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Optimization of the Use of Biomass Residues in the Poplar Plywood Sector

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Abstract

This work of research deals with the optimization of the use of biomass residues within an enterprise working in the poplar plywood sector. Productive process analysis showed that biomass residues deriving from production represent more than 54% of the raw material, sensibly influencing production costs. The management of these production residues needs the definition of optimal strategies in order to increase system efficiency. Every residue is characterized by specific features that distinguish it from other scraps: chemical composition, moisture content, calorific value and price. These characteristics determine the next use of each residue: some of them are burnt to produce thermal energy, others are reused into the productive process and others can be sold in the market. The main objective of this study is represented by the definition of the optimal quantities of the biomass residues for the different purposes in order to maximize the enterprise profit and the definition of the implementation tool in order to apply operatively the defined models. In particular, the proposed tool permits a reduction of the production costs (i.e energy saving) and a consequent increasing of the profit of 15% with respect to the current production policy.

Keywords: biomass residues; production system optimization; energy scheduling;

1. Introduction

The plywood is the most traditional and proven wood-based composite material. The current level of industrialization of production and of the quality control processes make it a highly reliable product for numerous

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types of use and particularly suitable for some specific applications. In addition, some technical characteristics, such as high structural efficiency and excellent thermal-acoustic insulation, differentiate the plywood from competing materials. In any type of design, the opportunities offered by a material that has good mechanical characteristics and limited density easily translate into an economic advantage.

Figure 1 shows the scheme of the production process of a plywood company. The starting point of the standard production process of the companies operating in this sector is represented by the cutting and splitting of the poplar at the end of its development cycle.

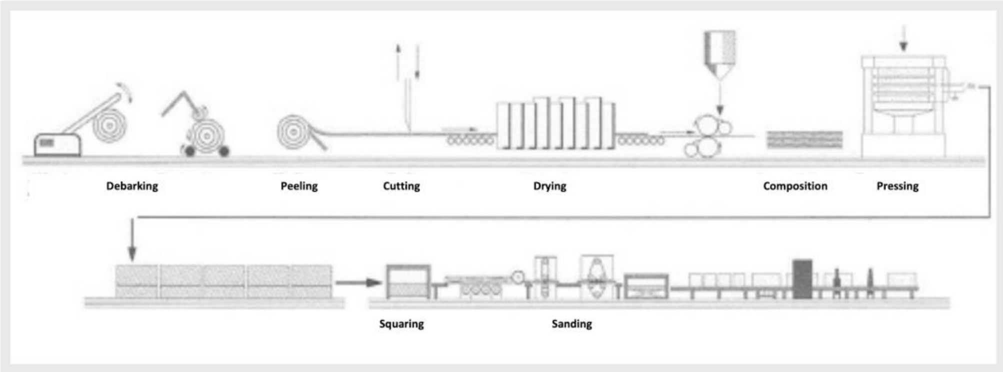

Fig. 1: production process of a plywood company.

At the end of these operations, the logs are sent to the plywood company and stored in the appropriate wood yard, obviously divided by length, quality and type. At this point, the first operation that is carried out is the debarking, during which the trunk is mechanically removed from the bark. The process takes place by means of a debarking machine, which carries out the operation by means of a relative helical motion between the blades and the trunk: the bark constitutes the processing residue of this operation. Subsequently, the logs are passed to the sheeter, a machine based on the same principle as the lathe. Specifically, the log, axially pivoted on a motor shaft, is rotated and at the same time a knife is pushed against it, at least as long as the trunk. At the end of this phase, the rod which constitutes the central part of the log that cannot be further peeled is obtained as production residue. At the exit from the sheeter there is a cutter, which cuts the various sheets according to the appropriate dimensions. These first three operations, grouped in this way, constitute the first processing department. At this point the sheets obtained are sent to the drying phase, in order to reduce their humidity rate below 12%, the maximum allowed value in order to avoid subsequent plywood panel peeling off. Following this operation, the composition of the panel is carried out. At this point the panel is pressed for the time required to reach the temperature of complete polymerization. Finally, the plywood panel is squared and smoothed, thus obtaining the dimensions and quality of the finished product. These operations result in finishing scraps consisting of residual biomass. As illustrated below, the wood chips are obtained along the plywood production cycle. Many researches are focused on energy saving in production with particular attention on energy-intensive companies, which are daily involved in the definition of solutions and approaches in order to minimize the energy consumption and reduce the energy costs ([1], [2], [11]). [3] provide a review of the state-of-the-art of decision support models by considering at the same time energy aspects and production and logistics aspects in order to define operational and planning strategies that consider energy consumption and costs. Some examples of the applications of decision support systems in energy-intensive firms can be found in [4] and [5]. The aim of this work is to define a model that permits to determine the right strategy in the use of the biomass residues in order to maximize the revenue by considering the energy costs. Moreover, we introduce a Decision Support System, based on the model designed, in order to suggest the optimal planning by considering the parameters variation. In particular, most studies in the use of biomass for energy optimization are based on the optimization of the interaction among the different players in a supply chain. Moreover, in the Literature, in our knowledge, are not present Decision Support Systems applied to this field.

[6] develop a model in order to determine optimal periodic shipment and capacity scheduling for each actor of the supply chain. They in particular consider the harvest, storage and transport of herbaceous biomass from on-farm storage locations to a centrally located plant.
[7] develop a system modelling framework for the simultaneous design and operations scheduling of a biomass to heat supply chain. They introduce a state-task-network (STN) approach adapted to provide a generic representation of harvesting, densification, drying, storage and transportation activities. In particular they consider the scheduling optimization under dynamic system influences affecting harvested yield, crop moisture content, ambient drying rates and seasonal demand. In the specific, period-specific harvest tasks, biomass moisture content variations throughout the dynamic processing chain and concurrent ambient drying in storage processes have been captured analytically and integrated into the modelling framework.
[8] develop a genetic algorithms (GA) and particle swarm optimization (PSO), integrated within a discrete event simulation model, in order to define the vehicles operational schedule in a typical forest-based biomass energy production supply chain.
[9] develop a simulation models for recovering biomass from the field of the biorefinery and they validate it using industry data. Their model minimizes biomass recovery cost by changing different strategies employed for recovering biomass. In particular, they propose a scheduling algorithm in order to enhance the flow of biomass and the involved resources. In the existing Literature current approaches appear to be highly problem focused and do not develop modelling frameworks or Decision Support System capable of suggest the right planning strategy by considering the different dynamic system influences affecting ambient drying rates. Furthermore, the Literature is also focused on the management of the supply chain and not on the operational management of the plant. The purpose of this research is therefore to develop a simple operational planning model that can support corporate decisions with the aim of maximizing revenues. In particular, the model was validated by applying it successfully in a real business context.

2. Residual wood biomass

In this analysis, the company considered is a leading European company in the production of plywood, multilayer, and chipboard. The data, collected during the analyzes carried out, is represented by the large quantities of waste, understood as residual biomasses coming from the various phases of production process and described above. In particular, the by-products generated in the year under review (2018) were found to be equal to:

• rods: 16,000 t / year;
• bark: 16,300 t / year;
• wood chips: 40,900 t / year;
• finishing scraps (treated): 4,500 t / year.

Table 1 shows the average values of the quantities of residual biomass produced and some of their physical and market characteristics, useful for identifying a possible use. In particular, with reference to the processed raw material, or to the poplar logs used, it is noted that:

• 10% is transformed into rods;
• 10% is transformed into bark;
• 29% is transformed into wood chips;
• 6% is transformed into finishing scraps treated.

Table 1: Residual wood biomass parameters.

Residual wood biomass (2018)	Quantity (t/y)	Average Humidity (%)	Lower calorific value (kcal/kg)	Market value (€/t)
Bark	16,300	50	1,900	12
Wood chips	40,900	45	2,500	41

Finishing scraps	4,500	8	4,200	0
Rods	16,000	55	1,800	67

Therefore, the analysis shows that 55% of the volume of the trunk purchased is not converted into a finished product but constitutes a processing residue. In this regard, it is of fundamental importance to analyze the possible uses of these residues in order to limit the effect on costs of this production inefficiency. Analyzing the various phases of the production process, it can be seen how the bark, understood as residual biomass, derives entirely from the debarking operation, while the rods are 100% as waste from the peeling operation. With regard to wood chips, this is produced as a percentage directly from the operations as presented in the following table:

Table 2: Wood chips production.

Drying	Splicing	Selection and repair (Stock)	Composition and pressing
5%	60%	7%	28%

With regard to treated finishing scraps, these are produced directly by operations presented in table 3.

Table 3: Scraps production.

Squaring	Sanding
72%	28%

These production waste can be used for various purposes by the company in relation to the type of residue considered; each processing waste is, in fact, characterized by intrinsic properties that distinguish it from the other types and each of these acquires, depending on the use, a specific market value. We pass, for example, from the treated finishing scraps which haven't no market value, to poplar rods, whose average market value in 2018 was 67 €/ton.

In this study the possible use considered for the various residual wood biomasses are:

- internal use, which translates into a use, in relation to the type of biomass considered, such as:
  - fuel for the internal production of thermal energy used in the chipboard panel production process;
  - raw material for the production of the chipboard panel (in this specific case the bark and the rods have the constraint that they cannot be used as raw material for the production of chipboard);
- direct sale on the reference market;
- storage, thereby giving the company to postpone the employment decision of the biomasses considered.

The latter strategy is not currently used by the company in question and is being evaluated. In particular, the objective of this study is to determine the optimal quantities (with respect to the maximization of the corporate profit) of residual biomass to be used for the various uses previously listed in a defined time horizon.

3. Energy saving

The energy recovery of residual processing biomass is one of the possible uses adopted in order to reduce the effect on company costs. This recovery takes place through combustion in a dedicated heating system and the transfer of the heat produced to the heat transfer fluid destined for process users: the total thermal requirement to be met amounts to approximately 45,000 kWh/year.

The fuels used in the analyzed system fall into the types of non-hazardous waste, according to the current CER classification (European Waste Catalog). These wastes, deriving from the woodworking process, are classified as follows:

- bark waste (type 030101 waste);
- wood chips, rods and chipboard panels (waste type 030105).

Sized waste, such as bark, discarded panels and squaring trimmings, can undergo a process of reducing the size in a special knife mill before storage and combustion. The biomasses that are burned in the thermal power plant are loaded into a special tank, which must continuously supply the fuel necessary for the thermal process. At the base of this container is the special extractor which, through rakes activated by hydraulic pistons, extracts the fuel using the metering piston, which compresses it until it enters the hearth. The accumulated fuel is immediately dried at the entrance to the hearth by the heat transmitted by the refractory walls, after which it is moved by a grid moved in three parts, which distributes it uniformly. Under this grill, primary combustion air is introduced into three zones which, passing through the fuel, creates the degassing and primary combustion of the fuel. At the end of the oxidation phase, the flue gases leave the post-combustion chamber and enter the diathermic oil heat generator. This heat exchanger is in a vertical parallelepiped version, with high-speed counter-current circulation of the heat transfer fluid in the areas with the most intense thermal load. Finally, the gases leaving the heat generator pass through a centrifugal separator and an electrostatic sensor for the removal of dust and particulates, to then be released into the atmosphere via a chimney.

4. Change in relative humidity and the market value of wood biomass

From a modeling point of view, the values of the physical characteristics of the residual biomass can vary over time. Particular attention is paid to the moisture content, which directly affects the calorific value and therefore the conversion of the biomass into thermal energy and which varies according to the storage period of the wood residue considered. Another fundamental parameter for the analysis presented is the change in the market price of the residual biomass, which is directly dependent on the relative humidity as well as on the demand for the biomass itself. To determine the change in relative humidity over time, a series of analyzes were conducted to monitor the progress of the water content in the processing waste stored in the warehouse. Figure 2 shows the average weekly water content of poplar wood chips detected during the year 2018 exposed to natural drying (covered by a roof).

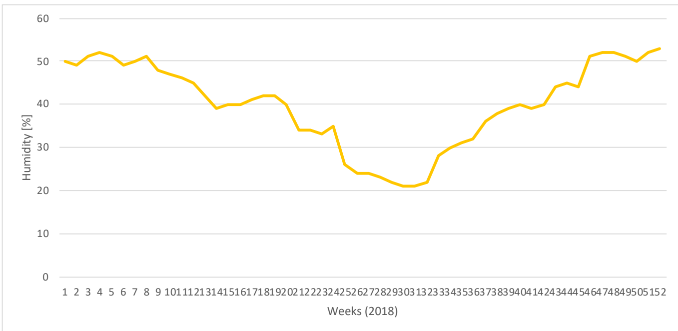

Fig. 2: the average weekly water content of poplar wood chips.

The effect of seasonality due to the climatic variation between the winter and summer months can be seen from the graph. This effect can be found on other types of waste stored under the same conditions. The only exception is the treated finishing scraps, which have a constant relative humidity of about 8%. As previously mentioned, the market value of the various types of biomass also has a direct connection with the moisture content, as well as with seasonal factors typical of the wood biomass market. As an example, Figure 3 shows the trend of the average market value of the wood chips as a function of the humidity detected and the seasonality of the demand detected in the year 2018.

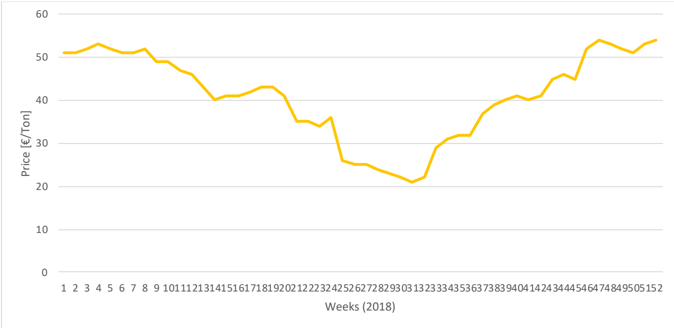

Fig. 3: the average weekly market value of poplar wood chips.

Also, in this case there is a marked seasonality due to the effect superimposed on the demand and the variation of the water content. The same effect can be seen in the other types of waste taken into consideration with the exception of treated finishing scraps, which cannot be marketed.

5. The model

This study presents a model that maximizes profit by defining the quantities of the different biomasses used for the different utilizations previously mentioned. Among the hypotheses formulated, the possible variation over time of the market value of the processing residues is considered due to the seasonality of the demand and the water content of these biomasses during their storage. It is therefore interesting to evaluate the possible effects deriving from the storage method of these biomasses, or to see if the variation in their water content can suggest the adoption of particular strategies, changing the time spent in stock. The proposed model has the objective of highlighting appropriate management logics to be implemented when particular conditions occur. In concrete terms, the possibility of seeing the water content in the processing waste reduced could lead to delaying the use of such waste to a subsequent period. At the same time, however, delaying the use or sale of these quantities in a future instant, increases storage and management costs. In the final analysis, it is a question of assessing whether it is convenient to deliberately use the stocking of some biomasses if this solution allows a better return on capital. However, it is necessary, first of all, to satisfy internal needs and then evaluate the possibility of stocking the unused biomasses in the warehouse rather than to sale them directly. Such a strategy does not is currently employed in the company.

The objective function consists in maximizing corporate profit and is given by the following relationship:

$$\sum_{t=1}^{104}\sum_{i=1}^{4} \boldsymbol{pv_{ti}qv_{ti} + pm_{ti}rm_{ti}qm_{ti} - ce(teq - pc_i qe_{ti}) - cs_{ti}qs_{ti} - ca_{ti}qa_{ti}} \qquad (1)$$

Where:

- $\boldsymbol{pv_{ti}}$: selling price of the i-th biomass;
- $\boldsymbol{qv_{ti}}$: sales quantity of the i-th biomass;
- $\boldsymbol{pm_{ti}}$: revenue from the sale of the finished product in relation to the i-th biomass used;
- $\boldsymbol{rm_{ti}}$: production yield of the i-th biomass;
- $\boldsymbol{qm_{ti}}$: quantity used for production of the i-th biomass;
- $\boldsymbol{ce}$: cost of purchased thermal energy;
- $\boldsymbol{teq}$: quantity of thermal energy required for the production;
- $\boldsymbol{pc_i}$: lower calorific value of the i-th biomass;
- $\boldsymbol{cs_{ti}}$: storage cost of the i-th biomass;
- $\boldsymbol{qs_{ti}}$: storage quantity of the i-th biomass;
- $\boldsymbol{ca_{ti}}$: purchase cost of the i-th biomass;

- qa_{ti}: purchase quantity of the i-th biomass;
- $qtot_i$: total quantity of the i-th biomass used in the time horizon (two years);
- $ptot_i$: total production quantity of the i-th biomass for the plant (it is possible to use for the production only the wood chips and finishing scraps).

Specifically, four different types of strategies (model variables) are analyzed which can be undertaken in the period t and which are summarized as follows:

• sale of the relative residual biomass;
• use of biomass for the production of chipboard panel by considering the production yield;
• use of biomass for the production of thermal energy (by considering the average value of ce equal to 0,2 €/kWh);
• storage of the relative residual biomass.

In this analysis, the time horizon is two years with a minimum weekly period (a total of 104 weeks). In defining the objective function, the following were considered:

• the profit from the direct sale of the residual biomass;
• the profit deriving from the use of residual biomass for the production of plywood (taking into account a different productivity depending on the residual biomass considered ([10]);
• the cost relating to the use of residual biomass for the production of thermal energy (taking into account a different lower calorific value depending on both the residual biomass considered and over time);
• the cost of biomass storage;
• the purchase cost of the residual biomass.

In the specific the constrains considered are:

$$\sum_{t=1}^{104} qv_{ti} + qe_{ti} + qm_{ti} = qtot_i \quad i = 1, \dots, 4 \tag{2}$$

$$qs_{ti} = qs_{t-1i} + qa_{ti} - qe_{ti} - qv_{ti} - qm_{ti} \quad i = 1, \dots, 4; t = 1, \dots, 104 \tag{3}$$

$$\sum_{t=1}^{104} qa_{ti} = qtot_i \quad i = 1, \dots, 4 \tag{4}$$

$$\sum_{t=1}^{104} qm_{ti} = ptot_i \quad i = 2, 3 \tag{5}$$

$$qa_{ti} \geq 0;\ qe_{ti} \geq 0;\ qv_{ti} \geq 0;\ qm_{ti} \geq 0 \quad i = 1, \dots, 4; t = 1, \dots, 104. \tag{6}$$

$$cs_{ti} = h \cdot ca_{ti} + wc \quad i = 1, \dots, 4; t = 1, \dots, 104 \tag{7}$$

In particular, the constraint (2) defines that the quantities used for the different strategies (selling, energy production, final product production) have to be equal than the maximum quantity used in two years of production; the constraint (3) permits to define the quantity in stock in a specific period t for a specific biomass i that is the quantity of the biomass i in previous period t-1 plus the purchased quantity minus the quantities used for selling, energy production and the production of the final products; the constraint (4) defines that the purchased quantity of a specific biomass i have to be equal than the maximum quantity used in two years of production; the constraint (5) defines that the production quantity of a specific biomass i have to be equal than the maximum production quantity of the plant (it is possible to use for the production only the wood chips and finishing scraps); the constraint (7) defines that the storage cost is equal to the purchasing cost multiplied by the opportunity costs (financial costs; considered equal to 10% of the biomass value) plus the material handling costs (physical costs; considered equal to 5 €/t); in particular the financial costs depends over the time on the purchasing costs whereas the physical costs is constant.

Summarizing, among the main constraints, it was imposed to respect, for each period, the quantity of biomass necessary for the production of the plywood (variable over time), considering the impossibility of using the bark and the rod for the production of the plywood. From an energy point of view, the thermal energy necessary to meet the company's needs can be purchased externally or self-produced through the use of residual biomasses. The minimum period of time considered is the week, during which the quantity of raw material purchased can be immediately used for the indicated uses.

6. The decision support system DSS

The company considered as reference for this work (not explicitly mentioned for privacy) operates in the poplar plywood sector in Northern Italy and currently is facing the digitalization of operational processes in order to increase the performances and reduce the variability induced by the choices of the workers. The main objective is to define a tool that takes into account the field parameters (as humidity of the biomass in the different stocks) in order to suggest the correct planning and eventually to change it. In fact, currently this information is not considered punctually in the planning and this causes inefficiencies (i.e. not correct use of the stocks in function of the biomass humidity). The tool proposed, coded in MS VB.net and integrated in the ERP system, consists in the definition of a Decision Support System (DSS) that permits the optimal setting of the production variables taken into account the field parameters recorded in specific databases. Following, the conceptual framework of the DSS is briefly illustrated.

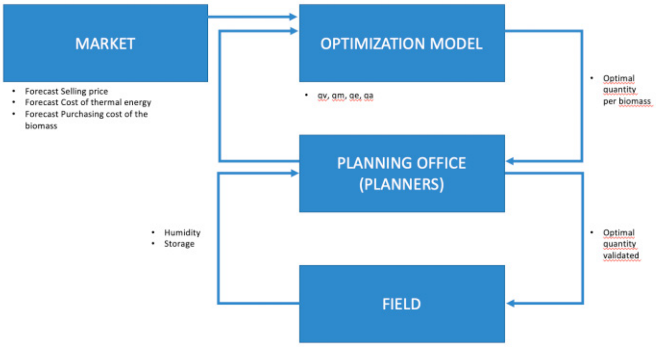

Fig. 4: Main macro-elements of the DSS.

The DSS is divided into three main-macro elements. The first relates to the data updating from the field that comes as from the reheating furnace as from the hot rolling line. The second concerns the planning office that validates the data from the field confirming or not the values received; moreover, the planning office can update eventually the plant data. The third element is the model that defines the optimal variables; in particular, these values are finally validated by the planners, who can make appropriate modifications and confirm the plan.

7. Results

The definition of the proposed model permits to evaluate a complex process in a simple and schematic way. In particular, by balancing the market value of the individual processing residues with the costs deriving from the specific use or from their short-term storage (with particular attention to the variation of the water content and therefore of all the physical and energy properties) it was possible define a model that optimizes the policy of using these biomasses, in compliance with the system constraints.

Company policy, to date, provides for a distribution of processing residues according to the annual percentages shown in table 4.

Table 4: Current production strategy.

Residual wood biomass	Energy production (% year)	Production (% year)	Sale (% year)
Bark	21	0	0
Wood chips	14	10	28
Finishing scraps	0	6	0
Rods	0	0	21

It can be seen that all the bark is used as a fuel for the production of thermal energy, the rods are always placed on the market and the finishing scraps are completely reused in the production process; the only residual biomass that is used for all purposes is wood chips. Table 5, on the other hand, reports the result obtained by using the proposed model, with the same conditions and parameters of the system considered.

Table 5: Optimal production strategy.

Residual wood biomass	Energy production (% year)	Production (% year)	Sale (% year)
Bark	21	0	0
Wood chips	0	52	0
Finishing scraps	0	6	0
Rods	0	0	21

The only variation identified consists in the use of wood chips, which in this case is used exclusively for the production of plywood.

From the point of view of maximizing the profit, the proposed model allows an increase of 15% mainly due to the introduction of the warehouse. The graphs shown in figure 4 show the trends over time of the variables optimized for the different types of residual biomass. From the graphs you can see the effect of the storage strategy, which allows you to identify the best use period for the specific wood biomass. For example, in the case of the rod, used exclusively for sale, it can be observed that first up to the period 30 it was bought and immediately sold (the green and red lines are completely superimposed). It is subsequently accumulated and then sold in the period between 50 and 60, corresponding to the winter season (period of greatest profit).

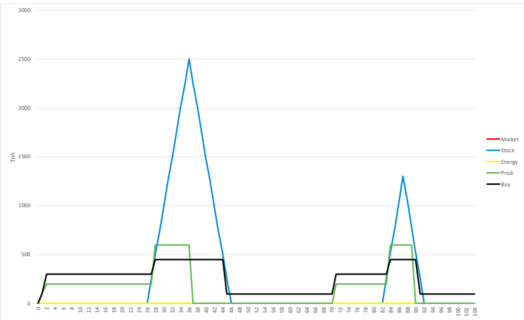

Fig. 5-a: trends over time of the variables optimized for the Wood Chips.

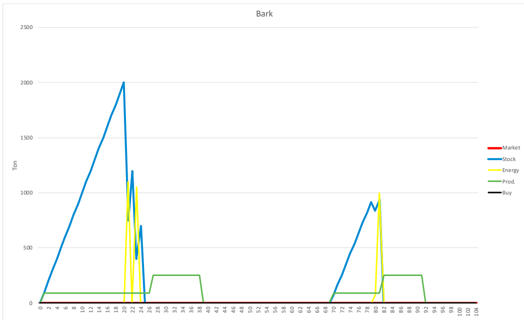

Fig. 5-c: trends over time of the variables optimized for the Rods.

Fig. 5-b: trends over time of the variables optimized for the Rods.

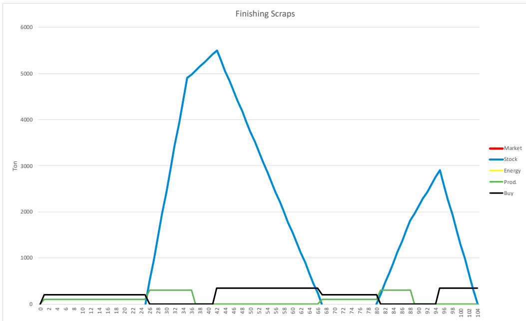

Fig. 5-d: trends over time of the variables optimized for the Rods.

The same thing is then repeated identifying the seasonality of the analyzed system. In essence, the model is able to define when and for how long to keep in stock in order to maximize profits according to the parameters considered.

8. Conclusions

The proposed model maximizes company profit by optimizing weekly the quantities of the various residual wood biomasses (deriving from the production process) to be destined for combustion, reintegration in the production cycle, sale and possibly storage. Among the hypotheses formulated are considered:

• the variation over time of the value of the physical characteristics (water content and calorific value) of these biomasses during their storage;

• the change over time of the market value of the processing residues due to the seasonality of demand and the variation in the physical characteristics of these biomasses during storage.

The results show the importance of the optimization of the wood processing residues use within the company; in fact, the overall improvement in the objective function (15% increase in profit) appears to be significant compared to the policy currently adopted. In particular it is proposed a tool that permits to implement the optimization method in the ERP system. The main benefit was brought about by the introduction of the maintenance of the various types of biomass: this possibility allows the valorization of the various residues at the most appropriate time (i.e. more profitable from the point of view of reaching the maximum profit), going to exploit depending on the various uses, the variation in physical characteristics and market conditions over time.

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