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Optimizing Apple Juice Extraction in Multiple Presses

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ABSTRACT: A method was developed to find the optimum hydration flow sheet that maximizes either the profit or the soluble solids recovery for a given number of presses in an apple concentrate juice plant. The pomace arising from a press can be wetted with either pure water or dilute juice from downstream presses, or a mixture of both in any proportion. The mass balance around the presses involving any hydration arrangement was posed as an array named connectivity matrix. The connectivity matrix and the economical balance were written in computer code in order to carry out the optimization procedure. The optimization started from a minimum amount of water, and stepwise increasing levels of hydration were evaluated. The best value of this combinatorial search was retained. The optimum arrangement was pure countercurrent in most of cases considered.

Key Words: extraction, hydration, apple juice, optimization, press

INTRODUCTION

IN APPLE JUICE MANUFACTURING, IT IS A COMMON PRACTICE TO hydrate the pomace resulting from one press and send it to the next for further extraction. This procedure can be repeated in a set of presses in series, and each one can receive the pomace from the preceding one previously hydrated. However, hydration has certain limits, because one press may be flooded if hydrated in excess, and it should be taken into account that if juice is to be concentrated, the evaporation cost increases.

A plant manufacturing apple juice concentrate (AJC) usually has 2 different working periods during the year, in accordance with the raw material supply, because it defines not only the price but also the way the evaporation costs will be considered. The evaporation stage is usually the bottleneck, hence if the apple availability is large, the evaporator will work at full capacity, the involved costs are fixed, and the incidence of apple costs is lower. Conversely, several months after the harvest season, apples are supplied from cold storage in smaller quantities, making the evaporating costs variable in accordance with the operation time required, and the relative weight of costs is inverted.

The objective of this work is to devise a method to find the optimum hydration flow sheet for a given number of presses, which maximizes either the profit or the soluble solids recovery. The model is posed for 2 alternative situations: The raw material is large enough to saturate the plant evaporation capacity or there is a shortage that makes the evaporator work on demand.

RESULTS AND DISCUSSION

THE ALGORITHM DESCRIBED WAS PROGRAMMED IN FORTRAN and tested with different examples of both saturated evaporator and raw material shortage seasons (González 1990; González and Urbicain 1998).

In Fig. 1, the results of the optimization set of five presses, in terms of both the net profit and the sugar recovery, are presented as a function of hydration level, expressed as percentage of the pomace mass processed.

Regarding the sugar recovery, it is apparent that the dotted line grows monotonically, suggesting hydrating as much as possible within practical limits. This is not unexpected because the larger the amount of water introduced, the larger the amount of sugar recovered from the solid matrix, which in turn means a saving in raw material. However, it also means a larger amount of water to be evaporated to get the concentrate, increasing the manufacturing costs.

It could be expected then to have a break-even point that makes the whole operation optimal in terms of the profit. In the analyzed example, the full line on Fig. 1 shows that the best results are obtained at a relatively low degree of hydration, in this case at 30%. It must be remarked that the simulation was performed for increments of 10% in the hydration level, finding the best result for 30%, though the fitting polynomial shows a maximum at approximately 27%. In a real case, it should be advisable to perform additional runs between 25% and 30% at 1% intervals to find the actual maximum.

The results show conclusively that the plant management must be careful in deciding the degree of hydration from the point of view of the raw material consumption only. A good figure in the raw material cost component could be a bad one when the general balance is drawn.

The optimal flow sheet for the selected example with that degree of hydration is shown in Fig. 2. Water wets press 5 at a flow

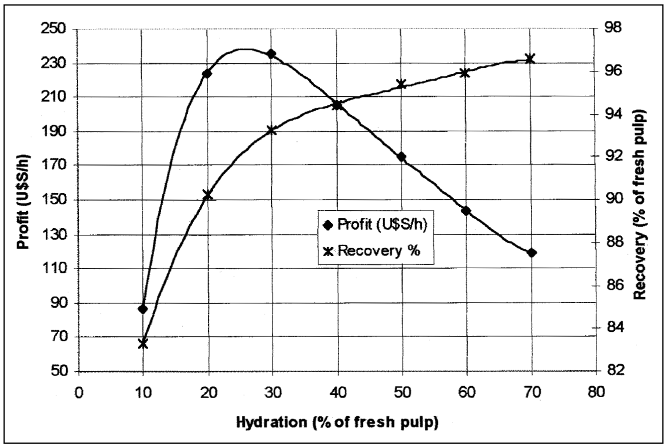

Fig. 1—Net profit and sugar recovery as a function of hydration level for a 5-presses set

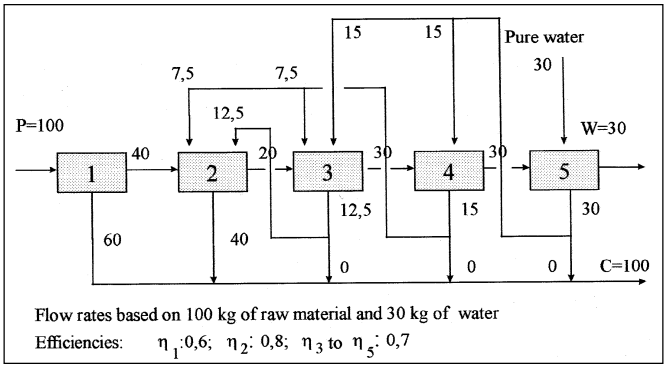

Fig. 2—Flow diagram of the 5-presses set for a hydration level of 30% of fresh pulp fed

rate of 30 kg/h while 100 kg/h of raw material feed the first one. The exhausted pomace at a rate of 30 kg/h leaves the system from press 5 while 100 kg/h of juice collected from presses 1 (60 kg/h) and 2 (40 kg/h) goes to clarification. Juice from presses 3, 4, and 5 are used to hydrate upstream presses at the rates indicated in the figure.

Finally, even though most of the examples showed an optimum for a purely countercurrent flow arrangement, as could be expected, the presented example shows that it is not always true. The result is a complex function of many economical and technical variables involved, so each case must be analyzed considering its cost structure and processing capacity at each particular season.

CONCLUSIONS

A SIMPLE ALGORITHM TO OPTIMIZE THE POMACE HYDRATION policybefore repressing is presented. It is to be applied to an existing plant having 2 or more presses, either piston or continuous, to determine the amount of water to be added and the connections flow sheet, in order to maximize the net overall profit of the whole plant operation.

MATERIALS AND METHODS

Material balance

Let N be the number of presses in a pressing train as sketched in Fig. 3, where η_j is the yield of generic press "j," the yield being defined as the mass of juice produced by the unit mass of fresh pulp. It must be recalled that this definition is only valid for the pressing of fresh pulp, being meaningless if hydrated pomace is being pressed.

In order to make the calculation general, and assuming the fresh water inlet is made in the last press, noted N, the water supply will be considered as a virtual press N + 1, which obviously will not produce any juice. With the exception of press 1, which processes fresh pulp and hence will be not hydrated, the remaining 2 to N units, can be hydrated in any proportion by juice provided by one or more of the following presses in the set, including "press" N + 1, which means fresh water. In summary, press j ($2 \le j \le N$) can receive either water or juice from anyone between press j + 1 and N + 1.

In what follows all equations are referred to 1 kg of fresh pulp.

Let V_{jk} be the juice produced by press k that is sent to hydrate the pomace in press j. An elemental material balance around press j gives Eq. 1:

$$W_{j-1} + \sum_{k=j+1}^{N+1} V_{jk} = W_j + J_j \qquad (1)$$

A similar balance on soluble solids gives Eq. 2:

$$W_{j-1}X_{j-1} + \sum_{k=j+1}^{N+1} V_{jk}Y_k = W_jX_j + J_jY_j \qquad (2)$$

Taking into account the definition of yield η_j given above, it is $\eta_j = 1 - W_j$, and the calculation of the difference of pomace mass delivered by 2 consecutive presses is straightforward:

$$W_{j-1} - W_j = \eta_j - \eta_{j-1} \qquad (3)$$

Eq. 1 can be written:

$$J_j = \eta_j - \eta_{j-1} + V_{jh} \qquad (4)$$

where V_{jh} is the summation of all wetting streams flowing onto press j from all presses located downstream it, as given by Eq. 5:

$$V_{jh} = \sum_{k=j+1}^{N+1} V_{jk} \qquad (5)$$

Mass balance can be completed with the following equations:

$$J_j = C_j + B_j \qquad (6)$$

where C_j is the fraction of juice following the process and B_j the fraction used for hydration of the preceding presses. Hence:

$$B_j = \sum_{k=2}^{j-1} V_{kj} \qquad (7)$$

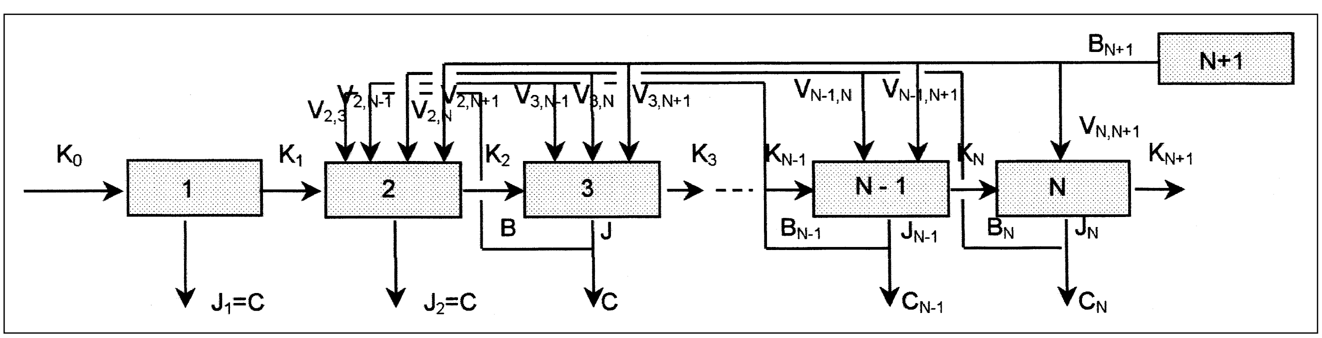

Fig. 3—Sketch of a set of N presses with a general flow diagram of hydrating steams

If W_0 is the mass flow rate of fresh pulp, assumed to be 1 kg, the yield of the first press is equal to the juice mass flow rate produced in that unit:

$$J_1 = \eta_1 = W_0 - W_1 \quad (8)$$

Overall mass balance:

$$W_0 + B_{N+1} = W_N + \sum_{j=1}^{N} C_j \quad (9)$$

Overall soluble solids mass balance:

$$W_0X_0 = W_NX_N + \sum_{j=1}^{N} C_jY_j \quad (10)$$

To analyze the influence of the hydration in a given press j, a concept similar to that of equilibrium stages is introduced (Urbicain and others 1990). When hydration takes place, fresh water or lean juice is mixed with richer juice trapped in the pomace, and sugar is expected to diffuse from the juice to the wetting liquid. Should that mixing be perfect, the final liquid should have an uniform, theoretical concentration $Y_{teor,\,j}$ given by the mass balance expressed by Eq. 11:

$$Y_{teor,\,j} = (W_{j-1}X_{j-1} + V_{jh}Y_{h)}/(W_{j-1} + V_{jh}) \quad (11)$$

and $Y_{j,ave}$ is the average concentration of V_{jh}, as given by Eq. 12:

$$Y_{j,ave} = \left(\sum_{J=+1}^{N+1} V_{jk}Y_k\right)/V_{jh} \quad (12)$$

$Y_{teor,j}$ cannot be attained in practical operation, but a lower equilibrium value $Y_j^* < Y_{teor,j}$ will be the actual concentration of the juice, while the concentration of the liquid originally wetting the pomace, X_{j-1}, is reduced to a value, $X_j^* > Y_{teor,j}$ in equilibrium with Y_j^*.

Let Z_j be a diffusion factor, in the form of a dimensionless concentration given by equation. (13), as a measure of how efficient the hydration has been in capturing sugar from the pomace:

$$Z_j = (Y_j^* - Y_{j,ave})/(Y_{teor,j} - Y_{j,ave}) \quad (13)$$

In a perfect mixer Y_j^* tends to $Y_{teor,j}$, and Z_j tends to 1. Y_j^* can be obtained rearranging equation. (13), with $Z_j < 1$.

X_j^* is given by the amount of soluble solids contained in W_j, and calculated by difference

$$X_j^* = (W_{j-1}X_{j-1} + V_{jh}Y_{j,ave} - Y_j^*V_{jh})/W_{j-1} \quad (14)$$

however, actual values X_j and Y_j leaving the press are equal to equilibrium ones in the particular case of $(\eta_j - \eta_{j-1}) = 0$ only. Should it be the case, press j is expected to produce the same amount of pomace than press $(j - 1)$, independent of the degree of hydration, so if no water is added, no juice is produced. Otherwise, any amount of water added should leave the press as juice J_j and the final concentrations in the juice and the pomace liquid would be $Y_j = Y_j^*$ and $X_j = X_j^*$ and respectively.

If $(\eta_j - \eta_{j-1})$ is not equal to 0, concentrations are to be calculated in a different manner. Let $(\eta_j - \eta_{j-1})$ be > 0. That means that press j will extract all the liquid added plus some of the liquid entering with the pomace. In this case:

$$X_j = X_j^* \qquad \text{for } (\eta_j - \eta_{j-1}) \geq 0 \quad (15)$$

$$Y_j = (W_{j-1}X_{j-1} + V_{j,ave}Y_h - W_jX_j)/J_j \qquad \text{for } (\eta_j - \eta_{j-1}) > 0 \quad (16)$$

Symmetrically, for $(\eta_j - \eta_{j-1}) < 0$, press j will not extract all the wetting liquid added, but part of it will remain diluting the pomace.

Hence:

$$Y_j = Y_j^* \qquad \text{for } (\eta_j - \eta_{j-1}) \leq 0 \quad (17)$$

$$X_j = (W_{j-1}X_{j-1} + V_{j,ave}Y_h - J_jY_j)/W_j \qquad \text{for } (\eta_j - \eta_{j-1}) < 0 \quad (18)$$

Eq. 11 and 18 are valid for presses 2 to N; for press 1 results $Y_1 = X_0$ and $X_1 = X_0$.

Economical balance

Profit, in terms of money units per time unit, is calculated by Eq. 19:

$$G = J_c\,(P_v - C_T) - C_F \quad (19)$$

where fixed costs C_F and selling price P_v are data, and concentrate flow rate J_c and variable costs C_T are calculated by the program as follows:

1) Juice concentrate flow rate, J_c:

$$J_c = J_FB_F/B_c \quad (20)$$

Calculation of juice mass flow rate fed to the evaporator, J_F, depends of the situation considered, which in turns changes along the year:

a) saturated evaporation (SE), corresponding to a situation of raw material surplus, usually encountered during harvest months season, which makes the evaporator work at full capacity, and

b) evaporation idle capacity (IC), corresponding to a shortage of raw material, usually encountered during post-harvest season, making the evaporator work "on demand."

In the first case J_F is a function of the actual evaporation capacity and is calculated by Eq. 21:

$$J_F^{SE} = E_v(1 - B_F/B_c) \quad (21)$$

In case b) J_F is calculated as a function of the mass flow rate of processed pulp, by means of Eq. 22:

$$J_F^{C} = PR_c(W_0X_0 - W_NX_N) \quad (22)$$

When J_F is calculated by means of Eq. 21, the pulp mass flow rate that can be processed is obtained by rearranging Eq. 22 and using the found value of J_F:

$$P = J_F^{SE}/R_c(W_0X_0 - W_NX_N) \quad (23)$$

If, alternatively, J_F is calculated by Eq. 22, the dependent parameter is the water to be evaporated, and it is calculated as the difference between the juice flow rate fed to the evaporator and the concentrate:

$$E_v = J_F^{IC} - J_c \quad (24)$$

2) Variable costs, C_T:

Factor C_T in Eq. 19 is the summation of 4 terms:

$$C_T = C_M + C_p + C_z + C_E \qquad (25)$$

where

$$C_M = P_M R_j \qquad (26)$$

the parameter R_j being the ratio between pressed pulp and-concentrate produced:

$$R_j = P/J_c \qquad (27)$$

C_p is a datum entered by the user.

C_z is the cost of enzyme treatment, which could be done to the pulp before pressing in order to increase the yield and depends on the enzymes price, C_z, and the applied doses, D_z, and it is calculated by Eq. 28:

$$C_z = P_z D_z R_j \qquad (28)$$

Regarding the evaporation cost C_E, when raw material is the process bottleneck (situation b) as mentioned above), it is calculated by means of Eq. 29:

$$C_E = E_v C_v / J_C \qquad (29)$$

where C_v is the cost of evaporate 1 kg of water.

Conversely, when the evaporator is saturated, evaporation cost is a constant included in C_P and $C_E = 0$.

Optimization

Optimization seeks the best hydration flow sheet, among all possible arrangements between presses, having as objective either the maximum profit or the maximum sugar recovery.

With reference to Fig. 1, V_{ij} is a fraction of J_j and can be expressed as:

$$V_{ij} = h_{ij} J_j \qquad (30)$$

where h_{ij} is a factor between 0 and 1.

Considering Eq. 6 and 7, inequality Eq. 31 must be true:

$$\sum_{i=2}^{j-1} h_{ij} \le 1 \qquad (31)$$

Coefficients h_{ij} are the elements of a triangular superior matrix, named connectivity matrix because its elements define the amount of juice from press k that goes to wet press j. This matrix has N−1 rows, representing the hydrated presses from 2 to N, and N − 1 columns, identifying the source presses, from 3 to N + 1.

We define a variable named "pitch," noted p, a natural number equal or larger than 1, to determine the minimum amount of juice allowed to flow from one press to another. The pitch is related to h_{ij} by a simple expression, valid for $i < j$:

$$h_{ij} = K_{ij}/p \qquad (32)$$

Fractions of juice going to clarification are defined as:

$$c_j = C_j/J_j \qquad (33)$$

The c_j's can be added to RHS of inequality Eq. 32 to make it an equation:

$$\sum_{i=2}^{j-1} (h_{ij} + c_j) = 1 \qquad j = 3, \ldots, N+1 \qquad (34)$$

Coefficients c_j can be related to pitch **p** by means of factors k_{jj} with a relationship similar to Eq. 32:

$$c_{jj} = k_{jj}/p \qquad (35)$$

Then Eq. 34 becomes:

$$\sum_{i=2}^{j} k_{ij} = p \qquad (36)$$

k_{ij} is also a natural number such that $0 \le k_{ij} \le p$ and Eq. 36 must be satisfied N − 1 times, namely for j = 3, …, N + 1.

Calculations to be performed are all material and economical balances for all possible combinations of k_{ij}. It must be noted that for a given p, there are (j − 2) degrees of freedom in each press, excepting the fresh water supply, virtual press N + 1, for which element $k_{N+1,N+1}$ is always 0, making (j − 3) degrees of freedom.

As an example, let it be a set of 4 presses, hence Eq. 36 can be posed 3 times. Let it be p = 2, which means that the juice delivered by any press is to be divided in 2 equal streams, one going to another press and the remaining half going either to clarification or to a third press. The resulting equations are:

$$\begin{aligned} k_{23} + k_{33} &= 2 \\ k_{24} + k_{34} + k_{44} &= 2 \\ k_{25} + k_{35} + k_{45} &= 2 \end{aligned} \qquad (37)$$

MATRIX A

k_{23}	k_{33}	k_{24}	k_{34}	k_{44}	k_{25}	k_{35}	k_{45}
		Submatrix 2			Submatrix 1		
0	2	0	0	2	0	0	2
0	2	0	0	2	0	1	1
0	2	0	0	2	0	2	0
0	2	0	0	2	1	0	1
0	2	0	0	2	1	1	0
0	2	0	0	2	2	0	0
0	2	0	1	1	Submatrix 1 is repeated		
0	2	0	2	0	Submatrix 1 is repeated		
0	2	1	0	1	Submatrix 1 is repeated		
0	2	1	1	0	Submatrix 1 is repeated		
0	2	2	0	0	Submatrix 1 is repeated		
1	1	Submatrix 2 is repeated					
2	0	Submatrix 2 is repeated					

MATRIX B

h_{ij}	3	4	5	c_j
2	0,5	0,5	0	0,5
3	0	0,5	1	0
4	0	0	0	0

The possible values of the k_{ij} are 0, 1, and 2 respectively, while k_{33}, $k_{44,}$ and k_{45} result from the values assigned to k_{23}, k_{24}, k_{34}, k_{25} and k_{35}.

The complete set of cases to be studied are represented by Matrix A.

In this case 108 alternatives will be evaluated. For example, if we assume $k_{23} = 1$, $k_{33} = 1$, $k_{24} = 1$, $k_{34} = 1$, $k_{44} = 0$, $k_{25} = 0$, $k_{35} = 2$, $k_{45} = 0$, the h_{ij}'s and c_j's will be those shown in Matrix B.

Elements of Matrix B show that fresh water will wet press 3 only, juice from press 4 will wet presses 2 and 3 in equal parts, while 50% of the juice from press 3 will go to press 2, and the remaining 50% will go to clarification. If p = 4, the number of cases to evaluate rises up to1125, and for p = 10, 47916 calculations will be required.

If the train has 5 presses, for p = 1, cases evaluated will be 96, for p = 2, 1800, for p = 4, 91875, and for p = 5, 395,136. This means an exponential growth in the number of calculations as p increases.

Optimization can be performed with either the net profit or the maximum sugar recovery as objective function. One constraint to be taken into account is the amount of fresh water added to the last press: It can not be unlimited so a certain maximum hydration must be defined. A practical way is to take it as a fraction of the total amount of pulp to be processed, selected with some heuristic criterion.

In the other end, it is the "critical hydration," a concept presented in a former paper (Elustondo and Urbicain, 1992), which is the minimum amount of water required for all the presses to produce some juice.

Hence, the program evaluates all possible configurations, starting with the critical hydration as the minimum value, selecting the best of them on the basis of the selected criteria, the hydration level is increased in a certain arbitrary, and the procedure is repeated until the maximum selected hydration isreached.

It is worth to mention that not all calculated configurations are physically or practically feasible, so some heuristics are introduced to discard them immediately. For example, the total hydration could be larger than the critical but could be distributed in such a way that for some particular press it is not. In that case the configuration is eliminated. Another case is when the amount of liquid entering to a given press is such that the unit would be flooded; it is also discarded.

One heuristic adopted is that $\sum_{k=j+1}^{N+1} V_{jk}$ in press j must be lower than 1.5 the mass flow rate of pomace fed to the press. If at a certain level of hydration all configurations are neglected because that condition is not satisfied, it means that no further hydration is possible, and the iteration stops.

In any case, once all best configurations have been selected at each level of hydration, the program selects the best among them, with it the corresponding hydration flow rate and reports the result.

Nomenclature and units

B_c	Brix degrees of concentrate [kg sol.solids / kg concentrate]
B_F	Brix of juice fed to evaporator [kg sol.solids / kg concentrate]
B_j	Juice flow rate from press J [kg / kg of raw material)
C_E	Concentrate evaporation cost [U$S / kg concentrate]
C_V	Water evaporation cost [U$S / kg vapor produced]
C_j	Juice flow rate to clarification from press j [kg / kg of raw material]
C_M	Raw material cost [U$S / kg concentrate]
C_p	Processing cost [U$S / kg concentrate]
C_T	Total cost [U$S / kg concentrate]
C_z	Enzymes treatment cost [U$S / kg concentrate]
D_z	Enzymes addition [kg / kg of raw material]
E_v	Water evaporated [kg/h]
G	Net profit [U$S / h]
G_F	Fixed costs [U$S / h]
h_{ij}	Fraction of juice from press **j** wetting press i [-]
J_c	Concentrate mass flow rate [kg/h]
J_F	Juice fed to the evaporator [kg/h]
J_j	Juice from press j [kg / kg of raw material]
k_{ij}	Factor in equation (32)
p	Pitch, variable in equation (32)
P	Fresh pulp mass flow rate [kg/h]
P_M	Raw material price [U$S / kg of raw material]
P_v	Concentrate selling price [U$S / kg concentrate]
P_z	Enzyme price [U$S / kg enzyme]
R_c	Clarification yield [kg of raw material / kg. conc.]
V_{jk}	Juice flow rate wetting press j from press k [kg / kg of raw material]
W_j	Pomace from press j [kg / kg of raw material]
X_j^*	Sugar concentration in pomace from press j [kg / kg pomace]
	Sugar equilibrium concentration in pomace from press j, [kg /kg pomace]
Y_j	Sugar concentration in juice from press j [kg / kg juice]

References

Elustondo MP, Urbicain MJ. 1992. Critical hydration in a series of presses for apple juice manufacture. J Food Engineering 17: 217–224.

González MT. 1990. Programa Hidrat, PLAPIQUI. NEED COMPLETE REFERENCE

González MT, Urbicain MJ. 1998. Optimización de la hidratación en un tren de prensas. II Congreso Iberoamericano de Ingeniería de Alimentos, Bahía Blanca March.

Urbicain MJ, Elustondo MP, Ramos MA. 1990. Computer Simulation of an ACJ Plant. Symposium of the International Federation of Fruit Juice Producers; May 17; Paris.

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