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Assessment and technological forecasting in the textile industry: From first industrial revolution to the Industry 4.0¹

Adriana Yumi Sato Duarte

adriana.duarte@ceunsp.edu.br

Centro Universitário Nossa Senhora do Patrocínio. Pç. Antônio Vieira Tavares, 73, Centro, 13320-219, Salto, SP, Brazil

Regina Aparecida Sanches

regina.sanches@usp.br

Universidade de São Paulo. Rua Arlindo Bértio, 1000, Vila Guaraciaba, 03828-000, São Paulo, SP, Brazil

Franco Giuseppe Dedini

dedini@fem.unicamp.br

Universidade Estadual de Campinas. Rua Mendeleev, 200, Cidade Universitária, 13083-860, Campinas, SP, Brazil

ABSTRACT

Each Industrial Revolution played a key role in the production-consumption pattern of textile products. Given the complexity of the Textile and Apparel Industry, the production systems have varying degrees of conceptual and technological innovation. Thus, the objective of this research is to present a model that includes the projection of technological changes in the production and consumption of textiles from the contrast between the descriptions of patents, scientific articles, and trends and tools of the Industry 4.0. It was possible to infer that the components of the Textile and Apparel Industry are undergoing an evolutionary process, which includes the automation of machinery parts and processes. The technological tools that characterize the Industry 4.0 are not yet fully integrated into textile production, and the challenge for the textile industry is to keep up with these innovations that impact on production, on business models, on consumer habits, and on social aspects.

Keywords: textile and apparel industry, Industry 4.0, assessment, forecasting.

Introduction

Textile production is intrinsically related to the origin of humanity. Clothing, as well as food and shelter, is considered a basic human need. In addition, it is a form of self-expression that becomes even more important for individuals and social groups (Ha-Brookshire and Labat, 2015).

The textile industry has played and still plays a major role in the Industrial Revolution. The textile and apparel industry includes the obtaining of raw materials, spinning, weaving and knitting, dyeing and printing, production and sale (Ülgen and Forslund, 2015).

Since the First Industrial Revolution, there have been modifications in the production-consumption and in the

organization of society. In the contemporary competitive context, technological tools, the need for a rapid response in the decision-making process, the demand for functional products and the appropriate social and environmental responsibilities of organizations are fundamental principles for the development of new products (Lu *et al.*, 2007; Duarte *et al.*, 2017).

The First Industrial Revolution allowed the mechanization of the productive process and stimulated consumption and the need for constant renewal of the products. The Second Industrial Revolution introduced new sources of energy, mass production and the revolution of consumer goods. The Third Industrial Revolution was characterized by the transition from analog to digital and by the segmentation of consumer markets. The Fourth Industrial Revolution

¹ This article is part of the doctoral dissertation (Duarte, 2017) that is closely related to the journal's scope and Industry 4.0.

tion, which is the one currently taking place, is based on the integrative and collaborative environment, on the adoption of Cyber-Physical Systems and on the active role of consumers in the production system (McNeil, 1990; Troxler, 2013; Flacher, 2005; Anderl, 2015).

Thus, this work aims to associate the textile industry and the Industrial Revolutions, analyzing the main innovations in the production system and machinery through the assessment by analyzing patents and technological forecasting. For this, the analysis was delimited to four production systems for the manufacturing of 100% combed cotton t-shirts: obtaining of textile fibers, spinning, knitting and garment confection.

Research contextualization

First Industrial Revolution

The First Industrial Revolution, between 1760 and 1830, began in Britain and spread throughout Europe and the United States (Sabo, 2015). The introduction of steam engines allowed the general mechanization of industries which replaced the artisan method of an individual's "know-how" with the high and rapid production of consumer goods (Schuh *et al.*, 2014). It was also in this period that coal began to replace other fuels, such as wood.

The First Industrial Revolution was particularly important for the textile industry. In 1733, John Kay patented his flying shuttle propelled by a cord that increased consumption of items produced in looms. Before this invention, the yarn was manually carried back and forth in the loom, which limited the width of the fabric. However, it was only in 1760 that the invention became popular with the possibility of use of yarns in different colors (McNeil, 1990).

In 1764, James Hargreaves invented the Spinning Jenny, a spinning machine that replaced the manual method of yarn production. According to McNeil (1990), an accident with his spinning wheel and the movement of the hands of craftsmen were inspirations for Hargreaves to develop this machine. After 36 years of the invention, the number of spindles increased over 15 times (Ribeiro, 1984).

Arkwright offered several contributions to textile machinery. In 1769, he patented the water frame, a spinning machine that combined Spinning Jenny's system with a waterwheel and cylinders that allowed for a more regular yarn. In 1775, he patented the carding machine, which consisted of a preparatory system for textile production (McNeil, 1990; Ribeiro, 1984).

One of the most important inventions of the spinning system was the introduction of a mechanical spindle in the water frame in 1779, which allowed the production of a high-quality yarn, and consequently replaced domestic production with mass production (Ribeiro, 1984; McNeil, 1990).

Joseph-Marie Jacquard, in 1801, combined different existing mechanisms to develop the Jacquard Loom. He was also the inventor of punch cards that were later considered the basis for the memory cards used in computers (McNeil, 1990).

The First Industrial Revolution had coal as main source of energy and the extraction of iron ore was effectively exploited in the 19th century. Braudel (2009) and Hobsbaw

(2011) claim that iron began to be used in the manufacturing of machines only at the end of the century; metallurgy was restricted to the production of tools, nails, screws, iron bars, among others. In some places in England, the birthplace of the First Industrial Revolution, textile machinery was still made of wood.

Second Industrial Revolution

The transition to the Second Industrial Revolution occurred between 1840 and 1870 and had as main catalyst the use of electricity for mass production that caused a significant impact on the productivity at the beginning of the 20th century (Schuh *et al.*, 2014; Sabo, 2015). The classic example of this form of production was the series production implemented by Henry Ford up to the 1910s. This revolution started not only in the USA but also in Britain and Germany. In addition, another important factor in this change was the technological development of Japan. The result of the changes was a rapid industrial development and an increase in the quality of life of the population (Sabo, 2015).

The Second Industrial Revolution was marked by an increase in productivity and by the introduction of new sources of energy in the textile industry. John Thorp created a new method of spinning in 1828: the Ring Frame. The most important feature of this frame is related to the possibility of spinning a greater amount of yarns simultaneously, allowing the combination of several steps into a single process (McNeil, 1990; Ribeiro, 1984).

In addition, the first circular knitting machine was patented in 1816 (McNeil, 1990). A few years later, in 1847, the tubular fabric became popular thanks to the Rib pattern, the most used in sweaters, socks, collars and cuffs (Frings, 2012). In 1856, Matthew Townsen invented the latch needle which simplified the production of knitwear. In 1864, William Cotton adapted a mechanical propulsion machine capable of knitting several socks at the same time. One of the first mass-produced consumer goods was the sewing machine. Despite it having been invented earlier, Isaac Singer patented the first domestic sewing machine in 1851, dramatically changing the consumption and production of clothes. As a result, this sewing machine was adapted for other segments, such as footwear (McNeil, 1990).

Third Industrial Revolution

The Third Industrial Revolution, also known as the digital revolution, is focused on the transition from analogue to digital technology, having as ultimate symbol the invention of integrated circuits that allow increasing computational capacity and decreasing production costs. As a result, the industry widely adapted itself to information technology (IT) and has a significant impact on the growth of economic performance until the present day (Schuh *et al.*, 2014).

Digital technology guided this change, as did communication technology, with which factories adopted digital logic circuits marking the beginning of the information age. The manufacturing processes of complex products were only manageable due to Information and Communication Technology (ICT), deployed in about 90% of all industrial manufacturing processes (Sabo, 2015). According to Mem-

mi (2014), the use of IT became the basis of communication channels.

The Third Industrial Revolution is characterized by the use of microprocessors, CAD (Computer-Aided Design), optical fiber, telecommunication, biogenetics and laser (Finkelstein and Newman, 1984).

Mass customization, in which large quantities of items individualized according to the user are produced, was a challenge for the textile industry (Davis, 1989; Fralix, 2001; Troxler, 2013). According to Fralix (2001), adjustments in clothing and color are two limitations to the application of mass customization in the textile industry. On the other hand, some technological solutions, such as scanning, 3D modeling and digital printing are being gradually adopted by the textile industry.

Fourth Industrial Revolution

The Fourth Industrial Revolution, also called the Industry 4.0, represents a profound change in the organizational structure of industries. For the first time, an industrial revolution is evaluated *a priori* and not *ex-post*, which in other words means a prediction of what is about to happen and not an evaluation of what has already happened (Hermann *et al.*, 2015). This concept became public in 2011 during the Hannover Fair (Germany), when representatives of the economy, politics and academia promoted the idea of strengthening the competitiveness of the German industrial sector.

The result of the Fourth Industrial Revolution will be the Intelligent Factory, where Cyber-Physical Systems (CPS), the Internet of Things (IoT) and Big Data are the key technologies to achieve production goals.

Cyber-Physical Systems are defined as physical and engineering systems which have their operations assessed, coordinated, controlled and integrated by a technology and communication center. The interconnection between cyber and physical environments will be manifested in nano scale and in various time scales. The CPS interconnect the physical environment with the information technology when "cyberifying the physical" and "physicalizing the cybernetic" (Lee, 2010), making it possible to specify the physical subsystems' software-controlled behavior. The IoT, on the

other hand, is an approach for equipping real systems with embedded systems so that they become interconnected in so-called "intelligent systems" (Anderl, 2015).

Data exchange is the basis for the Industry 4.0; thus, the amount of data generated must be efficiently integrated during the product development process between the interested parties. The Big Data includes information from various sources and emphasizes a change in data quality and not just quantity (Chandler, 2015).

In the context of the textile industry, Gloy *et al.* (2013) developed an autonomous system of textile production, which enables rapid and flexible production. This system foresees the use of digital technologies and cyber-physical systems so that machines communicate with each other and with their operators, reporting status and possible operation and maintenance issues. Thus, it is possible that machines reconfigure and adapt themselves to a new demand. Part of this research is the development of an optimization system of mesh tension in flat weaving and an automatic fault detection system in the manufacturing of knitwear. According to the authors, e-textiles, the manufacturing of 2D and 3D textiles and medical textiles represent promising fields for the use of the Industry 4.0.

Bruno (2016) describes the future of the production and consumption of textiles with the end of low-cost advantages in the textile production system in underdeveloped and developing countries, the intensive use of ubiquitous technology in the so-called wearables, new production systems (mini-factories, digital factories, 3D printers) and the use of biotechnology and nanotechnology in the manufacturing of functional fabrics.

Research methodology

The methodological procedures adopted in this research have a predominantly exploratory character, based on a case study which had as main aim the technological forecasting of the textile industry.

The delimitation of the research is the manufacturing of 100% combed cotton t-shirts. To this end, four production systems were determined: the obtaining of cotton fiber, spinning, knitting and garment confection.

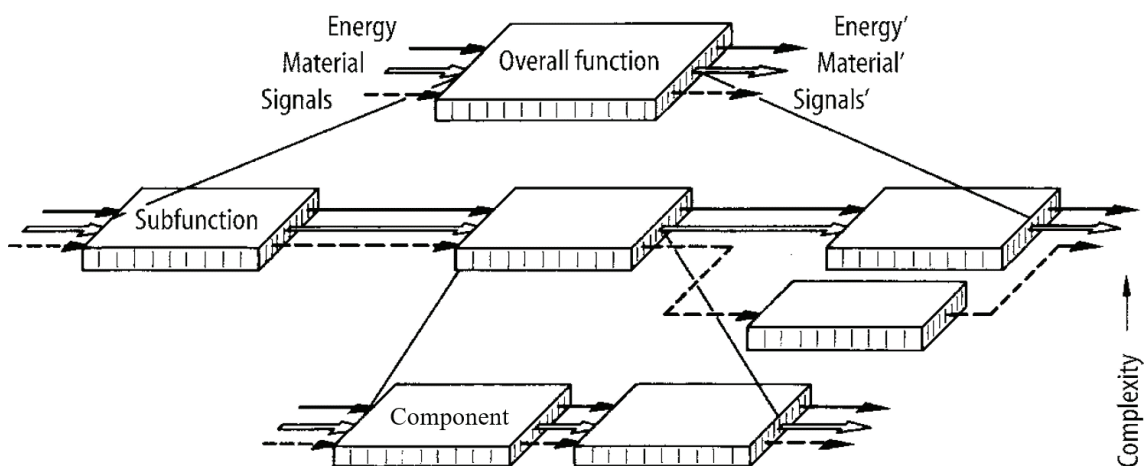


Figure 1. Functional deployment (Pahl *et al.*, 2007).

The functional deployment described by Pahl *et al.* (2007) was applied for each production system. This technique relates inputs and outputs, which correspond to material/energy/information, functions and subfunctions. Each system was detailed in subsystems, and each subsystem was associated with one or more components (machinery and/or machine elements), as shown in Figure 1.

The technology forecasting model contemplated two methods: Assessment, with the aim of monitoring the development of the factors that can be agents of change, and Forecasting, which is the projection of technological changes.

The Technological Assessment was based on documents obtained in patent databases, including Brazilian and foreign patents, from 2011 to the present day. For this research, two databases were selected: an international one in English (Google Patents) and a Brazilian one in Portuguese (*Instituto Nacional da Propriedade Industrial* – INPI).

Finally, the Forecasting was performed using historical information and the theoretical modeling of trends (Amparo *et al.*, 2012).

Results

The results will be presented in two topics: (a) specification of production systems and components, which describes the four systems (the obtaining of cotton fiber, spinning, knitting and garment confection) using the functional deployment method, and (b) the assessment and technological forecasting of these systems.

Specification of production systems and components: General view

The textile production systems adopted in this research are the processing of cotton fiber, spinning, knitting and garment confection that correspond to the following systems, respectively: "Obtain Textile Fibers", "Turn Fibers into Yarn", "Turn Yarn into Fabrics" and "Turn Fabrics into Ready-to-Wear Clothing", as shown in Figure 2.

However, due to the complexity of the systems, a new ramification was created to specify the subsystems. The ramifications were determined by analyzing the shop floor

operations, including the machinery, techniques and machinery elements. All the new deployments will be presented in the next sections.

"Obtain Textile Fibers" system

The "Obtain Textile Fibers" system encompasses the steps of cotton cultivation, post-harvest separation of fibers, removal of impurities from the fibers, production of cotton bales and distribution of the bales for marketing, as illustrated in Figure 3.

The cultivation of cotton requires a wide range of agricultural machinery that perform tasks of soil preparation, distribution of seeds in the soil at a specific depth and spacing, and harvesting of the products.

The separation of fibers consists in the use of the Stripper Harvester and the Cotton Gin, machines which harvest and separate the cottonseed fibers, respectively. The elimination of impurities from the fibers is made with a Cotton Cleaning Machine.

The cotton baling is performed by the elements Cotton Condenser, Module Feeder and Bailing Press. The Condenser starts the process of removing of air from the fibers, forming a blanket, which will be taken by the Feeder to the Press so that the bale can finally be formed (Ampasul, 2010). For the distribution of cotton bales, the transportation conduit and the assessment system will be needed.

"Turn Fibers into Yarn" system

The "Turn Fibers into Yarn" system encompasses the opening of the bales, the elimination of impurities such as bark and leaves, parallelization, stretching and twisting of the fibers, gathering of the yarn produced and its subsequent distribution, as shown in Figure 4.

The opening of the cotton bales is performed in the Blow Room, where they are opened for separating the fibers in order to facilitate the formation of the yarn. The carding machine performs the individual rearrangement of the fibers to eliminate impurities and parallelize them.

In the Drawing machine, the fibers are first stretched and the weight/unit length is determined. The Pre-Combing Drawing Frame, the Lap former machine and the Comber

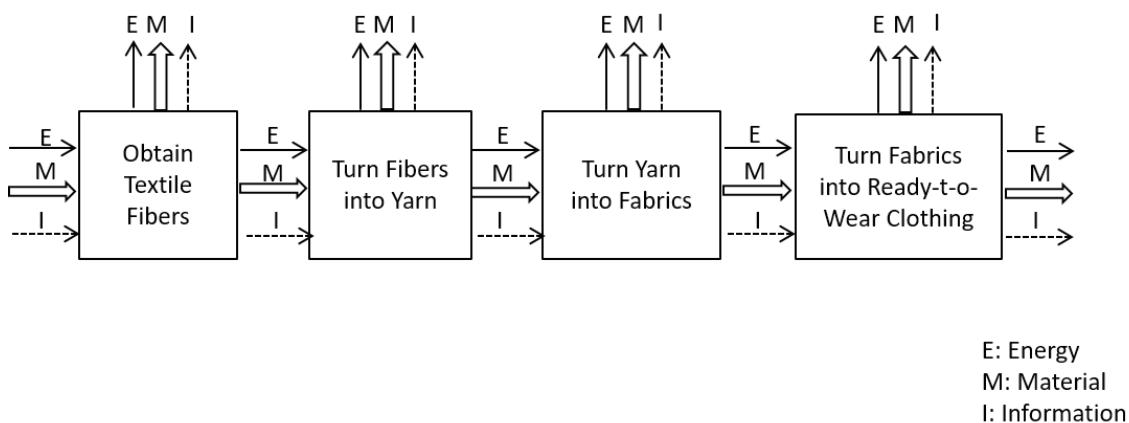


Figure 2. Four systems.

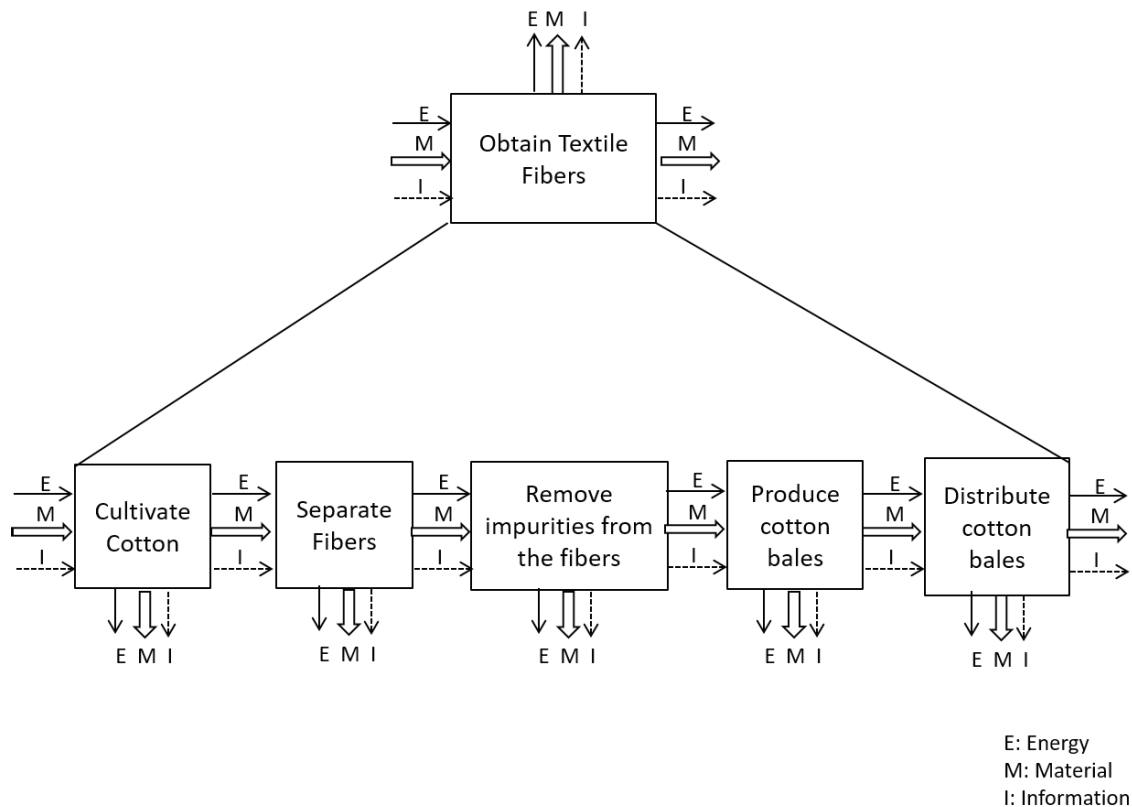


Figure 3. Ramification - "Obtain Textile Fibers" system.

are the set of machines responsible for parallelization and for the removing of short fibers. The Rover and Spinner stretch the fibers and spin them together (Ribeiro, 1984). The distribution of the finished yarn is conducted through a transportation conduit and assessment system.

"Turn Yarn into Fabric" system

The production system "Turn Yarn into Fabric" has the knitted fabric as basis. The knitted fabric can be formed by a single yarn (weft knitting) or several yarns (warp knitting), loops being the basic constructive element of this fabric.

The specification of the components of this function is related to the constructive elements of the single-cylinder circular knitting machine, which produces single Jersey fabrics intended for the production of t-shirts. In this machine, the formation of the fabric corresponds to the action of the components: yarn guide (responsible for guiding the yarn onto the needles) and steel needle bed. The movement of the needles for the formation of the fabric is performed by the set of components: cam, needles and sinker. Finally, the fabric is rolled up by a winding machine to prevent the formation of creases or tearing (SENAI, 2015), as shown in Figure 5.

After the fabric has been made, it is necessary to prepare it for the finishing processes. The preparation for dyeing involves the impregnation of the fabric with a chemical solution for removal of impurities and paraffin from the yarn that hamper the absorption of dyes and pigments in the fibers using equipment known as the Over Flow, which

is also responsible for the actual dyeing process. The softening of the fabric is held with the Foulard. The fabric is then dried and calendered. The distribution of the finished fabric is conducted through a transportation conduit and assessment system.

"Turn Fabric into Ready-to-Wear Clothing" system

The last productive chain system studied, "Turn Fabric into Ready-to-Wear Clothing", consists of several activities and components. This system includes the stages of development of the spec sheet, sampling, cutting, sewing and printing (Figure 6).

The spec sheet contains the technical drawings, fabric samples, measuring and sizes of the articles and notions used and can be done manually or with the aid of a software (Manoel and Pereira, 2016).

Sampling encompasses the drawing of outlines and size grading of the articles. The samples can be created manually or with the aid of a software (Silveira and Silva, 2016).

The cutting of the fabric involves the planning of the cut outs and the cutting itself, which could be done manually or with the aid of computer programs and automatic machines. The planning of the cut outs requires knowing the characteristics of the fabric and the fitting of the sample, and can be done manually or with the aid of a software. Finally, the cutting itself can be executed with the aid of electric tools such as saws or knives, or with an automatic

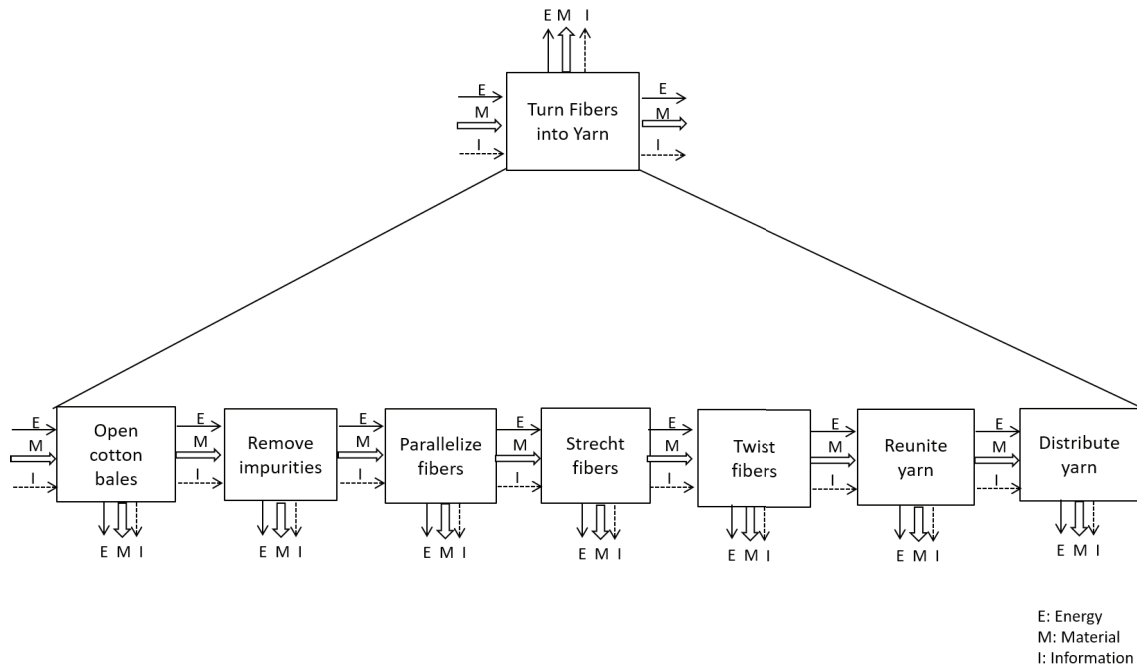


Figure 4. Ramification - "Turn Fibers into Yarn" system.

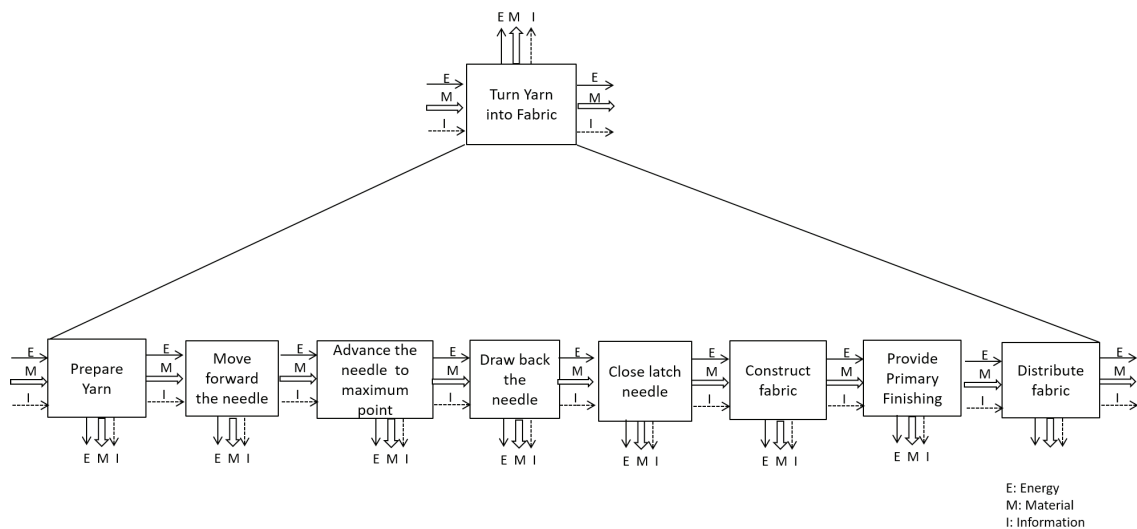


Figure 5. Ramification - "Turn Yarn into Fabric" system.

machine (Nishida, 2015). The articles cut are then sewn together with the use of sewing machines.

The dyeing of the fabric can be performed in the total (Dyeing) or partial (Printing) area of the textile substrate. Printing, specifically screen printing, requires screens and dryers. A print is engraved into the screen and decomposed according to the colors required for the formation of the image, and the preparation of the screen depends on the frame and form of fixation; the feeding of the machine is manual and the thermofixation is done with dryers (SENAI, 2015; Ribeiro, 1984). The finishing of the articles corresponds to the revision and quality inspection of the final product (Andrade *et al.*, 2016).

Assessment and technological forecasting of the systems

The Technological Assessment was developed based on patents in Brazilian and foreign databases. In the present research, two databases have been selected, one in English (Google Patents) and one in Brazil (National Institute of Industrial Property – INPI). It is important to select parameters such as keywords, depositor country, and year so that the search can be precise and unambiguous. Thus, the components specified in each system were the parameters in this research. In order to analyze the patents regarding the main innovations and/or technolog-

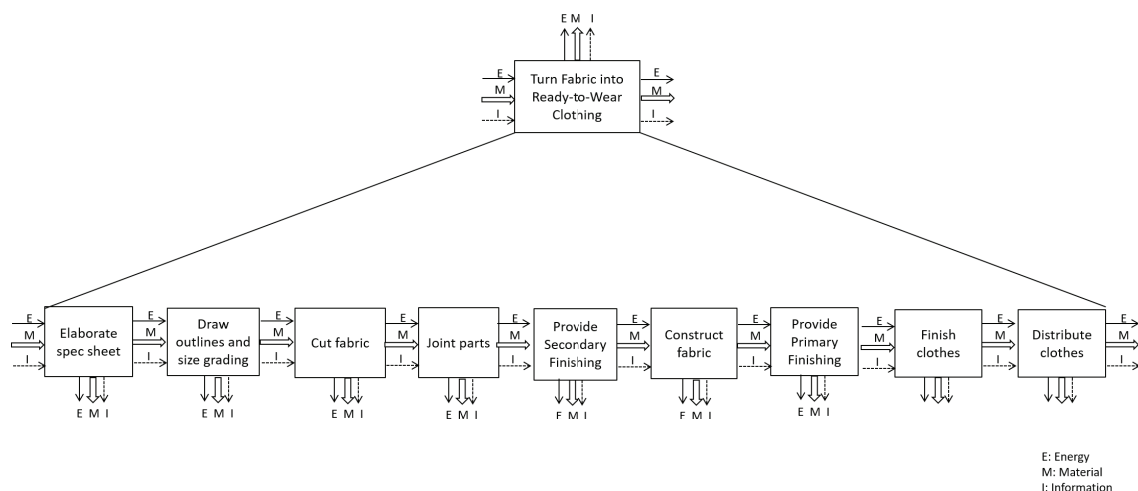


Figure 6. Ramification - "Turn Fabric into Ready-to-Wear Clothing" system.

ical advances, the following design typologies were adopted (Fonseca, 2000):

- Original design: has a high degree of conceptual novelty and high degree of configuration complexity;
- Redesign: has a low degree of conceptual novelty and low degree of complexity in the changing of its configuration;
- Adaptive design: has a high degree of conceptual novelty and low degree of configuration complexity;
- Development design: has a low degree of conceptual novelty and high degree of complexity in the changing of its configuration.

The components of the production system "Obtain Textile Fibers" are classified as redesigns, since many patents described adaptations of existing machines or improvements of the method. Examples of such adjustments include the various devices plugged into the soil preparation machines, harvester and feeder (Bertino, 2013; Klein, 2014; Rylander, 2013; Marchesan, 2016; Silva *et al.*, 2015; Orlanda, 2014) and the changes in the configuration of the machines (Seki and Balestri, 2017; Henkels, 2015; Yang *et al.*, 2013). The automatic devices that aid in the harvesting and manual ginning of cotton (Jun and Liang, 2016; Xiuyun, 2012) are considered development designs, because they assist in the execution of a function with complex variables without adding conceptual novelties. This also applies to the use of robots for the harvester (Kahani, 2016) and the robotics platform for tillage (Cavenders-Bares and Bares, 2015). Still in this system, the systems of communication, control and real-time assessment of the means of transport (Foster *et al.*, 2013; Santos, 2016; Ferguson and Dolgov, 2013) are considered original designs, for having a high degree of complexity and conceptual novelty.

In the productive system "Turn Fibers into Yarns", most of the patents describe a redesign, when indicating the development of the constructive elements and of the methods of execution of the function with a low degree of conceptual novelty; examples of this design include the systems of opening of cotton bales (Huazhong, 2014), the additional carding device (Muller, 2015) and the devel-

opment of the constructive elements of the rover, spinner (Havliczek, 2013) and foulard (Zhao, 2013). On the other hand, the quality control system of the Comber (Zhi, 2012) is understood as a development design, due to its high degree of complexity and low degree of conceptual novelty.

The patents of the components of the production system "Turn Yarns into Fabrics" have development design (Min *et al.*, 2013; Aramaki and Shimosakoda, 2013) and redesign (Chen, 2012; Gao, 2013; Mayer, 2012) features. In addition, there are also examples of adaptive design, with conceptual changes in the component and a low degree of complexity, as in the case of the needle and sinker patents that prevent the accumulation of cotton fibrils (Tian, 2013; Hong, 2016).

Finally, in the productive system "Turn Fabrics into Ready-to-Wear Clothing", the components are classified as variant design and development design. The patents of the variant design components are adaptations of the elements of the screen for printing (Sedrez, 2013), dryers (Zonggen, 2012; Hwa, 2016), cutting table (Tong, 2012), sewing machine (Chen, 2015; Medeiros, 2015) and iron (Ong, 2016; Soares, 2013). The development design components are related to the control system of positioning of the screen for printing (Xingxing, 2012), and to the positioning of the fabric on the sewing machine (Guerreschi, 2016). The automatic cutting table is the component associated with the development design, bearing high complexity and low degree of conceptual novelty.

In general terms, it is possible to notice that there are few original designs among the components described; the patents examined indicate adaptations to the machines or addition of components to the control system of the equipment. Thus, the importance of technology forecasting in the determining of technologies that have already been developed, though not yet applied in their entirety, and in the identification of possible new technologies that meet the demands of the Fourth Industrial Revolution, is notable.

Technological Forecasting indicates the need for technological change in all production systems. For the obtaining of textile fibers, agricultural implements must obtain and manage information in real time pertaining to the

weather and soil conditions, to the quality of the seeds and inputs to assist the process of decision-making associated with the actions involved in the processes from cultivation until harvest. There are patents that concern the systems of data acquisition and management (Curkendall *et al.*, 2006), the transmission of data via the IoT to the consumer (Dlott *et al.*, 2008) and the management of climatic conditions (Frey, 2014), but these tools are not extensively used in agricultural machinery yet.

The Industry 4.0 will change the organization of factories and business models. Two models are widely used: the intelligent factory and the mini-factory. The Intelligent Factory has as principle the integration between various stakeholders in a virtual and collaborative environment, the remote control and assessment of industrial activities through virtual copies of the physical environment and the intensive use of ubiquitous technologies in portable devices. Mini-factories are based on on-demand production, in which the production depends directly on consumer demand. For the production of yarns and fabrics, the remote assessment of machines and environmental conditions and the use of a QR Code (Quick Response Code) and RFID (Radio Frequency Identification) for data access, are examples of additional machinery components. It is worth mentioning that the information contained in the monitoring devices are located in packaging and labels that will be discarded in the next steps of textile production. Thus, the information need to be contained on the yarn.

The confection stage can be reconfigured in a mini-factory, which encompasses the orders, sampling, dyeing, cutting, sewing, finishing and shipping departments. It is worth noting that in this mini-factory, all components must be automated, an original design being needed for each machine.

Conclusions

In the contemporary competitive context, the industrial production process foresees the adoption of technological tools, the need for a rapid response with regard to the decision-making process and the demand for functional products. By analyzing the main innovations in the production system and machinery through the assessment and technological forecasting, this paper showed that the degree of conceptual novelty and complexity of configuration of the components of the Textile and Apparel Chain analyzed are undergoing an evolutionary process, which includes the automation of machinery parts and processes. In fact, most components are located between the Second and Third Industrial Revolution. The technological tools that characterize the Industry 4.0 are not yet fully integrated into production, and the challenge for the textile industry is to keep up with these innovations that will impact not only on production, but also on business models, on consumer habits and on social aspects. Few components have already been integrated with technological tools from the Fourth Industrial Revolution, but these components are not directly related to the textile production process. By analyzing technological development throughout the history of humanity, it is clear that the Textile and Apparel Chain has always played a pioneering role in the innovation of

industrial production and in the influence of consumer behavior. However, in recent decades, other industries began adopting technological innovations, such as the automotive industry, while the textile industry remained within its industrial park. For this reason, technological assessment is a way of responding to the industry's innovation gap.

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