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Influence of raw material moisture on the synthesis of black tea production process

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ABSTRACT

Tea industry is one of the main activities in the northeast of Argentina. It presents some particularities respect of tea production in other regions of the world, mainly in the high level of automation in tea shoots harvesting. Besides, the factory configurations in terms of the equipment used in tea production are different and it is not clear if they are efficient or not. The objective of this work is to study the effects of the moisture in the raw material (tea shoots) in the optimal design of a tea manufacturing plant not only in the investment but also in the operation costs. A superstructure that includes all the equipment involved in black tea manufacturing is proposed and a Generalized Disjunctive Programming model (GDP) is formulated to find the optimal flow sheet to produce black tea minimizing investment and operation cost, considering different wet contents in the tea shoots. A comparison was also made among the optimal plant and typical factories configurations to analyze their performance. From the results obtained can be observed that if the moisture of raw material is below of 4.5 kg of water per kg of dry matter the optimal plant configuration does not change; above this value more investment is needed to extract the extra water content. A similar conclusion can be obtained from the analysis of the operation costs. The optimal configuration is formed by conventional preservation chambers, continuous withering belts, Rotorvane crusher, continuous fermenting machines and fluid bed dryers. Comparing other typical configurations against the optimal one, the operative unit cost is about 20%–60% greater.

1. Introduction

Tea industry in Argentina is mainly located in the northeastern region of the country, particularly in the provinces of Corrientes and Misiones. From 2003 to 2011, this industry which is focused on black tea production had an annual average production of 77.810 tn, of which 95% is meant for export. In 2011, exports reached 86.011 tn and 108.6 million dollars FOB (MAGyP, 2012). Despite these numbers, the industry received little attention from academics and researchers.

The process stages involved in black tea manufacturing are the harvesting, withering, leaf crushing, fermentation and drying. Each of these steps may be performed by various equipment or groups of them. In Fig. 1 is observed a superstructure representing the alternatives and interconnections of equipment that can be selected for black tea processing. Each piece of equipment presents differences in moisture ranges in which it works properly, its production capacity, as well as its investment and operating costs.

Processes related to black tea production have been studied from different perspectives but mainly in Asia and Africa. Ullah et al. (1984) studied that withering periods and process conditions affect the product quality, particularly the found that chemical withering can be applied to obtain a similar product than traditional withering; also they conclude that a high moisture loss during this process step is in detrimental of brightness, briskness and body of tea. The work of Kr-Mahanta and Baruah (1989) find that excessive withering goes in detrimental the formation of volatile compounds which are responsible of the tea flavor. Botheju et al. (2011a) presented a relationship between withering process and rate of moisture decrease of fresh leaves. Later, the moisture content in withering process was predicted using process simulation by Botheju et al. (2011b) and a model using fuzzy logic in Gupta et al. (2012). Both articles have the objective of providing models to help in the decision making of withering tea leaves.

Owuor and Orchard (1992) studied the variations in quality of

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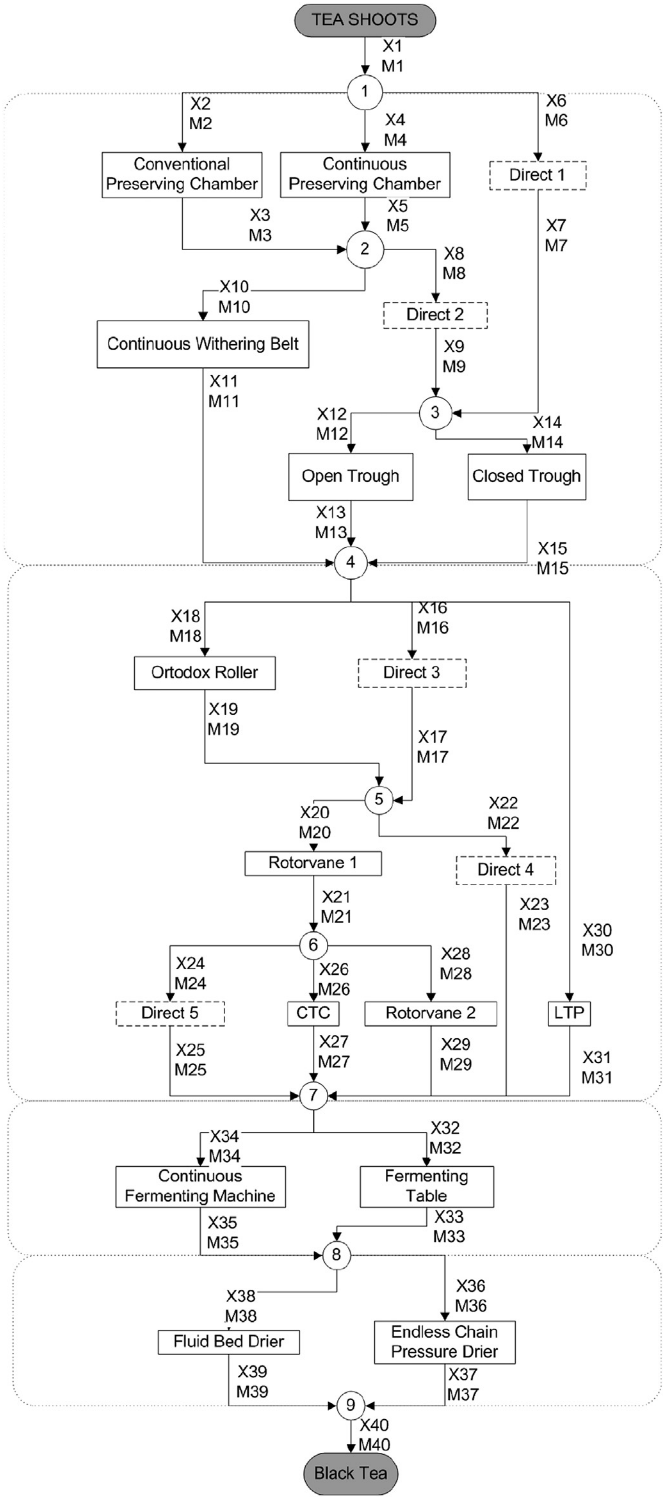

Fig. 1. Superstructure for black tea process.

normal tea with withering times until 18 hs, these authors found that for tea coming from seed plantations the variations are minimal while for tea leaves coming from of high quality cloned varieties can be found important differences in parameters such as brightness and theaflavins content, for chemical withering periods longer than 18 h (Owuor et al., 1990).

Tomlins and Mashingaidze (1997) perform a review of the withering stage and its influence in other process steps of tea manufacturing, focusing primarily on the modalities and process characteristics. They also detailed modalities of traditional, chemical, physical and in two stages withering. The advantage of the latter alternative is that initial storage can be performed using less space, thus reducing installation costs.

Five types of equipment can be combined to perform the withering task. Preservation chambers, including either static or continuous belt equipment, which are denominated Conventional Preservation Chamber and Continuous Preservation Chamber respectively, are designed to store large amounts of fresh shoots in little space to eliminate the surface moisture of the leaves. Continuous belt withering equipment allows for moisture extraction from large volumes of shoots, while open and static withering equipment (Open Troughs) allows for withering in a batch process. There is also a static closed equipment (Closed Trough) which is designed to achieve faster moisture loss than that in the open version (Yadav, 2006). The desired moisture at the end of the withering process depends on the selected equipment for leaves crushing, and its value is generally between 1.21 and 2.45 kg of water per kg of dry matter. Preservation chambers can also act as a "buffer" between shoot reception and subsequent production phases.

The leaves crushing stage involves the reduction of withered leaves into smaller particles. There are four pieces of equipments which are the most widely used for this process, Orthodox Roller, Rotorvane, CTC (Curl, Tear and Cut), and LTP (Lawrie Tea Processor) (Baker et al., 1997). Harris and Ellis (1981) studied the cellular and structural damage produced in the tea shoot during the crushing process and its influence in the properties of the final product. They conclude that final product characteristics strongly depends on the fermentations process where is important that the cellular juices must be in contact with the atmosphere oxygen. The authors made a micrographic qualitative analysis from which they infer that the process with CTC and LTP equipments facilitate a direct contact between cellular juices and the air, while the process whit Orthodox Roller and Rotorvane give more intracellular spaces which facilitate the air diffusion, for those reasons the final product has similar properties for all alternatives. Cloughley et al. (1981) compared the crushing methods respect to the evolution of biochemical reaction during the fermentation process. They reported that teas processed by CTC and LTP equipment produce infusions with more color and with major content of theaflavin which are important quality properties for plain teas. Owuor et al. (1989) agree with these results. These authors compared manufactured teas using orthodox roller and CTC using aromatics species, in this case, the orthodox methods present better quality. Although the final product has differences depending on method used in the crushing stage, each one has features that make it commercially acceptable.

Most chemical reactions associated to black tea production occur during fermentation (Owuor and McDowell, 1994). This process aims to maintain the product at temperatures around 20 °C, which can reach a maximum of 30 °C for some varieties of *Camellia sinensis*. A good contact with air should also be ensured so that reactions involving oxygen are properly performed. These conditions must be maintained for a period that depends on the cultivated variety and harvesting conditions of the raw material (Owuor and Obanda, 2001; Hojjat Ansari et al., 2011). This process can be carried out in two main ways. One of them is leaving the shredded tea leaves coming from the crushing stage on tables, layered with a height between 3.5 and 7 cm, remaining there during the proper time fermentation (Belitz et al., 2009). The other way is loading the crushed leaves on perforated conveyor belts, which have fans to force air flow through the product layer, these are denominated CFM (Continuous Fermenting Machine).

The purpose of drying step is to reduce the moisture to 3–4% permitting product conservation. In addition, the rise in temperature increases enzymatic activity, contributing to theaflavins formation, with temperatures exceeding 55 °C (Belitz et al., 2009; Kurian and Peter, 2007) the enzymes are inactivated. The articles of Temple and van Boxtel (1999a) and Panchariya et al. (2002) studied the relationships among the drying rate, product moisture and process conditions. The ECP (Endless Chain Pressure) drying equipment and the FBD (Fluid Bed Drier) are the most widely used for this processing step. Temple and van Boxtel (1999b) developed a simulation model for the FBD dryer. This model was extended to other dryers used in the industry. Later Temple and van Boxtel (2000) compare the performance of FBD and ECP equipments. They conclude that ECP equipments are more efficient in energy consumption. However, analyzing the energy needed in Argentinean tea manufacturing plants, it has observed that ECP dryers need more energy than FBD. The explanation for such behavior is because it must be maintained the outlet temperature of the air above 55 °C in order to produce the enzymatic deactivation of the input product. In order to obtain the maximum energy yield the outlet temperature of the air must be the lower possible. Considering this issue, the energy consumption of the ECP dryers are estimated 50% greater than FBD equipments.

Some other works in the literature also studied the influence of raw material characteristics in the final product quality. Owuor and Obanda (1998) investigated the influence of the maturity of crushing shoots and the fermentation duration in the quality of black teas. They found that working with a high percentage of mature leaves is in detrimental of tea quality. Another work of the same authors (2001) presented the influence of the variety of the tea plants where the shoots come from, the temperature and fermentation time. They conclude that depending on the clonal variety and the temperature it is possible to find the duration of the fermentation process to obtain a good quality product.

Due to the increase in labor costs, there is a trend towards mechanization of the various stages in the elaboration of black tea, particularly at the stage of harvesting, where can be found changes in operations. These changes present new problems, such as the increase in the moisture content of the feedstock. The *C. sinensis* shoots harvesting in Argentina is made mechanically using a special purpose machine and loaded into trucks that transport the shoots in bulk to the processing facilities. A common practice is to make the harvest at times of the day in which solar radiation is low, even at night or early morning. This aims at keeping low shoot temperature during plucking, because it can be increased significantly when carried in bulk, causing the raw material damage. As a result of the hours of the harvesting schedule, the collected shoots usually contain dew on their surface. In addition, Misiones state is characterized by having highly frequent rainfalls with variable intensity, so the variability of that water content the harvested shoots is increased. As a consequence of the aforementioned, the raw material loads in this region commonly have between 3.5 and 5.5 kg of water per kg of dry matter when entering the processing plant, although a moisture below that 4 are expected if shoots were picked up during the day in a non rainy day.

In spite of the variety of works that have been published so far, there are no references in studies about the influence of raw material moisture in the optimal synthesis of black tea production process.

So, the objective of this work is to perform an optimal synthesis of the black tea production plant that minimizes capital and operating costs, given a required minimum productivity, considering the industrial range of raw material moisture and contemplating the spectrum of alternatives for each process stage. The decision variables of the model consist of the number, sizes and equipment type to install.

2. Methodology

The optimal process synthesis is done by formulating a mathematical programming problem. For this purpose, the model was formulated using a General Disjunctive Programming (GDP) approach. This model aims to find the optimal configuration for the black tea production process, satisfying the productivity constraints with the objective of having a minimum cost. After that, a sensitivity analysis is made by varying raw material moisture to analyze the effect on production costs. GDP modeling approach is chosen to facilitate the problem formulation of process synthesis (Vecchietti and Grossmann, 2000).

2.1. Develop of mathematic programming problem

For the problem formulation, it is assumed that the total investment is done at the beginning of the project. In practice, moreover, black tea production plants can be run for at least 20 years without any other requirements than daily and planned maintenance.

In order to consider the investment an operating costs together which occur during the plant running it is used the value of the actualized cost to the beginning of the project, which is called actual value of cost (AVC) (Nassir Sapag Chain, 2011).

The equivalent value of the cost at the beginning of the period *p*, with an interest rate *r* is calculated according to Eq. (1).

$$ve_p = \frac{1}{(1-r)^{p-1}} \cdot Cost_p \tag{1}$$

Thus, the objective is to minimize the AVC, formed by the initial investment plus the equivalent value of operating costs for the first 20 years of the project, as expressed in Eq. (2).

$$MIN\ \ Z = AVC = \sum_i CIn_i + \sum_{p=1}^{20} \frac{1}{(1+r)^{p-1}} \cdot \left(\sum_i CWo_i + \sum_i EPC_i + \sum_i CPC_i \right) \tag{2}$$

Where *i* is the index of pieces of equipment that can be installed. *InvC* represents investment costs for equipment. *CWo*, *EPC*, and *CPC* are annual expenses on workers, electric power, and caloric power per machine respectively.

In addition, the mathematical problem is subjected to the following constraints:

$$\sum_{j \in JIN_{j,nod}} X_j - \sum_{j \in JOUT_{j,nod}} X_j = 0 \qquad \forall nod \tag{3}$$

Eq. (3) corresponds to dry matter balance in each node *nod* of the superstructure. *Xj* is dry matter flow that circulates through connection *j*; *JIN* and *JOUT* are sets that relate nodes with the input and output connections, respectively.

$$M_j = Mn_{nod} \qquad \forall nod, j \in JIN_{j,nod} \vee j \in JOUT_{j,nod} \tag{4}$$

The expression given by Eq. (4) indicates that moisture of the entering and leaving material flow must be equal in each node. M_j and Mn_{nod} are moisture of flow *j* and node *nod*, respectively.

$$X_j = X_{j'} \qquad (j, j') \in REL_{j,j'} \tag{5}$$

The expression in Eq. (5) states that dry matter entering the equipment should be equal to that leaving the equipment, where $REL_{j,j'}$ is a set that relates input flow *j* with output flow *j'* of each piece of equipment.

$$M_j \geq M_{j'} \quad \left(j,j'\right) \in REL_{j,j'} \tag{6}$$

Eq. (6) implies that moisture of an output flow will never be higher than that of the input flow.

$$M_1 = MMR \tag{7}$$

Eq. (7) determines that moisture of the flow entering the production plant will be equal to moisture of raw material *MMR*.

$$X_1 \geq \text{MinimunProductivity} \tag{8}$$

Eq. (8) establishes that the input flow to the plant should not be lower than minimal required productivity.

$$Mn_4 \leq 2.45 \tag{9}$$

$$Mn_4 \geq 1.21 \tag{10}$$

Constraints given by Eqs. (9) and (10) restrict the allowable range of product moisture after the withering stage.

$$\sum_{i \in ILR1_{i,lr1}} Y_i = 1 \quad \forall lr1 \tag{11}$$

Eq. (11) establishes that for each group of pieces of equipment in the set *ILR1*, only one of them must be selected.

$$\sum_{i \in ILR2_{i,lr2}} Y_i \leq 1 \quad \forall lr2 \tag{12}$$

Similarly to Eq. (11), the Eq. (12) formalizes that only one piece of equipment of those in group *ILR2* must be selected.

$$Mn_2 - MinMoisOutPC \geq -G \cdot \left(1 - Y_{Conventional\_PC}\right) \tag{13}$$

$$Mn_2 - MinMoisOutPC \geq -G \cdot \left(1 - Y_{Continuous\_PC}\right) \tag{14}$$

Constraints (13) and Eq. (14) establish that product moisture leaving the installed “conventional preservation chambers” or the “continuous preservation chamber” must be higher than 2.7 kg of water per kg of dry matter *(MinMoisOutPC).*

$$M_{40} \leq 0,03 \tag{15}$$

Constraint provided by Eq. (15) limits output moisture to be lower than 3%.

$$CWo_i = \left(\sum_{wm \in IWM_{i,wm}} wm \cdot Om_{i,wm} + \sum_{wc \in IWC_{i,wc}} wc \cdot Oc_{i,wc}\right) \cdot WoCost \quad \forall i \tag{16}$$

In Eq. (16), the labor cost related to each piece of equipment is calculated. Where $Om_{i,wm}$ is a binary variable, which is equal to a unit when *wm* workers are assigned in process *i* for manipulation activities, and null in any other case. Similarly, $Oc_{i,wc}$ is a binary variable which is equal to a unit when *wc* workers are employed in process *i* for controlling activities. $IWM_{i,wm}$ and $IWC_{i,wc}$ are sets that link quantities of workers that can be selected for each process, for manipulation and control activities respectively.

$$\begin{aligned}&\left[\sum_{n \in In_{ConvPC,n}} \left(\sum_{t \in IT_{ConvPC,t}} n \cdot PCCap_{ConvPC,t} \cdot W_{ConvPC,t,n}\right)\right] \\ &+ \left[\sum_{n \in In_{ContPC,n}} \left(\sum_{t \in IT_{ContPC,t}} n \cdot PCCap_{ContPC,t} \cdot W_{ContPC,t,n}\right)\right] \\ &- 24 \cdot X_1 \geq -G \cdot \left(1 - Y_{ContWB}\right)\end{aligned} \tag{17}$$

$$\begin{aligned}&\left[\sum_{n \in In_{ConvPC,n}} \left(\sum_{t \in IT_{ConvPC,t}} n \cdot PCCap_{ConvPC,t} \cdot W_{PCConv,t,n}\right)\right] \\ &+ \left[\sum_{n \in In_{ContPC,n}} \left(\sum_{t \in IT_{ContPC,t}} n \cdot PCCap_{ContPC,t} \cdot W_{ContPC,t,n}\right)\right] \\ &+ \left[\sum_{n \in In_{OpenTrough,n}} \left(\sum_{t \in IT_{OpenTrough,t}} n \cdot PCCap_{ContPC,t} \cdot W_{ContPC,t,n}\right)\right] \\ &- 24 \cdot X_1 \geq -G \cdot \left(1 - Y_{OpenTrough}\right)\end{aligned} \tag{18}$$

$$\begin{aligned}&\left[\sum_{n \in In_{ConvPC,n}} \left(\sum_{t \in IT_{ConvPC,t}} n \cdot PCCap_{ConvPC,t} \cdot W_{ConvPC,t,n}\right)\right] \\ &+ \left[\sum_{n \in In_{ContPC,n}} \left(\sum_{t \in IT_{ContPC,t}} n \cdot PCCap_{ContPC,t} \cdot W_{ContPC,t,n}\right)\right] \\ &+ \left[\sum_{n \in In_{ClosedTrough,n}} \left(\sum_{t \in IT_{ClosedTrough,t}} n \cdot PCCap_{ContPC,t} \cdot W_{ContPC,t,n}\right)\right] \\ &- 24 \cdot X_1 \geq -G \cdot \left(1 - Y_{ClosedTrough}\right)\end{aligned} \tag{19}$$

Eqs. (17)–(19) require the processing plant has a preservation capacity of tea leaves equal to or higher than the amount of raw material required for working 24 h/day. This constraint has an empirical origin. For reasons associated to weather conditions and harvest methods, there is no constant arrival of raw material into the processing plant. Parameter *G* in those constraints is a high value to define a Big-M-type constraint. Constraint (17) will be active if a continuous withering belt is used; otherwise, the constraint is relaxed and redundant in the model. Eqs. (18) and (19) are activated if open and closed static withering machines are used, respectively.

For each possible piece of equipment there is a constraint set related to amount, productivity, cost, energy consumption, manpower needed and moisture content. These constraints must be satisfied only in the case where the equipment is selected to be installed. A disjunctive formulation was selected to represent this discrete decision (Eq. (30)), where variable Yi must be 1 when unit i is chosen to be installed and 0 otherwise; when variable Yi is set to 1 constraints related to moisture content (Eqs. (20)–(21)) and manpower are forced (Eq. (22)). Disjunction 30 is an embedded ones, since some other discrete decisions are involved once the equipment is selected, binary variable $U_{i,t}$ is set to 1 to select the size *t* for unit *i*; once the size is chosen the next step is to determine the amount of equipment *i* fo size *t* must be installed which is stand for variable $W_{i,t,n}$ where the suffix *n* is to denote the number of units. In this last disjunction constraints about number of control workers needed, equipment productivity, investment cost and energy consumption must be satisfied.

Eqs. (20)–(21) settle the limits for moisture in material flow, depending on which equipment has been installed.

Eq. (22) determines the relationship between the amount of workers *wm*, for manipulation activities, selected for a piece of equipment and the production limit for that machine. $ManWoCap_i$ is processing capacity of a worker in that piece of equipment. *IE* is the investment for each piece of equipment.

If a piece of equipment is not installed, constraint in Eq. (29) makes the material flow entering the equipment null.

Disjunction 30 and 31 are similar, with the difference that Eq. (30) applies for units that remove moisture in the product while Eq. (31) does not. Stages that do not reduce moisture are crushing and fermentation.

$$\left[\begin{array}{l}
Y_i\\
M_j \le MUp_i \;\; j\in IJIn_{i,j} \;\; (20)\\
M_j \ge MLow_i \;\; j\in IJIn_{i,j} \;\; (21)\\
\sum\limits_{wm\in IWM_{i,wm}} wm\cdot ManWoCap_i\cdot Om_{i,wm} \ge \sum\limits_{j\in IJIn_{i,j}} X_j \;\; (22)\\
\underset{t\in IT_{i,t}}{\vee}\left[\begin{array}{l}
U_{i,t}\\
\underset{n\in In_{i,n}}{\vee}\left[\begin{array}{l}
W_{i,t,n}\\
\sum\limits_{wc\in IWC_{i,wc}} wc\cdot ContWoCap_i\cdot Oc_{i,wc} \ge n \;\; (23)\\
n\cdot C1_{i,t}\cdot M_j + n\cdot C2_{i,t}\cdot M_{j'} + n\cdot C3_{i,t} \le C4_{i,t}\cdot X_j \;\; j\in IJIn_{i,j}, j' \in IJOut_{i,j'} \;\; (24)\\
X_j \le n\cdot XUp_{i,t} \;\; j\in IJIn_{i,j} \;\; (25)\\
InvC_i = n\cdot IE_{i,t} \;\; (26)\\
EPC_i = n\cdot EC1_{i,t}\cdot X_j + n\cdot EC2_{i,t} \;\; j\in IJIn_{i,j} \;\; (27)\\
CPC_i = n\cdot CC1_{i,t}\cdot X_j + n\cdot CC2_{i,t} \;\; j\in IJIn_{i,j} \;\; (28)
\end{array}\right]
\end{array}\right]
\end{array}\right] \vee \left[\begin{array}{l}
\neg Y_i\\
X_j = 0 \;\; \forall j\in IJIn_{i,j} \;\; (29)
\end{array}\right] \;\; i\notin RemoveMois \tag{30}$$

$$\left[\begin{array}{l}
Y_i\\
M_j \le MUp_i \quad j\in IJIn_{i,j} \quad (32)\\
M_j \ge MLow_i \quad j\in IJIn_{i,j} \quad (33)\\
\sum\limits_{wm\in IWM_{i,wm}} wm\cdot ManWoCap_i\cdot Om_{i,wm} \ge \sum\limits_{j\in IJIn_{i,j}} X_j \quad (34)\\
\underset{t\in IT_{i,t}}{\vee}\left[\begin{array}{l}
U_{i,t}\\
\underset{n\in In_{i,n}}{\vee}\left[\begin{array}{l}
W_{i,t,n}\\
\sum\limits_{wc\in IWC_{i,wc}} wc\cdot ContWoCap_i\cdot Oc_{i,wc} \ge n \quad (35)\\
M_j = M_{j'} \quad j\in IJIn_{i,j}, j' \in IJOut_{i,j'} \quad (36)\\
X_j \le n\cdot XUp_{i,t} \quad j\in IJIn_{i,j} \quad (37)\\
InvC_i = n\cdot IE_{i,t} \quad (38)\\
EPC_i = n\cdot EC1_{i,t}\cdot X_j + n\cdot EC2_{i,t} \quad j\in IJIn_{i,j} \quad (39)\\
CPC_i = n\cdot CC1_{i,t}\cdot X_j + n\cdot CC2_{i,t} \quad j\in IJIn_{i,j} \quad (40)
\end{array}\right]
\end{array}\right] \vee \left[\begin{array}{l}
\neg Y_i\\
X_j = 0 \quad \forall j\in IJIn_{i,j} \quad (41)
\end{array}\right]
\end{array}\right] \quad i\notin RemoveMois \tag{31}$$

Moreover the constraint in Eq. (23) determines the relationship between the amount of workers for control activities *wc* selected and the quantity of pieces of equipment to be used.

Eq. (24) relates input and output moisture in a piece of equipment with the highest material flow that can be handled by that equipment under those conditions. *C1*, *C2*, *C3*, and *C4* are coefficients that relate, through a linear equation, input and output moisture with the product flow that can be processed by a given piece of equipment. Constraint in Eq. (25) establishes that the product flow cannot be higher than the feasible amount for the selected type, size, and quantity of the piece of equipment. *IJIn* and *IJOut* are sets that relate equipment with their input and output flows, respectively.

Equalities given in Eqs. (26)–(28) determine investment costs, electric power consumption costs, and heating costs. *EC1*, *EC2*, *CC1*, and *CC2* are coefficients for calculating energy costs in relation to product flows.

Constraint defined in Eq. (36) settles equality of input and output moisture in equipment that do not extract moisture from the product. On the other hand, constraints of Eqs. (32)–(35) and (37)–(41) are analogous to those of Eqs. (20)–(23) and (25)–(29), respectively.

For the model implementation and solution, disjunctions were manually transformed into Big-M constraints, turning the disjunctive model into a Mix-Integer Linear problem (MILP). The model was formulated in GAMS (General Algebraic Modeling System) (Brooke et al., 1992).

3. Results and discussions

The influence of moisture of raw material in the operation of a black tea process plant have been studied considering two situations: first, it was determined the optimal design and associated

Table 1
Installed equipment and selected size alternatives for different raw material moisture values with a productivity of 400 kg/h.

Piece of equipment installed	Raw material moisture [kg of water per kg of dry matter]								
	3.5	3.75	4	4.25	4.5	4.75	5	5.25	5.5
Conventional preservation chamber	1	1	1	1	1	1			1
Continuous preservation chamber							1	1	
Continuous withering belt	2	2	2	2	2	2	2	3	4
Rotorvane	2	2	2	2	2	2	2	2	2
Continuous fermenting machine	1	1	1	1	1	1	1	1	1
Fluid bed dryer	1	1	1	1	1	1	1	1	1

Table 2
Quantities of installed pieces of equipment for each raw material moisture value, with a productivity of 400 kg/h.

Piece of equipment installed	Raw material moisture [kg of water per kg of dry matter]								
	3.5	3.75	4	4.25	4.5	4.75	5	5.25	5.5
Conventional preservation chamber	6	6	6	6	6	8			20
Continuous preservation chamber							1	1	
Continuous withering belt	1	1	1	1	1	1	1	1	1
Rotorvane	1	1	1	1	1	1	1	1	1
Continuous fermenting machine	2	2	2	2	2	2	2	2	2
Fluid bed dryer	2	2	2	2	2	2	2	2	2

costs for a processing plant having different feedstock moistures; in second place it is studied how affect the production costs of a plant already installed having a higher wetness in the raw material that enters the processing plant.

3.1. *Sensitivity of optimal plant configuration as regards input moisture*

From the described model, the process synthesis was performed for a productivity of 400 kg of dry tea per hour, which is a common value used in the northeastern region of Argentina, gradually increasing the moisture in the raw material. Selected equipment and size alternatives for various leaf moisture values are shown in Table 1. The quantities of each selected piece of equipment for those conditions are presented in Table 2.

It can be noted that below 4.5 kg of water per dry matter, which is relatively high, the plant configuration remains the same. The flow sheet of this arrangement is shown in Fig. 2 and corresponds to 6 Conventional Preservation Chambers working in parallel, 1 Continuous Withering Belt, 1 Rotorvane, 2 parallel Continuous Fermenting Machines and 2 parallel Fluid Bed Dryers. The reason for this behavior is that preservation chambers play the role of a raw material buffer and also help in the extraction of water excess. When leaves moisture value is higher than 4.5 kg of water per dry matter, a greater capacity is required for extracting water content. This can be done by selecting larger pieces of equipment or using a higher quantity of them. For example, when moisture is increased from 4,5 to 4.75 kg of water per kg of dry matter, the optimal solution switches from 6 to 8 conventional preservation chambers, as shown in Table 2. Then, when there are 5.0 kg of water per kg of dry matter instead of 4.75, a continuous belt preservation chamber is used (Table 1), which has a greater capacity to store and process much more product than the conventional version. When there are 5.5 kg of water per kg of dry matter instead of 5.25, conventional preservation chamber are used again (Table 1) and its quantity will be 20 units (Table 2). This occurs as continuous withering belt capacity is increased, since size alternative 4 is selected instead of 3.

As shown in Fig. 3, the cost resulting from applying the synthesis model to achieve a desired productivity of 400 kg/h of dry product gradually increases with input moisture. Fig. 3 also shows that under a moisture value of 4.5 kg of water per dry matter, actual value of costs remain constant, while over this critical value, higher investments and operation costs are required to keep the productivity. Critical moisture value is relatively high and will depend on the productivity settled for the plant being designed.

3.2. *Influence of input moisture on a given plant design*

It is also interesting to analyze a supposed situation in which a plant has been designed for given maximum moisture level and a raw material with higher moisture arrives to the plant. For that purpose, the model was used to design a plant that processes leaves containing 3.5 kg of water per kg of dry material and for a minimal production of 400 kg/h. After that, logical variables of discrete decisions were fixed for equipment type, size alternatives, and quantity, as well as for the number of workers; then, with the plant

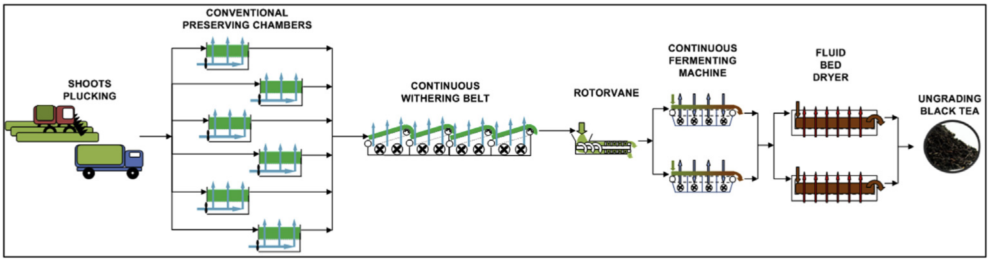

Fig. 2. Flow sheet of the configuration for low moisture raw material.

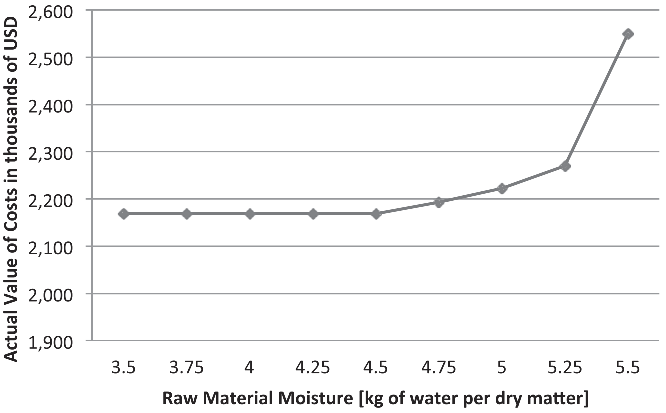

Fig. 3. Variation of actual value of costs subjected to raw material moisture (productivity of 400 kg/h of dry product).

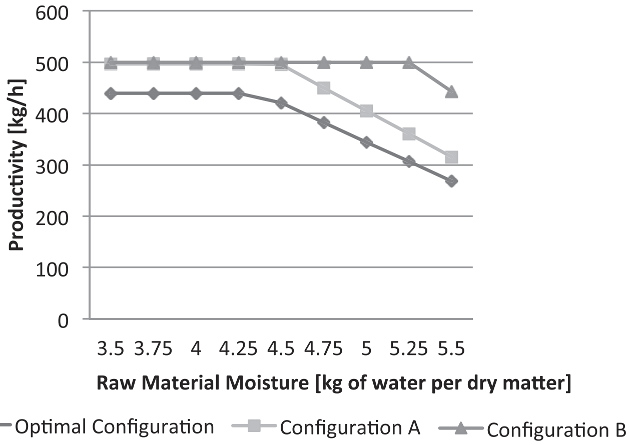

Fig. 4. Optimal productivity reached according to raw material moisture.

configuration fixed, the model was executed with the maximization of the productivity as objective function (Eq. (42)), and varying the moisture values in the raw material. In addition, Eq. (8) is not included in the model for this case.

$$Max\ Z = X_1 \tag{42}$$

Once the optimization program reaches a feasible solution, the operating cost per kg of dry product -unit operation cost-, given by the Eq. (43) was calculated.

$$UOC = \frac{\sum_i CWo_i + \sum_i EPC_i + \sum_i CPC_i}{X_1 X_1^{MAX}} \tag{43}$$

Where UOC is the unit operation cost of the configuration, X_1^{MAX} is maximum productivity above obtained.

This study was performed for other two plant configurations (A and B) which are representative installations for several tea companies in Argentina. The equipment for the three process configurations analyzed are summarized in Table 3, the maximum productivity and unit operation cost are presented in Figs. 4 and Fig. 5, respectively.

The comparison of the three configurations is presented in Fig. 4, where can be observed that at low moisture values similar maximal productivities are obtained for the A and B configurations, but the optimal design has a lower one around the design value. This suggests that the A and B plant configurations are better in terms of productivity, but when are analyzed the operating costs (Fig. 5) both require significantly higher costs than the optimal plant in the whole moisture range.

From Fig. 5 it can be seen that configurations A and B have a higher processing cost of U$D 0.42 per kg and U$D 0.57 per kg respectively (for low moisture of raw material), while that the optimum configuration cost is U$D 0.35 per kg. This represents a 20% greater for case A and 60% for topology B.

It is also observed that there is an interval of input moisture in which the plant productivity is not affected by an increase (from 3.5 until 4.5). With values over that interval, productivity falls and operation costs per kg of dry product rapidly increases and depends on the plant configuration.

In summary, according to cases studied it is observed that, while the preservation chambers perform a function of conditioning of the raw material, the same is not enough to compensate large increases in moisture input. So to ensure good performance of the total process is necessary to establish harvest policies to have a reasonably low average moisture (less than 4.5 kg of water per kg of dry matter), even in rainy periods.

4. Conclusions

In this work a Generalized Disjunctive Programming model (GDP) is formulated to find the optimal flow sheet to produce black tea minimizing investment and operation cost having different wet content in the raw material (tea shoots). The optimal configuration

Table 3
Analyzed configurations.

Optimal configuration (for 400 kg dry matter/h and 3.5 kg water/kg dry matter)					
Piece of equipment selected	Conventional preservation chamber	Continuous withering belt	Rotorvane	Continuous fermenting machine	Fluid bed drier
Size	1	2	2	1	1
Quantity	6	1	1	2	2
Plant configuration A					
Piece of equipment selected	Conventional preservation chamber	Continuous withering belt	Rotorvane	Continuous fermenting machine	Endless chain pressure drier
Size	1	1	2	1	1
Quantity	16	2	2	2	2
Plant configuration B					
Piece of equipment selected	Conventional preservation chamber	Continuous withering belt	Rotorvane	Continuous fermenting machine	Endless chain pressure drier
Size	1	4	2	1	1
Quantity	10	1	3	3	3

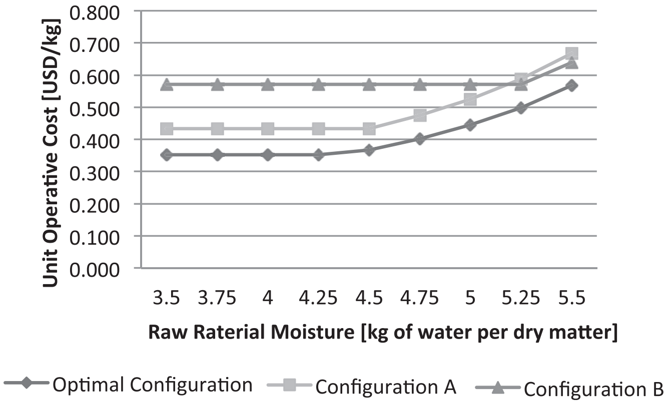

Fig. 5. Optimal unit operation cost subjected to raw material moisture.

of the plant obtained in the model differs from those typical equipment flow sheets found in tea factories in Argentina. Over a particular level of wet content in the tea shoots, the optimal plant configuration is affected involving more investment and operation costs. It was found that in a relatively wide moisture interval, between 3.5 and 4.5 kg of water per kg of dry matter, optimal configuration is kept unchanged. Over that interval, the model incorporates equipment with higher moisture extraction capacity or increases the quantity of installed pieces of equipment. This enhances investment and operation costs in plants. On the other hand, for a given plant configuration and over a moisture value in the raw material, the operation costs per kg of dry matter increase rapidly. This threshold value depends on the plant arrangement, and in optimum configuration is 4.25 kg of water per kg of dry matter.

In the optimal configuration of the process you will come to a trade off between the installation of economic processes but with great operation cost and automated pieces of equipment but at high investment cost. The recommended equipments are: conventional preservation chambers, continuous withering belts, Rotorvane crusher, continuous fermenting machines and fluid bed dryers. With the optimal configuration, the operative unit cost when the raw material moisture is low, is about 0.35 U$D per kg of dry matter, it increase at 0.56 U$D per kg for moistures around of 5.5 kg of water per kg of dry matter.

The results obtained in this work can help in the definition of harvesting policies and in the reception of Camellia sinensis leaves at production plants. In this way, these policies take into account not only issues related to leaf quality but also economic conditions associated to the process.

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Glossary

Index

p: Years computed
i: Pieces of equipment
j: Connections
nod: Nodes
wm: Workers for manual activities
wc: Workers for control activities
n: Number of pieces of equipment installed
$lr1$, $lr2$: Indexes for logical relationship between pieces of equipment

Continuous variables

$InvC_i$: Investment cost, $USD \times 10^3$
WoC_i: Labor cost, $USD/yr \times 10^3$
EPC_i: Electric power cost, $USD/yr \times 10^3$
CPC_i: Caloric power cost, $USD/yr \times 10^3$
X_j: Flux of product on connection j, $10^3 \times kg_{dry\ matter}/h$

M_j: Moisture of product on connection j, $kg_{water}/kg_{dry\ matter}$

Binary variables

Y_i: Decision variable that takes the unit value when the piece of equipment i is installed
$U_{i,t}$: Decision variable that takes the unit value when the piece of equipment i and size t is installed
$W_{i,t,n}$: Decision variable that takes the unit value when the piece of equipment i, size t is installed in number n
$Om_{i,wm}$: Decision variable that takes the unit value when a manual operation in piece of equipment i is performed by wc workers
$Oc_{i,wc}$: Decision variable that takes the unit value when a control operation in piece of equipment i is performed by wc workers

Sets

$JIN_{j,nod}$: Set of connections j that enter to node nod
$JOUT_{j,nod}$: Set of connections j that out to node nod
$IRL1_{i,rl1}$, $IRL2_{i,rl2}$: Sets for logical relationships between pieces of equipment
$IWM_{i,wm}$: Set of pieces of equipment that have associated an manual activity
$IWC_{i,wc}$: Set of pieces of equipment that have associated an control activity
$In_{i,n}$: Set of numbers of pieces of equipment n available for to be installed in parallel
$IT_{i,t}$: Set of sizes of pieces of equipment t available for to be installed
$IJIn_{i,j}$: Set of incoming connections j to a piece of equipment i
$IJOut_{i,j}$: Set of outcoming connections j of a piece of equipment i
$RemoveMois_i$: Set of pieces of equipment i that can perform water extraction

Parameters

HWY: Hours worked per year, $h/yr \times 10^3$
r: Discount rate
RMM: Raw material moisture, $kg_{water}/kg_{dry\ matter}$
G: High value constant for Big-M constraints
$MinMoisOutPC$: Minimum moisture at end of Preservation Chambers, $kg_{water}/kg_{dry\ matter}$
$MinProductivity$: Minimum plant productivity, $kg_{dry\ matter}/h$
$WoCost$: Labor cost of one worker for an hour of work, $USD/h \times 10^3$
$PCCap_{i,t}$: Preservation Chamber capacity, $kg \times 10^3$
M_i^{Up}: Maximum processing moisture of an piece of equipment i, $kg_{water}/kg_{dry\ matter}$
M_i^{Low}: Minimum processing moisture of an piece of equipment i, $kg_{water}/kg_{dry\ matter}$
X_i^{Up}: Maximum processing capacity of an piece of equipment i, $10^3 \times kg_{dry\ matter}/h$
$ManWoCap_i$: Maximum capacity of a worker for a manual activity, $10^3 \times kg_{dry\ matter}/h \times worker$
$ContWoCap_i$: Maximum capacity of a worker for a control activity, *Pieces of equipment/worker*
$C1_{i,t}$, $C2_{i,t}$; $C3_{i,t}$; $C4_{i,t}$: Coefficients for maximum productivity calculation
$IE_{i,t}$: Investment for a piece of equipment i and size t
$EC1_{i,t}$, $EC2_{i,t}$: Coefficients for electric power cost calculation
$CC1_{i,t}$, $CC2_{i,t}$: Coefficients for caloric power cost calculation