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Operational change as a profitable cleaner production tool for a brewery

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ABSTRACT

The development and implementation of new procedures and operational changes in the production processes constitutes a powerful tool for the practical application of Cleaner Production in industries. In this work an operational change (new procedure) was developed for the elaboration of a type of beer which uses sugar as malt adjunct. The change consists in processing separately the three main components of the beer wort: malt extract, sugar and water, and use them properly in a different sequence than that used up to date in the traditional process. The new procedure was successfully assayed on industrial scale in Tínima brewery, located in Camagüey, Cuba, obtaining a good quality beer, technological and economical advantages with benefits for the environment, registering significant savings in energy (49%), sugar (4%), water (7%) and caustic soda (3%) consumption; and diminishing the surplus hot water (74%), waste generation (11%) and greenhouse gases emission (21%). Beer production capacity is increased also almost three times. With the application of the new technology to the Cuban beer type of 8 °P, it was achieved a total saving of US$ 481.83/1000 hL of beer produced.

1. Introduction

As defined by the United Nations for Industrial Development Organization (UNIDO), cleaner production (CP) implies for production processes, the conservation of raw materials and energy, the elimination of toxic raw materials, as well as the reduction in quantity and toxicity of all the emissions and wastes before they leave the process. CP is reached through the know-how application, improving technologies and changing working attitudes.

Several tools exist for the application of CP approach to a company [1]. These can be classified in two main groups of CP options:

(1) oriented to waste and emissions minimization and
(2) oriented to the reuse of those waste and emissions.

In the first group, there are the CP options that imply a reduction at the source (reuse inside of the own company) of the wastes and emissions generated by it, before leaving the production process. This group of CP options includes the adoption of modifications to products and production processes.

The CP options related with modifications to production processes comprise in turn: adoption of good house keeping, selection of new materials for the process and the development of new technologies/procedures. The development and implementation of new technologies/procedures constitutes a powerful tool for the application of practical CP in the industries, although as for any CP option, its technical, economical and environmental implications should be assessed.

Tínima brewery is the second largest in Cuba, with an annual production capacity of 500,000 hL of beer. It was assessed by a working team of the National Cleaner Production Network of Cuba (NCPN), for the introduction and implementation of CP practices. The main objective of the CP assessment was the diminishing of energy and water consumption, given the current conditions of the constant rise in the fuel prices and the shortage of water. So, when analyzing the energy and water balances of the brewery, for the generation of CP options, a new idea arose linked with the elaboration of beer with high substitution of malt by sugar in its formula (characteristic of Cuban beers). This new idea considers basic operational modifications in the industry with the specific objective of saving energy and water.

To produce beer in Tínima brewery, like in most breweries around the world and as shown in Fig. 1, the malt grains received at the silo (a) are mixed with water and milled in the mill (b), undergoing a mashing process further in the mash tun (c). In the lauter tun (d) the wort and the spent grains are separated (e). Later the wort undergoes boiling in the wort kettle (f), adding the hop which contributes to flavour and a characteristic bitterness, then it goes to the whirlpool (g) to separate hot trub. Afterwards the wort is cooled (h), filtered (i) separating the kieselghur (j), and pumped to fermentation tank (k), where the yeast is added. Once finished the fermentation process, the beer is filtered (l) separating the cold

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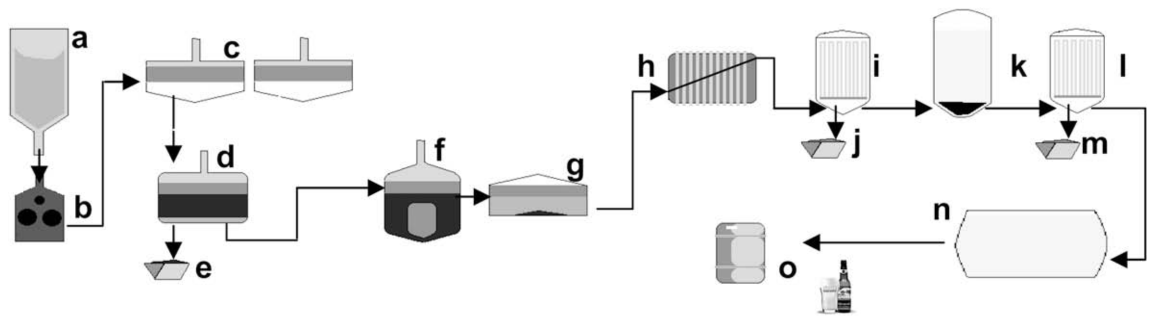

Fig. 1. Main equipments involved in beer production in Tínima brewery.

trub and the kieselguhr (m). Then the beer is sent to the bright beer tank (n) to be later bottled and pasteurised (o). The process described above applies for *malt cooking, malt brew or wort brew.*

However, sugar is used as partial substitute (adjunct) to malt in proper amounts, so it is normally prepared as syrup and cooked, going also through the lauter tun (d) and the subsequent steps until the fermentation tanks (k). This process is known as *sugar syrup cooking* or *sugar brew*.

Usually in most of the breweries the capacity of equipments dealing with the brewing process is smaller than the one on charge of the fermentation process [6].

In the case of Tínima brewery, like in many others, to fill up completely one fermentation tank (k) what is usually needed is the making of four brews (two of malt and two of sugar) involving its pass through all the technological equipments from malt silo (a) to wort filter (i), which implies their normal energy and water consumptions.

Since there is a possibility to separate the three main components of the beer wort: malt extract, sugar (adjunct) and water, and to use them properly in different stages of the beer elaboration process, there is also the possibility to change the thermal and electric energy consumption patterns involved in the process. So, sugar syrup brews could be avoided, by preparing concentrated sugar syrup and sending it directly to the fermentation tank, after concentrated malt wort have been fermented previously in the same reactor. This means that there is a significant amount of liquid volume (more than 70% of total volume of a fermentation reactor) that will not be consuming thermal and electrical energy, water and caustic solutions for cleaning, and no sugar losses due to the pass through all the hot process equipments.

It is known from previous CP assessment performed at Tínima brewery [5] that the hot processes (dilution of sugar used as adjunct, mashing, wort extraction, wort boiling, hop separation and sedimentation) are the highest thermal energy consumers and have a relevant weight regarding electric energy consumption at the brewery as it is shown in Figs. 2 and 3.

So, the objective of this work was to assess a new operational procedure for the beer elaboration, based on the possibilities of separating the three main components of the beer wort: malt extract, sugar (as adjunct) and water, and use them properly in different stages of the beer elaboration process; as a CP tool for a reduction in operations, energy and water consumption.

2. Materials and methods

The new operational procedure to be assayed consists in elaborating beer wort of 100% malt extract with a strong flavour induced by hops, according to the correspondent consumption index of the studied formulation.

So, the produced wort is cooled down and it is inoculated with the yeast cream, being allowed to ferment until the exponential phase of yeast multiplication is finished. Once the required time for this operation is completed, concentrated sugar syrup (50–60 °Bx) is elaborated, establishing the necessary parameters which guarantee its microbiological quality, then it is cooled down also and sent to the fermentation reactor. Immediately after, water is added to achieve the desired wort concentration but previously it is cooled to the proper fermentation temperature and adjusted to the required pH. The mixture is allowed to ferment; it is matured and filtered as usually, to conclude the process [2].

To carry out an industrial assay using the new procedure, three malt brews were elaborated, one of 10 °Bx (brew **A**) and two of 11 °Bx (brews **B** and **C**). The brew **A** was divided in the two fermentation reactors that were used (**I** and **II**), while the other two brews were sent, one for each reactor with the addition of the required hop, according to the established consumption index in the formula of 8 °P beer and 50% malt weight.

As it was expressed previously, the wort was allowed to ferment until the conclusion of multiplication phase of the yeast, considering this moment as the starting time for sugar addition.

Two batches of sugar syrup ($\mathbf{S_I}$ and $\mathbf{S_{II}}$) were previously prepared at 50–60 °Bx, heated up to 95 °C with 15 min retention time and sent to the fermentation reactors **I** and **II**, respectively; continuing with the addition of the required amount of water, which was cooled down to 10 °C and acidulated to pH 5.0 in a reactor dedicated for it. Final beer volumes achieved in reactors **I** and **II** were measured as 2452 and 2464 hL, respectively.

Chemical and physical characteristics of the produced beer were evaluated [3] and also sensorial aspects according to the method established by the National Centre for Inspection & Quality of Food (CNICA) with a panel of five trained judges [4].

Energy balances of the productive processes involved were performed for comparison, using the information provided by the test brews done applying the new procedure and the available data of malt brews (**TW**) and sugar brews (**TS**) of the typical beer

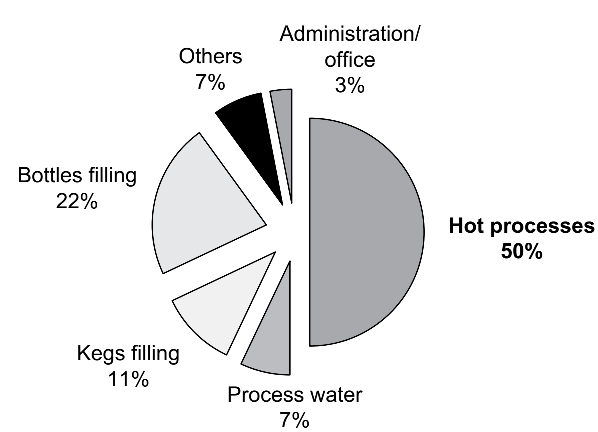

Fig. 2. Thermal energy consumption in Tínima brewery (121 MJ/hL of 8 °P beer produced).

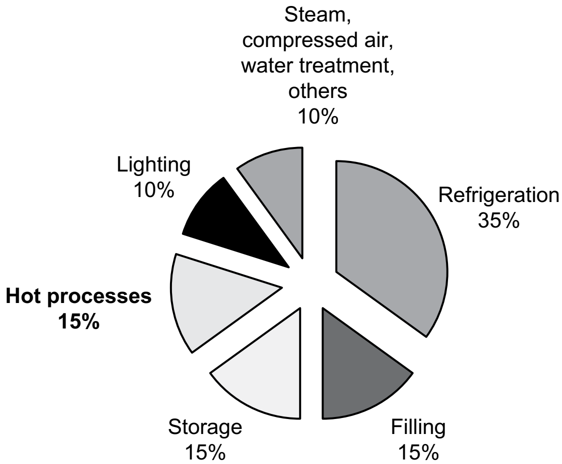

Fig. 3. Electric energy consumption in Tínima brewery.

formulation (50% malt/50% sugar), elaborated before the test by usual procedure. Data of **TW** and **TS** represent the mean values for 10 typical runs of beer elaboration performed at Tínima brewery under normal operational procedure. The mean value of the beer volume achieved inside of one fermentation reactor when one **TW** and **TS** are added is 1180 hL.

Tables 1 and 2 show the main data related to the malt and sugar brews involved in this study.

The corresponding equations used for the energy balances are shown in Appendix 1.

3. Results and discussion

Comparison of the results obtained in the industrial test with those of the current technology may be appreciated in Table 3. The consumption of malt stays almost the same for both technologies, since the malt brews of both procedures gothrough the same process stages and the differences that may occur, will only depend on the efficiency and regularity kept during the elaboration process.

The specific consumption of sugar shows a remarkable decrease (0.2152 kg/hL), due to the fact that in the new procedure, the sugar is added directly to the reactor, avoiding the losses that usually happen during the current process of wort elaboration. So, in this way the sugar is completely used since it is added directly to the reactor and not passing it through the kettle or the whirlpool and after of its pumping, even the possible residue remaining in the pipelines could be recovered by circulating water in the system, sending it to the reactor. Comparing the mean consumption index, a saving of 4.39% of sugar is appreciated when applying the new procedure, equivalent to 215.2 kg of sugar for 1000 hL of produced beer whose cost is US$ 94.00, according to the price of sugar at this time.

Table 1
Main data related to malt brews used in the study

Characteristic	Unit	Malt brews			
		A	**B**	**C**	**TW**
Malt mass	kg	8700	8000	8000	5900
Wort volume in the mash tun	hL	420	380	380	280
Initial wort volume in the kettle at 75 °C	hL	620	530	530	540
Initial wort concentration in the kettle	°Bx	10.3	10.5	10.5	8.1
Final brew volume to be pumped from the kettle	hL	635	515	530	555
Final brew concentration to be pumped from the kettle	°Bx	10.0	11.2	11.2	8.0

Table 2
Main data related to sugar syrup brews used in the study

Characteristic	Unit	Sugar syrups		
		$\mathbf{S_I}$	$\mathbf{S_{II}}$	**TS**
Sugar mass	kg	11,490	11,570	5900
Volume of sugar syrup prepared at 20 °C	hL	175	141	96
Concentration of sugar syrup prepared at 20 °C	°Bx	52.7	62.9	50
Final brew volume to be pumped from the kettle	hL	–	–	740
Final brew concentration to be pumped from the kettle	°Bx	–	–	8.0

As it is observed in Table 4, after ending the process, both obtained beers fulfil the demanded specifications of quality for the type elaborated. In the sample taken from reactor **I** the colour was much lighter because colouring candy was not used like it is usual in this brewery. This result was expected since the addition was not made deliberately looking for determining the specific colour that could be obtained when applying the new procedure in other breweries.

Table 5 shows the sensorial evaluation carried out to the beer coming from reactor **I**. The obtained results show a complete coincidence among the panellists with regard to the most important attributes in the sensorial characteristics: scent, flavour and oral sensations; so the beer elaborated with the new procedure received the maximum score in all the cases. With regard to the foam a GOOD punctuation was obtained, with a total of 4.6 over 5.0, this is equivalent to 92% of the maximum of all its characteristics. Only the shine, cleaning and transparency of the beer was affected, but these aspects depend on the filtration operation and the type of filtering material being used, so it could be said that they are not attributable to the kind of procedure assayed for beer elaboration. Nevertheless, this last aspect influenced on the reduction of the definitive punctuation of the sensorial evaluation, diminishing from 19.2 over 20.0 to 18.0 according to the sensorial methodology used. This final value still qualifies the beer as GOOD.

Regarding the energy balances, Tables 6–9 should be analyzed.

In Table 6 it could be appreciated that the specific heat consumption in the mashing operation is practically the same in both procedures; that was expected since the water/malt ratio was kept approximately constant (4:1) and the mass to be heated was the same and for the same temperature variation. The heat used in wort heating is lower (25%) due to the fact that it was used for wort of higher concentration in the kettle (10.5 °Bx) with less specific heat capacity value (C_p) and less total mass to be heated also. Regarding evaporation, the required heat is also decreased (25%), because the new procedure involves the use of less volume. The specific heat consumption in the preparation of the sugar syrup, expressed upon the quantity of produced beer, is also less (10%) on account of being working with less mass. The greatest difference in heat consumption and at the same time that which constitutes the point of major

Table 3
Consumption of malt and sugar when applying the new and former procedures

		New procedure	Former procedure	Difference
Specific consumption (kg/hL wort)	Malt	5.0244	4.9060	0.1184
	Sugar	4.6908	4.9060	0.2152
Relative proportion in weight (%)	Malt	51.72	50.00	1.72
	Sugar	48.28	50.00	1.72
Relative proportion in extracts	Malt	43.05	42.38	0.67
	Sugar	56.95	57.62	0.67

Table 4
Physical–chemical analyses of beer elaborated by the new procedure

Determinations	Reactor I	Reactor II	Quality specifications[a] for 8 °P beer
Original extract (°Bx)	8.20	7.70	7.50–8.50
Content of CO_2 (% vol)	2.87	2.85	$\geq$ 2.50
Alcohol (% vol)	4.16	4.04	4.0–5.0
Colour (mL Iodine 0.1 N)	0.37	0.54	0.00–1.80
Acidity (% lactic acid)	0.11	0.10	0.10–0.20
pH	3.7	3.9	3.5–4.8
True extract (°Bx)	1.46	1.40	0.5–1.50

[a] Quality specifications established for 8 °P beer according to the Tínima brewery standards [2].

Table 5
Sensorial evaluation of the beer elaborated by the new procedure

Attributes		1	2	3	4	5	Sum	Mean	Factor	Total
Foam	Formation, structure	5	4	4	5	5	23	4.6	0.5	2.3
	Persistency, adherence	5	5	4	4	5	23	4.6		
Liquid phase	Brightness, cleaning and transparency	4	4	4	5	4	21	4.2	0.5	2.1
Odour	Standardization	5	5	5	5	5	25	5	1	5
	Pureness	5	5	5	5	5	25	5		
	Standardization and pureness	4	5	5	5	5	24	4.8	1	4.8
Flavour	Sourness (quality)	5	5	5	5	5	25	5		
	Sourness (intensity)	5	5	5	5	5	25	5		
Oral sensations	Body, carbonation	5	5	5	5	5	25	5	1	5
Score										19.2

benefit of the new procedure lies on the fact that there is no any dilution of sugar syrup in the kettle, with no heating or evaporation, saving the 100% of the heat normally used in this operation. This aspect is the main principle of the new procedure and it is summarized in the comparison between the specific consumptions of fuel, 0.7011 kg/hL for the former procedure and 0.358 kg/hL for the new one representing a saving of 51% and as it could be inferred from Table 6, a cost decrease of US$ 74.34/1000 hL is achieved.

In Table 7, the electrical energy balance for cooling the wort and syrups according to old and new procedures is presented. It stands out that a marked difference is obtained among the specific energy consumptions for both technologies, with 30% in favour of the new technology. This result, expressed in economic terms represents a saving of US$ 107.07 for each 1000 hL of produced beer. On the other hand it is important to notice that besides the less energy consumption, the way of performing this consumption brings an additional benefit of great value for the industry, because the water cooling, which represents 50% of the total consumption approximately, is now carried out in the reactor over a long period (up to three days), contributing to eliminate the consumption peaks and making possible an appropriate accommodation of the electricity loads and easier operation of the cooling system.

High volumes of water are used in most breweries to cool down the wort beer produced at the "Cooking Room", in order to avoid foaming at the subsequent filtering stage. So, commonly there is a "production" of hot water which should be sent to a collection tank from where it will be taken for use in other processes. Often, if the water balance is not well performed there is a "surplus hot water" which represents economical losses in energy. When analyzing the hot water consumption in Table 8, it is observed that the new procedure uses 90% of the produced hot water, while the

Table 6
Thermal energy consumption for wort elaboration when applying the former and the new procedures

	Former procedure						New procedure			
	kcal	kcal/hL	kg_F/hL	$/1000 hL			kcal	kcal/hL	kg_F/hL	$/1000 hL
$Q_{m_{TW}}$	917,879	845	0.08880	19.12	Q_m	**A** **B** **C**	3,862,427	854	0.08897	17.31
Q_{cm}	1,725,820	1590	0.16565	35.95	Q_{cm}		5,419,003	1198	0.12477	27.07
Q_{em}	1,626,353	1498	0.15602	33.86	Q_{em}		5,056,941	1118	0.11643	25.27
Q_s	265,999	245	0.02548	5.53	Q_{S_I}		608,097	134	0.01402	3.05
					$Q_{S_{II}}$		386,901	85	0.00892	1.93
Q_{cd}	227,861	2095	0.21829	47.37	Q_{cd}					
Q_{ed}	368,471	339	0.03533	7.68	Q_{ed}					
Q_{metal}	240,000	111	0.01154	2.50	Q_{metal}		182,340	47	0.00484	1.04
Total	5,372,383	6723	0.70111	152.01	Total		15,515,709	3436	0.35795	77.67

kg_F, kg of fuel oil; $Q_{m_{TW}}$, heat consumed in the mashing step of typical wort brew **TW**; Q_{cm}, heat consumed for wort preheating; Q_{em}, heat consumed for wort evaporation; Qs, Heat consumed for sugar syrup preparation (adjunct to malt); Q_{cd}, heat consumed for sugar syrup heating in the kettle; Qed, heat consumed for sugar syrup evaporation; Q_m **A**, **B**, **C**, heat consumed in mashing step of brews **A**, **B**, **C**; Q_{S_I}, heat consumed for preparation of sugar syrup to be sent to reactor **I**; $Q_{S_{II}}$, heat consumed for preparation of sugar syrup to be sent to reactor **II**; Q_{metal}, heat consumed for rising the brew temperature going from the mash-tun to the kettle equipments.

Table 7
Energy consumptions for wort cooling when applying the former and new procedures

	Former procedure					New procedure			
	kcal	kWh	kWh/hL	$/1000 hL		kcal	kWh	kWh/hL	$/1000 hL
E_{TW}	−1,936,772	2252	2.074	150.56	E_A	−2,233,589	2597	0.574	41.66
E_{TS}	−2,582,363	3003	2.766	200.84	E_B	−1,820,183	2116	0.467	34.00
					E_C	−1,820,183	2116	0.467	34.00
					E_{S_I}	−444,353	517	0.113	8.32
					$E_{S_{II}}$	−322,417	375	0.082	5.97
					Ca_I	−7,837,412	9113	0.817	59.42
					Ca_{II}	−8,044,841	9354	0.840	60.96
Total	−2,195,035	5255	4.840	351.40	Total	−22,522,978	26,189	3.360	244.33

E_{TW}, energy consumed for cooling of a typical wort brew **TW**; E_{TS}, energy consumed for cooling of a typical sugar syrup brew **TS**; $E_{A, B, C}$, energy consumed for cooling of wort brews **A**, **B** and **C**; $E_{S_{I, II}}$, energy consumed for cooling of sugar syrups brews for reactors **I** and **II**; $Ca_{I, II}$, energy consumed for cooling of water required for reactors **I** and **II**.

Table 8
Hot water balance when applying the former and the new procedures

Former procedure				New procedure			
Brew	Production (hL water at 76 °C)	Consumption (hL water at 76 °C)	Difference (hL water at 76 °C)	Brew or syrup	Production (hL water at 76 °C)	Consumption (hL water at 76 °C)	Difference (hL water at 76 °C)
TW	586	497	89	**A**	659	525	134
TS	780	695	85	**B**	501	449	52
				C	501	449	52
				$\mathbf{S_I}$	134	105	29
				$\mathbf{S_{II}}$	97	70	27
Total	1366	1192	174	Total	1787	1598	189
hL hot water/hL mixture in reactor	1.158	1.010	0.148	hL hot water/hL mixture in reactor	0.363	0.325	0.038

Brew TW, typical wort brew **TW**; Brew TS, typical sugar syrup brew **TS**; Brew A, B, C, wort brews **A**, **B** and **C** prepared to test the new procedure; Syrups $S_{I,\ II}$, sugar syrups to feed reactors **I** and **II**, prepared to test the new procedure.

Table 9
Comparative summary of procedures regarding energy consumption and hot water production

	Former	New	Difference	%
Thermal energy consumption for wort elaboration (kg fuel/1000 hL)	701	357	343	48.9
Electric energy consumption for wort cooling (kWh/1000 hL)	4840	3360	1480	30.5
Surplus hot water (hL/L)	0.148	0.038	0.110	74.3

former procedure uses 87%. These values are similar considering the use of the hot water produced, but the most significant information that is presented in Table 8 is given by the fact that with the former procedure is produced 69% hot water more than with the new procedure for the same quantity of beer, indicating that this is an important source of energy loss in the process.

Table 9 sums up the differences of energy consumptions and hot water usage when applying the former and the new procedures; as can be seen there is a favourable balance for the new procedure, with 48.9% less thermal energy consumption, 30.5% less electric power consumption and 74.3% less hot water in excess.

The results presented and discussed above are referred mainly to the basic aspects of the process of beer elaboration and especially to those steps where savings were achieved as a consequence of the adoption of a new operational procedure. However, other savings were achieved in collateral activities as shown in Table 10. These savings were calculated considering several data obtained from a previous Cleaner Production Assessment performed in Tínima brewery [5].

As it has been explained before, the new operational procedure doesn't carry out sugar brews. This situation allows a saving of 7% in the overall water consumption of the brewery when considering the water related to cooling; rinsing of the beer filtration line; evaporation in the kettle and the amount used in the Cleaning In Place (CIP) system. Consequently a decrease of 11% is obtained in wastewater generation with a reduction in the polluting load discharged into the environment (54 t of Chemical Oxygen Demand (COD)/year; 0.2 t COD/1000 hL beer produced). This wastewater generation decrease is associated with the diminishing of the water used for cleaning the kettle; the treated water used for rinsing of the beer filtration line and the water used in the CIP system. There is also a reduction of 12% of the electric power consumption in terms of energy used for mixing and heating in the preparation of the sugar syrup; pumping to the kettle and the whirlpool equipments and the cooling operation. The soda consumption diminishes in 3% due to the reduction of cleaning operations in the "Cooking Room". Last but not least, the less electric energy consumption could be also expressed as less amount of fossil fuel burnt, with less generation and emission of greenhouse gases into the atmosphere (21% less compared with the former procedure for beer elaboration). When observing Table 10, it can be seen that the most important economic effect of these collateral activities is given by the saving related to the electric energy consumption, while the second aspect of relevance is the decrease of the polluting contribution, expressed as the COD discharged and the greenhouse gases emissions into the environment.

Table 11 shows the annual costs when applying the former and the new operational procedure for the elaboration of 8 °P beer at

Table 11
Comparison of economic costs of some inputs for the production of 8 °P type beer when applying the former and the new operational procedure

Consumption	Annual cost using former procedure (US$/ 1000 hL)	Annual cost using new procedure (US$/ 1000 hL)
Fuel oil for wort elaboration	152.01	77.67
Electric energy for wort cooling	351.40	244.33
Sugar as malt adjunct	2330.35	2228.13
Water (in collateral activities)	114.00	105.8
Electric energy for pumping and equipments	1161.60	1025.60
NaOH (40%)	126.58	122.55
Total	4235.94	3804.11

The cost indexes were calculated for the production of 273,829 hL of 8 °P beer during 2006 at Tínima brewery.

Table 10
Savings in collateral activities when applying the new procedure for the elaboration of 8 °P type beer

Indicator	Annual saving	Specific annual saving[a]	Saving related to total consumption (%)	Economic annual saving (US$/1000 hL)
Water consumption	22,527 m^3	0.082 m^3/hL beer	7	8.2
Wastewater generation	20,873 m^3	0.076 m^3/hL beer	11	–
Electric energy consumption	514,405 kWh	1.879 kWh/hL beer	12	136
NaOH (40%) consumption	3281 L	0.012 L/hL beer	3	4
Greenhouse gases emissions	610 t CO_2	2.22 kg CO_2/hL beer	21	–

[a] The specific annual saving was calculated on the basis of the production of 273,829 hL of 8 °P beer during 2006 at Tínima Brewery.

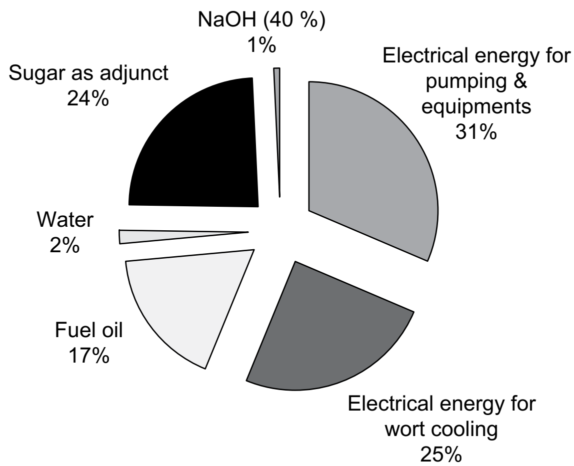

Fig. 4. Total annual saving of US$ 431.83/1000 hL of produced beer when applying the new procedure for elaboration of 8 °P beer.

Tínima brewery. The total annual saving achieved with the implementation of the new procedure is around US$ 431.83 for each 1000 hL of produced beer. This represents a diminishing of 10.2% of the total cost.

Fig. 4 shows the individual percentage contribution to the total economic saving achieved with the application of the new procedure; the higher contributors were the decreasing of the total electricity consumption used for wort cooling, pumping and operation of equipments (56%) and the decreasing of the sugar consumption (24%), since they involve higher unitary costs.

4. Conclusions

It was demonstrated that the implementation of operational changes in the production processes constitutes a powerful tool for the application of cleaner production in industries.

A new elaboration procedure was successfully assayed at industrial scale for the production of a beer that uses sugar as malt adjunct, obtaining a good quality beer, technological and economical advantages with benefits for the environment, significant savings in energy (49%), sugar (4%), water (7%) and caustic soda (3%) consumption; and diminishing the surplus hot water (74%), wastewater generation (11%) and greenhouse gases emission (21%). Beer production capacity is also increased almost threefold. With the application of the new technology, a total saving of US$ 481.83/1000 hL of 8 °P type beer produced was achieved.

Appendix 1. Equations applied for the energy balances [6]

$$Q_c = m \times C_p \times \Delta t \times \frac{1}{f} \quad (1)$$

$$Q_e = m \times C_l \times \frac{1}{f} \quad (2)$$

$$T_m = \left[\frac{m_1 \times C_{p1} \times (t_1 - t_2)}{(m_1 + m_2) \times C_{pm}}\right] + t_2 \quad (3)$$

$$C_p = \frac{h}{100} + 0.2\left[\frac{(100 - h)}{100}\right] \quad (4)$$

$$E = V \times 100 \times \mathrm{fc} \times d \times C_p \times \Delta t\left(\frac{1}{0.85}\right)\left(\frac{1}{860}\right) \quad (5)$$

$$V_A = \frac{V_m \times \mathrm{fc}_m \times d_m \times \Delta t_m}{\Delta t_A \times \mathrm{fc}_A} \quad (6)$$

$$C_A = V_t + V_e + V_a + V_{am} - (V_{Tm} - V_r) \quad (7)$$

$$V_{Tm} = V_{45}\left(\frac{0.9920}{0.9765}\right) \quad (8)$$

$$V_r = m \times \left(\frac{0.80}{97.65}\right) \quad (9)$$

where

Q_c : consumed heat during heating operations (kcal);
Q_e : evaporation during heating operations (kcal);
m : mass (kg);
C_p : heat capacity at constant pressure (kcal/kg °C);
Δt : temperature fluctuation (°C);
f : efficiency factor (generator + system losses = 0.85);
C_l : latent heat of water (540 kcal/kg);
T_m : mixture temperature (°C);
h : humidity (%);
E : energy consumption for cooling (kWh);
V : liquid volume to cool (hL);
fc : contraction factor (dimensionless);
d : density (kg/L);
V_A : volume of water at 76 °C (hL);
V_m : hot wort volume (hL);
fc_m : wort contraction factor (dimensionless);
d_m : density of wort (kg/L);
Δt_m : wort temperature fluctuation (°C);
Δt_A : water temperature fluctuation (°C);
fc_A : water contraction factor (dimensionless);
C_A : consumption of water at 76 °C (hL);
V_t : volume of filled kettle at 75 °C (hL);
V_e : volume of evaporated water (hL);
V_a : volume of water in the fake bottom of the lauter-tun equipment (hL);
V_{am} : volume of water at 76 °C, conditioned after mashing step (hL);
V_{Tm} : total volume of water at 76 °C in the mashing step (hL);
V_r : volume of water contained in the spent barley grains (hL);
V_{45} : volume of water at 45 °C used in mashing step (hL);

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