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PROCESS INTEGRATION AND PINCH ANALYSIS IN SUGARCANE INDUSTRY

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Abstract. *Process Integration techniques were applied, particularly through the Pinch Analysis method, to sugarcane industry. Research was performed upon harvest data from an agroindustrial complex which processes sugarcane plant in excess of 3.5 million metric tons per year, producing motor fuel grade ethanol, standard quality (VHP) sugar, and delivering excess electric power to the grid. Pinch Analysis was used in assessing internal heat recovery as well as external utility demand targets, while keeping the lowest but economically achievable targets for entropy increase. Efficiency on the use of energy was evaluated for the plant as it was found (the base case) as well as for five selected process and/or plant design modifications, always with guidance of the method. The first alternative design (case 2) was proposed to evaluate equipment mean idle time in the base case, to support subsequent comparisons. Cases 3 and 4 were used to estimate the upper limits of combined heat and power generation (CHP) while raw material supply of the base case is kept; both the cases did not prove worth implementing. Cases 5 and 6 were devised to deal with the bottleneck of the plant, namely boiler capacity, in order to allow for some production increment. Inexpensive, minor modifications considered in case 5 were found unable to produce reasonable outcome gain. Nevertheless, proper changes in cane juice evaporation section (case 6) could allow sugar and ethanol combined production to rise up to 9.1% relative to the base case, without dropping cogenerated power.*

Keywords*: process integration, pinch analysis, pinch technology, sugarcane ethanol, bioethanol.*

1. INTRODUCTION

This is a Process Integration case study, performed through application of the Pinch Analysis method (Linnhoff and Hindmarsh, 1983), and directed to produce preliminary assessments, as far as it is concerned to thermal-economic performance, on selected retrofit alternatives for the plant under research.

Process Integration in such framework is defined by the International Energy Agency as “systematic and general methods for designing integrated production systems, ranging from individual processes to total sites, with special emphasis on efficient use of energy and environmental effect reduction” (Gundersen, 2000).

1.1. Pinch Analysis features

As regards industrial activities, while most design practices generally seek to locally optimize the use of energy, Pinch Analysis aims to identify optimal design, operation practices for the system as a whole (Karp, 1990). And along with Exergy Analysis (Szargut *et al.*, 1988), Pinch Analysis is a Process Integration method with a particular focus on Thermodynamics (Gundersen, 2000).

Pinch Analysis tools are strongly based on graphical representations of mass and energy transfers taking place throughout the industrial site:

- Composite Curves (Linnhoff *et al.*, 1979) play an important role as a concise representation of heating and cooling demands of each process, the heat amounts required as well as its associate temperatures;
- The Grand Composite Curve (Kemp, 2007) illustrates the pinch location and is also helpful in checking utility/stream correct matching;
- The Site Source-Sink Profiles (Dhole and Linnhoff, 1993) enables gathering of all site demands along with utility usage and Combined Heat and Power generation (CHP) in a single comprehensive frame;
- Stream Grid (Linnhoff and Flower, 1978) ease the searching for violations of the Appropriate Placement Principles (Townsend and Linnhoff, 1983), i.e., heat transfer across the pinch, which invariably is the reason behind deviations from energy best possible usage (energy targets).

The tool pack of the Pinch Analysis is completed with numerical resources, such as the Problem Table Algorithm (Linnhoff and Flower, 1978), to support quantitative assessments and enable accurate, easy targeting.

1.2. Plant features

The plant under study operates in 34 to 39-week cycles to fit sugarcane crop seasons. Main income sources are international standard (VHP) sugar and motor fuel grade (hydrated) ethanol, with excess cogenerated electric power delivered to the grid as a valuable byproduct.

The bagasse that remains after cane crushing is the primary energy source: it is burned in furnace, providing high pressure steam supply (45bar, 430°C) for a back pressure turbine and generator set (Fig. 1). Low pressure steam from turbine exhaust is the heat source for evaporation section; and distillation operates mainly with heat recovered from juice vapors. The 13 to 18-week outages apart, the plant is energetically self reliable.

Regarding the greenhouse gas emissions, sugarcane agriculture and industry can be taken as environmentally friendly, due to the fossil fuel burning avoided (Macedo, 1998, Macedo *et al.*, 2008).

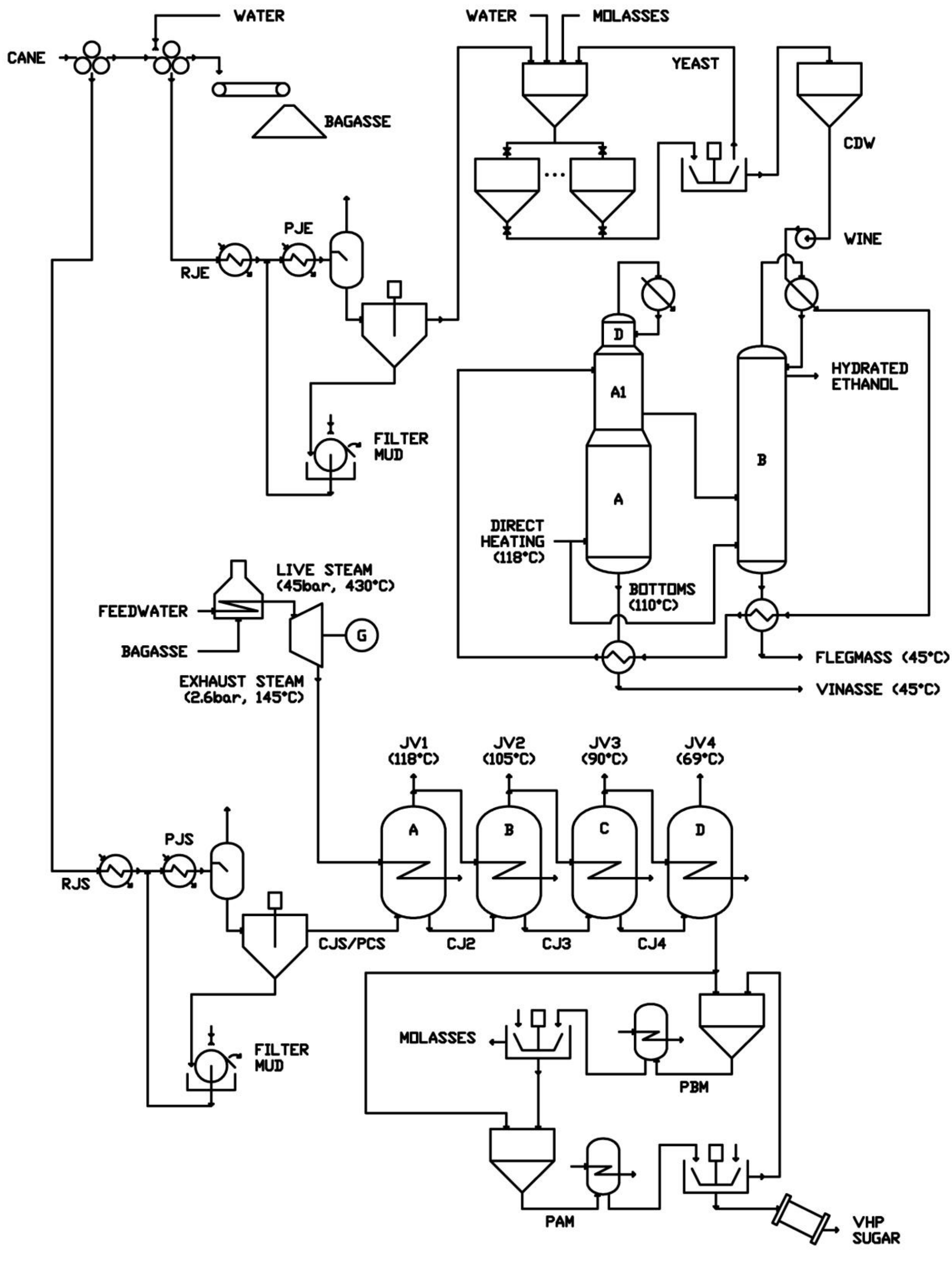

Figure 1. Plant flow sheet (simplified), including crushing, evaporation, drying (sugar factory), distillation (ethanol factory) and cogeneration sections. (Mnemonic labels were assigned to main streams, to ease later references.)

Considering such plant features (eco sustainability, energy self-reliability), the major benefits of Pinch Analysis application to the site must lie in the field of production bottleneck finding and removing.

2. EXPERIMENTAL

2.1. Data extraction

In order to take full advantage of the Pinch method, analysis of the site must be as wide (inclusive) as possible (Gundersen, 2000). So a broad survey was performed, with raw data being obtained from

- industrial technical reports,
- operation team notes,
- design specifications and/or
- equipments data sheets.

Reference values taken from literature (Fernandes, 2003; Hugot, 1969) were used to fill some few important lacks of the data set.

2.2. General assumptions

In order to be conservative, establishing truly achievable targets only, all assumptions taken in the present work were made with special attention to avoid overestimation of resources and/or underestimation of demands.

2.2.1. Sucrose inversion inside streams

Since most of mass flowing throughout the plant has enough amounts of water and sucrose to enable hydrolysis to take place, it does not exactly match the definition of process stream (Kemp, 2007), in the sense that a chemical change happens: in Eq. 1, the chemical process of sucrose inversion, reactants are sucrose and water, and products are equal amounts of glucose and fructose.

$$C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6 \tag{1}$$

Even so, the energy released per kg sucrose inverted is not greater than 44kJ (Goldberg *et al.*, 1989), and the reacted mass is on the order of 1% or less, so that the total energy release due to chemical inversion is very small (7kW in juice treatment, the worst case) compared to uncertainty limits of the main heat transfers (0.1MW). Thus the energy released in inversion was neglected so that cane juice and all sucrose-rich mass flows could be treated as genuine process streams.

2.2.2. Cane juice thermodynamic properties

For the purpose of specific enthalpy and entropy evaluation, properties of cane juice and all other sucrose-rich streams were approximated as functions of its solid content fraction and its purity on sucrose, according to Nebra and Parra (2005) data compilation.

2.2.3. Time dependence

Approximation was made to consider production process as in stationary state all crop season long. Product outputs and raw material consumption mean rates were inferred from inventory variations up to the end of crop period. Start and stop transients were neglected.

2.2.4. Stream mixing

Models used herein to set energy consumption targets assume all streams mixing could be performed isothermally, i.e., streams could be brought to same temperature prior to mixing, in order to be aware of avoidable entropy increase (irreversibility generation).

2.2.5. Choosing ΔT_{min}

The heat exchange network that was considered here includes a sort of different equipment types: evaporators, heat recovers, condensers. To take into account its different features, minimum temperature differences needed for heat recovery (ΔT_{min}) were set differently (independently) for each stream, based on which equipment it flows through, as a means to guarantee accurate target procedures (Kemp, 2007).

Large, deep equipment changes are out of the scope of this work, thus ΔT_{min} were set to be the same as found in the base case survey, to avoid equipment discard/substitution as much as possible.

2.2.6. Combined Heat and Power generation (CHP) policy

Cane bagasse generated on crushing was assumed to be fully available to burning and steam production, i.e., no cost was assigned to the use of bagasse produced inside the plant, so that no reason stands to seek for its consumption reduction, at all. Instead, bagasse burning must be increased as long as it enables any production increment, either of sugar and/or ethanol and/or electric power.

2.2.7. Distillation column

Column calculations were performed according to Almeida (1985), in order to match plant personnel procedures and data available for the base case, and to avoid misinterpretation of succeeding simulations, which could arise if another method had been applied.

2.2.8. Economic scenario

All economic evaluations were based on averaged market prices for the three commodities (VHP, fuel grade ethanol and electric power), observed in the period 2006-2009, as reported by CEPEA (2010) and CCEE (2010).

In all the simulated cases, VHP sugar to ethanol production ratio was assumed to be the same as in the base case (business as usual scenario).

2.3. Data validation and reconciliation: mass, energy balance

A set of electronic worksheets were used in solving mass and energy balance for each section of the plant (Fig. 2): crushing, juice treating, must preparation, filtering and juice concentration (evaporation), distillation. Redundant information was explored to evaluate data accuracy and to point possible coarse errors out.

An iterative method (quantity guess/refinement) was applied whenever thermodynamic properties had to be known prior to the complete knowledge of stream conditions of temperature, pressure and concentration (situations indicated by dotted lines in Fig. 2). Convergence was reached after 3 to 4 iteration steps for each case.

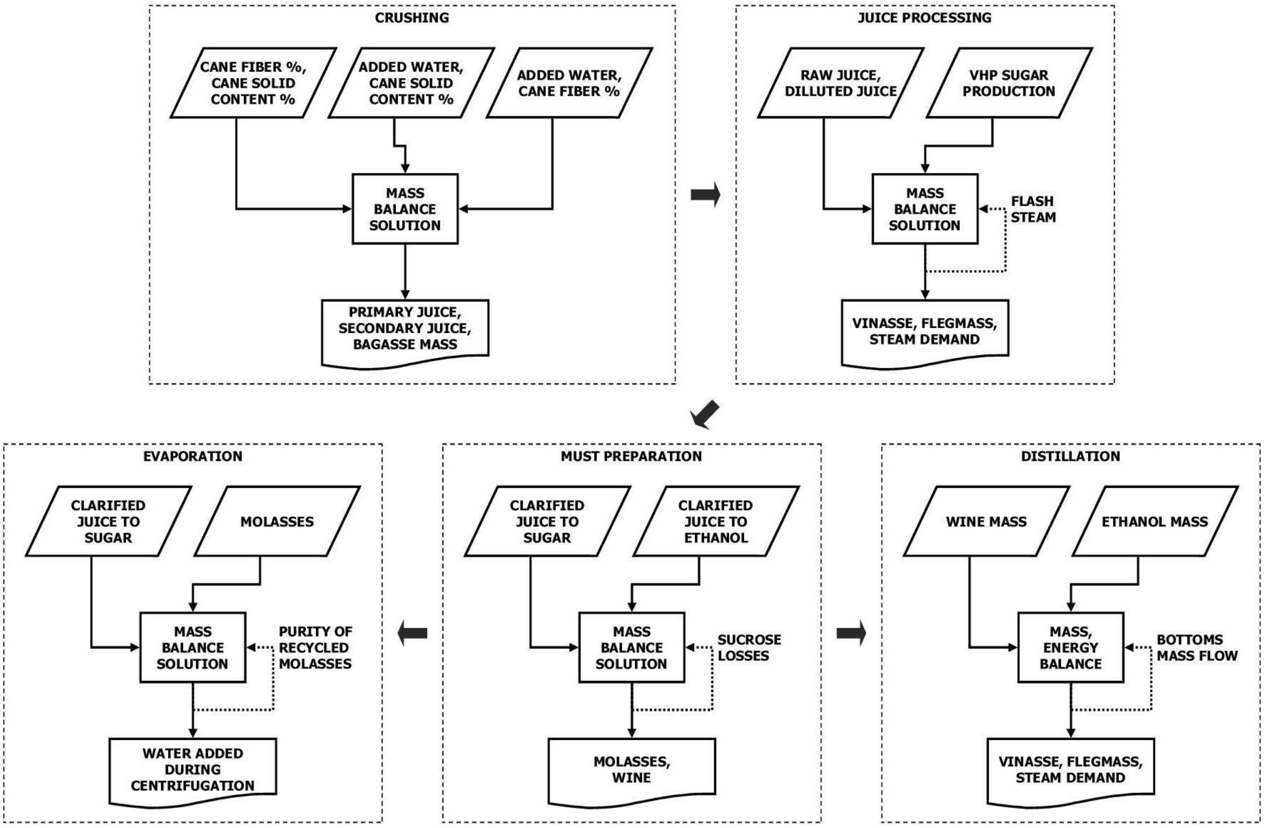

Figure 2. Mass and energy balance consistency check procedure flow sheet. Dotted lines indicate guessed/refined quantities on iteration loops.

2.4. Optimization resources

In general, the potentially large number of structural alternatives in process design and integration can be significantly reduced by the use of heuristics (insight) and thermodynamics (Gundersen, 2000). Accordingly, in this study Pinch Analysis itself poses the thermodynamic constraints, economic trade-offs are dealt with by means of ΔT_{min} choosing (Section 2.2.5), and heuristics is used to address the remaining problem, based on the search and removal of appropriate placement principle violations.

3. CALCULATIONS

All stream data were compiled from the results of mass and energy balances, developed along data validation and reconciliation phase (Section 2.3).

The Problem Table Algorithm (Kemp, 2007) was implemented in MatLab® language (trademark of The MathWorks Inc.), as well as Composite Curves (CC) and Site-Wide Source-Sink Profile (SSSP) generators. The computer code was further developed to perform graph formatting and printing, and to output text reports on the results.

As a means to test and to validate the present method implementation, a proven application (Norwood, 2007) was also fed with the base case data: the both results positively matched.

4. RESULTS

4.1. Pinch analysis of the base case

The relevant set of streams for the base case analysis was defined after data validation and reconciliation. The main hot (H) and cold (C) streams are presented in Tab. 1, along with its inlet temperatures (T_{inlet}), outlet temperatures (T_{outlet}) and respective heat loads. As stated previously in Section 2.2.5, ΔT_{min} was set independently for each stream to avoid inaccurate targeting.

Table 1. Main process streams of the base case.

Process	Stream	Label	T_{inlet} (°C)	T_{outlet} (°C)	ΔT_{min} (°C)	Heat Load (MW)	Hot/ Cold
Sugar factory	Effect 1 juice vapor released	JV1	118	118	0	148.5	H
	Preheated clarified juice (sugar factory)	PCS	119	119	2	147.2	C
	Effect 2 juice vapor released	JV2	105	105	0	48.6	H
	Effect 2 condensed juice	CJ2	107	107	11	44.8	C
	Effect 3 juice vapor released	JV3	90	90	0	30.4	H
	Effect 3 condensed juice	CJ3	93	93	12	27.2	C
	Raw juice (sugar factory)	RJS	32	83	10	25.4	C
	Pan A mixture	PAM	64	67	51	21.5	C
	Effect 4 condensed juice	CJ4	73	73	17	14.5	C
	Preheated juice (sugar factory)	PJS	83	105	10	14.4	C
	Effect 4 juice vapor released	JV4	69	69	25	17.6	H
	Clarified juice (sugar factory)	CJS	91	119	11	16.4	C
	Pan B mixture	PBM	64.0	67.0	38	4.9	C
Ethanol factory	Reboiler direct heating		118	118	0	57.9	H
	Cold wine	CDW	32	92	6	27.1	C
	Vinasse/flegmass		110	45	6	36.7	H
	Raw juice (ethanol factory)	RJE	32	83	30	10.1	C
	Preheated juice (ethanol factory)	PJE	83	105	24	5.9	C
Boiler	Make-up preheated water	MPW	75	97	45	2.1	C
	Make-up hot water	MHW	97	118	2	2.1	C

4.1.1. Targeting

Reconciled data were submitted to Pinch Analysis targeting procedures, as described in experimental, calculation sections. Pinch Analysis for the base case indicates that the minimum turbine exhaust steam would be equivalent to 152MW (Fig. 3) in order to support operations, while actual consumption amounts to 169MW, 11% above the minimum. Heat recovery target was calculated as 71MW, while actual recovery was evaluated as 54MW, the difference (17MW) being the improvement potential, achievable through heat exchange system rearrangements.

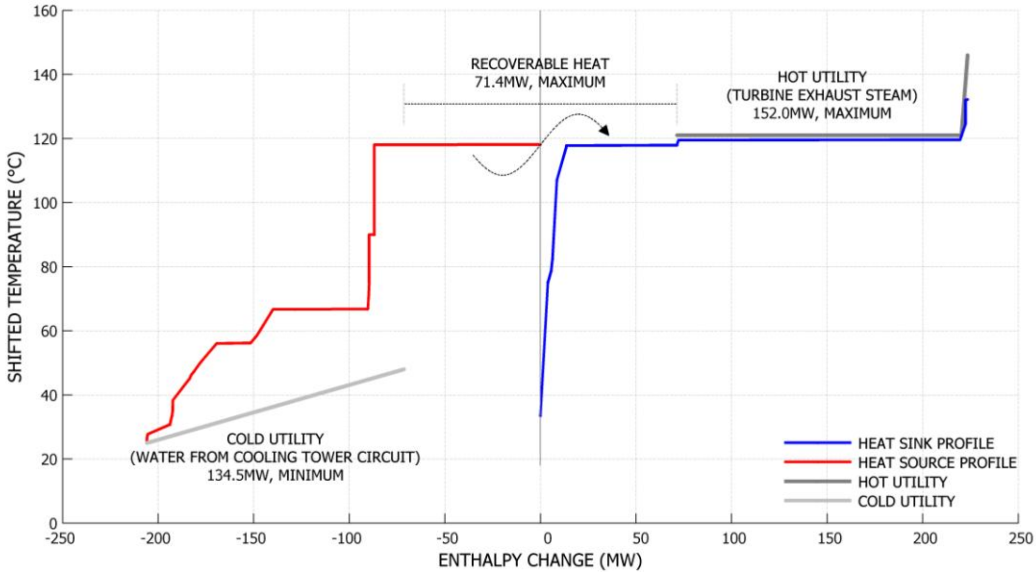

Figure 3. Site-Wide Source-Sink Profiles (SSSP) of the base case.

Combined heat and power (CHP) site targets were evaluated accordingly (Dhole and Linnhoff, 1993). Maximum power available by expanding boiler live steam was calculated as 54.7MW (Fig. 4), which includes 11.2MW that could only be developed with use of a condensation turbine, not available in the base case although (the same restriction applies also to the 9.7MW available from low temperature hot process streams).

Actual gross power generation averages 24.1MW during crop season, and power cycle losses take other 6.0MW. About 3.6MW cannot be developed due to the minimum temperature difference requirement in delivering exhaust steam heat to process cold streams. The remaining 9.7MW availability (exergy) loss is undetermined, but in some degree it happens due to the steam relief valve operation, during stops and starts of the plant, for instance. Integrated grid controller restrictions are also possible causes of generation losses.

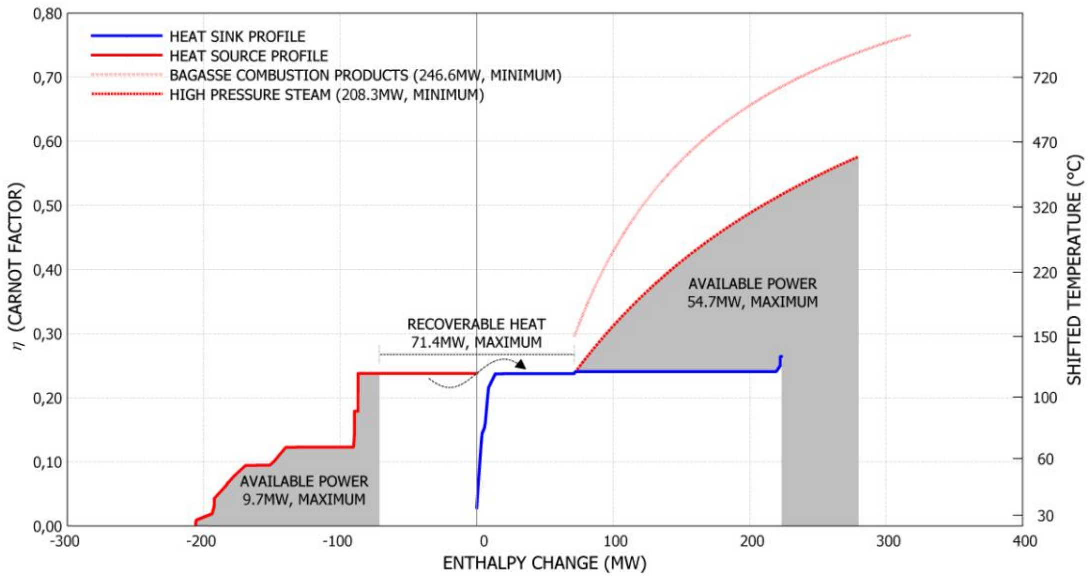

Figure 4. Combined heat and power targets for the base case.

4.1.2. Searching for Appropriate Placement Principle violations

With the aid of the Problem Table Algorithm (Linnhoff and Flower, 1978), pinch location on sugar factory was found, as well as on ethanol factory (Fig. 5).

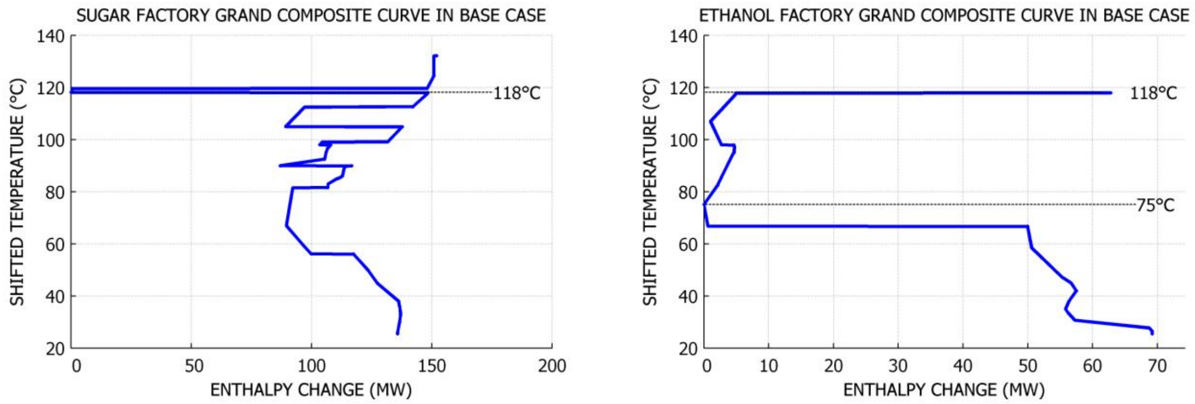

Figure 5. Grand Composite Curves (GCC) for sugar, ethanol factories in the base case.

The stream grid (Linnhoff and Flower, 1978) was drawn to illustrate the base case heat exchange network. It supported further investigation on the possible causes of the deviation from best performance, which was found in targeting. The most relevant fragment of the base case stream grid is shown in Fig. 6.

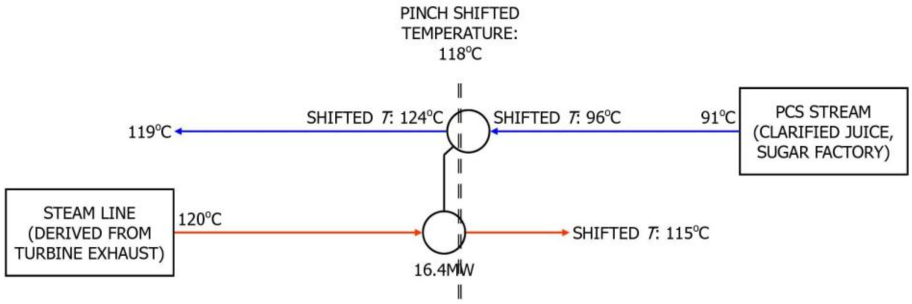

Figure 6. Selected fragment from the base case stream grid.

One major appropriate placement principle violation was found: hot utility usage (16.4 MW) in heating a cold stream (clarified juice, PCS stream) from below the process pinch temperature (Fig. 6). Alone, this single violation is responsible for 70% of heat recovery target missing in the base case. Potential heat recovery with process hot streams (juice vapors) in this case was calculated to be 12.0MW.

4.2. Plant modification simulations

4.2.1. Case 2: equipment idle time estimation

Idle time was estimated by simulating uniform, small increasing of raw material flow, which had been reiterated until any equipment maximum capacity was exceeded (idle time here so includes production breaks caused by supply chain disruption and equipment malfunction). Bottleneck appears in multiple effect evaporators (MEE) if crushing rises 3.2% relative to the base case (juice concentration/evaporation capacity is reached). That was taken as the potential production increment due to operation improvements only (without system modifications), which is considerably small, indicating that in the base case the overall equipment effectiveness (Hansen, 2001) is not far from optimum.

4.2.2. Case 3: exhaust steam saving, power generation enhancement

Appropriate placement principle main violation (Fig. 6) directed the analysis to the MEE section. To escape from the base case heat recovery target missing, a few different juice feed schemes (Urbaniec *et al.*, 2000) were devised (heuristically) and tested in searching for heat recovery improvement, eventually leading to the proposition of a new MEE configuration, which is shown in Fig. 7.

Process steam economy achievable through MEE modification (Fig. 7) was calculated to be equivalent to 6.4MW relative to the base case, meaning 3.9% of sugar factory hot utility demand. Similar flow schemes were already considered and reported in the literature, e.g. parallel feed (Hugot, 1969), reverse feed and mixed feed (Higa, 2003).

On the other hand, even if a condensation turbine should have been installed (Fig. 7) to make a better use of the steam saved from process (surplus steam), the net average power generation increase would not exceed 167kW$_e$ (where the subscript *e* stands for electric power), meaning 0.7% of the base case power generation, only. A preliminary economic assessment showed that the associated investment would have unacceptably large payback time.

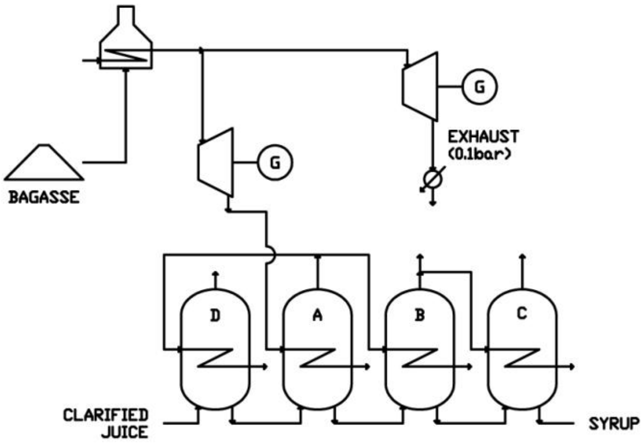

Figure 7. The case 3 configurations of combined heat and power system and multiple effect evaporators.

4.2.3. Case 4: exhaust steam saving, power generation maximization

Juice vapors from the case 3 configuration were found to be not completely integrated: 12.8MW must be rejected via cold utility. In order to recover that excess vapor, in case 4 it was considered the use of thermal vapor recompression (thermocompressor, Fig. 8).

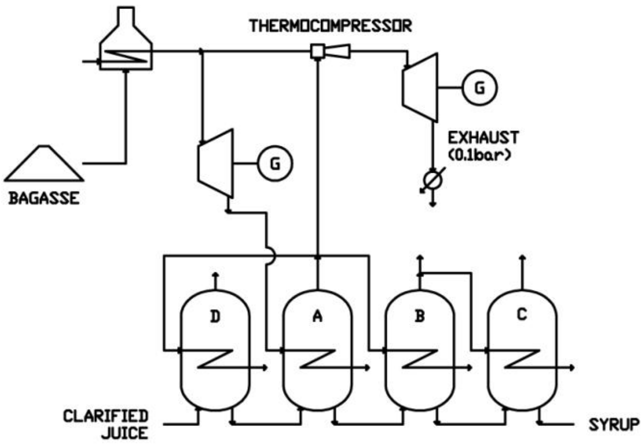

Figure 8. Case 4: electric generation maximized.

The case 4 configuration (Fig. 8) could provide a net electric generation increase of 676kW$_e$ (2.8% relative to the base case gross power, 4.9% of exported power), and again it is not likely to justify all the associated investment costs.

4.2.4. Case 5: production enhancement

Back to the configuration of the case 3, this simulation was performed to establish the worth of the excess exhaust steam as if it were used to evaporate a juice surplus (for sugar, ethanol surplus), instead of power generating. It was found that MEE equipment maximum capacity is reached if crushing rises only 3.0% relative to the base case.

Although case 5 was better valued than cases 3 and 4, it is not significantly different from case 2, also having quite a small economic value.

4.2.5. Case 6: production enhancement combined with MEE area addition

The case 6 simulation was performed departing from case 3, as in case 4, but this time with freedom for MEE heat exchange area addition. Juice feed as well as MEE B evaporator area were iteratively increased until maximum heat integration of juice vapors was reached: a bound is set by the process heat source demand at low temperatures.

Plant performance simulations are summarized in Tab. 2, along with the base case facts.

Table 2. Plant performance summary.

Quantity		The Base Case	Case 5	Case 6
Exhaust steam minimum heat demand	(MW)	152.2	161.5	161.5
Available exhaust steam heat	(MW)	164.6	164.6	164.6
Cross pinch heat transfer penalty	(MW)	12.4	3.1	3.1
MEE B effect evaporator exchange area	(m^2)	3000	3000	3960
Total raw juice processing	($kg \cdot s^{-1}$)	189.2	194.7	206.4

Most of the case 6 remaining cross pinch heat transfer (Tab. 2) was found to take place due to use of hot utility in heating MPW stream, preheated make-up water (purified water that is introduced in the boiler circuit to replace losses by leakage, blowdown and to keep control of solids concentration). Changing heat supply to that stream was left for future research.

Although demanding 32% area increase in evaporator B (from 3,000m^2 to 3,960m^2 area), heat recovery in the case 6 was calculated to be 10.9% higher relative to the base case (60MW against 54MW in the base case).

MEE flow modification (as described earlier in case 3) combined with heat exchange area addition in evaporator B (Tab. 2) would allow for cane processing capability to increase from 703.3 to 768.0 metric tons per hour (9.1% increase), with VHP and ethanol annual production reaching 245,800 metric tons and 141,200 m^3 respectively.

With gross power generation considered constant relative to the base case, in the economic scenario for simulations (as described in Section 2.2.8) the above results for the case 6 would mean an 8.5% increase in the annual income of the plant.

4.2.6. Remarks on the case 6 simulation assumptions

Evaporator B was supposed to be the best choice for MEE heat exchange area addition, since compared to effects C, D it would allow for largest heat transfer increase by unit area added.

Since average temperature of juice rises 0.3°C in evaporator A relative do the base case, exhaust steam temperature must rise correspondingly, to keep mean temperature difference and sustain heat transfer rate. The respective turbine power generation loss was estimated as 0.07%, so it was considered negligibly small.

5. CONCLUSIONS AND DISCUSSION

Demanding reasonable efforts, Pinch Analysis has proven effective in tackling such a remarkably complex plant model (46 different streams were distinguished in midst of the site operations), which demonstrates comprehensiveness, an alleged advantage of the method.

Actual system energy performance was successfully evaluated through the application of the method: targeting procedures revealed that the potential for improvements was large enough to justify further research.

The finding of process pinch temperatures led to location and measurement of appropriate placement principle violations, which in turn were effective in guiding a set of simulated process and/or design enhancements.

As any case study, this work it bears inherent, important (not detachable) plant-specific features. Nevertheless, some relevant comparisons may be devised against slightly similar researches, as follows:

- Actual steam consumption in the base case was calculated as 374kg process steam per metric ton of cane crushed, which is consistent with Pizaia (2005), since it correctly places the plant between a typical, non optimized mill (500kg steam/t cane) and an intermediate-stage enhanced plant (340kg steam/t cane), with Flegstil distillation technology embedded.
- Optimization approach adopted here was found to be consistent with Ensinas *et al.* (2007a), which concludes toward the absolutely high importance of MEE section design on the overall thermal-economic performance of the plant.
- Pinch Analysis performed on a sugar factory by Ram and Banerjee (2003) revealed that minimum hot utility requirement was lower than the actual by roughly 9%, which is in good agreement with the present study results (11% target deviation). For process optimization, although, Ram and Banerjee (2003) recommended a (costly) quintuple effect addition to MEE.
- Results of the cases 3 and 4 are far less promising than similar modeling made by Ensinas *et al.* (2007b), where 30% increase was expected in surplus power generation. However, in cases 3 and 4 an additional condensation turbine is considered to use surplus steam only (with the back-pressure turbine kept from the base case), while in Ensinas *et al.* (2007b) condensation-extraction turbines of 60 to 100bar live steam are actually considered to fully replace a back-pressure turbine. Due to such differences, further comparisons were not allowed.

Finally, the present work was conducted successfully in the sense it allowed fixing a roadmap toward the best use of energy in the site, particularly in the form of the case 6 process/design alternative configuration.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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