldwide. This is explained by the consumption growth of hygiene products because of the increase in quality-of-life expectations. The main tissue paper products that can be found on the market include paper towels, napkins, facial tissues, and toilet paper, and they play an important role in modern life. These tissue paper products contribute to improving hygiene, comfort, and convenience in our society, helping to reduce the spread of diseases. Figure 1 presents the graph of evolution and forecast demand of consumption for domestic and sanitary tissue paper products, based on the data published by Lamberg *et al.* (2012), in the ten global regions considered, namely in the Northern and Western Europe, Southern Europe, Eastern Europe, the North America, South America, Africa, Western Asia, Southern Asia, South-Eastern Asia, and Eastern Asia.

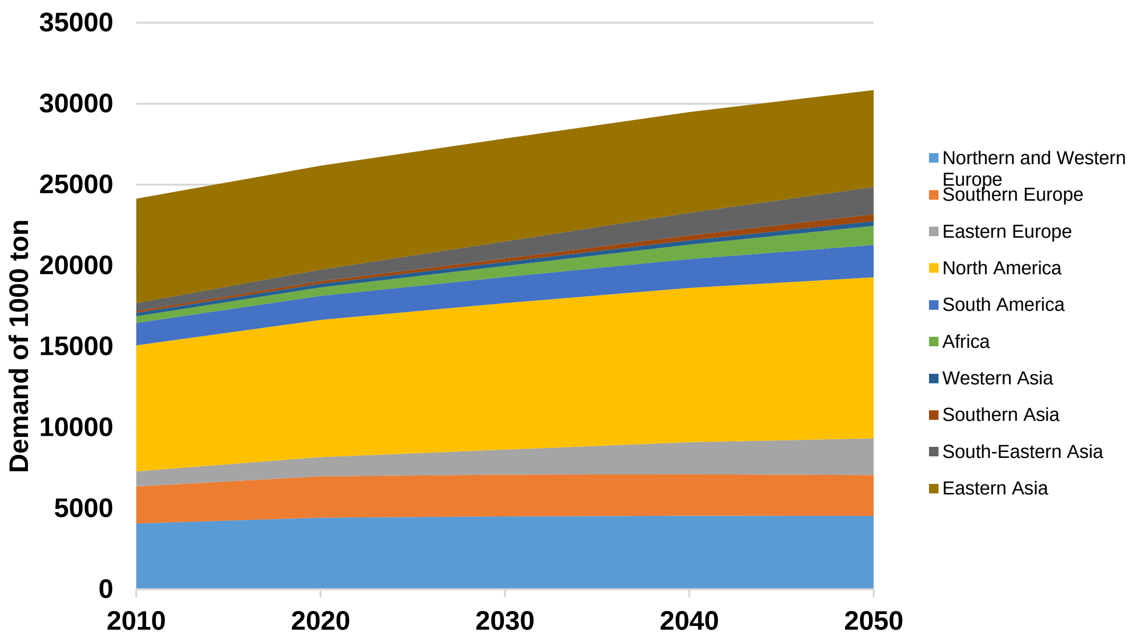


Fig. 1. Consumption evolution and forecast demand of 1000 ton for domestic and sanitary tissue paper products in world regions between 2010 and 2050

From the analysis of Fig. 1, it is relevant to point out that the consumption of tissue paper products in developed countries is more or less stable, while for developing countries, there is room for greater growth in these types of products. Figure 2 shows the growth rates as a pie chart of the main types of domestic and sanitary tissue paper products, based on the data published by Lamberg *et al.* (2012), in the global regions considered.

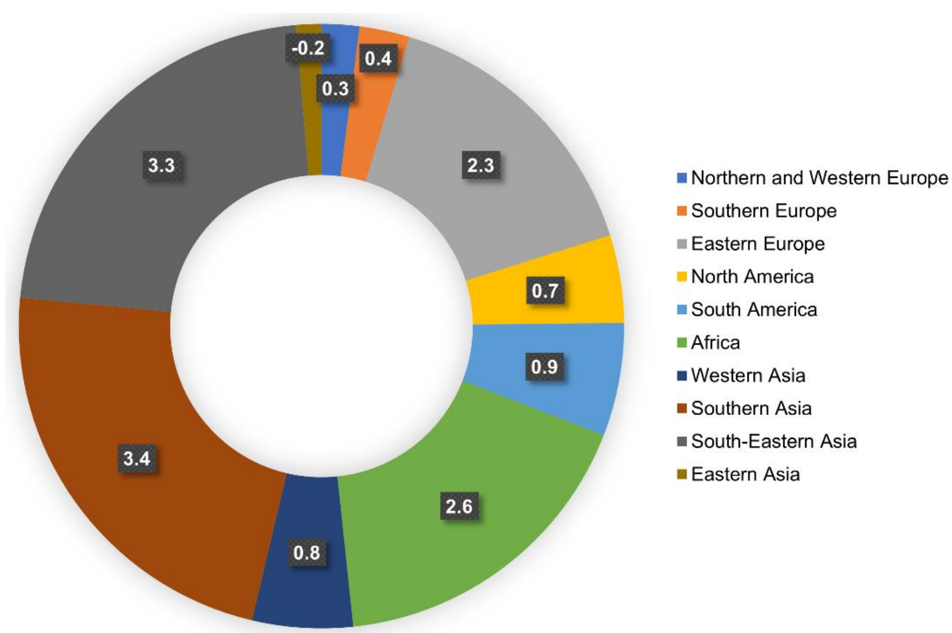


Fig. 2. Growth rates (%/year) of major types of household and sanitary tissue paper products in world regions

Figure 2 confirms the growth trend in consumption of these types of products, apart from Eastern Asia, where there is an inverse trend. The growth in demand for these products has led to an increase in the number of producers to satisfy the market and make it more competitive. For the companies to achieve a competitive advantage, they are always looking for continuous improvement, optimization of production processes, and reduction of operating costs, to increase product quality levels and satisfy customer requirements. An important factor in the tissue paper market segment is the satisfaction of customers, who look for softness as a main property in certain products or absorbency in others, depending on their final purpose (Vieira *et al.* 2020a; Galli 2022). Thus, the properties of tissue paper must be in accordance with consumer requirements (Fig. 3). Tissue paper can then be defined as a cellulosic-based product composed of virgin and/or recycled fibers, produced with a low grammage, high flexibility, high bulk, creped, and depending on its application (toilet paper, paper towels, or napkins), embossed (Vieira *et al.* 2020a; Galli 2022). Commercially, tissue paper products can be classified according to the purpose of use both at-home (referred to as "consumer" or At Home – AtH products) and away-from-home (referred to as HORECA products - HOtel REstaurants and Coffee, or Away From Home – AFH) (Galli 2022).

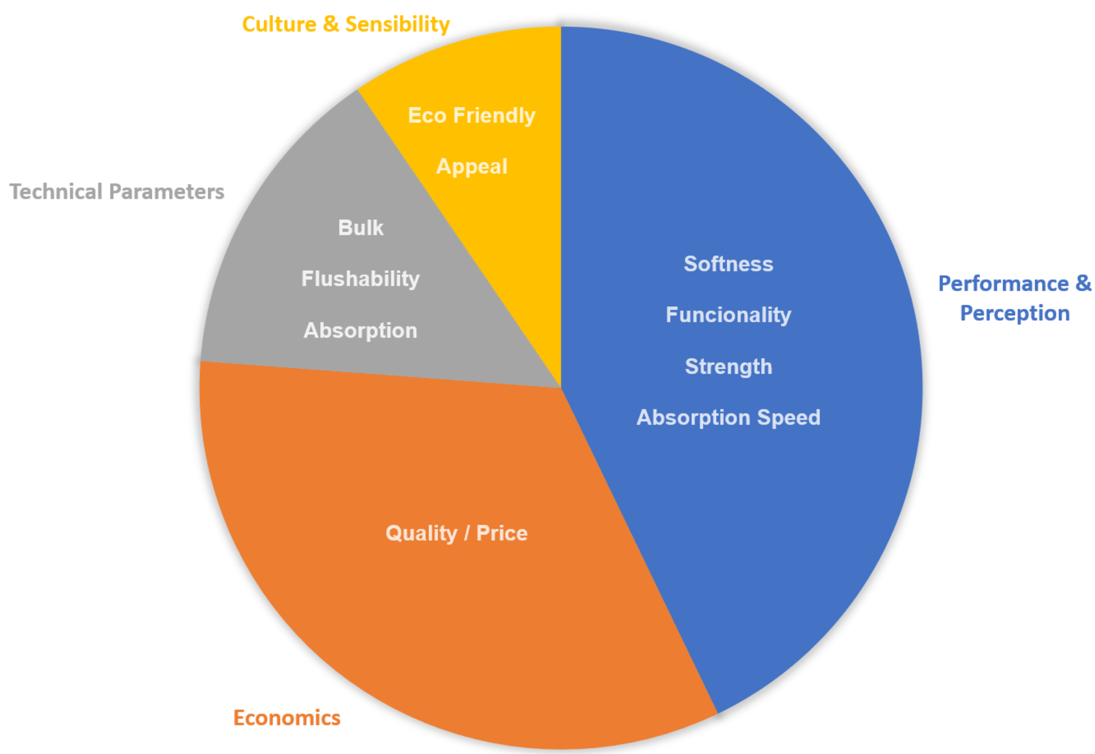


Fig. 3. Factors that affect tissue paper product consumer requirements (based on the data furnished by Galli 2022)

It is through tissue paper conversion technology that, based on the requirements determined by the consumer, it is possible to produce finished paper products with the desired special properties and of high quality (Kimari 2000; Spina and Cavalcante 2018). The tissue paper converting process is characterized by several operations. The main ones include: unwinding, winding, printing, laminating, perforating, cutting, packaging, and palletizing (Kimari 2000; Cigolini and Rossi 2004). Products can be divided into two groups: rewound products, such as kitchen rolls and toilet paper, as they are unrolled and rolled up in the conversion process, and folded products such as napkins and handkerchiefs. The sequence of the converting operations for the rewound products can be seen in Fig. 4 and for the folded products in Fig. 5.

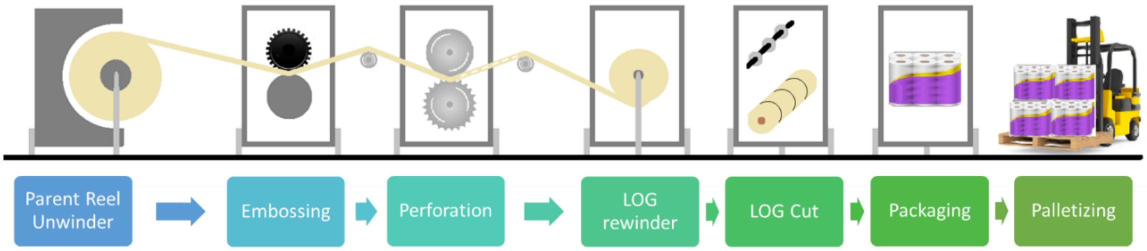


Fig. 4. Processes involved in converting the paper reel to the finished rewound products

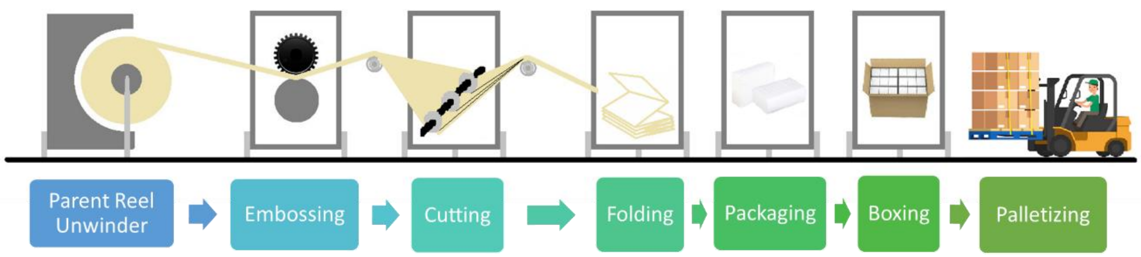


Fig. 5. Processes involved in converting the paper reel to the finished folded products

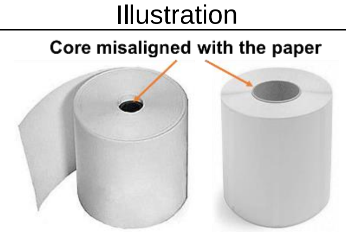
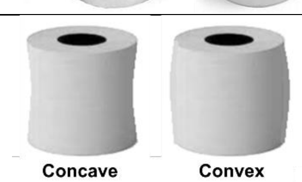
Paper converting technology needs to deal with all these processes to give paper products special properties. One of the most important aspects to face during paper converting is the control of the production process, because of its nature as a continuous process. In fact, modern paper machines cannot operate efficiently without strict quality control of products and processes. One way to perform quality control is by analyzing process problems and automatically recommending effective corrections. This can be done by monitoring the paper converting operations, including the lamination of paper sheets, using a control program that gives the corresponding correction procedures. The paper properties are monitored by a set of actuator arrays, which act perpendicularly to the direction of movement of the paper sheet passing through the machine. Controller feedback is tailored to provide performance, ensuring robust uncertainty modeling. Basically, it is important to use both offline and online analyzes to define the characteristic product and process properties to guarantee the high quality of the final product (Spina and Cavalcante 2018). To better understand the converting process and how it impacts on the properties of the final product, a detailed analysis of each of the involved operations separately is presented in the following sections.

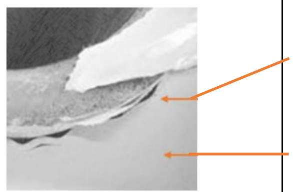
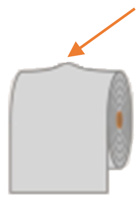
Unwinding

In the tissue paper industry, winders and rewinders are key components in the first stage of the complex converting process. Winding, unwinding, and then rewinding on a spool are, in fact, operations that require a precise execution to obtain a final product that, once wound, maintains the characteristics and quality resulting from the production process. This is due to the delicate nature of the material itself and the need to preserve the creping and density obtained in the production process to maintain the softness and bulk that distinguish it (Pejic 2016; D'Olivo 2021). The unwinders are responsible for unwinding the parent reel that leaves the tissue paper machine to obtain finished reels with smaller dimensions, the mother reels, if necessary. The reels used in tissue paper converting are generally heavy. It is possible to use coils with a length of 2 to 5 m and a diameter of up to about 3 m, with weights that can reach 5 tons (Paolinelli *et al.* 2022). The tissue paper converting machine may need up to four unwinders, as the final product is made up of several sheets. If the number of sheets of the finished product exceeds the number of unwinders of the converting machine, a mother reel with multiple sheets will be created using external rewinders. For example, in a converting machine with two unwinders, to produce a finished product of 3 sheets, you will have to feed the machine with a mother reel of 2 sheets and another with 1 sheet (Paolinelli *et al.* 2022). For tissue paper reels, the unwinding itself takes place *via* motorized belts, called peripheral unwinding. Each material has certain properties and characteristics that will affect the correct winding and/or unwinding process. An incorrect or inaccurate rewinding/unwinding process can cause permanent damage to the tissue paper sheet, where excessive elongation of the wound material implies substantial loss of desired characteristics such as crepe and bulk (D'Olivo 2021; A.Celli Group 2022).

Sheet tension control during the unwind/rewind operation is complex and subject to many variables. However, it is important to obtain proper control of the spool tension to avoid defects and compromise the properties of the sheet of paper. In addition, high-quality, automated tension control of the sheet is dependent on the traction provided by the machine's idler rollers. It is important to identify the reasons behind the production problems in this section of the converting machine. As far as is known, winding defects occur less than 5% of the time. Table 1 presents the most common problems and the corresponding solutions that may occur (Williams 2019).

Table 1. Problems and Respective Solutions that May Occur in the Unwinding/Rewinding Operation (Williams 2019)

Troubleshooting	Illustration	Problem	Solution
Offset Core		Abrupt shift in location along the edge of the roll.	The web should be wound uniformly, but faster at the start of the roll.
Concave or Convex Rolls		Caused by progressive roll edge misalignment. Only noticed after the roll has started to be unwound.	Controlling the hardness of the wind, reducing web tension, or reducing cross-deckle caliper variation.
Crushed Core		The core has been mishandled or was incorrectly inserted into the shaft.	Paper core restorer (only restore the ends of the roll).

Poor Start		Appearance between the web near the core *vs* Appearance of the remaining roll.	The web needs to be tightened before attaching to the core. Must use good quality cores and properly stored or start with proper tension, nip and/or torque.
Edge Curl		Revealing curled or shaggy paper edge.	Slitters should be adjusted to a proper depth or reducing sheet tension.
Baggy or Slack Ends		Web width is not uniform, loose, and tight zones will occur across the entire width of the sheet. This lamination defect can cause difficulties in subsequent operations.	They are a result of non-uniform web thickness and cross-deck gauge variation needs to be kept to a minimum. Wind as smoothly as possible and adjust the clamp accordingly.
Machine Tension Burst	Not available	Defects are related to fiber separation. In the case of cross-machine the defect is not visible at the edge of the roll, whereas it is in full machine-direction.	The roll needs to be wound softer. Partial breakdown of tension in the machine direction can be caused by non-uniform variation of the transverse clamp, needs to be minimized.
Dished Rolls		Rolls that are wound with a forward edge misalignment.	Cores hardness does not increase during winding, and have a good, hard start at the core.
Trim Wound in Rolls	Not available	When winder trim is not collected properly into the trim removal system, it will follow the web into the winding roll.	The air velocity at the system inlet must be greater than the winding velocity, or make sure that the displacements are not greater than the width of cut.
Starred rolls	Not available	Rolls have a star pattern at the ends of the rolls; it is due to the shifting of the layers of web, usually beginning at or near the core and continuing outward toward the outer wraps.	Start wind tight then steadily soften roll hardness as diameter increases. Additionally, make sure the cross-caliper variation is at a minimum.

For an automatic unwinder in which the spool is unwound through a combination of a peripheral and a central unwinder, the finished spool is lifted by motorized counterpoints of the central unwinder and placed on top of the unwinding station, to be later removed. Thus, through a shuttle, it is possible to insert a new spool into the unwind station. The central unwinder is double and has two pairs of tailstocks, thus allowing the first pair of tailstocks to be in the upper position when a spool is running low, while the second pair of tailstocks is available to engage the new spool inserted by the shuttle. In combination with the peripheral unwinder, it then allows the start of the unwinding of the sheet (Paolinelli *et al.* 2022). The tissue paper sheet is then routed to the embossing section for both rewound and folding products, and lamination in the case of rewound products.

Embossing / Lamination

According to the standard ISO 12625-1 (2019), embossing is a converting operation by which a raised or depressed pattern is produced on a tissue paper sheet, generally by pressure between engraved rolls or between an engraved roll and an elastic or a deformable supporting surface. On the other hand, and considering the same standard, lamination is also a converting operation to join/bonding together two or more plies of a tissue paper sheet to form a multi-ply tissue product, which can be associated or not to the embossing process.

Embossing of tissue paper products is a sensitive process because of the presence of different factors such as flexibility, weight, softness, and attractive design of the paper (DeMaio and Patterson 2008; Pejic 2016). Therefore, several aspects of processing need to be addressed with control methodologies. Product quality also depends on various physical parameters such as temperature, humidity, and pressure.

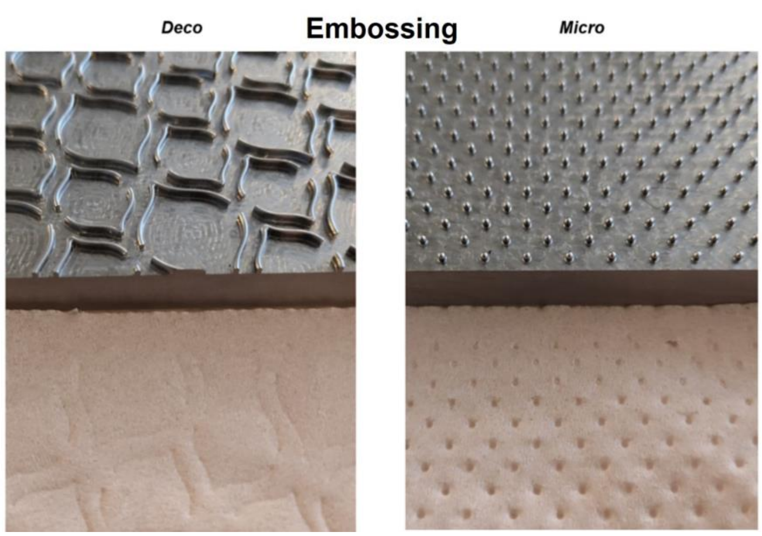


Fig. 6. Images of the deco and micro engraving patterns and the corresponding embossed tissue paper sheets (Vieira *et al.* 2022a)

The influence of geometrical and material parameters on the mechanical response of fibers used in papermaking is also critical (Kimari 2000; DeMaio and Patterson 2008). Embossing is an example of compressive formation on paper in the converting process. These can be stamped to increase the properties of the finished product, such as liquid absorption capacity, and softness. This process can produce papers with aesthetically pleasing designs, occasionally for the purpose of product identification distinguishing them from other competitors. Embossing is performed layer by layer, for instance, the deco and micro engravings can be produced on the top of a single layer or in several layers for a multi-layer paper. In general, the deco pattern appears on the top embossing roll and the micro pattern appears on the bottom embossing roll. The resulting product with more than one layer has properties that cannot be obtained in a paper with a single layer (Digby 2012). Figure 6 shows examples of the deco and micro engraving patterns and the corresponding embossed tissue paper sheets.

Embossing patterns for tissue papers serve to improve several properties such as porosity, hygroscopicity, thickness/bulk, flexibility, and absorbency. Embossing creates a graphic element allowing drawings to be raised or depressed on paper. A metallic cylinder (embossing roll) with a relief image engraved on its surface is pressed against the sheet(s) of paper (Fig. 7).

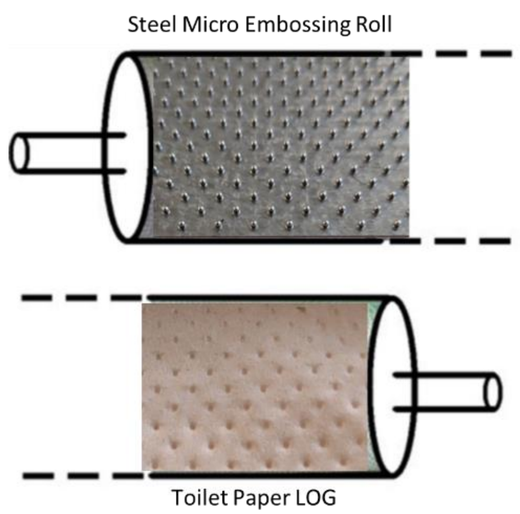


Fig. 7. Example of a steel embossing roll and its toilet paper LOG

Currently, several types of embossers are used, and the pressure, rubber hardness, temperature, and humidity of the paper can be varied to obtain different products (DeMaio and Patterson 2008; Biagiotti 2017).

During tissue paper production, the greatest bulk loss usually occurs in the pressing stage. Therefore, in the transformation process, the most common method that is used to increase bulk is dry embossing, but depending on the pressure used in this step, the bulk created can be short-lived, and it can also be lost when tissue paper is wetted again (Janda 2017). Each tissue paper fibrous composition has a predetermined limit to the embossing pressure, beyond which the strength properties of the sheet are destroyed, consequently impairing the runnability of the converting machine, and/or the quality requirements of the finished product. Thus, the tissue paper sheet loses engraving marks if embossing takes place in its elastic zone. In contrast, if the embossing is produced close to the breaking point of the sheet (excessive pressure applied), then the paper becomes fragile, which can cause failures in the converting process (Assis *et al.* 2018; Giannini 2019). As embossing is a mechanical compression process in the tissue paper converting, the pressure used is an operating condition that is essential to control to produce quality toilet paper (Spina and Cavalcante 2018). From the work developed by Vieira *et al.* (2022a), it was shown that the mechanical properties suffer a negative impact with the embossing operation in comparison with the corresponding industrial creped tissue paper sheet without embossing. In addition, the micro-embossing pattern was shown to have a greater impact on thickness, increase in volume, and loss of mechanical properties. From the same study developed by Vieira *et al.* (2022a), the authors concluded that there is an optimal pressure for the embossing process, in which the mechanical strength properties are maximized (through the densification of the tissue paper sheet) without impacting too much on the softness and absorption of liquids. This optimum pressure is the limit beyond which the structural degradation of the tissue paper sheet takes place. This study is in line with the previously mentioned in which the micro pattern is the one that most affects the structure of the sheet of paper. Contrastingly, from the samples under study, it was possible to perceive that the greater or lesser loss of mechanical properties or softness depends on their fibrous composition, since the industrial tissue paper samples used show different morphologies. In particular, one of them depicted a presence of recycled fibers/process broke.

With the evolution of the embossing and lamination process, different solutions have emerged until now, and the most common is the use of an engraved steel roller working against a roller with a rubber cover that can vary from 45 to 98 Sh-A (Shore-A means the hardness unit for elastomers). Recent advances have included an increase of the hardness of the rubber covering. On the other hand, new studies encourage the change of the conventional rubber covering by introducing a double layer covering: an inner layer with low hardness and an outer layer with high hardness (in contact with the tissue paper sheet). The aim of this procedure is to make the outer layer (surface of the rubber roll) more flexible (Biagiotti 2017). Each type of rubber has its own characteristics and depending on these they can be chosen as they are better for temperature resistance, and/or chemical resistance, and/or abrasion resistance, and/or long service life. The rubber of the roll undergoes different stresses with the embossing process. If the rubber hardness value were determined during the embossing process, it would be altered due to the stresses caused both in terms of pressure and temperature. Thus, the performance of the rubber roll will influence the engraving of the embossing pattern and, consequently, the properties of the tissue paper and directly the final product (Huff and Bell 2005). As demonstrated in the study developed by Vieira *et al.* (2022c), where the evaluation of the impact by changing rubber hardness on the embossing operation was performed, it was found that the highest softness value was achieved for the double layer solution, with an inner layer of 48 Sh-A (upper layer) and an outer layer in contact with the tissue paper sheet of 60 Sh-A (bottom layer). The results of the work also highlight an increase in softness with increasing rubber hardness for the replication of conventional coverage. The loss of mechanical strength and greater bulk, on the other hand, became more accentuated for the micro pattern and for lower rubber hardness.

The dimensions and the finishing geometry of the embossing elements (lines or points) are a limitation of this process. For example, patterns with thin embossing elements cannot be engraved too deeply, as they are prone to tearing the tissue paper sheet. In contrast, to obtain a high-quality embossing pattern engraving, the tissue paper's ability to stretch and adapt to the relief is equally important, which is also a physical limitation. Currently, there are no standardized finishing geometries and/or designs that objectively define the impact they will have on the final properties of the tissue papers/products (Pál *et al.* 2020). Khan (2021) showed that the mechanical properties of the embossed product were affected both by the density of dots (number of dots/cm^2) of the embossing pattern, as well as by the height of the dots and the angle that the dot makes with the base. Khan

(2021) concluded that there is a greater loss of mechanical properties for a higher density of dots, and a greater height of the dots, which consequently lead to a greater deformation of the tissue paper sheet. In contrast, a dot with a higher base angle (cylindrical dot geometry – 90° angle with the base) leads to a lower loss of mechanical properties because of less deformation of the tissue paper sheet. In addition to the work developed by Khan (2021), another study was carried out in this area by Vieira *et al.* (2022d). In this study, the authors showed that the finishing geometry of the line and dots (straight or round) of the embossing pattern has an impact on the mechanical properties and softness of the products. The finishing of the straight embossing elements showed a higher softness value when evaluated individually. When mounting the 2-ply prototype of the deco and micro patterns, with the same finishing, the greatest softness was obtained for the prototype with the round finishing geometry. Because the micro pattern is the one that impacts the most the structure of the paper, resulting in greater bulk, it is with this pattern that the lowest values of softness and mechanical strength are obtained. In contrast, within both relief patterns (deco and micro), the straight finishing geometry is the one with the greatest loss of mechanical strength. With this work, in terms of finishing geometry of the embossing elements of the two patterns, the round finishing also stands out, as it doubles the bulk value when compared to tissue paper before embossing.

A tissue paper sheet laminating process presupposes that at least in an engraving NIP of one of the patterns, at least two tissue paper sheets are combined and engraved. Thus, another factor that can influence the properties of tissue products in this section of converting is the stacking sequence of sheets in a finished multilayer product with an odd number of sheets. In the study developed by Vieira *et al.* (2020a), two different stacking sequences of a 5-ply toilet paper were analyzed (Fig. 8), as well as their impact on their final properties of the final consumer.

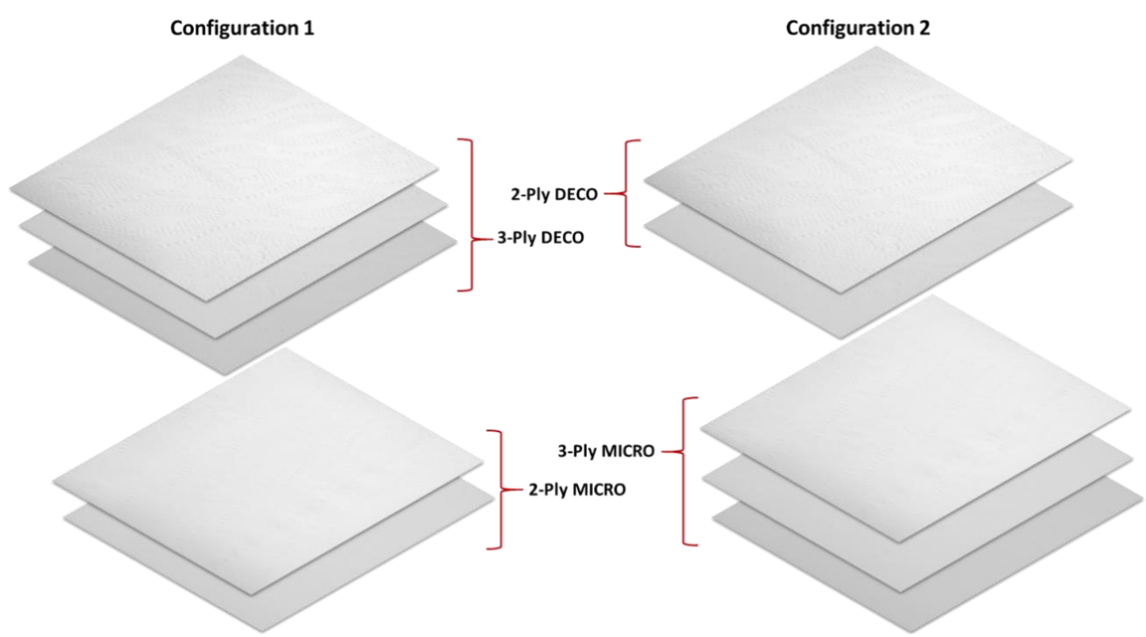


Fig. 8. The 5-ply toilet paper with the two stacking sequence configurations (Vieira *et al.* 2020a)

Configuration 1 is composed of 3 sheets with deco embossing and 2 sheets with micro embossing, and configuration 2 is composed in reverse. It was found, when comparing with same 5-ply tissue paper without any embossing, that in configuration 1 the bulk and water absorption capacity increased 46% and 2%, respectively. While for configuration 2, bulk and water absorption capacity increased 40% and 17%, respectively. The mechanical properties decreased considerably due to the embossing process. However, configuration 1 was shown to have the lowest losses. Regarding softness, the stacking sequence also affected the results, where configuration 2 proved to be the softest and most pleasant to the touch product, with an overall handfeel value of 75.3 HF, and the product produced with configuration 1 presented rougher and less pleasant to the touch, with an overall handfeel value of 68.0 HF (Mendes *et al.* 2020). Thus, it can be concluded that the number of sheets that enter each embosser in the stacking sequence influences the final properties of the paper and thus can be adapted to meet the requirements.

Liquid absorption is an important property for many tissue products, whose main purpose being to clean/absorb liquids. Liquid absorption is generally divided into absorption capacity, absorption time, and absorption rate. The absorption capacity reflects the maximum amount of water that the paper can absorb, and it is expressed in g_{water} / g_{fiber}, absorption time is the time, expressed in secs, to absorb the maximum capacity, while the absorption rate, expressed in g_{water} / $g_{fiber} \times$ sec, measures how quickly the product absorbs this amount of water (Kullander 2012). In European and International trade, both water absorption time and water absorption capacity represent important parameters in the field of tissue paper product comparison (Tutuş *et al.* 2016). In the work developed by Vieira *et al.* (2020b), it was shown that the embossing operation significantly increases the thickness and bulk of tissue paper while it has no impact on the water absorption time. Regarding the water absorption capacity, the embossing operation proved to have a great impact. The greater increase in bulk achieved with the embossing operation resulted in greater water absorption capacity. Currently, the embossing operation is a common step in the tissue paper converting because it creates empty spaces between the sheets of paper, such that the absorption capacity of the paper increases. Thus, the absorption performance of an embossed multilayer paper is far superior to that of an embossed single-layer paper (Zhipeng *et al.* 2022).

The Finite Element Method (FEM) is a numerical technique used to perform finite element analysis of any given physical phenomenon. For example, the authors Khan (2021) and Vieira *et al.* (2022a,b,c,d) used this tool to simulate structural behavior of their materials, and to validate and therefore corroborate the experimental obtained results. This tool proved to be useful, as it can allow simulating other studies with different parameters variations, providing approximate results to the real ones.

Within this section, tissue paper decoration also takes place. This decoration can be done by colored glue or by printing. Any of these techniques are coupled to the converting machine as an additional process to embossing/laminating and the result is shown in Fig. 9 (Star Label 2018; Galli 2022).

The most used printing process is flexography, which allows printing at high speed, being suitable for these types of products. In addition, it allows cost-effective, high-quality printing of mass-produced products (Star Label 2018). Ink is transferred to tissue paper from the Anilox roll and through cells etched onto the printing plate (Johnson 2008).

a) Flexographic Printing b) Color Glue lamination

Fig. 9. Decorated tissue products: a) tissue napkin printing with aqueous flexographic ink, and b) tissue kitchen towel lamination with blue color glue

To print a porous paper, such as tissue paper, it will be necessary to employ more ink, as it penetrates the structure of the paper instead of staying on the surface inducing a more rigid structure. Consequently, it will negatively affect absorption, softness, and mechanical properties (Theohari *et al.* 2014). The lamination with the glue decoration technique implies the replacement of the traditional transparent glue by a colored one that will bind the sheets making up the final product by joining dots/lines (Galli 2022). This methodology has a lower impact on the properties of tissue papers than the printing technique. The greater or lesser impact of these decoration techniques on the tissue paper properties are related to the greater or lesser decorated area, for example, a larger decorated area implies a greater impact on the final properties.

Perforation

Perforation in tissue paper products is used for the purpose of facilitating the portioning of paper sheets. The main products in which this process is used are toilet paper, kitchen towels, and facial tissues (Ogg and Habel 1992; Schulz and Gracyalny 1998; Baggot *et al.* 2006; Pejic 2016).

In the converting machine, perforation takes place at high speed. A roll with several diagonally arranged blades is pressed against the tissue paper sheet, cutting it at the points of contact (Perini *et al.* 2021). Then, the called perforation line is created, in which there are bonding areas, uncut areas that prevent the sheet from separating prematurely, and holes with a predetermined cut distance. The distance between two perforation lines determines the length of the "sheet" to be detached by the end consumer (Ogg and Habel 1992; Baggot *et al.* 2006; Chih 2018). Figure 10 schematically presents these concepts.

The strength required in the perforation zone to ensure that the paper separates is called the perforation tensile strength. This must be optimized to fulfill both the easy detachment of the sheet by the consumer, and to withstand the high speed and tensions to which the converting machine is subjected (Schulz and Gracyalny 1998; Mukai and Shimizu 2003). Thus, it is extremely important for producers to control the puncture resistance through the evaluation of the puncture efficiency, which according to the ISO 12625-1 (2019) standard is defined as "…the difference between the tensile strengths of an unperforated and perforated material from the same sample divided by the tensile strength of an unperforated material…".

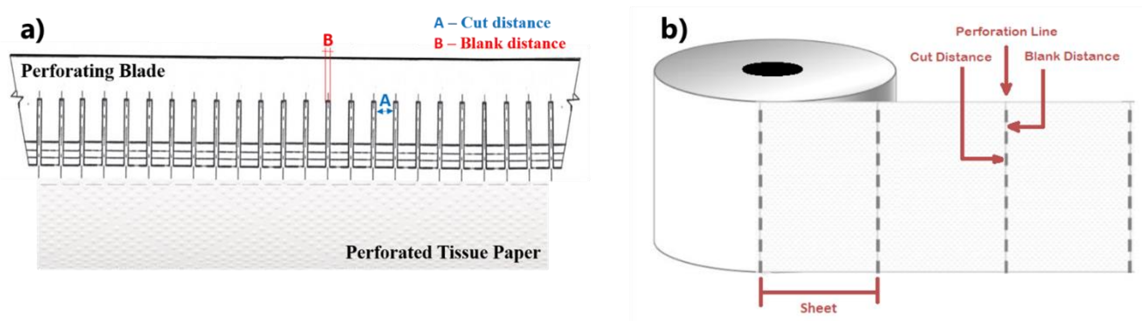


Fig. 10. a) Perforation scheme with identification of the cut and the connection areas (Vieira *et al.* 2021); b) Schematic of a roll with identification of the perforation lines (Vieira *et al.* 2022e)

From the work carried out by Vieira *et al.* (2021, 2022e) related to tissue paper perforation, the optimization of perforation efficiency was reached for an industrial cutting distance of 5 mm. It was also evidenced in these studies that the dimensions of the perforation cuts have greater impact on the perforation efficiency than the fibrous composition and/or number of sheets that make up the tissue paper product. Furthermore, it has been determined that above a stress concentration factor in the perforation cuts of 0.11, the sheet separates outside the perforation line. Both results were corroborated by the simulation analysis of the finite element method (FEM).

LOG Rewinding

The production of tissue paper LOG's is performed using a rewinder that is calibrated to wind a predetermined amount of paper (Kimari 2000; Pejic 2016). This process is mainly used in the production of toilet paper rolls or kitchen rolls. It starts with feeding cardboard tubes, also known as "colors", to this section of the converting machine. Then, a predetermined amount of glue is applied to its surface to which the perforated sheet of paper will adhere. The paper sheet is then rolled up until the defined amount of paper is reached. This operation is completed by gluing the last sheet of paper, commonly called "flap closure" or "tail sealing" (Brown 1991; Perini *et al.* 2021; Galli 2022). Then, the complete LOG is unloaded from the rewinder to the LOG slitting section, and a new LOG starts the production process. Whenever a new cycle of tissue products begins, when this stage is reached, the first LOG's must be discarded, as the sheet arrives at the rewinder without being properly tensioned (Brown 1991; Perini *et al.* 2021). As with the rewinding of the mother reels, the LOG's also show winding problems that will manifest as defects. The most common defects are offset core, poor start, crushed core, and a flap without glue or other sealant (Brown 1991; Pejic 2016).

Rewound coreless products

Most rolled products comprise a tubular core made of a more rigid paperboard material, which allows it to be placed in a holder which is inserted through the hollow for ease of consumption. After the product is consumed, the tubular core is discarded and can be sent for recycling; otherwise it is traduced into waste with an expected environmental impact (Maddaleni and Gelli 2011; Wojcik *et al.* 2013). When the coreless products appeared, the application of an adhesive was required. This was intended to stiffen the sheets near the center of the roll, to prevent deformation during use. This processing rendered the entire end of the roll unusable. Thus, it was also implied wasting a part of the product, which is not easy to recycle. Another disadvantage was the difficulty to place the roll in conventional supports, since the opening was small, non-existent, or non-circular. Nowadays, with the development of converting technology, coreless rolls are produced by spirally winding the tissue paper sheet, a process that defines a hollow passage through the center of the roll. This process makes unnecessary the usage of a tubular core and/or an adhesive that allows the inner layers to adhere to each other, and the entire product can be consumed reducing waste. However, in this type of processing the hydrogen bonds must be promoted by the introduction of moisture into the system. On the other hand, the key properties of these products remain unaltered, as they are not altered by contact with the adhesives and the roll core (Wojcik *et al.* 2013). Figure 11 shows two different ways of dispensing the product services from coreless rolls.

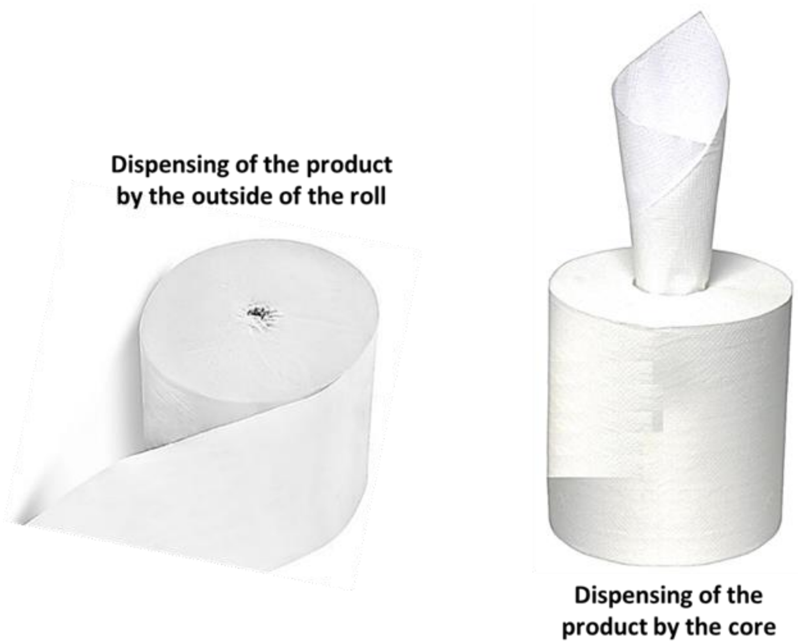


Fig. 11. Two ways of dispensing the product from coreless rolls

Fig. 12. Coreless toilet roll and the detachable toilet paper core

Another way to produce coreless roll consists of the creation of a first portion of tissue paper to form the inner core of the roll, and then a separator material (tissue paper obtained through a local variation in density or calendering) is applied at least in one turn around the outer of the pseudo-core. The remaining tissue paper is rolled around-up from the outside of this separation layer. This layer enables an easy extraction of the core from the roll, as can be seen in Fig. 12. These types of coreless rolls allow the end-user to use them in different supports. Tissue paper pseudo-core can also be used and transported in smaller spaces such as wallets or backpacks, that can also be used in their entirety with no waste (Maddaleni and Gelli 2011).

LOG Cut / Cutting

Now the complete LOG is transferred to the cutting section where the finished product rolls will be obtained with the required dimensions. The saws used for cutting the LOG’s are made of thin steel with a toothless blade (disc blades), and they can have a continuous or intermittent movement. Continuous motion saws can reach higher speed and are usually composed of several blades arranged side-by-side separated by the distance defined for the dimension of the finished product. In contrast, the intermittent motion saw applies the cut along the LOG that moves at intervals defined by the distance required for the dimension of the finished product (10 to 60 cm depending on the type of product) (Brown 1991; Kimari 2000; Pejic 2016; Guarini *et al.* 2022). Both types of saws are always placed perpendicular to the LOG (Brown 1991; Guarini *et al.* 2022).

This section of the converting machine includes at least one sharpening unit placed on the opposite side of the cut, which is composed by an abrasive material to be in contact with the cutting blade. The sharpening units come into operation as soon as the sensors detect the wear of the saw. Periodically the blades must be replaced as the wear and sharpening of the blade progressively decreases both the diameter of the blade and its cutting capacity (Guarini *et al.* 2022).

The most common problems that can be found due to LOG cutting blades are crushed core caused by increased axial eccentricity and blade distortion due to cutting speed limitation, ragged edges caused by an unadjusted blade life, and consequently stoppages for successive blade changes, bias cut caused by poor blade orientation in relation to the LOG (Ahuja *et al.* 2009), and dirty rolls of dust caused by the maintenance of LOG’s saws (Pejic 2016).

When cutting tissue paper for folding, the saws are presented as those of continuous movement for the LOG’s, in which they are arranged side-by-side and separated by the distance defined for the dimension of the finished product, as schematically represented in Fig. 4.

Folding

Folding is a typical converting operation for hand towels, facial tissues, napkins, and folded toilet paper. There are two types of converting machines that produce folded tissue paper products: those that fold the paper sheets with vacuum, and those that fold the paper sheets through a folding head composed by a pair of rotating steel cylinders with folding clamps, called the inter-folders. To produce premium products, it is necessary to guarantee a good bending quality as well as a good alignment of the sheets (Yasui 2017).

Regarding the folding itself, there are several types. The most common types of folds are represented in Fig. 13.

Fig. 13. Schematic representation of the main types of tissue paper folds

The most traditional form of folding is the C-fold. This type of folding is used in low quality products, but it creates an additional difficulty in its usage, making the end consumer take several sheets at the same time, which is more than essential. Then, there is the V-fold, also known as the Zig Zag fold, which is also used in low quality products. With this style of folding, the user can already have a greater control over its use, as it dispenses one sheet at a time. The V-fold type of folding is commonly used in facial tissue products. The most used fold for premium products is the Z-fold. This type of fold provides controlled use by the user, with one sheet at a time being dispensed. The sheets feature a clean cut and open automatically. Finally, there is the quarter fold (or ¼ Fold), which is the main fold used in napkins. This type of fold does not require a dispenser for its use (Galli 2022; Pearroc Ltd. 2022).

Regarding the product marketing, the type of folding can also be used as a way for the producer and the consumer to distinguish the quality of the product and perceive its respective final properties.

Packaging / Boxing

Generally, in converting machines, the packaging section is closed, and production is performed at high speed, and so it is important to have means of detecting the problems that occur in the packaging sequence to solve them as quickly as possible to guarantee improved quality of the products (Rempel 2022). It is rare that the packaging process damages the integrity of rolls/stacks of tissue paper, affecting their properties, but sometimes deformation can occur during bagging (Pejic 2016).

Generally, rolled products are vertically stacked with the core, while folded products (without core) are placed inside cardboard boxes. This is because during the storage of the pallets, they are often superimposed, so the lower pallet needs sufficient strength to support the upper pallet, thus jeopardizing the integrity of the products. Thus, for products with a core, the strength is provided by the core itself, and for products without a core, the strength is provided by the cardboard box in which the products are packed (Galli 2022).

Rewound products

The tissue paper rolls then arrive at the packaging section. Because of the high number of packaging configurations used for roll tissue products (from single roll packages to multi-packs up to 90 rolls), it is challenging for converting machines to comply with these configuration changes smoothly. In contrast, it is equally challenging for this type of machine to be adaptable to the material used for packaging, as it is increasingly necessary to consider the sustainability of the materials used (Alberti 2020).

In this section, the rolls are grouped according to the amount predetermined by the machine operator, and then wrapped in a paper sheet for packaging (which can be closed with glue) or in a plastic, which is usually done with polyethylene or bioriented polypropylene (whose packaging is closed using hot air) (Brown 1991; Pejic 2016). Depending on the model of the converting machine, the rolls can be packed in several layers. Each set of rolls that form a layer is lifted and placed on the bottom layer, and so on, until achieving the number of layers predetermined. Then, they are all packed together or bagged (Michelini 2022). Next, these packages can be placed directly stacked on pallets or first in cardboard boxes, and then on pallets to be stored in the finished product warehouse (Brown 1991; Pejic 2016).

Folded products

After the embossing, cutting and folding process, the stacks of folded paper are sent to the packaging section. These tissue paper stacks, depending on their final application, can undergo various types of packaging. For example, the napkins are packed in a plastic film in predetermined amounts, and then the napkin packs are packed in a cardboard box. Hand towels, contrastingly, are wrapped in a paper or plastic film and then stacked inside a cardboard box. The packs of facial tissues, with about 8 to 10 tissues per pack, are packed in a plastic film, which will be perforated, and a self-adhesive label will be glued (creating the opening and closing of the pack), then a predefined group of these packs is placed in a bag and later in a cardboard box for later dispatch (Michelini 2022).

Palletizing

Now that the products are packed, they go to the palletizing section. The main problem that can exist in this section is the fact that the suction cups/robot arms can deform the packages, damaging the product contained therein. In addition to the bad appearance caused in the packaging, this results in a problem for the palletization itself, as deformed packaging takes up more space, reducing the efficiency of packaging stacking. It can also increase the amount of plastic wrap used to close the pallet (Reynolds 2015).

Conversely, there are deformations that can be purposeful. In Brazil, a considerable portion of the population goes to the supermarket by public transport or on foot, traveling long distances, and therefore transporting toilet paper is challenging. Additionally, the apartments are very small, and the toilet paper takes up a lot of space. Thus, the packing of a set of rolls with the packaging film will compress them, and this will considerably reduce their size, solving the transportation problem. This packaging method of reducing the size of roll packaging by compression is called *Just One Hug* (Kim and Mauborgne 2021). With the reduction in packaging, the efficiency of palletization is also improved, as a greater number of rolls per pallet can be transported, as shown in Fig. 14.

In Brazil, cargo is transported mainly by road, and thus, being able to transport more rolls per pallet caused a decrease in transport costs. With the *Just One Hug* packaging method, there was a drop of approximately 15% in transport costs and 19% in the amount of packaging material used, thus reducing the price for the consumer, in addition to satisfying the packaging dimensions reduction requirements, without reducing the amount of product. As this compression impacts the properties of the finished product, such as bulk and softness, this packaging method was combined with products composed by recycled fibers (lower quality products) (Kim and Mauborgne 2021).

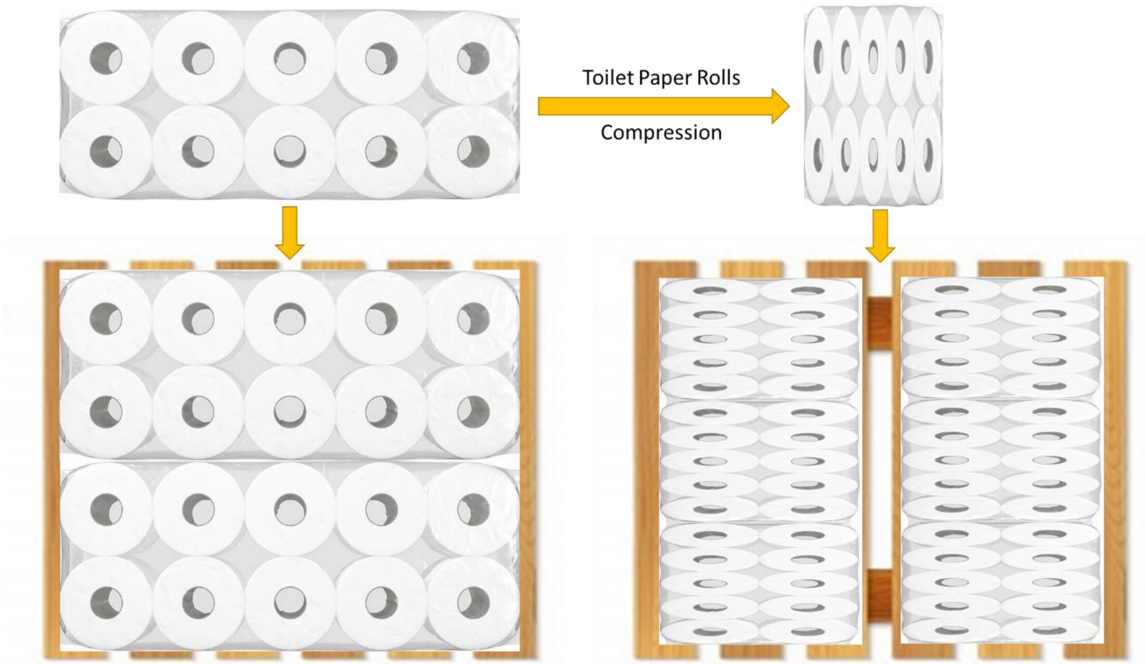


Fig. 14. Schematic representation of rolls packages palletization with and without compression

Dusting & Linting

Tissue paper products, in general, can release extremely high concentrations of dust (fibers with a length approximately 0.4 to 2.0 mm) and lint (fibers with a length approximately 4.0 to 5.0 mm and a width of 500 µm), which are encountered during stages of processing and packaging (Baum 2001; Frazier *et al.* 2022). In the manufacturing process of this type of product, these fibers and dust accumulate on the surface of the paper and in the elements of the converting machines, which translates into product quality problems and difficulties in runnability, and later, in the usage of the final consumer (Kuryllowicz 1984; Linder *et al.* 2017).

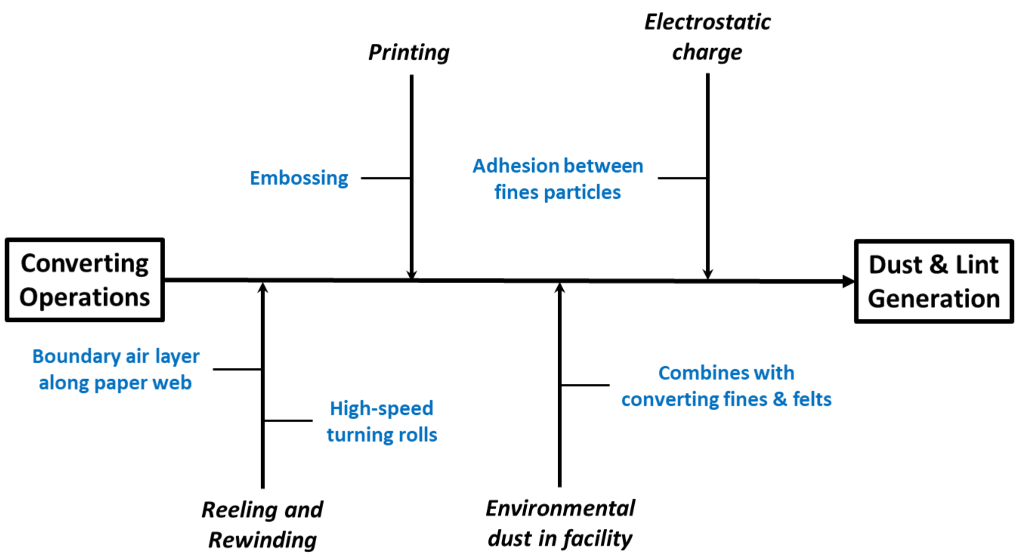


Fig. 15. Major contributing factors to dust and lint generation in tissue converting

This lint and dust accumulation form agglomerates on the surface of the tissue paper sheet, and consequently decreases its softness with a roughness increase. Due to this fact, the usage of these products contaminated by lint and dust becomes unpleasant, such that the product does not meet the requirements of the final consumer (Frazier *et al.* 2022). The fishbone diagram presented in Fig. 15 shows the major contributing factors to dust and lint generation in tissue converting (Frazier *et al.* 2022).

FINAL CONSIDERATIONS

It is in the converting machine where value is added to tissue paper products, which is why these machines are constantly evolving. At the beginning of the tissue paper transformation, the paper was rewound by hand on a mandrel, and when the first semi-automatic machine appeared, it was wound at a few LOG's per minute. Currently, product design plays an important role, as in addition to its apparent sophistication, it is the key to optimizing its properties. Therefore, increasingly more products are engraved and printed, and design patterns are constantly changing and optimizing. These machines have become sophisticated and uninterrupted, being able to be computer-controlled and quickly programmed to produce the desired product. The fact that the automation of the converting machines goes all the way to the end of the line (palletization), allows the producer to have better control of the quality and price of the product presented to the consumer. As a result, the products that reflect the needs and desires of customers have an improved chance of success for the producer. The competitive advantage will be found by producers who use the latest technology, because with the actual slowdown in the economy, products will have to be redesigned to find a lower price, which means making an additional effort to produce the products at the lowest possible price cost as well as lowering the cost of transportation through distribution channels. Thus, the digital twining of the several converting processes provides a modeling tool, which allows optimization in a digital environment, without having to undergo several trial-and-error cycles to determine the optimal parameters of the processes (Spirent 2020). According to recent publications, the simulations were carried out on a macroscopic scale considering an orthotropic homogeneous fiber distribution in a quasi-static loading. An improvement of the simulations will be made by taking into account a microscopic characterization of the fiber's distribution and orientation. This information is then used to represent in a mesoscale considering representative elementary volumes, and finally replicating them into space to achieve the macroscale mechanical behaviors, and also considering a dynamic loading using time-dependent constitutive models.

Because of the high competition and secrecy between different tissue paper producers and suppliers, there are few studies and publications related to the production, and its impact on the final properties of these types of tissue paper products, as already observed by other authors (Assis *et al.* 2018). This review article has shown that some progress has been made and that most of the findings referenced here are recent, which indicates a slight opening of the industry in creating partnerships to deepen these mechanical impacts on the properties of the finished products. Figure 16 summarizes in a fishbone diagram the impact of the converting operations on the final properties of the finished tissue products.

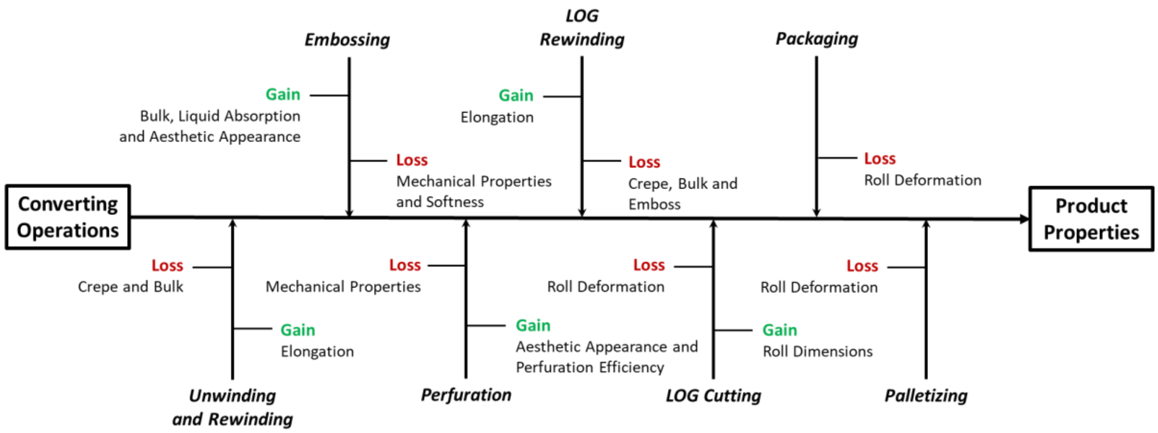


Fig. 16. Impact of the converting operations on the final properties of the tissue products

FUTURE DIRECTIONS

1. Within the converting operations, embossing has a major impact on the quality of tissue products. Therefore, in the near future, it deserves special attention in new and innovative research and development methodologies to follow-up the digital transition and fulfill the exigent consumer requirements.
2. The natural evolution of the embossing process tends to go in the direction of changing the conventional rubber covering by the introduction of a double layer covering with an inner layer with low hardness and an outer layer with high hardness rubbers.
3. The final quality of the tissue products is mostly related to the patterns and the corresponding finishing geometries of the embossing. It is a challenge to be able to integrate the design of the embossing patterns, the respective type of finish geometry, and the density of the marked area in an automatic procedure that allows to predict the final properties and quality of the final tissue product.
4. Due to the market demands, the adaptability of converting machines, and their rapid updating, is imperative for the producer since the response to consumer requirements is their main motivation.
5. The digital twining of several converting processes is an emerging simulation tool that will be a trend in the near future. It will enable optimization in a digital environment transition.

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