DECISION MAKING IN A LEMON PROCESSING PLANT USING DATA RECONCILIATION

D.C. MACIEL†, A.P. INGARAMO†, S.M. PEREZ‡ and H. HELUANE†

† *Dpto de Ingeniería de Procesos y Gestión Industrial, FACET – Univ. Nacional de Tucumán, Tucumán, Argentina {aingaramo, hheluane}@herrera.unt.edu.ar*

‡ *CITRUSVIL SA Ruta 302 - Km 7 - Cevil Pozo (T4178XAX), Tucumán, Argentina. mperez@citrusvil.com.ar*

***Abstract*— Argentina is one of the largest producers of citrus fruit and Tucuman is the principal producer of lemons worldwide. The lemon agro industrial complex of Tucuman has reached a high degree of competitiveness. In fact, large quantities of fruit and of industrial derivatives are produced in that province, which are placed mainly on the demanding international market. Data reconciliation and gross error detection were performed on a lemon processing plant. The results of the reconciliation allowed the detection of malfunctioning of certain instruments. Data reconciliation was used to compare two different configurations of the manufacturing process, and also allowed to detect a better variable values acquisition system by reallocating the existing instruments and incorporating new ones to the system.**

***Keywords*— lemon industrialization, essential oil process, data reconciliation.**

I. INTRODUCTION

In 2014 Argentina´s lemon fruit production reached 954.000 tons which represents 15.42% of worldwide production. Argentina is the largest exporter of fresh fruit (153.000 tons in 2014) followed by Spain and the United States, and it is also the largest exporter of products from lemon industrialization with a market participation of 36.95% in the period 2013/2014. Lemon essential oil is widely used in non-alcoholic beverage industry as well as in perfume and cosmetic industries. Argentina is the first worldwide producer of lemon essential oil which is mainly produced for international markets. In 2014, the total production of lemon essential oil was 2413 tons, which represents approximately 115 millions of dollars (Federcitrus, 2015).

In most processes, variable measurements are performed in order to obtain a large amount of information which allows quality control, yield evaluation, operation optimization, among other tasks in the industrial plant. Due to technological advances in the latest decades, data acquisition and data registration can be automatically done which allows manipulating a larger amount of measurements obtained at more frequent periods of time. On the other hand, computational tools for management and verification of data have been developed. Nevertheless, although instrument accuracy and precision have been improved, presence of various types of errors are inevitable during measurement, processing and transmission of the measurements of the variables.

Many authors have developed data reconciliation methods and strategies (Romagnoli and Sanchez, 2000; Arora and Biegler, 2001; Yuan *et al.*, 2015; Llanos *et al.*, 2015; Özyurt and Pike, 2004; Tjoa and Biegler, 1991, Veverka and Madron, 1997), and many others have applied reconciliation theory to different processes (Weiss *et al*., 1996; Madron and Veverka, 1992; Colombo *et al.*, 1999, Lid and Skogestad, 2008; Srinivasan *et al.*, 2015). In this work, data reconciliation and gross error detection were performed for a lemon processing factory located in Tucumán, Argentina. Also, a selection of measuring points in the plant was made in order to reduce the number of necessary instruments that permit that all measured variables to be reconciled, and the nonmeasured variables were observables (calculated).

II. METHODOLOGY

In order to achieve the objectives of the work, the following methodology was adopted.

- System configuration survey
- Plant data acquisition
- Formulation of the mathematical model (*f*) of the plant: mass conservation balances
- Use of data reconciliation for gross error detection and as a tool for key variables monitoring.

Through data reconciliation, a set of statistically adjusted process variables is obtained and therefore, reconciled data are more accurate than the original ones.

Let´s consider a mathematical model represented by a set of nonlinear equations *f*.

$$f(x,y)=0\,, \tag{1}$$

where x and y represent vectors of measured and unmeasured variables, respectively. The following model represents the variable measurements.

$$\hat{x}=x+e\,, \tag{2}$$

where $\hat{x}$ represents the measurement value, x the real value of the variable, and e the measurement error. It is assumed that e are random quantities with zero mean value and with a known positively definite covariance matrix F. In most cases F is a diagonal matrix with squares of the standard deviation on the diagonal ($F_{ii}=\sigma_i^2$). The reconciliation is carried out as follows. Statistically adjusted values $\tilde{x}$ are searched for $\tilde{x} = \hat{x}+v$, where v is the vector of adjustments.

The adjusted values must satisfy exactly the equations of the mathematical model and, at the same time, they have to be minimal in some way. The quadratic function of adjustments is then minimized (so-called generalized least squares method) (Veverka and Madron, 1997).

$$Q_{min} = v^T F^{-1} v. \quad (3)$$

The presence of systematic errors (gross errors) in the system can occur due to malfunctioning or inexact calibration of instruments, mass leaking in the tubing, non-steady state of the system under study, etc. The presence of gross errors invalidate all data reconciliation results. The measurement credibility method was used to detect the presence of gross errors (Madron, 1985). The "Status" parameter can be used to indicate the presence of gross errors. The definition of the "Status" parameter is given in Eq. 4.

$$Status = \frac{Q_{min}}{Q_{crit}} \quad (4)$$

Assuming Normal distribution of the errors, a χ^2 test can be performed and Q_{crit} is thus obtained for a given significance level.

When data reconciliation is performed for the system, the "Status" parameter is calculated and if its value is less than 1, no gross error is present in the system.

III. CASE STUDY

This work was carried out in the essential oil production area of a lemon processing plant in Tucumán (Argentina). A scheme of the studied plant section is shown in Fig. 1.

The fresh fruit is washed, air-dried, and the essential oil is extracted by introducing the fruit into high speed rotating rollers where the citrus peel oil is continuously removed. Water is used to haul the essential oil and solid particles produced during the operation. To eliminate large particle size impurities, the emulsion is filtered before entering to the centrifuge system. Finally, the small size impurities are eliminated by a 3 consecutive centrifuge stages. The final product contains approximately 95% essential oil which is stocked in stainless steel tanks.

Experimental assays

Several assays in steady state were done in the plant. Main features are listed below,

- Waiting until the variables were stable on a time basis.
- Sampling to analyze the concentrations of the flows every 2 hours.

Initially, data reconciliation and gross error detection was performed at the centrifugation system that consists in three consecutive stages, as follows:

- Primary centrifuges: four centrifuges working in parallel
- Secondary centrifuge: one centrifuge
- Third centrifuges: two centrifuges working in parallel

Afterwards, data reconciliation and gross error detection was performed for the whole process, including essential oil extraction, filtration and centrifugation system. In all cases, the confidence level was 95%. In all study cases of this work, data reconciliation model as well as plant model were nonlinear.

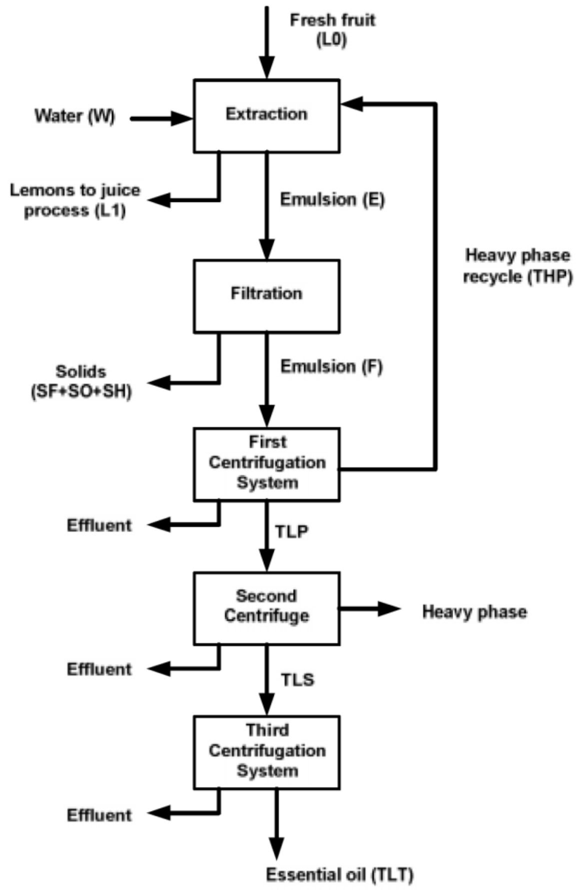

Figure 1: Flowsheet of the studied lemon essential oil process.

The flow of essential oil leaving the third centrifuges were measured with flowmeters based on the float principle and the flow of emulsion fed to the first centrifuges as well as the total recycle flow (THP) with electromagnetic flow meters. The amount of processed lemon was weighted with load cells weighing sensors and the fruit processed per hour was calculated. All concentration values were obtained by titration with BrO_3. Most of the studied variables are actually measured at the plant on a regular basis but some of them were acquired exclusively for this work.

A. Centrifugation System

The centrifuge system of the process is shown in detail in Fig. 2. Initially, data reconciliation was performed for the primary, secondary and third sets of centrifuges separately. Gross error was only detected on the third set of centrifuges. In that case, the measurement suspected of introducing that error was the value of the outflow of the emulsion from a centrifuge. The corresponding flowmeter was checked and it was malfunctioning. The instrument was replaced and no gross error was found in the following reconciliation assays. Eleven assays were performed for the first set of centrifuges, nine for the second set and thirteen for the third set. Only the results for the third set of centrifuges are presented in this work (see Table 1).

Table 1: Data reconciliation results for the third centrifuges.

Status			0.888932		
Stream	Variable	Type	MV	RV	SD
DT_1	G [kg/s]	MC	4.63E-03	4.40E-03	2.50E-04
	X [%]	MC	5.00E-02	5.00E-02	1.50E-03
DT_2	G [kg/s]	MC	3.42E-03	3.33E-03	3.09E-04
	X [%]	MC	1.10E-01	1.10E-01	3.00E-03
LT_1	G [kg/s]	NO	--	4.08E-02	5.00E-04
	X [%]	MC	9.29E+01	9.38E+01	6.75E-01
LT_2	G [kg/s]	MC	4.07E-02	4.12E-02	1.37E-03
	X [%]	MC	9.12E+01	9.15E+01	7.05E-01
FT_1	G [kg/s]	MC	4.51E-02	4.52E-02	4.42E-04
	X [%]	MC	8.66E+01	8.46E+01	5.65E-01
FT_2	G [kg/s]	NO	--	4.45E-02	1.42E-03
	X [%]	MC	8.66E+01	8.46E+01	5.65E-01
TLS	G [kg/s]	MC	9.02E-02	8.96E-02	1.44E-03
	X [%]	MC	8.66E+01	8.46E+01	5.65E-01

Ref.: **G** (mass flow); **X** (essential oil concentration);**MV** (measured value); **RV** (reconciled value); **SD** (standard deviation); **MC** (measured variable, adjustable); **NO** (unmeasured variable, observable).

The number of measured variables were 12 (5 flows, and 7 compositions) while the unknowns among flows and compositions were 9. The mathematical formulation of the model in each centrifuge consisted of 12 mass balances. All unmeasured variables are observables (Mah, 1990). The "Status" value that is informed in every assay evaluates the presence of gross errors. When the "Status" value is less than 1, then no gross error is present in the system. Afterwards, data reconciliation was performed for the whole centrifugation system. Five assays were performed and no gross error was detected in any of them. The number of measured variables were 31 (11 flows, and 20 compositions) while the unknown ones were 32 including mass flows and compositions. The mathematical formulation of the model consisted on 37 mass balances. All unmeasured variables are observables (Mah, 1990). Table 2 shows the results for one of the reconciliation assay for the whole centrifugation system.

B. Extraction, Filtration and Centrifugation System

The operations of extraction, filtration, and centrifugation were considered for the new case study. The filtration stage consisted of 3 different kinds of equipment: finishers, filters, and hydrocyclones and all of them are used to eliminate solids from the emulsion (lemon essential oil + water). In the first assay, gross error was detected in the system with a Status value of 13.71. In Table 3, variables identified as possible source of errors are shown. "New Status" values are the results that will be obtained when the correspondent variable is classified as unmeasured variable in a new model. For example, as it is shown in Table 3; if the concentration of essential oil at the inflow to the first centrifuge of the first stage (FP_1) is not considered as measured variable, the status value is equal to 0.2788, therefore the system will present no gross errors.

As the value of the essential oil concentration of the stream FP_1 was the probable source of error, the corresponding measurement instrument was checked and it was correctly functioning, therefore, isolated human error was supposed for the variable measurement in the assay. Following assays did not present gross error which confirms the former hypothesis of isolated human error.

The estimated values of the variables and the standard deviation for the system are show in Table 4. The number of measured variables are 40 (15 flows and 25 compositions) while the unknowns among flows and compositions are 42. All non-measured variables are observables (Mah, 1990).

C. Alternative essential oil process

In order to improve the efficiency of the process, the plant engineers decided to modify the original essential oil process.

Figure 3 shows the three modifications that were made to the original industrial process which is depicted in Fig. 1. The referred modifications are the following.

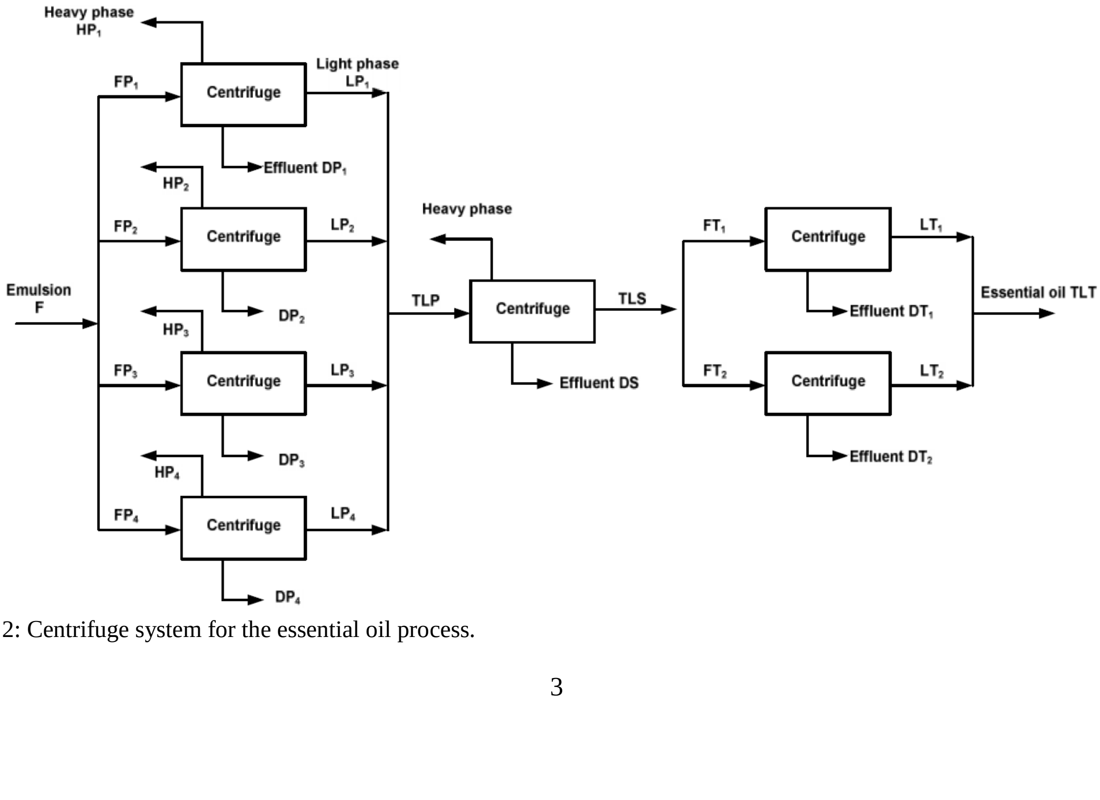

Figure 2: Centrifuge system for the essential oil process.

Table 2: Data reconciliation results for the centrifugation system.

Stream	Variable	Type	MV	RV	SD
Status			0.448165		
DP_1	G [kg/s]	MC	7.58E-02	7.56E-02	1.11E-02
	X [%]	MC	5.80E-01	5.80E-01	8.50E-03
DT_1	G [kg/s]	MC	3.63E-03	3.00E-03	4.59E-04
	X [%]	MC	5.00E-02	5.00E-02	5.00E-04
DT_2	G [kg/s]	MC	3.33E-03	2.48E-03	4.50E-04
	X [%]	MC	1.10E-01	1.10E-01	1.10E-03
DP_2	G [kg/s]	MC	5.13E-02	5.13E-02	1.11E-02
	X [%]	MC	2.00E-01	2.00E-01	3.00E-03
DP_4	G [kg/s]	MC	6.03E-02	6.01E-02	1.11E-02
	X [%]	MC	4.40E-01	4.40E-01	6.50E-03
DS	G [kg/s]	MC	1.07E-02	8.72E-03	8.25E-04
	X [%]	MC	1.50E-01	1.50E-01	1.50E-03
LP_1	G [kg/s]	NO	--	4.30E-02	7.85E-04
	X [%]	MC	8.05E+01	8.07E+01	7.35E-01
LT_1	G [kg/s]	NO	--	4.20E-02	5.65E-04
	X [%]	MC	9.17E+01	9.21E+01	8.30E-01
LT_2	G [kg/s]	MC	4.07E-02	3.83E-02	1.14E-03
	X [%]	MC	9.12E+01	9.15E+01	8.30E-01
LP_2	G [kg/s]	NO	--	2.70E-02	4.59E-04
	X [%]	MC	7.42E+01	7.43E+01	7.15E-01
LP_4	G [kg/s]	NO	--	2.46E-02	4.34E-04
	X [%]	MC	7.74E+01	7.75E+01	7.55E-01
TLS	G [kg/s]	NO	--	8.58E-02	1.24E-03
	X [%]	MC	8.66E+01	8.60E+01	6.90E-01
HP_1	G [kg/s]	NO	--	5.38E+00	5.50E-02
	X [%]	MC	1.90E-01	1.90E-01	2.85E-03
HP_2	G [kg/s]	NO	--	2.59E+00	2.85E-02
	X [%]	MC	7.00E-02	7.00E-02	1.05E-03
HP_4	G [kg/s]	NO	--	2.61E+00	2.88E-02
	X [%]	MC	1.10E-01	1.10E-01	1.65E-03
FP_1	G [kg/s]	MC	5.49E+00	5.50E+00	5.45E-02
	X [%]	MC	8.20E-01	8.24E-01	7.50E-03
FT_1	G [kg/s]	MC	4.51E-02	4.50E-02	3.59E-04
	X [%]	MC	8.66E+01	8.60E+01	6.90E-01
FT_2	G [kg/s]	NO	--	4.08E-02	1.26E-03
	X [%]	MC	8.66E+01	8.60E+01	6.90E-01
FP_2	G [kg/s]	MC	2.66E+00	2.66E+00	2.66E-02
	X [%]	MC	8.20E-01	8.24E-01	7.50E-03
FP_4	G [kg/s]	MC	2.69E+00	2.69E+00	2.68E-02
	X [%]	MC	8.20E-01	8.24E-01	7.50E-03
TLP	G [kg/s]	NO	--	9.45E-02	1.27E-03
	X [%]	NO	--	7.80E+01	3.90E-01

Ref.: G (mass flow); **X** (essential oil concentration); **MV** (measured value); **RV** (reconciled value); **SD** (standard deviation); **MC** (measured variable, adjustable); **NO** (unmeasured variable, observable).

Tabla 3: Measured variables suspected to introduce errors to the system

Stream	Measured variable	New Status
FT_1	Mass flow	54.20
FP_2	Mass flow	3.802
FP_3	Mass flow	3.599
FP_1	Mass flow	3.587
THP	Mass flow	14.72
LT_1	Essential oil concentration	4.976
LP_2	Essential oil concentration	1.577
LT_2	Essential oil concentration	9.433
FP_1	Essential oil concentration	0.2788
TLS	Essential oil concentration	16.25

Table 4: Data reconciliation results for the extraction, filtration and centrifugation system.

Stream	Variable	Type	MV	RV	SD
Status			0.001413		
DP_1	G [kg/s]	MC	7.82E-02	7.82E-02	3.91E-03
	X [%]	MC	3.30E-01	3.30E-01	8.00E-03
DP_3	G [kg/s]	MC	5.00E-02	5.00E-02	2.50E-03
	X [%]	MC	1.10E-01	1.10E-01	2.75E-03
DP_4	G [kg/s]	MC	4.95E-02	4.95E-02	2.48E-03
	X [%]	MC	3.10E-01	3.10E-01	7.50E-03
DS	G [kg/s]	MC	1.35E-02	1.35E-02	6.67E-04
	X [%]	MC	2.70E-01	2.70E-01	6.50E-03
DT_1	G [kg/s]	MC	3.61E-03	3.61E-03	1.80E-04
	X [%]	MC	5.20E-01	5.20E-01	1.30E-02
DT_2	G [kg/s]	MC	2.58E-03	2.58E-03	1.29E-04
	X [%]	MC	3.00E-01	3.00E-01	7.50E-03
F	G [kg/s]	NO	--	1.05E+01	8.98E-01
	X [%]	MN	8.70E-01	8.70E-01	2.20E-02
LP_1	G [kg/s]	NO	--	5.50E-02	3.06E-03
	C [%]	MC	7.42E+01	7.43E+01	1.42E+00
LP_3	G [kg/s]	NO	--	2.61E-02	1.95E-03
	C [%]	MC	7.51E+01	7.51E+01	1.79E+00
LP_4	G [kg/s]	NO	--	2.13E-02	1.71E-03
	X [%]	MC	7.83E+01	7.83E+01	1.90E+00
TLS	G [kg/s]	NO	--	8.90E-02	3.82E-03
	X [%]	MC	8.67E+01	8.67E+01	9.15E-01
LT_1	G [kg/s]	NO	--	4.08E-02	3.63E-03
	X [%]	MC	9.44E+01	9.44E+01	1.13E+00
LT_2	G [kg/s]	MC	4.20E-02	4.20E-02	2.02E-03
	X [%]	MC	9.21E+01	9.20E+01	9.95E-01
HP_1	G [kg/s]	NO	--	5.18E+00	2.39 E-01
	X [%]	MC	1.20E-01	1.20E-01	3.00E-03
HP_3	G [kg/s]	NO	--	2.50E+00	1.25E-01
	X [%]	MC	1.30E-01	1.30E-01	3.25E-03
HP_4	G [kg/s]	NO	--	2.42E+00	1.21E-01
	X [%]	MC	2.20E-01	2.20E-01	5.50E-03
FP_1	G [kg/s]	MC	5.32E+00	5.31E+00	2.40E-01
	X [%]	MC	8.92E-01	8.91E-01	1.60E-02
FP_3	G [kg/s]	MC	2.58E+00	2.57E+00	1.26E-01
	X [%]	MC	8.92E-01	8.91E-01	1.60E-02
FP_4	G [kg/s]	MC	2.49E+00	2.49E+00	1.22E-01
	X [%]	MC	8.92E-01	8.91E-01	1.60E-02
FT_1	G [kg/s]	MC	4.43E-02	4.44E-02	3.63E-03
	X [%]	MC	8.67E+01	8.67E+01	9.15E-01
FT_2	G [kg/s]	NO	--	4.46E-02	2.03E-03
	X [%]	MC	8.67E+01	8.67E+01	9.15E-01
L_0	G [kg/s]	MN	1.37E+01	1.37E+01	8.21E-01
	X [%]	MN	6.34E-01	6.34E-01	1.60E-02
L_1	G [kg/s]	NO	--	1.36E+01	8.17E-01
	X [%]	MN	7.50E-02	7.50E-02	1.88E-03
THP	G [kg/s]	MC	1.01E+01	1.01E+01	2.75E-01
	X [%]	NO	--	1.46E-01	2.25E-03
SF	G [kg/s]	MN	3.69E-02	3.69E-02	3.69E-03
	X [%]	MN	3.90E-01	3.90E-01	1.00E-02
SO	G [kg/s]	NO	--	7.19E-02	9.27E-01
	X [%]	NO	--	1.65E+01	2.48E+02
SH	G [kg/s]	MN	1.50E-02	1.50E-02	1.50E-03
	X [%]	MN	1.10E-01	1.10E-01	2.75E-03
W	G [kg/s]	NO	--	3.27E-01	9.21E-01

Ref.: G (mass flow); **X** (essential oil concentration); **MV** (measured value); **RV** (reconciled value); **SD** (standard deviation); **MC** (measured variable, adjustable); **MN** (measured variable, nonadjustable), **NO** (unmeasured variable, observable).

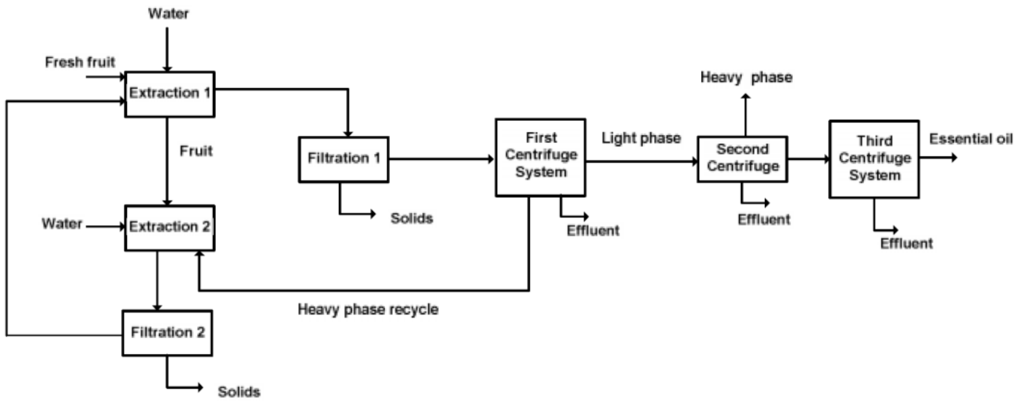

Figure 3: New configuration of the lemon essential oil process.

i) A new extraction stage was added.
ii) The emulsion obtained in the second extraction stage is recycled to the first extraction stage.
iii) The heavy phase outflow from the first centrifuge was recycled to the new extraction stage.

A mathematical model of the modified process was developed, data collection and reconciliation assays were performed when the stationary state was reached for the new configuration. No gross errors were detected. Reconciled variables values of the original and modified processes allowed the evaluation of efficiency parameters and the decision making process with more reliable information. The results of the assays made for the modified process are not presented due to confidentiality issues.

D. Determination of the allocation points for measurement instruments

The objectives of this assay was to determine a strategy to measure the variables that permits to accomplish the following goals.

i) All the measured variables should be reconciled and all non measured variables should be observables.
ii) The more important variables of the process should be measured.
iii) The instrumentation of the process should include as few instruments as possible to achieve the i) and ii) goals.

Fifty-nine possible alternatives were evaluated. Only 9 of them accomplished goals i) and ii) simultaneously and only 1 alternative accomplished all three goals together.

The studied system consisted of 48 mass flow, 134 variables, 53 of which were measured and redundant, and 81 were unmeasured variables but they were observables ones.

The implementation of the resulting scheme of instrumentation required the following actions.

a) Installation of new online measurement instruments: Continuous measure of the amount of lemon fed to each extractor. Those measurements are imperative to reconcile all measured variables.
b) Eliminate unnecessary concentration measures: Originally, the concentration of the emulsion fed to every first centrifuge were measured. Due to process design the inflow to all first centrifuge are identical, therefore, just one measure is enough.
c) Reallocation of the existing measurement instruments: The instrument that was measuring the emulsion flow to one of the first centrifuge should be reallocated in order to measure the outflow of the same centrifuge. This action would increase the number of reconciled and observable variables.
d) Data registration: In order to be able to perform data reconciliation, the heavy phase recycled mass flow must be registered. At this moment that flow is being measured but the information is not being registered.

All the other variable measurements should be kept as it is done at the present time.

IV. CONCLUSIONS

In this work data reconciliation and gross error detection were performed for a lemon processing plant. Two different schemes of the essential oil process were studied. Besides, data reconciliation allowed the detection of the more convenient allocation points of the measurement instruments for the process.

Due to lack of information to perform data reconciliation, the value of other variables of the process had to be acquired. The new data acquired included mass flows and essential oil concentrations.

Gross error was detected on the centrifuge stage due to malfunctioning of a flowmeter. The instrument was replaced and thus, the gross error was eliminated from the system.

Data reconciliation allowed comparing the performance of two different schemes of essential oil production with more reliability and precision. The results of this study were used for decision making at the plant.

The more convenient measurement points for the plant were also detected with data reconciliation. The proposal included elimination of unnecessary variable measurements, reallocation of existing instruments and addition of new instruments in order to attain complete data reconciliation of measured variables and, simultaneously, the calculation of the unmeasured ones. This instrumentation system will allow the permanent monitoring of the process and will facilitate instruments maintenance with a fast detection of instrument failure.

NOTATION

DP,DS,DT	Effluent from 1st, 2nd or 3rd centrifuges.
E	Outflow of emulsion from extraction stage
FP,FS,FT	Flow fed to 1st, 2nd or 3rd centrifuges
HP,HS,HT	Heavy phase flow from 1st, 2nd or 3rd centrifuges
L0	Lemon fruit entering to be processed
L1	Lemon fruit leaving the extraction stage
LP,LT	Flow leaving 1st or 3rd centrifuges
THP	Total recycle flow of heavy phase from centrifuges
TLP,TLS,TLT	Total flow of light phase leaving 1st, 2nd or 3rd centrifuges
SF,SO,SH	Outflow of solids from finishers, filters or hydrocyclones
W	Inflow of water to extraction stage
Index	
i	Number of centrifuge at the stage (1=first, 2=second, 3=third).

ACKNOWLEDGEMENTS:

This work was partially supported by a grant from Consejo de Investigaciones de la Universidad Nacional de Tucumán (Argentina). The authors would like to thank Eng. Federico Sosa and factory personnel for their collaboration during the assays.

REFERENCES

Arora, N. and L.T. Biegler, "Redescending estimators for data reconciliation and parameter estimation," *Comp. Chem. Eng.,* **25**, 1585-1599 (2001).

Colombo, M.A., H. Heluane, M.R. Hernández and M.R. Cesca, "Achieving objectives through data reconciliation," *Proceedings CAIP´99*, Costa Rica (1999).

Federcitrus, *La Actividad Citrícola Argentina*, http://www.federcitrus.org/noticias/upload/informes/La_Actividad_Citricola_2015.pdf (2015).

Lid, T. and S. Skogestad, "Data reconciliation and optimal operation of a catalytic naphtha reformer," *J. Proc. Control*, **18**, 320-331 (2008).

Llanos, C.E., M.C. Sanchéz and R.A. Maronna, "Robust Estimators or Data Reconciliation," *Ind. Eng. Chem. Res.*, **54**, 5096-5105 (2015).

Madron, F., "A new approach to the identification of gross errors in chemical engineering measurements," *Chem. Eng.Sci.*, **40**, 1855-1860 (1985).

Madron, F. and V. Veverka, "Optimal selection of measuring points in complex plants by linear models," *AIChE J*., **38**, 227-236 (1992).

Mah, R., *Chemical Process Structures and Information Flows*, Butterworths, Boston, UK (1990).

Özyurt, D.B. and R.W. Pike, "Theory and practice of simultaneous data reconciliation and gross error detection for chemical processes," *Comp. Chem. Eng.*, **28**, 381-402 (2004).

Romagnoli, J.A. and M.C. Sanchez, *Data Processing and Reconciliation for Chemical Process Operations*, Academic Press, San Diego, California, USA (2000)

Srinivasan, S., J. Billeter, S. Narasimhan and D. Bonvin, "Data Reconciliation in Reaction Systems using the Concept of Extents," *Comp. Aided Chem. Eng.*, **37**, 419-424 (2015).

Tjoa, I.B. and L.T. Biegler, "Simultaneous strategies for data reconciliation and gross error detection of nonlinear systems," *Comp. Chem. Eng.*, **15**, 679-690 (1991).

Veverka, V.V and F. Madron, *Material and Energy Balancing in the Process Industries*, Elsevier, The Netherlands (1997).

Weiss, G.H., J.A. Romagnoli and K.A. Islam, "Data reconciliation - An industrial case study," *Comp. Chem. Eng.*, **20**, 1441-1449 (1996).

Yuan, Y., S. Khatibisepehr, B. Huang and Z. Li, "Bayesian method for simultaneous gross error detection and data reconciliation," *AIChE J*., **61**, 3232-3248 (2015).

Received: March 14, 2016.
Accepted: July 30, 2016.
Recommended by Subject Editor: Mariano Martin Martin