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URUGUAY

FOREST-BASED BIOECONOMY AREAS

Strategic products from a technological point of view

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1 Introduction

The current project between the Technical Research Centre of Finland (VTT) and Oficina de Planeamiento y Presupuesto, Presidencia de la República[1], Uruguay (OPP) aims to produce a strategy to further the development of the wood industry in Uruguay. The project will analyse diverse variables with a holistic approach, identifying gaps in areas such as capabilities, markets, and institutions. In addition, a central output of this project will be the identification of opportunities for the wood industry, with a description of value chains ranked according to their economic potential. In this report, a team from the Faculty of Engineering, Universidad de la República, acting as consultants for the OPP, proposes a technological and economic analysis of key products and value chains to be fabricated with the actual forest resource. In addition, a detailed description of the current situation of Uruguayan timber as building material is presented, including a summary of mechanical properties and construction costs.

2 Objectives

2.1 Principal

Present systematic technological information to contribute to the generation of policies destined to add value to the Uruguayan forest resource.

2.2 Secondary

1. Describe strategic value chains using variables that allow for qualitative comparison among the value chains.
2. Present a detailed techno-economical description of those few value chains identified as of paramount importance for the forest-wood system.
3. Produce a strategy for the development of the wood industry focused on aspects within the range of government action.

2.3 Background

- The global development of wood construction has the potential to energize the forest bioeconomy.
- The wood products fabricated in Uruguay for the international market, namely pine sawn wood, eucalyptus sawn wood, and plywood, and particularly bleached eucalyptus kraft pulp (BEKP), are commodities that currently enjoy strong markets but are subject to price fluctuations and decreasing prices.
- Electric energy in Uruguay: future oversupply and decreasing prices.
- High regional cost for chemicals, including basic chemicals and adhesives.
- Production of chemicals from wood shows high potential, but profitability is not foreseeable in the near term.

[1] Budget and Planning Bureau, Presidency of the Republic

3 Uruguay: current technological situation of wood transformation industries

Uruguay is currently transforming its forest resource into a limited group of products. In terms of chemical transformation of the wood, the only process available is the production of short-fibre kraft pulp (and very small packaging paper mills and tissue plants), whereas regarding mechanical transformation there are two products: plywood and sawn wood (Table 1).

Table 1. Status of forest resource transformation technology in Uruguay

Wood transformation	Product	Produced in Uruguay?	Technology
Chemical	Bleached eucalyptus kraft pulp (BEKP)	Yes	Up-to-date (BAT)[2]
	Softwood pulp	No	
	Softwood chemi-thermo mechanical pulp (BCTMP)	No	
	Biorefinery products	No	
	Packaging paper	Yes (national market)	Old-fashioned
	Tissue paper	Yes (regional market)	Up-to-date
Mechanical	Medium-density fibreboard (MDF)	No	
	Oriented strand board (OSB)		
	Plywood	Yes	Up-to-date
	Laminated veneer lumber (LVL)	No	
	Sawmills	Yes	Up-to-date
	Glued laminated timber (GLT)	Yes*	Up-to-date *
	Cross-laminated timber (CLT)	No	
	Thermally modified wood	No	

* Non-structural uses only

3.1 Bleached eucalyptus kraft pulp

The raw material is eucalyptus wood (logs or chips). After debarking, logs are chipped and screened. White liquor, containing mainly active chemicals – sodium hydroxide and sodium sulphide – cooks the chips at high temperature (150–170 °C) and pressure. Approximately half of the wood composition degrades and dissolves during cooking. After cooking and washing, a brown pulp and black liquor are obtained. Printing, writing, and tissue papers require the pulp to be bleached, which removes the excess lignin and chromophores. Finally, the pulp is dried to approximately 10% moisture content (MC) and packed for shipping. The black liquor – composed mainly of lignin fragments, part of the hemicelluloses, and dissolved inorganic salts – is evaporated to a solids content of around 80% and later sent to the recovery boiler. There, the black liquor is burned for two main purposes: recovering the inorganic chemicals (from the white liquor) and producing high-pressure water vapour. The smelt from the recovery boiler is dissolved in water to form green liquor, which is later reacted with lime to regenerate the white liquor to be used in the earlier stages of the process. Vapour is used to generate electricity based on renewable energy and to cover the heat demand of the different processes of the

[2] Best Available Techniques (BAT)

plant. All modern mills produce a surplus of thermal energy that is converted to electricity (Gullichsen and Paulapuro, 2000, 1999; IPPC, 2015; Sixta, 2006).

Stages of production process (Figure 1):

1. Debarking. Remove bark from logs.
2. Chipping and screening. Chips are formed by cutting with wedged knives. The length and thickness of the chips vary within species and mills. Chips require screening before cooking to eliminate oversize pieces and fines.
3. Cooking (Digestion). The purpose here is fibre liberation thought delignification. Chemicals which dissolve the maximum amount of lignin and the minimum amount of cellulose are best for use in pulping. The chemicals react mainly with lignin to form a current of black liquor.
4. Washing and screening. The aim of washing is to recover the dissolved organic material (from wood) and inorganic material (from cooking chemicals). Both materials are mixed with the black liquor from the digestor and sent to the recovery cycle. The objective of screening is to separate the non-cooked wood (bark and chips) and contaminants (e. g. sand) from the pulp.
5. Oxygen delignification. Part of the residual lignin is removed using oxygen and alkali.
6. Bleaching. The purpose of bleaching chemical pulp is to obtain pulp with certain properties of brightness, brightness stability, and strength. The two main types of bleaching methods are elemental chlorine free (ECF), which means no molecular or gaseous chlorine is dosed in the bleaching, and totally chlorine free (TCF).
7. Screening.
8. Drying. The pulp is first dewatered and then dried with steam.

Recovery cycle. The recovery cycle consists of the following stages:

1. Evaporation. After the brown pulp is washed, black liquor is sent from the digestor to the evaporator where it is concentrated in a multiple-effect evaporators system.
2. Recovery boiler. Concentrated black liquor is burned here. The organic compounds that come principally from the wood (lignin, hemicelluloses, etc.) are combusted to generated steam, which is used for as heat for the plant and to generate energy. The inorganic compounds from the reacted white liquor form the smelt.
3. White liquor preparation. The smelt from the recovery boiler is dissolved to form green liquor. After filtrating, the green liquor is causticized with lime to regenerate the white liquor, with lime mud formed as a by-product.
4. Lime cycle. In the lime kiln, the mud is converted back to lime to be used in step 3).

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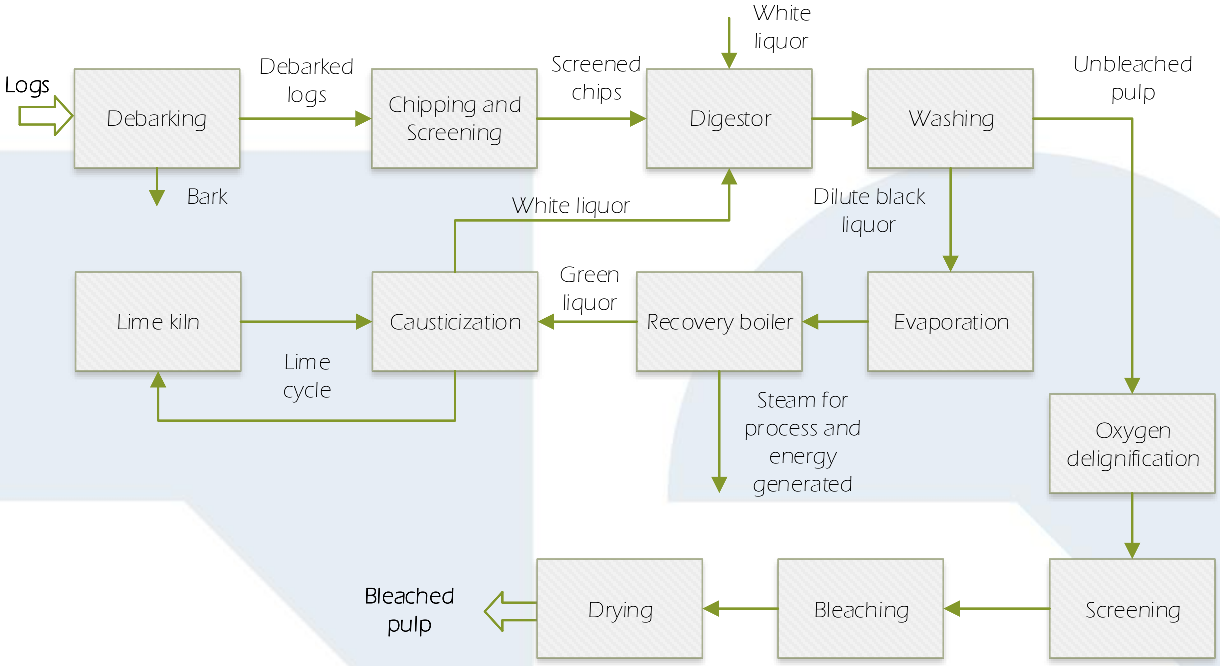

Figure 1. Schematic flow chart of BEKP production

The export market size for bleached kraft pulp, which includes the eucalyptus pulp produced in Uruguay, is growing, while in a 30-year time series, the price of the product is decreasing (Figure 4a).

3.2 Plywood

In Uruguay plywood for the construction market is produced from eucalyptus and pine logs. Logs are debarked and heated to soften the wood, which is later peeled in a rotating lathe to obtain sheets of wood (veneers) of a few millimetres in thickness. Veneers are aesthetically graded, cut to length, and dried to below 10% MC. Later, dried veneers are glued orthogonally to each other with phenol formaldehyde (PF) resin, hot-pressed (at temperatures in excess of 140 °C), cut to dimension (width and length), and sanded for finishing (Sellers, 1985; Walker, 2006). The transformation efficiency from logs to veneers varies within a range from 50% to 60% (Wagenführ and Scholz, 2008). The resulting sub-product is used to produce thermal energy and electricity; it can also be sold as biomass.

Stages of the production process (Figure 2)

1- Debarking and pre-conditioning.
2- Rotary peeling. A lathe turns the log into a thin continuous sheet, usually with a thickness of approximately 3 mm, which is then guillotine-sized.
3- Drying of veneers (5–6% MC dry basis).
4- Appearance grading of veneers.
5- Assembly. Stacking of glued sheets to achieve the desired thickness.
6- Pre-pressing and pressing.
7- Cutting to dimension. The panel is longitudinally cut to obtain the beams.
8- Finishing.
9- Packaging.

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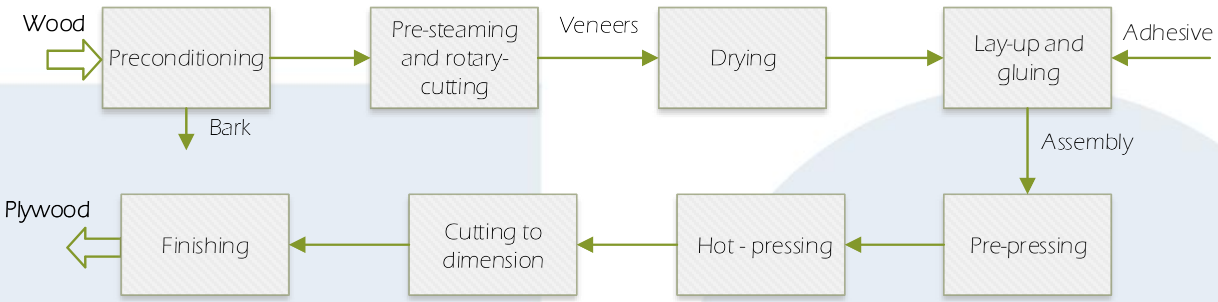

Figure 2. Schematic flow chart of plywood production

The reported export prices for Uruguay show variable behaviour (Boscana and Boragno, 2018) (Table 2), in alignment with the 30-year trends in the global export market of the product (Figure 4e).

Table 2. FOB prices reported for plywood (2009–2017) (Boscana and Boragno, 2018)

	2009	2010	2011	2012	2013	2014	2015	2016	2017
Plywood FOB price (USD/m^3)	268	323	275	288	418	381	399	188	284

3.3 Sawn wood

Sawmill production in Uruguay is highly concentrated in a few sawmills that produce more than 50,000 m^3 per year of sawn boards (Boscana and Boragno, 2017). These mills use the modern technology described here, since small sawmills with older technology face severe challenges in being profitable (Dieste, 2014a).

Local sawmills produce kiln-dried (KD) and classified boards for packaging and appearance wood, destined for carpentry products such as mouldings, doors and furniture. Logs are graded, debarked, and scanned for log geometry information which is used to set the saws in the mill, either manually or automatically. The transformation efficiency from logs to boards ranges from 40% to 50% (Wagenführ and Scholz, 2008). Green boards are aesthetically classified and dried in kilns to approximately 10% MC. Dried boards are classified according to appearance wood criteria. Some mills might include remanufacturing plants, which process dried boards to add value by means of surfacing, cutting to length, optimization, and finger jointing. Remanufactured products represent 6% and 8% of the total production for pine and eucalyptus, respectively (Boscana and Boragno, 2017). These processes could be highly automatized, with the needed technology readily available in the market.

Currently, sawn timber is not structurally graded by sawmills, so no structural products originate in the Uruguayan market. The first standard of visual grading of Uruguayan pine was recently published by the Instituto Uruguayo de Normas Técnicas (UNIT, 2018a), and a eucalyptus standard is under development (UNIT, 2018b).

Over a 30-year period, the price of sawn wood has been decreasing (Figure 4c and 4d). However, there has been a significant expansion in the export market: 14% and 33% from 2010 to 2016 for coniferous and for non-coniferous sawn wood, respectively. The market for coniferous sawn wood is large (in 2016, 120 x 10^6 m^3), approximately five times larger than for non-coniferous sawn wood, but the market for non-coniferous sawn wood is growing more rapidly. The worldwide expansion of wood construction could be one cause for this phenomenon (Dangel, 2016; FAO, 2018). Once inflation is considered, export prices reported for Uruguay show a trend of decreasing prices (Boscana and Boragno, 2018) (Table 3).

Table 3. FOB prices reported for pine and eucalyptus sawn timber (2009–2017) (Boscana and Boragno, 2018)

	2009	2010	2011	2012	2013	2014	2015	2016	2017
Pine timber FOB price (USD/m^3)	240	284	304	323	333	331	337	296	261
Eucalyptus timber FOB (USD/m3)	306	330	326	351	336	374	358	381	300

Since pine and eucalyptus (*Eucalyptus grandis*) have low durability, they must be protected for uses exposed to the weather. The impregnation of wood with chemicals, or chemical protection, allows for significant increases in the service life of wood components of low natural durability, such as pine, and therefore, adds value to timber. The most commonly used product for wood impregnation in Uruguay is an aqueous solution of chromium, copper, and arsenic (CCA), which represents a technological gap in comparison with other countries. The CCA impregnation solution is highly toxic, but the treated wood, in which the fixing reaction of the product has already taken place, does not represent significant risks to users. The biggest drawback lies in the final disposal of the treated wood and the waste from the construction process (cuttings, sawdust, dust, etc.). Pine wood is easily impregnated with a pressure treatment, but only the sapwood of eucalyptus can be impregnated (Dieste, 2014b). Due to the toxicity of wood treated with CCA, there is a growing global tendency to restrict its use (Ibáñez et al., 2009; Wagenführ and Scholz, 2008). In countries such as Switzerland, Denmark, Vietnam, Japan, and Indonesia, CCA is now banned, while other countries (the US, the EU, Canada, and Australia) basically limit its use to those services where the wood will not be in contact with people or animals (JWPA, 2014; Schreiber et al., 2007). As an example, in the US the use of CCA-treated wood is permitted in the following products: poles in contact with salt water, fence posts, support pillars of structures, foundations, and so on (Forest Products Laboratory, 2010). In addition to national regulations, several countries have wood protection industry associations that have established application standards for protective impregnation solutions: examples include the US (AWPA, 2014), Japan (JWPA, 2014), Australia (TPAA, 2014), and the UK (WPA, 2012). Since 2007, the importation of wood treated with CCA into Europe has been prohibited (WPA, 2012). There are no restrictions in Uruguay on using wood treated with CCA (Dieste, 2014). There are many commercial alternatives to CCA, but in Uruguay the market for such chemical products is underdeveloped.

3.4 Glued laminated timber

Glued laminated timber (GLT) is produced in Uruguay from eucalyptus wood exclusively for non-structural use like door and window frames. Boards of sawn timber are dried to approximately 12% MC to produce lamellas, which are formed by several boards longitudinally connected through finger joints. The face lamellas are glued and pressed to produce rectangular cross-section elements of different lengths.

Stages of the production process (Figure 3)

1. Drying of sawn boards.
2. Structural grading of boards.
3. Optimization.
5. Finger jointing.

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6. Planning laminations.
7. Adhesive application.
8. Cold-pressing and curing.
9. Planning and finishing GLT members.
10. Cut joints using numerical control machinery (optional)
11. Packaging and labelling

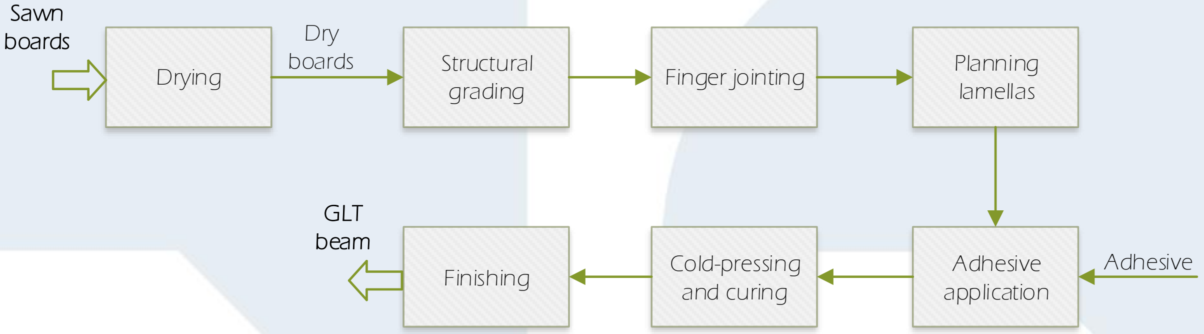

Figure 3. Schematic flow chart of glue laminated timber production

Although there is no Uruguayan production of structural GLT, there are many examples of structures built in Uruguay with these products, which present uncertainty in terms of manufacturing procedures. The fabrication of structural GLT has the following requirements: 1) structural grading of the sawn timber; 2) control of the length of the boards between finger joints; 3) longer sizing of the finger joint; 4) control of the location of the finger joints between lamellas; 5) application of structural adhesives to both finger joints and lamellas; and 6) structural certification of the finished GLT members by mechanical and delamination tests, among others.

Even though structural GLT is not manufactured in Uruguay, results of research projects with local manufacturers (Moya, 2017) have demonstrated the feasibility of producing structural GLT with pine and eucalyptus species.

4 Analysis of Forest-based Bioeconomy Areas

The project has identified five strategic forest-based bioeconomy areas (Table 4).

Table 4. Forest-based Bioeconomy Areas (FBAs)

FBA	Product
1	Forest management
2	Mechanical wood processing
3	Fibre-based biomaterial processing
4	Biorefining
5	Bioenergy

The present work is focused on describing products and value chains that chiefly involve FBAs 2 and 3, using the best information available.

4.1 Identification and description of key products

By no means should this study be considered either a description of current operations or a pre-feasibility analysis for different wood products. It is simply an analysis performed with information available to the public, aimed at comparing products using similar assumptions and with the objective of identifying promising products over a medium- to long-term time frame (2018–2050).

The selection of key products was based on the following premises (Table 5):

- Mature technologies
- Market size and product price could be estimated
- Market could potentially absorb the production in question
- Scale in accordance with production costs (Spelter et al., 1996)
- Products could be fabricated using the local forest resource

Table 5. Strategic products

Transformation	Product (pine)	Product (eucalyptus)
Chemical	Packaging paper (pine)	Bleached eucalyptus kraft pulp (BEKP)
	Chemo-thermo-mechanical pulp (CTMP)	
Mechanical	Sawn timber	Sawn timber
	Laminated veneer lumber (LVL)	Laminated veneer lumber (LVL)
	Cross-laminated timber (CLT)	Cross-laminated timber (CLT)
	Oriented strand board (OSB)	Oriented strand board (OSB)
	Medium-density fibreboard (MDF)	
	Laminated timber (GLT)	Laminated timber (GLT)
	Thermally modified timber (TMT)	Thermally modified timber (TMT)

The operations described rely on a series of assumptions that enable technical and economical evaluations, following Spelter (1996). Examples include chemical consumption, conversion factors, and product design; they are presented in the description of each product. All operations are located 400 km from the port of Montevideo. Products and wood (raw material) are transported by road 400 km and 130 km, respectively, using the cost presented by the public administration (Dirección

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Nacional de Transporte, 2015). The exception is BEKP, where the product is estimated to be exported directly from the plant located near a port [3]. The project life was 10 years and the discount rate was 8% (Banco Central del Uruguay, 2018). The residual value of the installation at the end of the project was 25%, except for BEKP and packaging paper, where it was 50%. Total operation investment was estimated using indexes (Peters et al., 2002).

Figures 4a-g present 28-year series (1998–2016) of export quantity and prices (adjusted for inflation) of BEKP, packaging paper, sawn timber (coniferous and non-coniferous), plywood, oriented strand board (OSB, from 1996), and MDF (from 1995). Figure 4h presents the global export quantity of some of these products to show that, from the perspective of Uruguay, they represent enormous markets to which the Uruguayan production currently makes very limited contributions.

[3] Road transport is not an option for such large volumes, and the estimation of Uruguayan freight train costs would require several assumptions which are outside the scope of this study.

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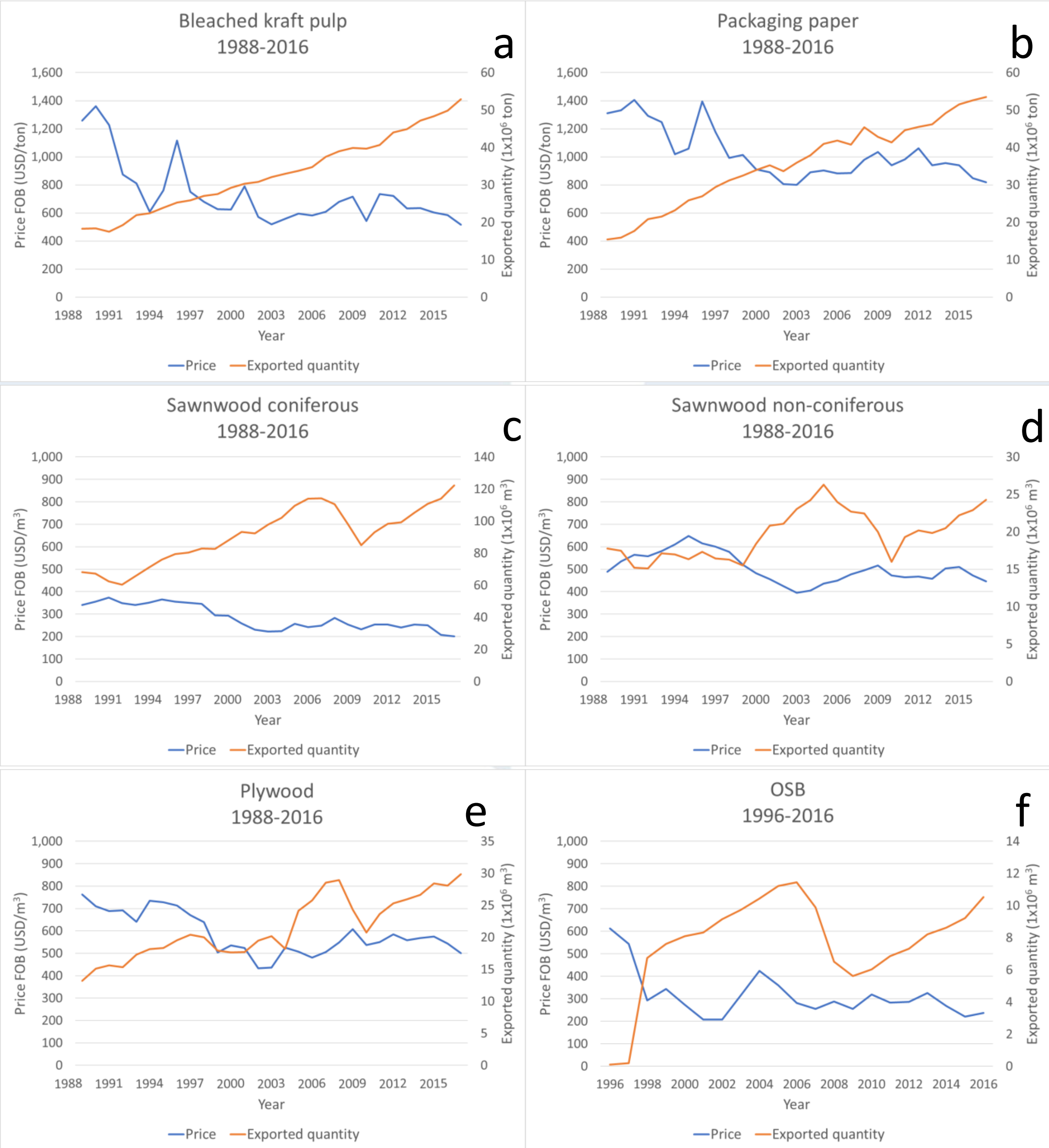

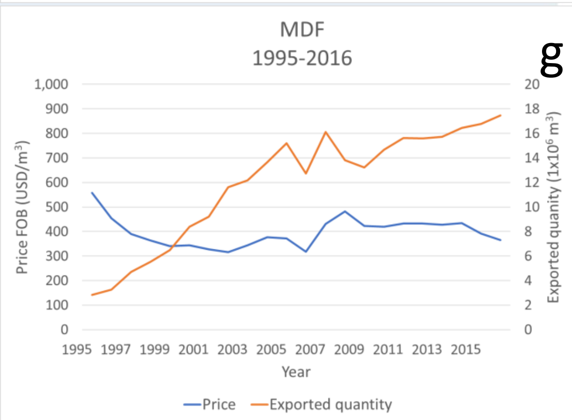

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Product	Unit	Export quantity World (2016)	Uruguay (2016)
Bleached kraft pulp	10^6 ADT ton	53	2.6
Packaging paper	10^6 ton	54	0.0
Coniferous sawnwood	10^6 m^3	122	0.1
Non-coniferous sawnwood	10^6 m^3	24	0.1
MDF	10^6 m^3	17	0.0
Plywood	10^6 m^3	30	0.2
OSB	10^6 m^3	11	

Figure 4. Evolution of prices of and export markets for selected wood products (*commodities*) on a global scale: a) bleached kraft pulp (BKP); b) packaging paper; c) coniferous sawn wood; d) non-coniferous sawn wood; e) plywood; f) OSB; g) MDF; h) global and Uruguayan export quantity for the presented products 2016 (FAO, 2018).

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4.1.1 Bleached eucalyptus kraft pulp

Since BEKP is produced locally, the technological process has been described above (see 4.1). BEKP is mainly used to produce printing and sanitary products like toilet paper and tissues. In early 2000 the production of printing and writing (P&W) paper reached a maximum and then started to decline; therefore, the main destination of BEKP today is raw material for the fabrication of soft paper for hygienic products (Arasto et al., 2018). For the model, the FOB price per air-dried ton (ADT) of BEKP is the average of the last five years, as reported by the Dirección General Forestal[4] (Boscana and Boragno, 2018) (Table 6).

Table 6. FOB prices reported for BEKP (2009–2017)

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017
BEKP FOB price (USD/ADT)	533	818	821	741	634	473	547	482	505

The plant modelled in this study sells its excess electric energy to the grid. Depreciation of the investment was considered to be 50% at the end of the project life. The product is shipped directly from the plant, without intermediate internal transportation in Uruguay. The technical data to construct the operation model was taken from different sources (EcoMetrix Inc., 2010; Gullichsen and Paulapuro, 1999; IPPC, 2015; Rasmussen, 2012) (see Tables 8 and 9).

4.1.2 Packaging paper (pine)

There is an increasing demand for long fibre pulp (Arasto et al., 2018); from 2010 to 2016, this market expanded by 10% (Figure 4b). Brazil is the largest producer of paper in In South America, and the primary volume produced is container and carton board, with production of 6.1 x 10^6 tons in 2016 (FAO, 2018).

In a preliminary analysis, the production of packaging paper (*liner*) from local pine is not feasible in Uruguay, due to the high timber levels required to reach a competitive production level. Assuming an operation of 300,000 tons (at an MC of 6–8%), the minimal foreseeable plant size, the wood procurement (sawmill chips and pulp logs) demands would be more than 170,000 ha, and the available area is approximately 180,000 ha (Uruguay XXI, 2017). In addition, this scenario would demand that all the chips produced by the mechanical transformation of pine timber, assuming a conversion factor of 45%, would be dedicated to supplying chips and pulp logs to this operation. This alternative would only be feasible if pine plantations were increased to at least 200,000 ha, which would require a plantation of 30,000 to 50,000 more ha, depending on the silvicultural system selected (Table 7).

[4] Dirección General Forestal, Ministerio de Agricultura, Ganadería y Pesca (General Forestry Direction, Ministry of Agriculture, Cattle and Fishery)

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Table 7. Wood demand for pine packaging paper

Variable	Unit	Value
Annual production	ADT/year	300,000
Forestry surface requirement	Ha	170,000
Forestry cycle	Year	24
Volume at end of forestry cycle	m^3/ha	318
Conversion to timber	%	45
Annual consumption	10^6m^3	1.5
Raw material per unit product	m^3/ADT	4.5

Considering that such increment in forestry area is not a major obstacle, the fabrication of packaging paper from pine wood is analysed. The process requires pine chips or logs and is like the BEKP process up to the brown pulp stage.

Stages of the production process (Figure 5)

1. Unbleached pulp production.
2. Stock preparation. Converts raw stock (i.e., unbleached pulp) into finished stock (furnish) to produce paper. Chemicals are added to the process to affect the final quality of the paper sheet (resins, wet strength agents, colours, fillers).
3. Paper machine, which consist mainly of a large dewatering device, a wire section, a press section, and a dryer section.
4. Cut to size and packaging.

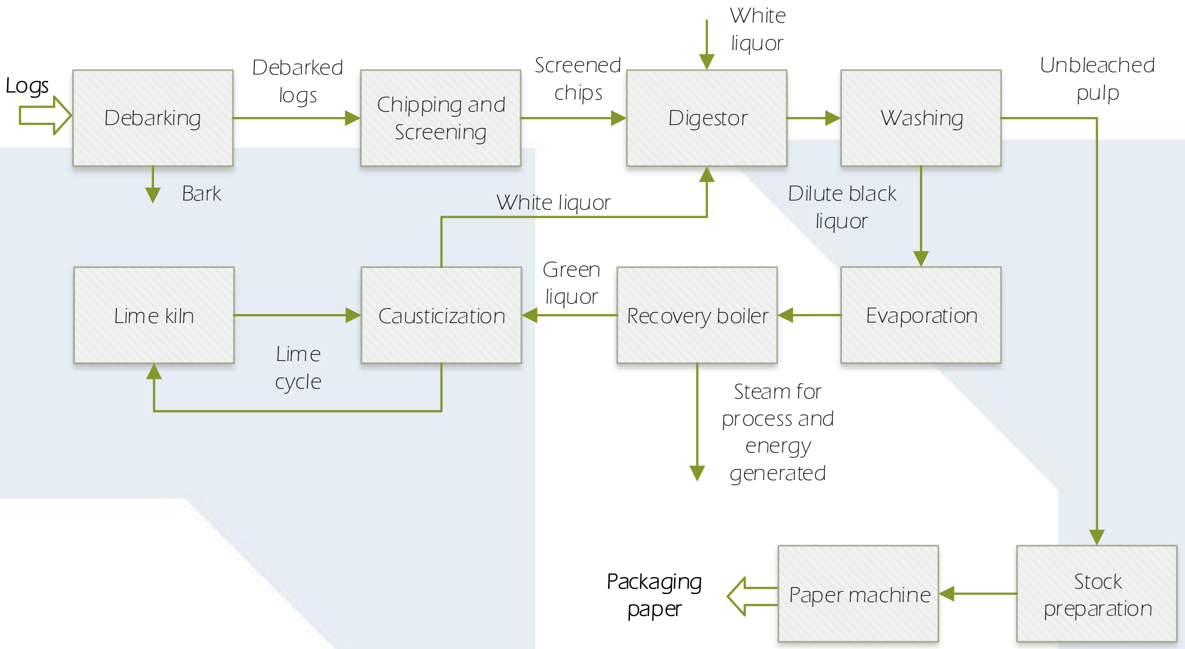

Figure 5. Schematic flow chart of packaging paper production

Exactly as for BEKP, the modelled pulp mill described in this study sells its excess electric energy to the grid. Depreciation of the investment was considered to be 50% at the end of the project life. The technical data to construct the operation model was taken from different sources (EcoMetrix Inc., 2010; Gullichsen and Paulapuro, 1999; IPPC, 2015; Rasmussen, 2012) (see Tables 8 and 9).

4.1.3 Chemo-thermo-mechanical pulp (CTMP) of pine

The properties of the fibre produced by bleached chemo-thermo-mechanical pulp (CTMP) fibre are affected by the processes, particularly by the mechanical one. Therefore, the mechanical properties of CTMP fibre are low. Another drawback is its low brightness level compared with similar products like alkaline-peroxide mechanical pulping (APMP) eucalyptus. Identified advantages are the production of lignosulphonate as a by-product and the low investment required. The main application of this pulp would be to as filler pulp in different grades of paper combined with short-fibre pulp to reduce the raw material costs of manufacturing paper. Consequently, its price should be lower than that of BEKP fibre.

Stages of the production process (Figure 6)

1- Debarking.
2- Chipping.
3- Mechanical pre-treatment.
4- Impregnation. Consists of a slight chemical pre-treatment of the chips to soften the wood for the next step. Softwood chips are usually impregnated with a weak alkali sodium sulphite solution.
5- Refining. Chips are ground between steel discs with bar patterns, normally in a multiple-stage refiner system.
6- Unbleached pulp washing.
7- Bleaching.
8- Drying.
9- Packaging.

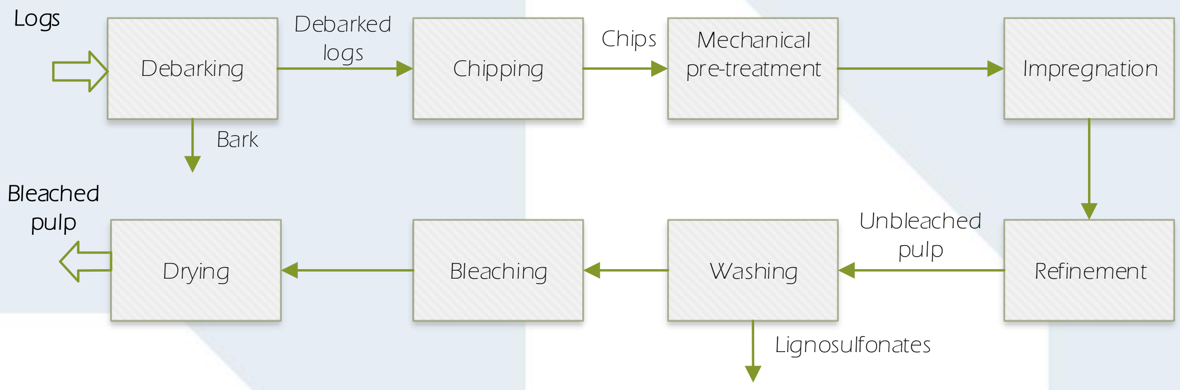

Figure 6. Schematic flow chart of bleached CTMP production

The technical data used to construct both operation models was taken from Cabrera et al. (2018). As there is no developed market for this product, the FOB price was estimated (Tables 8 and 9).

4.1.4 Medium-density fibreboard (MDF)

Fibreboards are produced by hot-pressing a mixture of dried lignocellulosic fibres and glue, usually PF or urea formaldehyde (UF) resins. Individual, homogeneous fibres are obtained from wood chips, and the mixture admits a certain amount of sawdust. Fibreboards present a thickness that ranges between 2 and 100 mm (Thoemen et al., 2010) and are classified according to their density: high (above 800 kg/m^3), medium (between 650 and 800 kg/m^3), and light (between 550 and 650 kg/m^3). The most common product is medium-density fibreboard (MDF), which is widely used for furniture and packaging.

Uruguay does not produce MDF, although there was a small plant operating from 2009 to 2014. Regionally, Brazil is the major exporter (6.2 x 10^5 m^3 in 2016) (FAO, 2018). The price evolution and export market size for the combination of MDF and high-density fibreboard (HDF) shows a growing market with a relatively constant price (Figure 4g).

The raw material for MDF is wood chips, obtained from any source.

Stages of the production process (Figure 7):

1- Debarking.
2- Chipping and screening of chips.
3- Pre-heating and digestion. The preparation of wood chips prior to refining consists of a heat treatment that softens the lignin before impacting the refiner.
4- Refining. An impact device (refiner) is used to convert the softened chips into fibres.
5- Drying and blending. High-temperature dryers reduce the MC of the fibres. Later, the fibres are blended with resin, wax, and any other additives.
6- Mat forming. The resin-coated particles are formed into mat.
7- Pre-pressing.
8- Hot-pressing. Heat and pressure are used to cure the resin and bond the fibres into a solid panel.
9- Sawing.
10- Cooling.
11- Sanding.
12- Cut to size and packaging.

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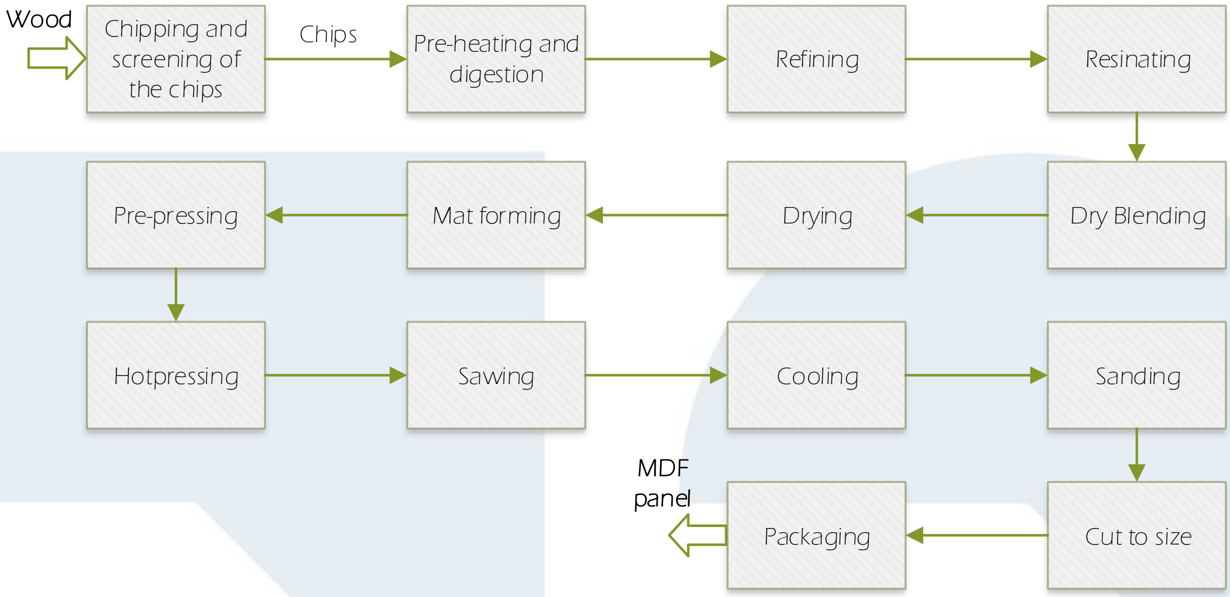

Figure 7. Schematic flow chart of MDF production

The model plant assumes an FOB price for 1 m^3 MDF from the average of the last five years reported by Argentina, Chile, and Brazil (FAO, 2018). The technical data used to construct the operation model was taken from Aguirre et al. (2017) (Tables 8 and 9).

4.1.5 Oriented strand board (OSB)

OSBs are panels with thickness ranging from 10 to 32 mm and made by hot-pressing wood flakes of approximately 0.5 x 20 mm x 100 mm (T x W x L) with a resin (isocyanate, PF, or UF). The flakes of the outer layers are oriented along the axis to improve the mechanical properties of the boards (Thoemen et al., 2010). OSB can be fabricated from small diameter logs, even pulp logs, and allows for the mixture of wood species. The transformation factor from log to product could be as high as 70% (Meil et al., 2007).

In recent years, OSB production has experienced a strong expansion, although the market suffered a steep decline during the housing crisis that started in 2006; since then, the market has recovered (Figure 4f). For many applications, OSB competes with plywood, being a lower-priced product. Regionally, Brazil and Chile export OSB (in 2016, 120 x 10^3 and 6.6 x 10^3 m^3, respectively) (FAO, 2018).

Stages of the production process (Figure 8)

1- Log wetting. Softens the bark to facilitate debarking.
2- Debarking.
3- Formation of chips (flaking). Flakes should meet the specifications for both the faces and the centre.
4- Drying of flakes.
5- Screening. The chips pass to the vibrating screens to be separated into the desired dimensions. Three flows result from the screening: 1) chips that meet the specifications for board faces, 2) chips that meet the specifications for the centre of the board, and 3) fines.
6- Gluing (blending). The dry chips are mixed with resin, wax, and other additives.

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7- Formation of the mat (forming). To achieve the correct orientation of the chips, three forming machines – two longitudinal layer forming machines and one transversal layer forming machine – are used to distribute them in such a way that the different layers are oriented perpendicularly to one another other.
8- Hot-pressing.
9- Finishing.

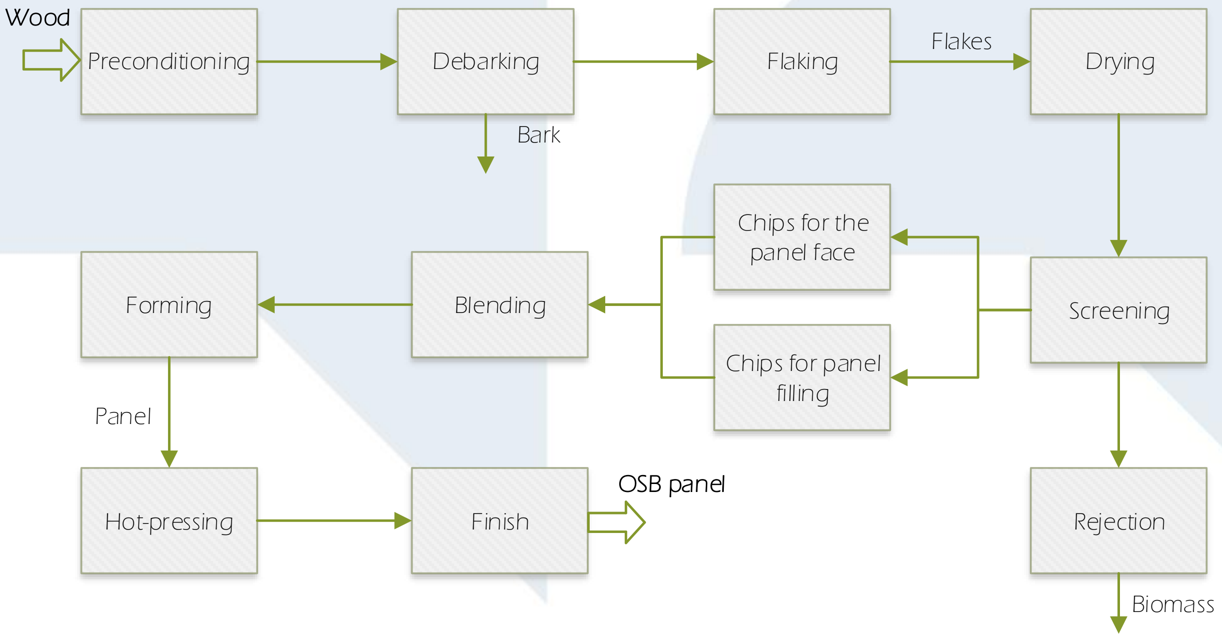

Figure 8. Schematic flow chart of OSB production

For the plant modelled in this study, the FOB price for 1 m^3 OSB was the average of the last five years, as reported by FAOSTAT for Brazil and Chile (FAO, 2018). At the price considered, OSB is not an option, since the production cost is higher than the price. The issues of the technology applied, and the high value of chemicals pose questions for future analysis. The technical data to construct the operation model was taken from Brizolara et al. (2015); see Tables 8 and 9.

4.1.6 Sawn timber of pine and eucalyptus

Since sawn wood is produced locally, the technological process is described above (section 4.3). The product known as sawn timber is actually a combination of products: high-value clear timber for the carpentry industry is the top product (appearance wood), and packaging wood (pallets) is the bottom product. The proportion is variable and depends on markets. For pine and eucalyptus, the conversion factor from logs to boards was estimated at 45% and 40%, respectively. Given equal thickness and similar initial MC, the drying time for pine boards is one-fifth of the drying time for eucalyptus (Redman and McGavin, 2008). The operating cost (electricity to move air inside the drying kilns) and the investment cost (more kilns to dry the same volume) is thus considerably higher for eucalyptus than pine. Therefore, a eucalyptus sawmill, like other hardwoods, requires a minimal operation size, below which the operation wold not be profitable. In this study, operation sizes of 40,000 ha and 100,000 ha were considered for pine and eucalyptus, respectively. The FOB price of 1 m^3 of sawn timber was the average of the last five years reported by the DGF-MGAP (Boscana and Boragno, 2018).

The technical data to construct the two operation models was taken from different sources (Fierro et al., 2009; Ligrone and Pou, 1996; Walker, 2006) (Tables 8 and 9).

4.1.7 Laminated veneer lumber (LVL)

Laminated veneer lumber (LVL) is produced by gluing dried wood veneers of thicknesses from 2.5 to 3.2 mm in the direction parallel to the axis, forming a multi-layered assembly that is hot-pressed and cut to size. The typical thickness is 38 mm (naturally, it could be thicker), the width ranges from 0.6 to 1.2 m, and the length is determined by the end use (Walker, 2006). The main adhesive used is PF resin. Logs are rotary-peeled in a lathe to obtain veneers that are dried, graded for mechanical properties (visually or using non-destructive equipment), and cut to size (Walker, 2006). LVL is a direct competitor to GLT. The production of LVL requires logs with a minimum diameter, since holding the logs against the peeling knife leaves a cylindrical residue that has a diameter of approximately 60 mm (Walker, 2006).

Stages of the production process (Figure 9)

1. Debarking and preconditioning.
2. Rotary peeling. A lathe turns the log into a thin, continuous sheet with a typical thickness of approximately 3 mm, which is then guillotine-sized.
3. Drying of veneers (5–6% MC dry basis).
4. Structural grading of veneers. Material that does not meet the grade is used for plywood production.
5. Assembly. Stacking of glued sheets to achieve the objective thickness.
6. Pre-pressing and pressing.
7. Cutting to dimension. The panel is longitudinally cut to obtain the beams.
8. Finishing.
9. Packaging.

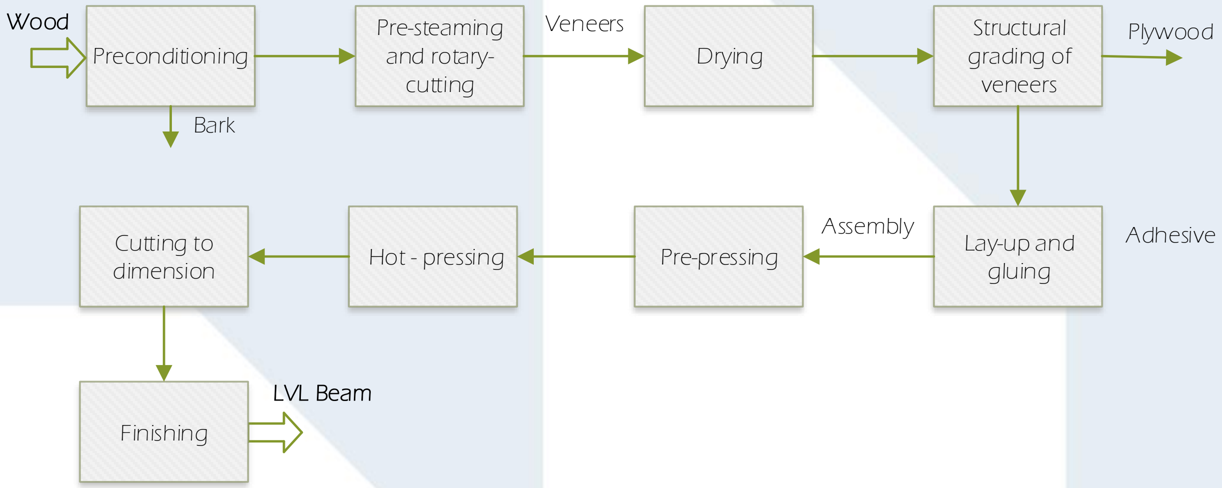

Figure 9. Schematic flow chart of LVL production

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For the model plant analysed in this study, the conversion factor from logs to LVL was considered to be 51%. FOB price of 1 m^3 LVL was estimated from the best available source. The technical data used to construct the operation model was taken from Caamaño et al. (2016); see Tables 8 and 9).

4.1.8 Glued laminated timber (GLT) of pine and eucalyptus

Since non-structural GLT is produced locally, the technological process is described above (section 4.4). In the operation considered for this study, pine GLT is produced from fresh boards that are chemically impregnated to improve the natural durability of the timber, and then dried to 12% MC before being glued to form the panel. Since *Eucalyptus spp.* cannot be impregnated, eucalyptus GLT is produced directly from dried boards. In both pine and eucalyptus, a certain number of knots are accepted. The conversion factors of timber to pine and eucalyptus beams were assumed to be 80% and 76%, respectively. The FOB price was estimated. The technical data to construct the operation models was taken from different sources (Frühwald et al., 2003; Stevens and Criner, 2000); see Tables 8 and 9).

4.1.9 Cross-laminated timber (CLT) of pine and eucalyptus

Cross-laminated timber (CLT) is a panel manufactured by orthogonally gluing layers of boards dried to approximately 12% MC. The number of layers usually varies between five and seven, with layers of up to 40 mm thickness. Panel dimensions varies from (0.1–0.3) x (3.0–4.0) m, T x W, and length according to need. CLT is usually manufactured using coniferous wood, but there is experience with other species, particularly eucalyptus (Lu et al., 2018). The actual market size is approximately 1 x 10^6 m^3, and the expected market growth for CLT in Europe in the coming years is more than 25% annually (Hildebrandt et al., 2017). Most production is concentrated in central Europe, but there are plants operating in the US, Canada, and other countries. Chile and Brazil have small CLT plants that produce against demand. In 2015, 60% of CLT production took place in Austria, 16% in Germany, and 24% in the rest of the world (Horx-Strathen et al., 2017). CLT is not commercially produced in Uruguay, although buildings have been built or are under construction using CLT imported from Italy and Spain.

The raw material for CLT is structurally graded timber, usually of low mechanical properties. CLT was invented to use this kind of wood for structural purposes.

Stages of the production process (Figure 10):

1. Drying of sawn boards.
2. Structural grading of timber.
3. Longitudinal and transversal optimization. The longitudinal optimizer, through a system of saws, adjusts the timber that enters the production line to standardize its width. Transverse optimization allows for the detection and correction of imperfections like large knots.
4. Finger joint timber pieces to create lamellas of the desirable length, allowing for panels to be fabricated from short pieces of timber. The finger joint must have structural length, and a structural adhesive is used.
5. Assembly of the panels, gluing, and cold-pressing. The panels are assembled inside the press, the structural glue is applied with an automatic head, and the assembly is vacuum-pressed.
6. Surface finishing.
7. Design and cutting of openings using numerical control machinery.

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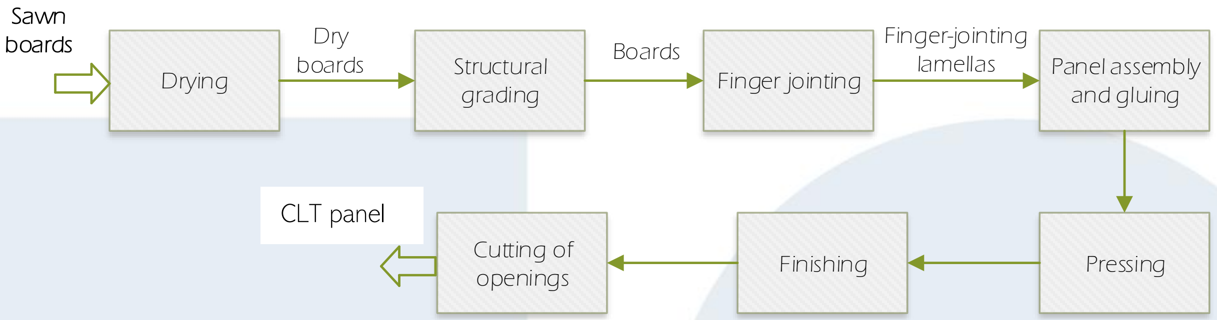

Figure 10. Schematic flow chart of CLT production

In the operation analysed for this study, pine CLT is produced from fresh boards, 50% of which are chemically impregnated to improve the timber's natural durability. Internationally, CLT is usually not impregnated, since the timber is protected by the construction design; in this study, CLT is mainly focused on the local and regional markets, so it was concluded that impregnation would enhance the end consumer's confidence in the product (D. Godoy, 2018). Since *Eucalyptus spp.* are not impregnable, eucalyptus CLT is produced from dried boards. The conversion factors of timber to CLT panels of pine and eucalyptus were taken to be 68% and 76%, respectively. The technical data to construct the operation models was taken from García et al. (2018). The FOB price was estimated (Tables 8 and 9).

4.1.10 Thermally modified timber (TMT) of pine and eucalyptus

The thermal modification of timber is an operation that increases the durability and dimensional stability of wood without impregnation (Hill, 2006). The product is mainly used for outdoor exposure timber such as façades, decks, windows, and doors. Thermally modified timber (TMT) is particularly promising for eucalyptus timber, a non-impregnable timber, since it is a technology that improves durability without the need to force chemicals into the wood (Calonego et al., 2012; Wentzel et al., 2018). TMT is a process that adds value to sawn wood, so it would be an alternative to impregnation to increase durability or to engineered wood products (EWPs). Currently, Europe is the main producer, at 400,000 m^3 in 2015 (Gamache et al., 2017). From 2012 to 2017, the International ThermoWood Association, which controls the primary TMT technology, reported a growth rate of 9% (Thermowood, 2018). In South America, there is a plant operating in Valdivia, Chile.

The process is based on heating dried timber (10–15% MC dry basis) to a maximum of 200 °C in an atmosphere deprived of oxygen (saturated steam, vacuum, or nitrogen are possible alternatives), so no chemicals are used in the process (Hill, 2006). TMT has better biological durability and lower MC than sawn timber that has not been thermally modified.

Stages of the production process (Figure 11)

1. Grading of dried board suitable for TMT.
2. Thermal treatment. All the applied processes have in common a thermal treatment at elevated temperatures (160–240 °C). The main differences between the various processes are the process conditions that are involved with different treatment technologies.
3. Grading of thermally modified timber.
4. Finishing (surfacing and moulding).

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5. Packaging.

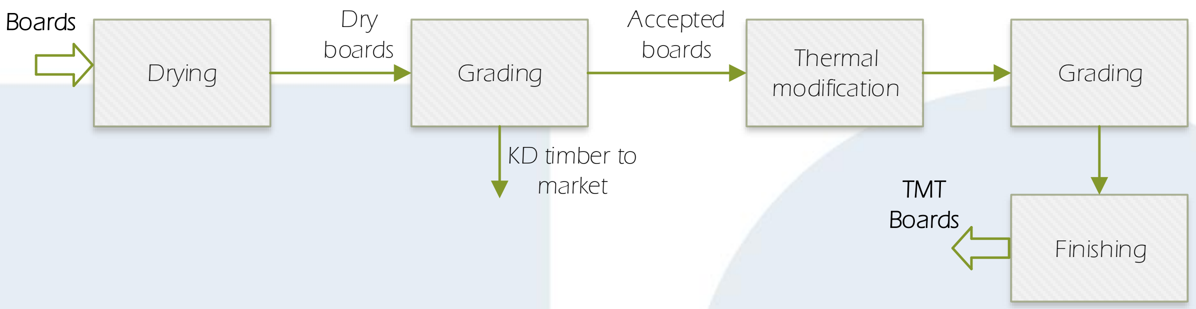

Figure 11. Schematic flow chart of TMT production

In this study, pine TMT is produced from fresh boards, while eucalyptus TMT is produced directly from dried boards. The technical data to construct the operation model was taken from Barragán et al. (2016). Since there is no established market for TMT, the FOB price was estimated from European suppliers (Tables 8 and 9).

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Table 8. Production operation description

Wood species	Products[1]	Wood consumption			Production		FOB price	Cost[2]	Investment[3]
		Units	format	Value	Units	Value	USD/unit	USD/unit	USD/unit
Pine	OSB	m^3	Pulp logs	300,000	m^3	150,000	250	288	529
	MDF	m^3	Pulp logs, chips	700,000	m^3	300,000	334	312	550
	LVL	m^3	Sawlogs	159,000	m^3	80,000	430	326	761
	CLT	m^3	Fresh timber	44,200	m^3	30,000	953	713	838
	GLT	m^3	Kiln-dried timber	22,100	m^3	15,000	600	538	619
	Sawn timber	m^3	Sawlogs	100,000	m^3	45,000	312	237	489
	TMT	m^3	Fresh timber	22,500	m^3	10,000	796	845	2,300
	BCTMP	ton	Pulp logs, chips	280,000	ADT	130,000	450	501	857
	Packaging paper	ton	Pulp logs, chips	1,350,000	ton	300,000	650	594	2,259
Eucalyptus	LVL	m^3	Sawlogs	159,000	m^3	80,000	430	346	761
	CLT	m^3	Kiln-dried timber	39,000	m^3	30,000	953	813	636
	GLT	m^3	Kiln-dried timber	22,100	m^3	15,000	993	746	619
	Sawn timber	m^3	Sawlogs	250,000	m^3	100,000	350	288	562
	TMT	m^3	KD timber	11,000	m^3	10,000	1,035	790	2,106
	BEKP	m^3	Pulp logs, chips	4,600,000	ADT	1,300,000	528	487	1,462

[1] OSB: Oriented strand board; MDF: Medium-density fibreboard; LVL: Laminated veneer lumber; CLT: Cross-laminated timber; GLT: Glued laminated timber; TMT: Thermally modified timber; BCTMP: Bleached coniferous thermo-mechanical pulp; BEKP: Bleached eucalyptus kraft pulp.
[2] Costs include wood, chemical products, energy, labour, depreciation, and taxes.
[3] Investment includes equipment, installation, land, services, depreciation, and amortization.

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Table 9. Values considered for the estimation of the operations results

Wood species	Item	Product	Unit	Value
	Electricity	Bought	USD/MWh	95
		Sold	USD/MWh	92
	Transportation	Road freight (product)	USD/ton-km	0.11
		Road freight (wood)	USD/ton-km	0.09
Pine	Chemicals	Packaging paper	USD/ton	17
		BCTMP	USD/ton	96
	Raw material	Chips	USD/m³	19
		Pulp logs	USD/m³	35
		Sawlogs	USD/m³	40
		Fresh timber	USD/m³	160
		Kiln-dried timber	USD/m³	250
	Adhesives	CLT (polyurethane)	USD/m³	121
		LVL (PF resin)	USD/m³	28
		MDF (PF resin)	USD/m³	81
		GLT (polyurethane)	USD/m³	36
		OSB	USD/m³	94
Eucalyptus	Chemicals	BEKP	USD/m³	57
	Raw material	Pulp logs	USD/m³	67
		Sawlogs	USD/m³	79
		KD timber	USD/m³	334
	Adhesives	CLT (polyurethane)	USD/m³	121
		LVL (PF resin)	USD/m³	28
		CLT (polyurethane)	USD/m³	36

Production costs per strategical product operation were divided by genus, disaggregated, and presented by unit of product to allow for comparison between alternatives (Figures 12 and 13).

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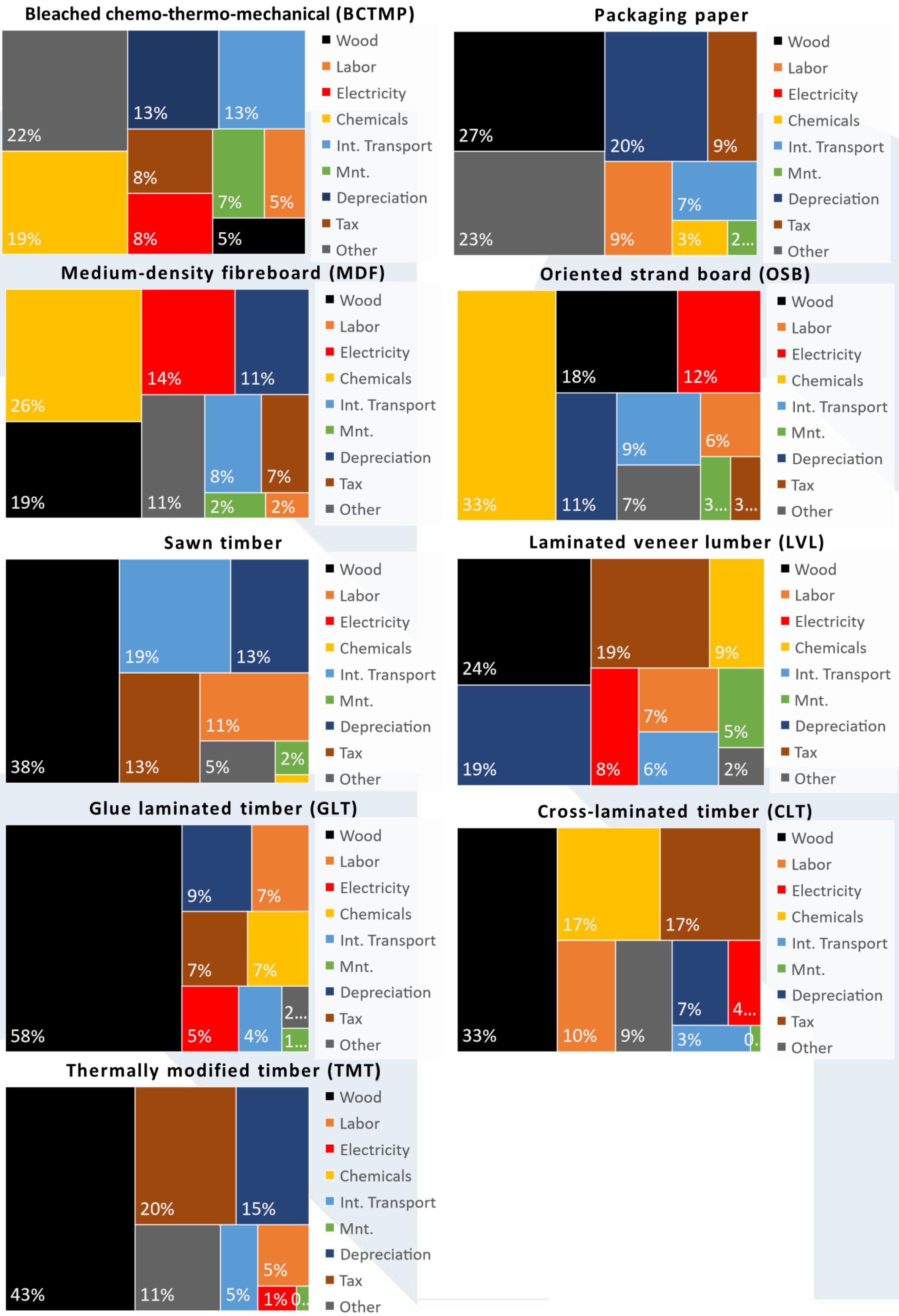

Figure 12. Pine operations: disaggregated costs per unit of production

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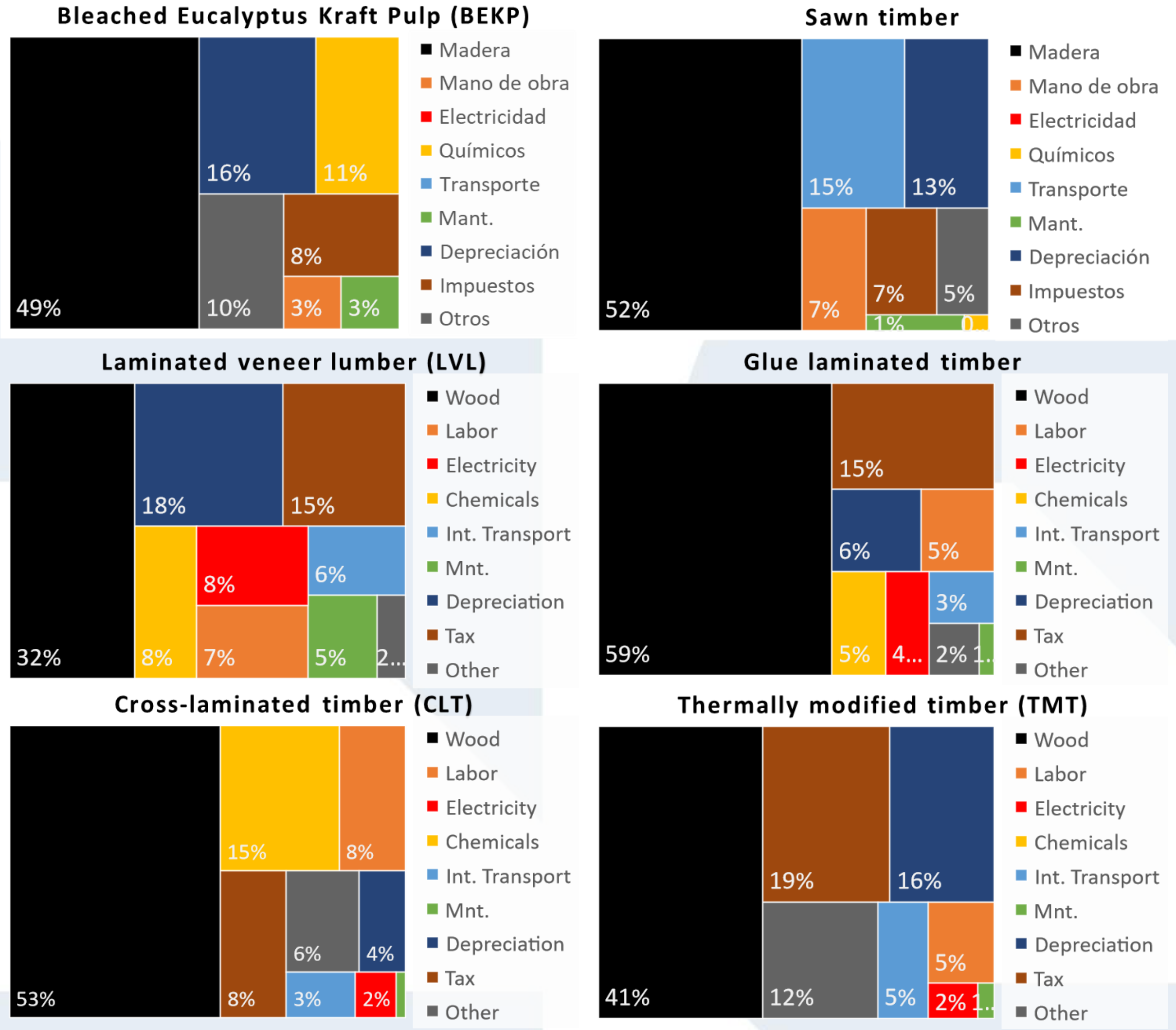

Figure 13. Eucalyptus operations: disaggregated costs per unit of production

The selected products were economically evaluated by estimating the following parameters (García Pouquette et al., 1998):

1. Earnings before interest, taxes, depreciation, and amortization (EBITDA).
2. Internal rate of return (IRR).
3. Net present value (NPV) at an interest rate of 8%.
4. Value added (VA), considered as benefits before tax plus labour costs.
5. Workforce intensity (investment/labour).

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Table 10. Economic evaluation per product operation

			Production	EBITDA	IRR	NPV	VA
Wood species	Products	Units	Value	USD/unit	%	10^6xUSD	USD/unit
Pine	OSB	m^3	150,000	1.8	-16.5	-79	-14
	MDF	m^3	300,000	78	4.8	-24	47
	LVL	m^3	80,000	234	18.6	35	219
	CLT	m^3	30,000	363	17.4	14	427
	GLT	m^3	15,000	147	3.6	-2	139
	Sawn timber	m^3	45,000	176	14.9	8	171
	TMT	m^3	10,000	581	10.1	2	495
	BCTMP	ADT	130,000	172	8.7	4	133
	Packaging paper	Ton	300,000	248	4.0	-141	186
Eucalyptus	LVL	m^3	80,000	205	15.8	26	190
	CLT	m^3	30,000	211	11.9	4	276
	GLT	m^3	15,000	406	33.9	14	397
	Sawn timber	m^3	100,000	124	6.0	-5	108
	TMT	m^3	10,000	523	10.2	2	435
	BEKP	ADT	1,300,000	178	5.0	-297	113

OSB: Oriented strand board; MDF: Medium-density fibreboard; LVL: Laminated veneer lumber; CLT: Cross-laminated timber; GLT: Glued laminated timber; TMT: Thermally modified timber; BCTMP: Bleached coniferous thermo-mechanical pulp; BEKP: Bleached eucalyptus kraft pulp.

Operations in Uruguay that meet certain criteria of contributing to development receive tax exoneration under Public Law 16.906 (Senado República Oriental del Uruguay, 1998). In addition, Uruguay can authorise the establishment of operations in tax-free zones, as it did with the pulp plants already in the country, Fray Bentos and Punta Pereira. Therefore, the economic evaluation of the different operations is presented both with and without taxes (Table 11).

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Table 11. Economic evaluation per product operation without taxes

Wood species	Products	Units	Production Value	EBITDA USD/unit	IRR %	NPV 10^6xUSD	VA USD/unit
Pine	OSB	m^3	150,000	1.8	-14.0	-73	-14
	MDF	m^3	300,000	78	9.3	11	47
	LVL	m^3	80,000	234	26.6	65	219
	CLT	m^3	30,000	363	27.5	32	427
	GLT	m^3	15,000	147	10.8	1	139
	Sawn timber	m^3	45,000	176	23.0	17	171
	TMT	m^3	10,000	581	15.7	9	495
	BCTMP	ADT	130,000	172	13.5	33	133
	Packaging paper	ton	300,000	248	7.4	-20	186
Eucalyptus	LVL	m^3	80,000	205	22.8	51	190
	CLT	m^3	30,000	211	20.4	15	276
	GLT	m^3	15,000	406	50.4	24	397
	Sawn timber	m^3	100,000	124	11.0	8	108
	TMT	m^3	10,000	523	15.4	8	435
	BEKP	ADT	1,300,000	178	8.8	79	113

OSB: Oriented strand board; MDF: Medium-density fibreboard; LVL: Laminated veneer lumber; CLT: Cross-laminated timber; GLT: Glued laminated timber; TMT: Thermally modified timber; BCTMP: Bleached coniferous thermo-mechanical pulp; BEKP: Bleached eucalyptus kraft pulp.

Some of the products selected, such as BCTMP, CLT, and pine GLT, appear to be potentially attractive options; however, they are relatively new in the market, and there is limited access to price series. Due to this price uncertainty, a price sensibility analysis of NPV was conducted, with NPV as a function of price variation. The results showed that BCTMP is extremely sensitive to price, while the other products are moderately dependent on price (Figure 14).

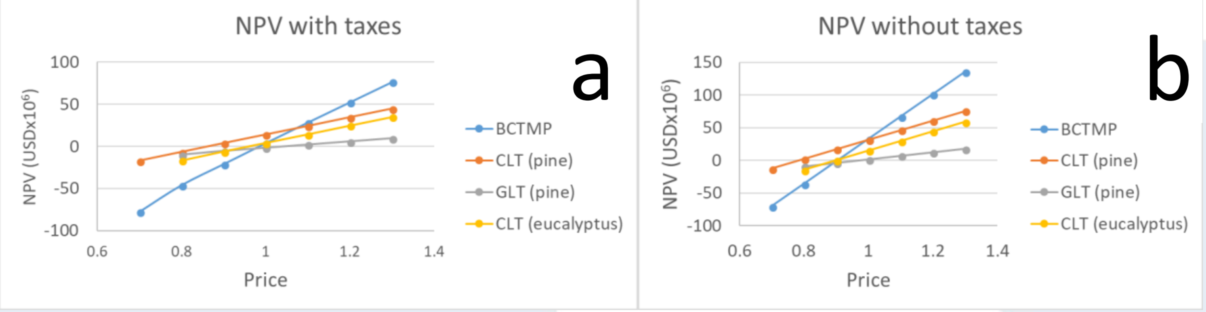

Figure 14. Price sensibility analysis of NPV (a) with and(b) without taxes

As reported, the discount rate used was 8%. For some products where the investment was large, a discount rate of 5% was tested. As expected, the economic evaluation improved for all products in that scenario (Table 12).

Table 12. Economical evaluation for high-investment products using a discount rate of 5%

	With taxes		Without taxes	
	NPV	IRR	NPV	IRR
Product	10^6xUSD	%	10^6xUSD	%
BEKP	-1.5	5.0%	441.0	8.8%
BCTMP	24.3	8.7%	58.6	13.5%
Packaging paper	-42.5	4.0%	99.7	7.4%
MDF	-1.7	4.8%	39.4	9.3%

BEKP: Bleached eucalyptus kraft pulp; BCTMP: Bleached coniferous thermo-mechanical pulp MDF: Medium-density fibreboard.

4.2 Description of value chains

The main goal of this approach is to show that an integrated techno-economic analysis of the forestry at the country level should start with at least the following information:

- Products
- Market size (local and international)
- Raw material availability
- Chain integration

In every value chain presented, production, cost structure, investment, and prices are approximate values, taken from the best available, referenced sources.

In Uruguay this information is only partially available, and efforts were made to construct feasible scenarios based on reasonable assumptions. The forestry lands dedicated to pine and eucalyptus are 180,000 and 600,000 ha, respectively (Uruguay XXI, 2017), while the 2017 industrial log extraction of pine and eucalyptus was 2 x 10^6 and 11 x 10^6 ton, respectively (Boscana and Boragno, 2018). Approximately 1.2 x 10^6 tons of pine wood were exported as logs in 2017 (Boscana and Boragno, 2018).

Clearly, the estimation of the market size for products such as CLT, structural eucalyptus GLT, TMT, BCTMP, among some of the products analysed, is limited due to the nature of the products. These are currently niche markets, but they could potentially become open to Uruguayan products. Since the determination of market size for each product exceeds the scope of this study, a criterion of potential global market for Uruguayan products was proposed, based on the data presented in Figure 1 for commodities (see Table 13).

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Table 13. Potential Uruguayan market for selected wood products

			Potential Uruguayan market
Wood species	Products	Units	Value
Pine	OSB	m^3	Unlimited
	MDF	m^3	Unlimited
	LVL	m^3	130,000
	CLT	m^3	60,000
	GLT	m^3	60,000
	Sawn timber	m^3	Unlimited
	TMT	m^3	60,000
	BCTMP	ADT	240,000
	Packaging paper	Ton	Unlimited
Eucalyptus	LVL	m^3	190,000
	CLT	m^3	60,000
	GLT	m^3	60,000
	Sawn timber	m^3	Unlimited
	TMT	m^3	60,000
	BEKP	ADT	Unlimited

OSB: Oriented strand board; MDF: Medium-density fibreboard; LVL: Laminated veneer lumber; CLT: Cross-laminated timber; GLT: Glued laminated timber; TMT: Thermally modified timber; BCTMP: Bleached coniferous thermo-mechanical pulp; BEKP: Bleached eucalyptus kraft pulp.

The objective in this analysis is to present the value of integrating various product operations rather than to estimate the maximum value to be extracted from the forest resource. The value chains described are constellations of products based on the analysis above. The scenario of wood input to this hypothetical forestry industry is divided into pine and eucalyptus. The selected size is taken from present wood consumption (Boscana and Boragno, 2018), given that the scenario is a module that could be repeated if different value chains were proposed. The system limits are simple: 1) the market for each product should be large enough to absorb a reasonable share of Uruguayan production (Table 13), and 2) there should be enough local wood to supply the proposed product constellations that make up the various value chains. Therefore, wood consumption units were designed for pine and eucalyptus. According to present estimates (Uruguay XXI, 2017), the current supply of timber could support more than one value chain (Table 14).

Table 14. Wood resource input scenario

Wood species	Forest product	Unit	Value ($x10^6$)
Pine	Sawlogs	Ton	1.0
	Pulp logs	Ton	0.2
	Total	Ton	1.2
Eucalyptus	Sawlogs	Ton	1.7
	Pulp logs	Ton	3.6
	Total	Ton	5.3

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The different value chains presented are intentionally simple and conservative: a group of products that could be produced using the same mass of raw material (1.2 x 10^6 tons and 5.3 x 10^6 tons for pine and eucalyptus, respectively (Table 14)), which is allocated to every operation according to its characteristics (e.g., pulp logs to MDF, sawlogs to LVL; see Table 15):

- The benefits of sharing services (land, electricity, chemicals cycle, effluent treatment, etc.) are not considered.
- Products are fabricated using only one species of pine or eucalyptus which is clearly not the case for many of the products selected (MDF, LVL, GLT, among others).
- Operation models are repeated until the allocated wood is used (e.g., five sawmills and one MDF plant).

Table 15. Value chains analysed

		Products[1]								
Wood species	Value chain	Electricity	Pulp logs	Pulp[2]	MDF	Sawn timber	LVL	GLT[3]	CLT	TMT
Pine	Baseline	X	X			X				
	1				X	X			X	
	2			X	X	X		X	X	
	3				X	X	X		X	X
Eucalyptus	Baseline			X		X				
	1					X	X	X	X	X

[1] MDF: Medium-density fibreboard; LVL: Laminated veneer lumber; GLT: Glued laminated timber; CLT: Cross-laminated timber; TMT: Thermally modified timber.
[2] Pulp: for pine and eucalyptus, the products are BCTMP and lignosulphonate and BEKP, respectively.
[3] GLT: For pine and eucalyptus the products are GL18h and GL24h, respectively.

The value chains proposed were analysed using the following parameters: investment, sales, VA, EBITDA, benefit before and after tax, and relation between investment and labour. The results were normalized against those of the baseline. As expected, the baseline presents lower results for VA and EBITDA than a more sophisticated constellation of products would. For pine products, value chain 3 presented the best results (Figure 15):

Figure 15. Value chain scenarios normalized against the baseline

To analyse the impact of the synergy of combining different operations, value chain Pine 1 was integrated in terms of wood supply, energy, and transport, which is a simple integration, since cost and investment were not scaled and waste water treatment, infrastructure, and labour, among other

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factors, were not included. Even in such a simplified scenario, value chain Pine 1 increases EBITDA and VA by 43% and 42%, respectively. The IRR and NPV of the whole chain with taxes were 16.5% and 177 x 10^6 USD, respectively; without taxes, they were 25.6% and 395 x 10^6 USD, respectively (Figure 16).

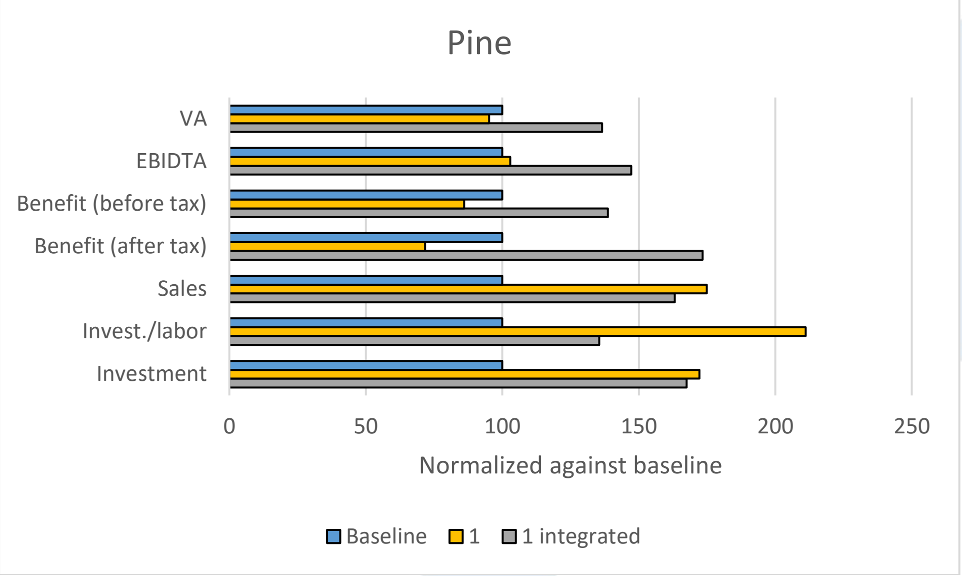

Figure 16. Value chain Pine 1 integrated in terms of wood supply, energy, and transport

5 Uruguayan wood as raw material for fibre and chemicals

5.1 Pulp and paper

Currently, two pulp mills are installed in Uruguay, Fray Bentos and Punta Pereira, with a joint production capacity of 2.6 million ADT. There is abundant research about the pulp and paper properties of Uruguay's eucalyptus wood (Balmelli and Resquín, 2005; Doldán, 2007; Resquin et al., 2005). By contrast, there is no information about the properties of pulp and paper fabricated using local pine.

5.2 Biorefinery products[5]

The biorefinery concept comprises a wide range of technologies able to separate biomass resources (wood, grasses, corn, etc.) into their building blocks (carbohydrates, lignin, proteins, triglycerides), which can then be converted into value-added products, biofuels, and biochemicals. A biorefinery is a facility that integrates biomass conversion processes and equipment to produce biofuels, power, and chemicals from biomass. This concept is analogous to today's petroleum refinery, which produces multiple fuels and other products from petroleum.

Although there are a wide variety of potential uses of new products derived from cellulose, hemicelluloses, and lignin, most are still at the laboratory or prototype study phase (Liitiä and Tamminen, 2016). This makes it extremely difficult to project the size of the market. In any case, given the importance of the chemical transformation of wood in Uruguay, the development of other industries that complement pulp production under the biorefinery concept is not unreasonable, since that is the direction in which the industry appears to be moving.

Structural changes began in the global forest industry in the early 2000s, when the production of printing papers reached its highest production volume; they started to decline after 2006. The recent evolution of business has been characterized by investments in other uses like bioenergy and cardboard production and the development of soft paper and sanitary products (Harlin et al., 2018). In the next few years, the consumption of printing papers will decrease, while packaging paper and tissue will remain strong markets (Arasto et al., 2018).

Sanitary and textile materials are among the most in-demand fibre products, due to population growth and improvements in living conditions. In the coming decades, cellulose could make up more than 30% of textile fibre demand, which represents a large market increase (Arasto et al., 2018). Due to innovation and cultural changes, such as the growing importance of bio-based materials and consumer awareness of environmental sustainability, cellulose will be used differently in the future than how it is used today, which will affect the way the industry operates (Harlin et al., 2018).

Cellulose-based products

[5] This section is a short literature review that will be expanded in a next report, dedicated to the chemical transformation of wood for the Uruguayan conditions.

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Increased demand for sanitary paper is related to changes in consumer behaviour. Fibres from the petrochemical industry are not environmentally friendly, with recycling being a major logistical and technological challenge. Nonwoven fabrics can be used in packaging and sanitary products (e.g., nonwoven bags can replace plastic bags), and small pulp mills could be modified to produce dissolving pulp. In addition, nonwoven fabric can be integrated into pulp production, just as it previously was with paper production, to obtain renewable, bio-based products (Harlin et al., 2018). Mouldable cardboard, which is both recyclable and renewable, is an exciting innovation that could replace plastic produced by the petrochemical industry. Thermo-mouldable cellulose is another environmentally friendlier alternative to bioplastics, applying mature technology developed for the manufacture of plastic products. In addition, the industrial application of micro- and nanocellulose is regarded as years away, due to the research needed to overcome the current challenges (Harlin et al., 2018).

Hemicellulose-based products

Even though hemicelluloses have a low calorific value, pulp mills burn hemicellulose to produce steam and energy; it would be sensible to extract hemicellulose to produce higher-value products (Norström et al., 2015). Hardwood hemicelluloses are rich in xylan (Cebreiros et al., 2017), which could be used to produce bioplastics, barrier materials, adhesives, and dissolving films (Arasto et al., 2018; Norström et al., 2015). Currently, dishwasher detergent is usually packed with dissolving plastics formed into tablets, so the polymer is carried away with the waste water; it is foreseeable that hemicellulose-based films could replace petrochemical plastic in this application (Arasto et al., 2018).

Lignin-based products

Lignin is the most important by-product of lignocellulosic biorefineries and a valuable renewable resource for the chemical industry. The pulping industry is the major source of lignin, but substantial amounts of lignin-rich side streams are expected to originate from bioethanol production in the future. Roughly 20–25% of black liquor lignin could be recovered without compromising a pulp mill's energy demands (Gellerstedt et al., 2013). The first industrial plant to manufacture lignin in Latin America recently opened in in São Paulo, with an annual capacity of 20,000 tons, and the main use for this lignin is adhesives (Suzano Pulp and Paper, 2018). If a third cellulose pulp mill is established in Uruguay, the total lignin production would represent roughly 500,000 tons per year.

Lignin can be functionalized for different uses. The alkali-O_2 oxidation of lignin can produce versatile lignin-based surface-active agents that have applications in several end uses with high market volumes, such as high-performance concrete plasticizers and versatile dispersants. In addition, lignin has the potential to replace synthetic dispersants. Lignin use in phenolic resins, particularly in adhesives for the wood industry, is one of the most promising uses of lignin (Arasto et al., 2018; Liitiä and Tamminen, 2016).

The growing global market for wood construction will heighten the demand for adhesives to be used in engineered wood structures. There is increasing interest in adhesives with no volatile organic compounds, particularly formaldehyde. Adhesives based on PF resin derived from petroleum are already widely used. Lignin is a natural source of phenol; in addition, it is renewable, abundant, and has low costs if obtained on a large scale (Kouisni et al., 2011). However, the current technological situation can only achieve a low replacement of phenol by kraft lignin: 30% at the most (Pizzi, 2016). The main technological issue that requires research attention is to increase the reactivity of lignin (Arasto et al., 2018; Liitiä and Tamminen, 2016).

Biocrude is a liquid matrix that is similar to petroleum and obtained from kraft pulp mill black liquor; up to 75% of the energy can be extracted to produce a gasoline hybrid fuel (Arasto et al., 2018). In addition, jet fuels can be produced from lignin by catalytic conversion (Bi et al., 2015; Sandquist and Guell, 2012).

6 Uruguayan timber as building material

Timber construction is increasing as a global phenomenon, mainly using EWPs like GLT and CLT for new structural systems (Dangel, 2016). Timber is commonly used in many countries to construct not only residential buildings but also office buildings, warehouses, and bridges; one new challenge is the construction of increasingly tall timber buildings (Gerard and Barber, 2013). Two examples of this trend are the 20% of new houses in the United Kingdom and up to 70% in Scotland that are timber-framed (Ramage et al., 2017), and the 10% of new road bridges built in Norway between 2000 and 2003 made with timber (Lauksteins, 2005).

The evolution of building systems went from light framing using small-sized sawn timber through the post-and-beam system that used EWPs like GLT and LVL to the current trend of mass timber, mainly using CLT, the production of which increased by a factor of 11 between 2000 and 2013 (Brandner et al., 2016), although all the systems mentioned still exist today and are complementary in the context of construction as a whole. The main barrier to any new building system is a lack of knowledge (Schmidt and Griffin, 2013). In addition, Uruguay lacks a tradition of wood construction, since forestry plantations are only a few decades old.

In choosing a construction method, cost is not the only determinant; other factors like fire safety, construction time, acoustic insulation, structural stability, energetic efficiency, durability, transport, aesthetics, sustainability, and recycling can all be important, and timber fares well against steel and concrete in most of them (Hemström et al., 2011).

The sections above have shown that EWPs are among the most attractive forestry products in terms of economic performance. However, questions remain for Uruguay; could it use its local timber to manufacture structural products, what kind of structures could it build with them (dwellings, tall buildings, warehouses, bridges, etc.), and at what cost? This chapter aims to shed light on these issues.

6.1 Mechanical properties of Uruguayan timber

The mechanical properties of wood depend on both species and the specific provenance of a species (*Pinus taeda* trees are different from *Eucalyptus grandis* trees, and South African *Pinus taeda* might have important differences from Uruguayan *Pinus taeda*). Strength classes or grades are internationally defined to group species of similar mechanical properties together (Figure 17). All the strength classes are related to structural use, so the structural design of a building is a compromise between strength and section[6]. The choice depends on the availability of material and cost. For example, it does not make sense to design with C50 when C24 is the standard available strength class in the market, because the reduction in section does not make up for the cost difference.

[6] In a beam, the relation between width and thickness.

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There is currently no market for structural timber in Uruguay. The first national standard for structural grading of local pine (*P. taeda* and *P. elliottii*) was recently approved (PU UNIT 1261:2017), based on the results of a research project funded by the Ministerio de Industria, Energía y Minería[7] (Baño *et al.*, 2016). The development of a national standard for *Eucalyptus grandis* is in progress. Both species reach values that are included in the European standard EN 338 (CEN, 2016a). Local pine timber could be graded strength class C14 (Domenech et al., 2017; Moya et al., 2017), while the mechanical properties of eucalyptus timber, according to preliminary results, would correspond to strength class C20 (Baño et al., 2018a), although with a higher modulus of elasticity that is similar to strength class C30 ((Figure 17).

Pinus (C14) — *Eucalyptus* (C20)

	Class	C14	C16	C18	C20	C22	C24	C27	C30	C35	C40
Strength properties in N/mm²											
Bending	$f_{m,0,k}$	**14**	16	**18**	20	22	**24**	27	**30**	**35**	40
Tension parallel	$f_{t,0,k}$	**8**	10	**11**	12	13	**14**	16	**18**	**21**	24
Tension perpendicular	$f_{t,90,k}$	**0,4**	0,4	**0,4**	0,4	0,4	**0,4**	0,4	**0,4**	**0,4**	0,4
Compression parallel	$f_{c,0,k}$	**16**	17	**18**	19	20	**21**	22	**23**	**25**	26
Compression perpendicular	$f_{c,90,k}$	**2,0**	2,2	**2,2**	2,3	2,4	**2,5**	2,5	**2,6**	**2,7**	2,8
Shear	$f_{v,k}$	**3,0**	3,2	**3,4**	3,6	3,8	**4,0**	4,0	**4,0**	**4,0**	4,0
Stiffness properties in kN/mm²											
Mean modulus of elasticity parallel bending	$E_{m,0,mean}$	**7,0**	8,0	**9,0**	9,5	10,0	**11,0**	11,5	**12,0**	**13,5**	15,0
Char. modulus of elasticity parallel bending	$E_{m,0,k}$	**4,7**	5,4	**6,0**	6,4	6,7	**7,4**	7,7	**8,0**	**9,0**	10,1
Mean modulus of elasticity parallel tension	$E_{t,0,mean}$	**6,5**	7,3	**8,3**	8,7	9,2	**10,1**	10,6	**11,5**	**12,4**	13,8
Mean modulus of elasticity perpendicular	$E_{m,90,mean}$	**0,23**	0,27	**0,30**	0,32	0,33	**0,37**	0,38	**0,40**	**0,45**	0,50
Mean shear modulus	G_{mean}	**0,44**	0,50	**0,56**	0,59	0,63	**0,69**	0,72	**0,75**	**0,84**	0,94
Density in kg/m³											
Char. density	ρ_k	**290**	310	**320**	330	340	**350**	360	**380**	**390**	400
Mean density	ρ_{mean}	**350**	370	**380**	400	410	**420**	430	**460**	**470**	480

Figure 17. Strength classes of coniferous and deciduous species (taken from European standard EN 338 (CEN, 2016a)

Other aspects like natural durability can play a role in the choice of a species for building. Uruguayan pine and eucalyptus have low resistance against biological activity (Böthig et al., 2008). Chemical solutions that protect timber from fungi or insects could be forced into pine by impregnation, whereas eucalyptus cannot be impregnated due to its anatomical characteristics.

EWPs (GLT, CLT, LVL, etc.) could potentially improve the mechanical properties of the raw material. Uruguayan pine and eucalyptus species are suitable for producing GLT (Pérez-Gomar et al., 2018; Vega et al., 2017). The mechanical properties of eucalyptus correspond to strength class GL24h, as defined in EN 14080 (CEN, 2013), and pine to the theoretical strength classes GL16h-GL18h.

For GLT beams, the relationship between mechanical properties and volume must be higher than in mass timber building systems such as those using CLT. In CLT the high wood consumption requires timber species that are readily available at a low cost. Research conducted in multiple countries is providing evidence that timber with low mechanical properties could be successfully used to produce

[7] Ministry of Industry, Energy and Mines

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CLT (V. Baño et al., 2016; Fortune and Quenneville, 2010; Sikora et al., 2016), leaving high-strength timber for other products like sawn timber or GLT.

6.2 Technical feasibility of constructing with Uruguayan timber

Recently, a bridge was designed for vehicles up to 36 tonnes using GLT made of chemically-impregnated Uruguayan pine, and a prototype was designed and built for vehicles up to 16 tonnes (Baño et al., 2018c). *Eucalyptus grandis* can be used in bridge design, but only if the structural members are not exposed to the environment (as in a covered bridge), since the wood cannot be treated using impregnation techniques like those used with pine.

The structural members of any building or bridge are sized based on the mechanical properties of the material (bending strength, compression strength, modulus of elasticity, etc.) and the common loads (gravity, wind, etc.) and accidental loads (fire, earthquakes, etc.) acting on the structure, regardless of the material with which it is built (timber, concrete, steel, etc.).

6.2.1 Mass timber buildings using CLT

To identify the potential structural use of Uruguayan CLT, several types of buildings (high- and mid-rise buildings, single-family dwellings, and social dwellings) were structurally analysed, based on existing building designs (Figure 18). The medium length of the CLT panels considered for the walls was 2.4 m, while the length of the CLT panels in roofs and slabs varied between 3.0 and 4.5 m, depending the type of building.

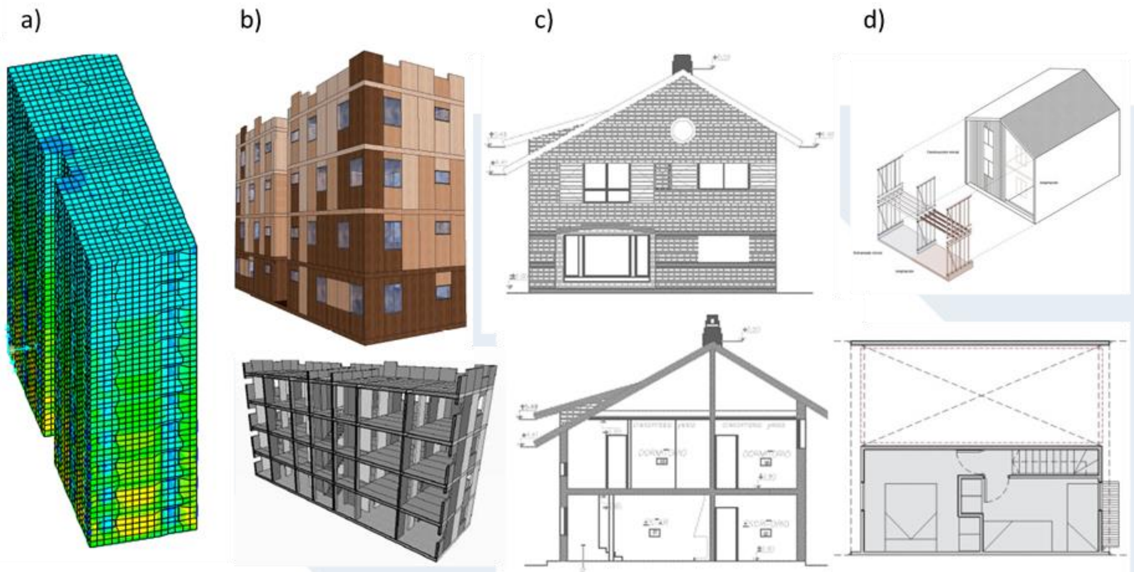

Figure 18. Prototypes of CLT buildings studied: a) 10-floor residential building, b) 4-floor residential building (González et al., 2014), c) single-family dwelling (Daniel Godoy, 2018), and d) social dwelling (Aravena et al., 2012).

CLT panels were sized according to

i) Loading capacity. The imposed loads on floors for residential use (2 kN/m^2) and the wind load corresponding to the worst exposure according to UNIT 50 (UNIT, 1994) were adopted.

ii) Fire resistance. Social and single-family dwellings were expected to resist 30 minutes (R30) of fire exposure, and mid- and high- rise buildings to resist 60 minutes (R60), according to international regulations (Ministerio de Fomento - España, 2010).

iii) Thermal insulation. The thermal transmittance coefficient required in common buildings in Uruguay (U = 0.85 WK/m^2) was chosen to design the roof and external walls of the studied buildings, with the aim being that the thickness of the CLT panel on its own could reach the required insulation, thus eliminating the need for complementary insulation.

The thickness of the CLT panels of slabs and roofs for buildings up to 10 floors (24 m tall) was defined by the loading capacity, while the thicknesses of the external and internal walls were defined by the thermal transmittance coefficient and by architectural design requirements, respectively. The buildings designed under the studied loads and with the defined thicknesses of CLT panels fulfilled fire resistance requirement. The fire resistance of traditional Uruguayan buildings is unknown because it is currently a requirement, although the concrete volume should probably be increased to reach the recommended fire exposure times.

The results showed that Uruguayan pine can be processed to manufacture CLT panels that can be used to build dwellings and tall residential buildings. Other uses for tall buildings (offices, commercial use, etc.), which involve higher imposed loads, should be most carefully analysed, although the early research shows the potential of using of Uruguayan CLT panels in designing them (Baño et al., 2018b).

It is common for the compression strength of walls to not be a limiting factor in the design of tall residential buildings. Slabs up to 6.5 m could be designed with CLT panels of pine from Uruguay. A comparison of Uruguayan CLT with the most common species used for manufacturing CLT panels in Europe indicates that the walls could be designed with the same volume of wood and that the wood volume of slabs and roofs might increase by up to 13% (Baño et al., 2018b).

6.2.2 6.2.2 Post-and-beam system using GLT

To identify the potential structural use of Uruguayan GLT, a non-residential building subjected to high stresses was studied. A common design for steel warehouses in Uruguay was structurally analysed according to the European Structural Design Code (CEN, 2016b), using GLT of Uruguayan pine and eucalyptus species for different spans (20 and 30 m). The wind load considered corresponded to the worst wind exposure according to UNIT 50 (UNIT, 1994). Fire resistance was considered in the sizing of the timber members for a fire exposure time of 60 min (R60). Steel protection against fire would incur a significantly higher cost than the one presented, due to the need to apply coatings to insulate the steel from hot temperatures (Figure 19).

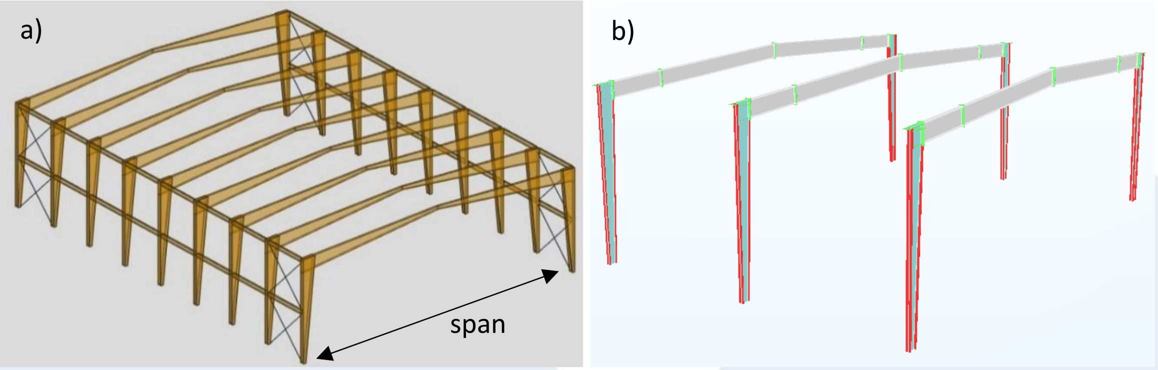

Figure 19. Prototype of studied warehouse: a) GLT; b) steel

The results show that Uruguayan GLT could be used to design warehouses of up to 30 m of span with *E. grandis* and of up to 20 m with *P. taeda* or *P. elliottii*.

6.3 Estimated costs of building with Uruguayan timber

6.3.1 Residential CLT buildings

Several types of buildings were analysed to estimate the cost per m^2 of using Uruguayan CLT, based on defined building designs (Figure 18); they are shown in Table 16. The cost and price estimates for CLT panels as a product were taken from Table 8.

Building Cost 1 assumes that the manufacturer of the CLT panels is the building agent, which is the most common business model in the mass timber construction system; by contrast, building Cost 2 covers the situation in which the builder buys the CLT panels from a manufacturer. The cost per m^2 decreases as the number of floors increases, although not linearly due to differences in the spans, depending on the type of studied building (Table 16).

Table 16. Costs per m^2 of CLT building using Uruguayan pine

Floors	Building prototypes	Cost 1 (USD/m^2)	Cost 2 (USD/m^2)
2	Two-room social dwelling	1,369	1,488
2	Single-family dwelling	1,634	1,771
4	Mid-rise residential building	1,204	1,280
10	High-rise residential building	809	889

Figure 20 shows the percentage of total building costs associated with the different components of construction: CLT panels, labour, fasteners and screws, interior finishing, lifting machinery, and other (installations and utilities); the cost for the last item is the same for all the buildings systems, whether timber or other structural material (Daniel Godoy, 2018).

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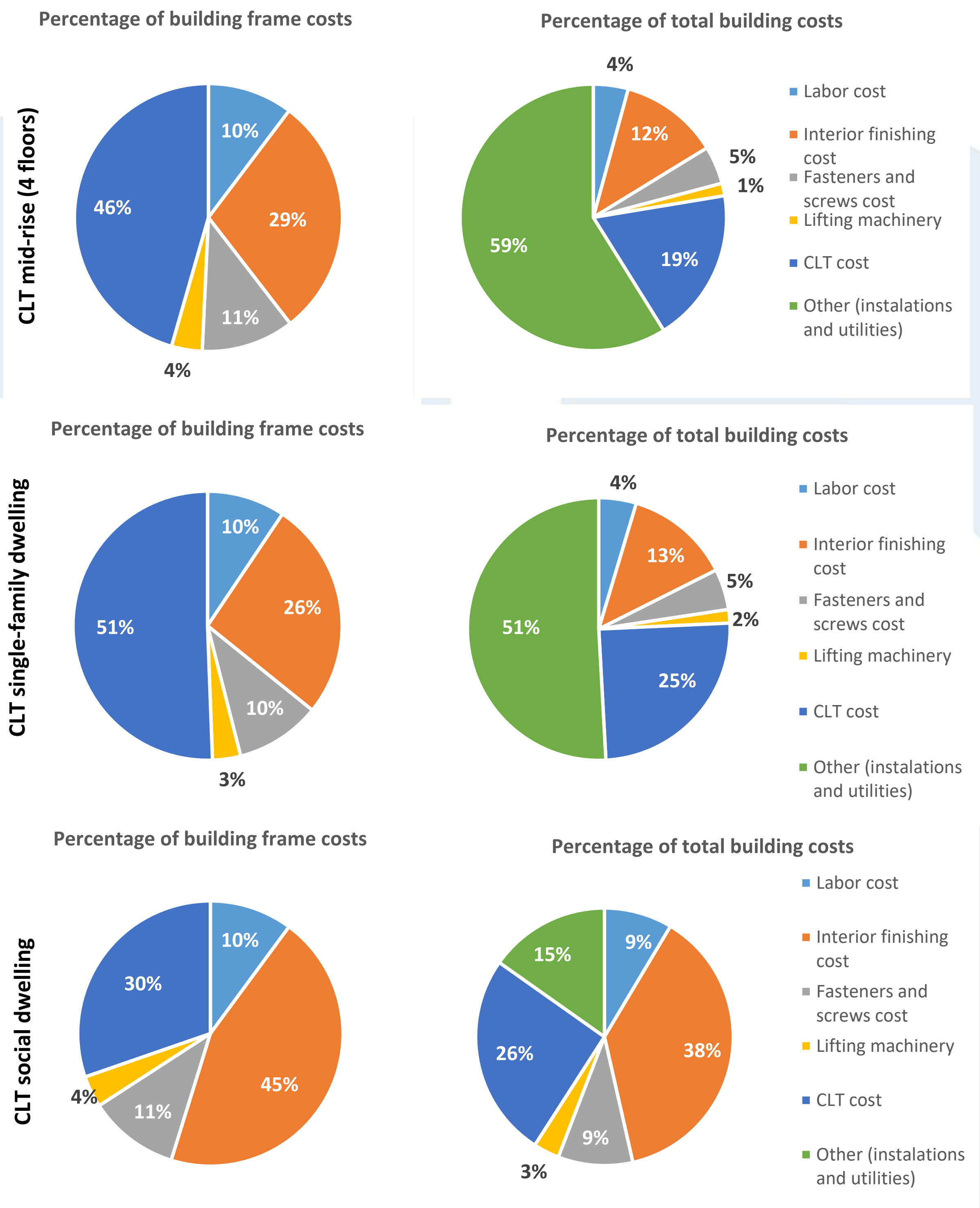

Figure 20. Estimates of the CLT residential building costs using Uruguayan pine (modified from Godoy 2018)

CLT panels were used for the slabs, roof, and internal and external walls (Figure 21).

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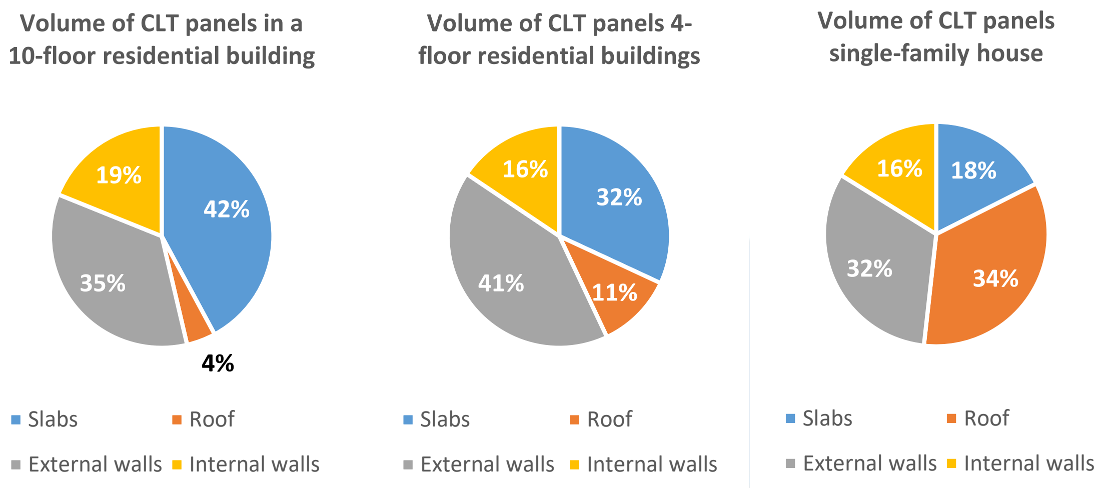

Figure 21. Volumes of CLT panels for different structural uses in residential buildings (modified from Godoy, 2018)

Due to lack of standardized information of costs of traditional building in Uruguay, it is difficult to make a comparison with the CLT system. Still, some examples of the buildings studied are presented, assuming that the manufacturer is the builder: i) CLT system (Cost 1) was 3% less expensive than the mid-range value published by (MVOTMA, 2016) for social dwellings; ii) according to the construction costs published by INE (Instituto Nacional de Estadística, 2016) for traditional construction systems, a CLT mid-rise residential building was estimated to be 8% less expensive and 10% more expensive than the high-quality (type 4) and medium-quality dwelling (type 3), respectively; and iii) the estimated cost of a CLT high-rise building was 31% lower and 9% higher than a high-quality (Type 10) and medium-quality residential tower (Type 9), respectively (Instituto Nacional de Estadística, 2016). These costs do not include the building's foundations, which would be considerably less expensive for a CLT building than for a concrete building, due to differences in the weight of the material.

As to time of construction, CLT buildings can be built over three times faster than concrete buildings (Van De Kuilen et al., 2011). For example, the frame and enclosure of an 18-story building at the University of British Columbia in Canada were built in nine and a half weeks (UBC News, 2016).

6.3.2 Post-and-beam buildings using GLT

A warehouse prototype was designed to compare the cost of building with GLT with the cost of building with steel in Uruguay. As in the case of CLT buildings, Cost 1 assumes that the GLT manufacturer is the building agent, and Cost 2 covers the situation in which the builder buys the GLT from a manufacturer. The costs per m^2 of Uruguayan GLT of pine and eucalyptus were compared with the corresponding steel costs for warehouses with 20 and 30 m spans, showing a cost reduction of 40% for the 20 m span using Cost 2 (Table 17).

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Table 17. Costs and prices per m² of GLT warehouses

Span (m)	Material	Cost 1 (USD/m^2)	Cost 2 (USD/m^2)	Difference (%)
20	GLT Pine	33	41	40
20	GLT Eucalyptus	37	49	28
30	GLT Eucalyptus	42	54	20
20–30	Steel	-	68[1]	

[1] Mazzey (personal communication, 2018)

7 Technological gaps between the Uruguayan wood transformation industry and the state of the art

Practically speaking, Uruguay produces three products on a large scale that involve the transformation of its natural forest resource: BEKP, sawn wood, and plywood. Overall, the technology of the leading companies is competitive with the state of the art in the sector. The greatest technological gap in Uruguay is the underutilization of the forest resource as a whole, given the limited range of products produced in the country. This characteristic appears to be associated with four factors:

1. The newness of the forest industry, since plantations only began in the last decade of the twentieth century.
2. Depressed international markets since 2007.
3. Absence of a local or regional market for wood construction products.
4. A geographical location far away from the centres that consume wood products and the resulting lack of contact with the end consumer. This is an especially sensitive issue for products aimed at niche markets.

The technological gaps are evident in the following points:

1) Absence of a network of qualified local suppliers of both products and services to sustain a diverse product offering and a dynamic industrial environment.
2) Scarce technological innovation (likely a consequence of item 1). In Uruguay, the wood processing industry buys technology to manufacture commodities that have established markets subject to price fluctuations.
3) Scarce supply of products manufactured locally, which limits the development of the industry. For example, there is a lack of destinations for the by-products of the mechanical transformation of pine (chips and sawdust).
4) High cost of chemicals in comparison to competitors. Chemicals are imported, and there is no local development of chemicals using local raw materials.
5) Deficit of transport alternatives to transfer production to ports. The wood and its products, which are bulky and inexpensive, are transported mostly by truck. The cost of transporting both raw material and finished products is high.
6) Scarce integration between existing production chains, especially between the first and second wood transformation industries.
7) Scarce local research on the subject, so there is limited systematized information on the properties of the local raw material and its technological possibilities. For example, there is an absence of information on the properties of pulp and paper produced from local pine.

In addition, the development of wood construction presents gaps that are not only technological but also have other roots: cultural, skills scarcity and other human resources issues, and regulations (EWP manufacturing requirements, structural calculation codes, and the existence of national and provincial regulatory limitations on wood construction).

8 Conclusions

8.1 General

- Uruguay's current forest resource would permit the establishment of a more sophisticated industry than the present baseline, with potentially higher output in terms of sales, benefits, and value added.
- Clearly, the diversification and integration of the different operations in a value chain produces higher outputs than the baseline. However, the expansion of integration depends on the development of markets, especially for eucalyptus products.
- EWPs (CLT, GLT, LVL) are the most attractive products. In this study, these products were targeted at niche markets, which could potentially expand into global mainstream markets. Both Uruguayan and regional wood consumption is very low, except for Chile. The opportunity to develop local and regional markets for Uruguayan EWPs is clear, since these products require proximity to the end user.
- The expansion of global timber construction is generating a market for high-value products of conifer wood; therefore, Uruguay's present pine forest plantation is an untapped resource that should be maintained and exploited.

8.2 Chemical transformation

- BEKP appears to have a relatively low economic output, likely due to being in a low-price phase. However, it appears to have a strong market over the short and medium terms. The price evolution in the last 30 years, and particularly in the last 10 years, indicates a commodity in high demand with a decreasing price.
- The pulp industry should evolve to produce soft paper, packaging, and textiles. The replacement of petrochemical plastic, driven by environmental issues and consumer behaviour, is a clear opportunity. The introduction of innovative technologies would allow the transformation of wood fibres with a lower investment level, leaving more lignin to be used to fabricate products instead of producing electricity.
- The development of a mechanical eucalyptus industry has the potential to supply the local BEKP industry with sawmill sub-products; in addition, pulp logs obtained from thinnings, a silvicultural practice aimed to leave space for the best trees to produce saw- and veneer logs, could be also sent to the BEKP industry. This synergy between mechanical and chemical transformation of wood is a common scenario in countries with long forestry traditions. However, the future expansion of the market for massive hardwood products, and particularly for eucalyptus EWP, is unknown. The development of the local and regional markets for *Eucalyptus grandis* products presents some simple advantages: 1) its mechanical properties are higher than those of pine; 2) as there is no wood construction tradition in Uruguay, graded eucalyptus timber would not replace other hardwood species; and 3) it is the only hardwood available in appreciable volume and constant quality.

8.3 Mechanical transformation

- Pine sawn timber, and consequently pine EWP, requires a destination for the sub-products of mechanical transformation: chips, sawdust, and bark. In addition, there is a need to find a suitable market for pine pulp logs. Under the present scenario and those foreseeable over the next five years, the production of electricity from biomass to supply the national grid appears to be a closed option, due to cost reduction caused by the generation of electricity using wind and solar power.

- Sawn timber as such is a commodity with price limitations. The expansion of global wood construction to meet low emission goals would require more sophisticated products like EWP. Pine is well situated to be the main species for the development of EWP, due to the lower cost of its raw material and the abundant technological know-how regarding the manufacture of coniferous EWP.
- Uruguayan pine and eucalyptus (*P. elliottii* and *P. taeda* and *E. grandis*) are valid building materials, and their characteristic values fall well within the European reference standard for strength classes (EN 338). Pine sawn timber could be graded class C14, and eucalyptus sawn timber between D18 and D24 of the cited standard. Additionally, Uruguayan pine and eucalyptus species could be used to produce GLT, and their mechanical properties would correspond to the strength classes defined in the European standard for glulam EN 14080 “GL16h-GL18h” and GL24h, respectively. Likewise, the structural aptness of Uruguayan pine for the manufacture of CLT panels has been experimentally demonstrated.
- The technical feasibility of the construction of dwellings and tall residential buildings (up to 10 floors) with CLT Uruguayan pine has been verified, as has the structural feasibility of using GLT of Uruguayan pine and eucalyptus for residential and non-residential buildings and for pedestrian and road bridges.
- Uruguayan CLT is competitive when compared to traditional building materials, and the cost per m^2 decreases as the number of floors increases. Additionally, CLT buildings are built more than three times more than rapidly than concrete buildings. The cost per m^2 of timber warehouses using Uruguayan GLT was compared with the corresponding cost of using steel for warehouses; a cost reduction of up to 40% was demonstrated.

9 Annex 1

9.1 Structural wood products

Structural wood products are defined as pieces of wood that have been structurally graded following rules of visual or mechanical grading and have known mechanical properties and density.

In addition to structural appropriateness, geometric quality and MC are essential aspects to consider. They are usually regulated by specifications established in technical documents or standards and are guaranteed through certificates or grade-stamps of structural quality. These stamps provide information about, among other factors, wood species, MC, natural durability and/or chemical protector treatment, visual grade, and strength class associated with the characteristic values of the wood's physical and mechanical properties (Baño and Moya, 2018).

Structural products can be classified into two large groups: solid wood products and EWPs.

9.2 Solid wood products

Solid wood products are classified as:

- logs or shafts of debarked trees;
- cubic wood, which consists of the stems rolled to a constant diameter for all their length;
- sawn wood, which consists of rectangular section pieces of different lengths cut from the shaft of the tree.

The last type is the most common product of mechanical transformation of wood in Uruguay.

9.3 Engineered wood products (EWPs)

EWPs are structural products derived from wood (sawn wood or wood particles) bonded with structural adhesives or other mechanical methods of fixation (screws, nails, etc.). They are often defined as a combination of smaller pieces of wood that together create larger high-strength structural members or components (Figure 22).

Figure 22. National *Eucalyptus grandis* boards

A first general classification of products can be carried out based on the type of material used: timber laminates, veneer, flakes, particles, and fibres, among others (Table 18 and Figure 23).

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Table 18. Classification of engineered wood products

Classification	
Sawn wood products	Finger-jointed blanks
	Glued laminated timber (GLT)
	Cross-laminated timber (CLT)
Veneer sheets	Laminated veneer lumber (LVL)
	Plywood
Wood chips	Parallel strand lumber (PSL)
	Oriented strand board (OSB)
Fibres and particles	Medium-density fibreboard (MDF)
	High-density fibreboard (HDF)
	Particleboards

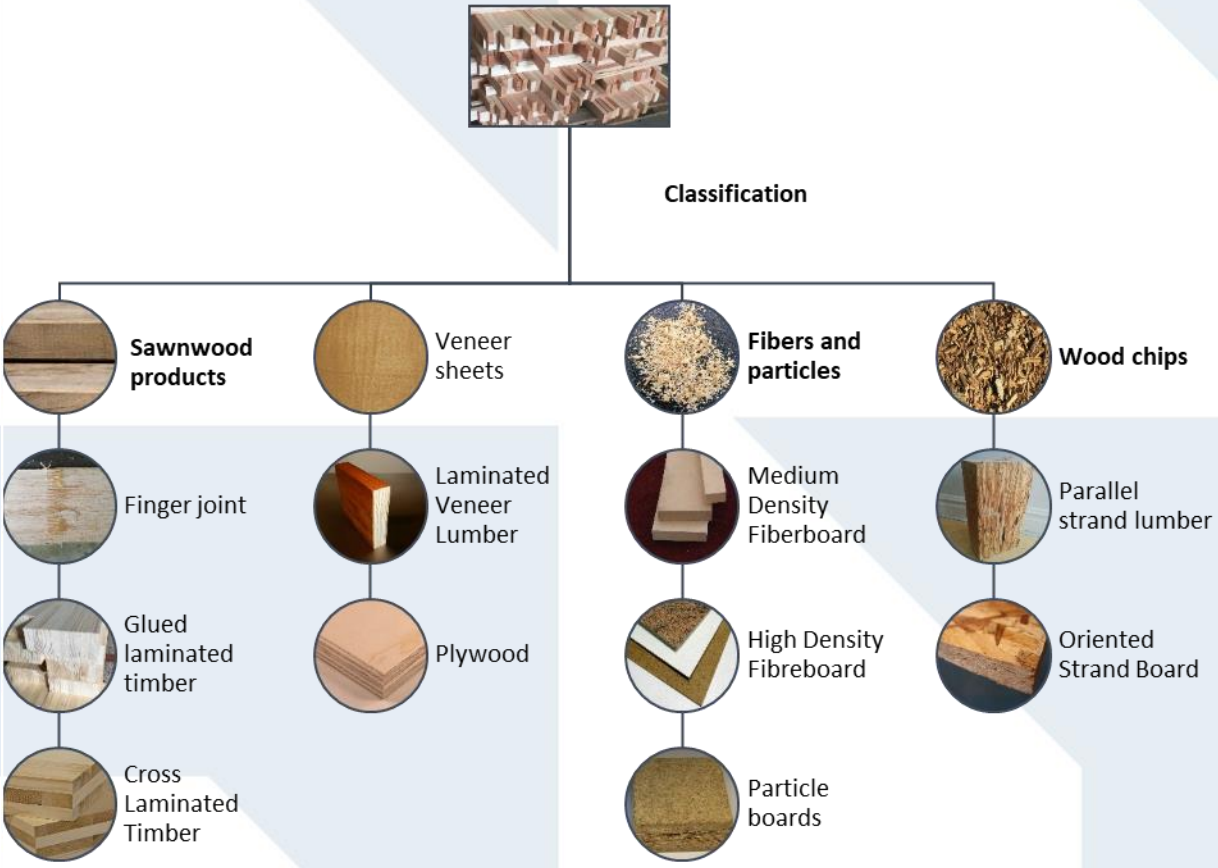

Figure 23. Classification of EWPs

9.3.1 EWP from sawn wood

Finger joint: Finger-jointed products are manufactured by taking small- and medium-sized pieces of quality KD dried lumber, machining a “finger” profile at each end of the short-length pieces, adding an appropriate structural adhesive, and squeezing the pieces together to make a longer piece of lumber. The orientation of the finger joints can be horizontal, vertical, or inclined 45°.The two major advantages of this product are its straightness and dimensional stability. There are five basic steps in manufacturing finger-jointed wood products: (1) grading and preparation of material, (2) manufacturing of finger joint (3) application of structural adhesive, (4) assembly of joint, and (5) curing of adhesive.

Glued laminated timber (GLT): Also known as glulam, GLT is the oldest member of the EWP family (Williams, 1999). GLT is a product of a structural application composed of lamellas, usually from a single species of wood. The timber lamellas are overlaid and glued together on their faces and parallel to the grain. The lamellas are horizontally oriented, and their thickness varies between 6 and 45 mm. The usual sections have widths that vary between approximately 70 and 250 mm and heights (thickness) of up to 2.0 m (Reffold and Whale, 2007).

The main advantages of GLT compared to sawn timber are as follows: a lower influence of defects and singularities because they are more homogeneous, which leads to higher strength; wider cross-sections and lengths of pieces that can be manufactured; and the versatility of forms (variable cross-sections, curves, etc.). These advantages, together with the good strength-to-weight ratio of the wood, make GLT very competitive with other materials, such as concrete and steel, for large spans such as sports hall roofs or warehouses (Baño and Moya, 2018).

Cross-laminated timber (CLT): CLT consists of self-supporting panels formed by orthogonally placed layers of sawn timber boards with thicknesses below 40 mm, bonded together with structural adhesives. They are placed in layers superimposed on one another, so that the direction of the boards in each layer is perpendicular to the previous one. Most panels are formed with three to seven layers, laid out symmetrically from the central layer. Panel thickness varies depending on the thickness of the board and the number of layers, but is usually between 60 and 400 mm. The width and length of the panel are defined according to each project and depend, in addition to the structural calculations, on the pressing capacity of the manufacturer; normally, panels range from 1.2 to 3 m wide and 5 to 15 m long. Openings (doors, windows, etc.) can be pre-cut to any dimension by numerical control machines for use in floors, roofs, and load walls in mid- and high-rise construction (Baño and Moya, 2018; Canadian Wood Council, 2018a; Reffold and Whale, 2007).

9.3.2 EWP from veneer sheets

Laminated veneer lumber (LVL): LVL is an engineered wood product intended primarily for construction, as it is generally used for beams, panels and studs. The product was developed in the

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late 1960s and has become well established as a high-strength beam and header component in both residential and commercial construction. Because it is manufactured from veneers, LVL makes up to 35% more efficient use of logs than is possible with solid lumber. Individual defects cannot be thicker than a single veneer and are distributed throughout the member. Consequently, a very uniform, high-strength product can be manufactured from lower grades of small, young trees. It is manufactured by the gluing and pressing of wooden sheets, approximately 3 mm thick, oriented in parallel. The sheets are obtained from the rotary cutting of logs in a lathe and are dried and structurally graded prior to the manufacture of the final product. The usual thicknesses of the beams varies between 27 and 90 mm, but it could reach up to 600 mm (Baño and Moya, 2018; Caamaño et al., 2016; Puuinfo Ltd., 2018; Williams, 1999).

Plywood: Plywood boards are manufactured by orthogonally gluing an odd number of veneers. The cross-laminated lay-up of the veneers provides strength, stiffness, and dimensional stability. The standard size of the plywood boards is 1.22 x 2.44 m^2, and the thicknesses usually varies between 3 and 36 mm (Baño and Moya, 2018; Puuinfo Ltd., 2018; Williams, 1999).

9.3.3 EWP from fibres and particles

Particleboards: Particleboard, also called chipboard, is a non-structural product formed by dried wood chips glued together with a resin which cures under the influence of high pressure and heat. Particleboards are produced in thicknesses from 3 mm to 40 mm and in various densities, commonly glued with UF. The amount of glue in a particleboard is around 10%. In terms of its basic properties, particleboard is comparable to solid wood. It also has the following benefits, owing to its method of manufacture: there is no grain direction, particleboard is homogeneous, and it has the same degree of strength in different directions. Particleboards are classified into several classes based on their physical and mechanical properties (Puuinfo Ltd., 2018; Stubdrup et al., 2016).

Fibreboards: Fibreboards are manufactured from wood fibres that are obtained from a mechanical process of defibration. They are classified according to their density into MDF (medium-density fibreboards), with an approximate density of 600 Kg/m^3, and HDF (high-density fibreboards), with a density higher than 800 Kg/m^3.

The production of HDF could be done without using adhesives in the manufacturing process; instead, the fibres are interlaced by pressing, which takes advantage of their thermoplastic properties. HDF is used mainly for carpentry and furniture. MDF is manufactured by gluing the fibres (adhesives represent more than in a hot-pressing process and its applications are more diverse: furniture, automotive industry, toys, footwear, insulation, etc. (Baño and Moya, 2018; Stubdrup et al., 2016).

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MDF is manufactured using a dry process, in which the lignocellulosic fibres are joined by an adhesive and a hot-pressing process. Additives may be introduced during manufacturing to impart additional characteristics. The surface is flat, smooth, uniform, dense, and free of knots and grain patterns. Regardless of the species of wood used, including recycled wood, sawdust, and fibres of any kind, the key to producing quality MDF lies in the use of fibres that are individualized and homogeneous. The adhesives used depend on the characteristics and properties desired; the most commonly used are UF, PF, and UF melamine (Aguirre et al., 2017; Composite Panel Association, 2018; Forest Products Laboratory, 2010; Rowell, 2013; Thoemen et al., 2010).

9.3.4 EWP from wood strands or flakes

Parallel strand lumber (PSL): PSL products are formed by bonding veneer strands together under high pressure. PSL is manufactured with a length-thickness ratio of approximately 300, oriented in parallel; it is glued and pressed to form beams, posts, and other structural members. The veneer strands are aligned in parallel to increase strength, resulting in the creation of a rectangular member. Typical cross-sections have widths of up to 180 mm and heights of up to 500 mm. PSL is used in post-and-beam structural system and in beams and lintels (Baño and Moya, 2018; Canadian Wood Council, 2018b; Puuinfo Ltd., 2018).

Oriented strand board (OSB): OSBs are made from flaked dried wood strands glued together (with a high length-to-thickness ratio) using adhesives (usually PF resins) that cure under high pressure and heat. The boards are formed by several layers of wood chips, oriented in such a way that the chips in each layer are orthogonally oriented to the next layer. The chips are glued with adhesives and hot-pressed to form the board. The usual dimensions are 1.22 x 2.44 m^2, with thicknesses of 6–28 mm. The density varies with the wood species, but it is usually around 650 Kg/m^3. OSB is a product in high demand, since it has lower costs than conventional construction materials. There are four types of OSB boards, all considered structural, except type 1; and their performance varies according to the environmental MC in which they are used (Baño and Moya, 2018; Brizolara et al., 2015; Forest Products Laboratory, 2010; Thoemen et al., 2010).

9.4 Cellulose pulp

9.4.1 Classification according to process yield

A general classification considering the mount of pulp produced per 100 kg of raw material (Table 19).

Table 19. Classification of pulp according to yield (Alén, 2000; Integrated Pollution and Prevention Control, 2015)

Type of process	Yield (%)
Mechanical pulping (stone groundwood; pressure groundwood; refined mechanical pulping; thermomechanical pulping)	90–98
Chemi-mechanical pulping ((chemi-thermomechanical; bleached chemi-thermomechanical, chemi-refiner mechanical pulp)	75–90
Semi-chemical pulping (neutral sulfite semi-chemical; alkaline-peroxide mechanical pulping)	55–85
Chemical pulping (kraft, soda-anthraquinone; acid sulphite; bisulfite)	40–60

Mechanical pulping: In a mechanical process, logs or wood chips are ground by abrasive action. The wood fibres are separated from the wood matrix by mechanical energy, causing the bonds to break gradually; the energy consumption is consequently very high. The pulp obtained is a mixture of fibre and fibre fragments. This process provides a high yield because the lignin remains mainly in the pulp, along with cellulose and hemicelluloses. The pulp produces a highly opaque paper with good printability, but its physical properties are inferior to chemical pulps, and it is more susceptible to yellowing caused by exposure to light. Mechanical pulps are mainly produced from softwood (Integrated Pollution and Prevention Control, 2015; Sixta, 2006).

Chemical pulping: In a chemical cooking process, a significant part of the wood components (mainly lignin) are chemically dissolved to obtain a solid with high cellulose fibre content. There are two main methods for chemical pulping: (1) sulphite pulping and (2) sulphate (kraft) pulping. The first, known as the sulphite cooking process, uses aqueous sulphur dioxide (SO_2) and a base of calcium, sodium, magnesium, or ammonium. The kraft process uses a treatment comprised of a mixture of sodium hydroxide and sodium sulphide, known as white liquor, at high pressure and temperature. After cooking, the spent liquor (named black liquor) is separated from the pulp, concentrated, and burned in a recovery boiler to recover the cooking chemicals and generate steam for the process itself and for energy production (Cabrera, 2017; Sixta, 2006). New kraft mills are self-sufficient in energy, and surplus energy is normally sold to the grid.

Semi-mechanical and chemi-mechanical pulping: This kind of processes combines chemical and mechanical methods, where wood chips are first softened or partially cooked with chemicals and then mechanically pulped.

Today, wood pulp production primarily uses the chemical treatment of wood; the production of mechanical pulp has declined over the last 30 years. There have been significant changes in the production of chemical pulp over the years. The use of the sulphite cooking process in pulp production compared to kraft pulping technology has decreased steadily; currently, 80% the chemical pulps are produced by the kraft process. The superiority of the kraft pulping process is explained by the following facts: (1) all wooden materials, including low-quality wood, can be used as raw material; (2)

the resulting pulp has superior fibre strength compared to other chemical pulping methods; (3) there is a simpler chemical and energy recovery process; (4) the economy of scale offered by kraft methods is highly competitive; and (5) it carries low environmental risks in modern mills (Alén, 2000; Cabrera, 2017; Sixta, 2006; Smook, 2003) .

9.4.2 Classification according to the wood used

Cellulose pulp can also be classified according to the type of wood used, by distinguishing softwood or long fibre (produced mainly from pine and spruce) from hardwood or short fibre (produced from eucalyptus, birch, poplar, etc.). After a gradual move from softwood to hardwood was observed (Alén, 2000; Cabrera, 2017), recent years have seen softwood pulp receive renewed attention (Arasto et al., 2018).

In addition, the final product can be classified according to the process; bleached pulp refers to a pulp that is bleached with chemicals to improve certain properties (brightness, brightness reversion, etc.), while unbleached or brown pulp is pulp that has not been subjected to any bleaching treatment (CEPI - Confederation of European Paper Industries, 2014).

Pulp can also be named according to the combination of materials and processes involved: for example, BEKP stands for bleached eucalyptus kraft pulp, as we have seen above, and NBSKP means non-bleached softwood kraft pulp (Figure 12).

Figure 24. Unbleached and bleached kraft eucalyptus pulp

9.5 Papers and boards

A broad classification of paper can be made according to its uses (Figure 25):

- Printing and Writing (P&W) (Figure 25a)
- Sanitary and household papers (tissue, nonwoven, etc.) (Figure 25b, Figure 25c)
- Newsprint (Figure 25d)
- Packaging papers (Figure 25e)
- Special papers (wallpapers, cigarette papers, insulated paper, etc.) (Figure 25f)

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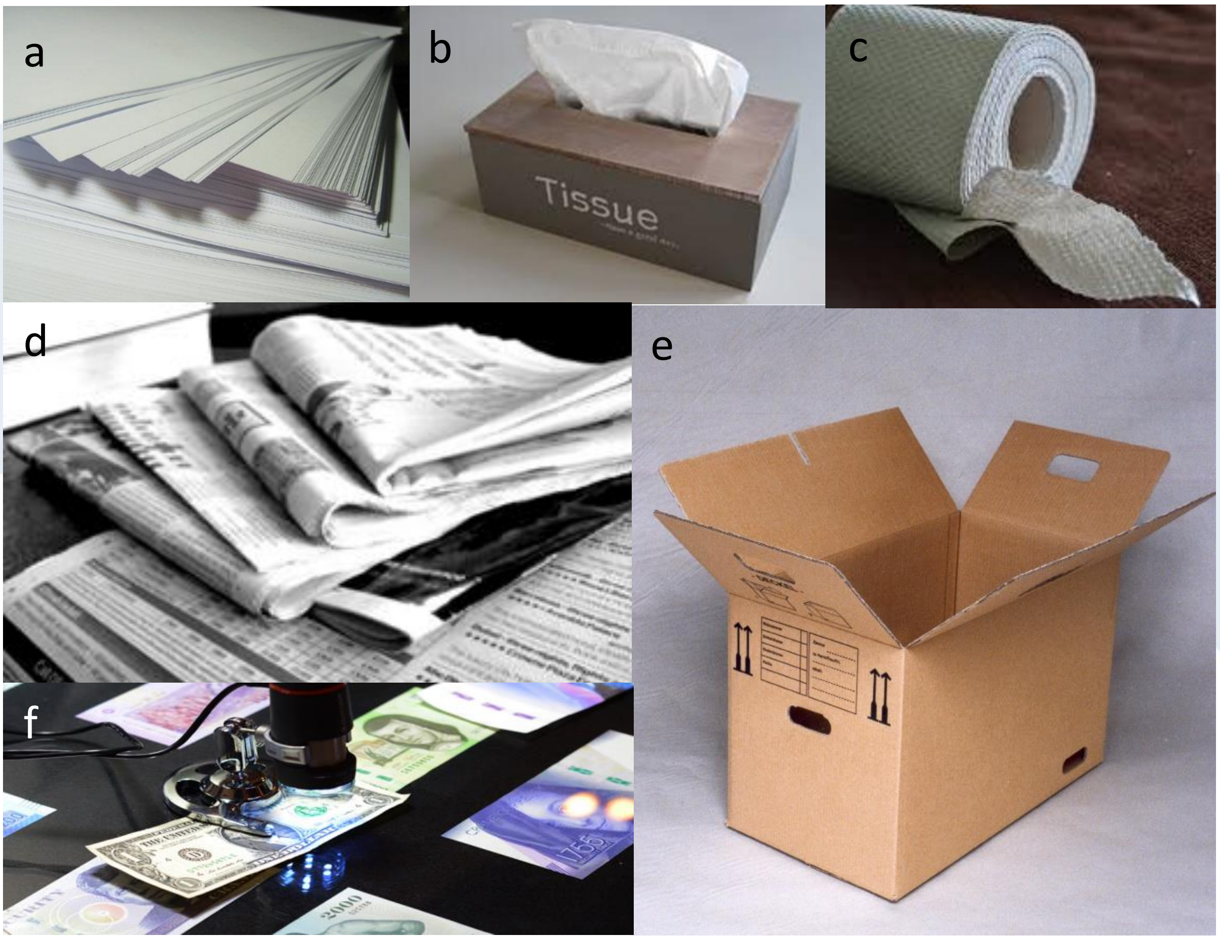

Figure 25. Different types of paper

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