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Reconciliation-based Dynamic Cost Analysis System for a Methanol Plant

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***Abstract*—A novel method for real time process data reconciliation and a modified serial compensation technique for gross error detection are developed in order to obtain balanced and accurate process data. Based on process data reconciliation, a new matrix algorithm is utilized to analyze the dynamic production cost of final product streams and intermediate product streams. As an application, these technologies have been implemented in a large scale coal-based methanol plant successfully.**

Keywords-Manufacturing Executive System (MES); Reconciliation; dynamic cost; matrix algorithm

I. INTRODUCTION

THE synthesis gas coming from Texaco furnace in which coal is gasified, is fed to two methanol units and two CO units in a methanol plant. There exist mass and energy transaction and interaction among these four units as shown in Figure1. It is found that the process data are unbalanced due to complexity of process and inaccuracy of the measurement device such as transmitters and/or analyzers. . Furthermore, material drawing-off and injection in the middle of the process make it very difficult to calculate the cost of product and mid-product in real-time therefore only long-term static data could be available for further applications. Such a situation causes extremely difficulty or impossibility of implementation of on-line production planning, schedule and optimization.

This work introduces a new on-line system for component data reconciliation and dynamic cost calculation (by shift, daily, monthly or yearly) based on the platform of Manufacturing Executive System (MES) as well as an application case in a large-scale coal-based methanol plant. This on-line application has achieved the prospective benefit after almost two years of development.

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II. THE DEVELOPMENT OF DATA RECONCILIATION TECHNIQUES

A. The development of Data Reconciliation

It is assumed that the measured data contains true value and

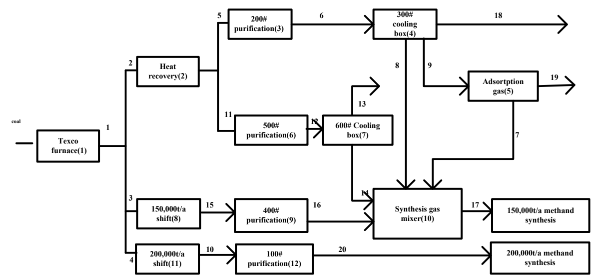

Fig. 1. Methanol Process

relatively small random errors, the process is stable, and the random error included in measured data is subject to normal distribution: $E(\varepsilon)=0, Cov(\varepsilon)=Q$.

A generic data reconciliation problem with linear constraints can be stated as follows:

$$\min_{\hat{X}}[(\hat{X}-X)^T Q^{-1}(\hat{X}-X)] \quad (1)$$

$$St. A\hat{X}+BU+C=0 \quad (2)$$

Where, $\hat{X}$ represents the reconciled value vector of measured data, U represents the vector composed by estimated value while A, B, C is coefficient matrices.

B. Gross error detection method on measured data

1) Solve the constrained least square problem: Constraint equations residuals:

$$r = AX - C \quad (3)$$

Residual covariance matrix:

$$V = AQA^T \quad (4)$$

Reconciled value of measured data:

$$\hat{X} = X - QA^T V^{-1} r \quad (5)$$

The difference of measured data and reconciled values:

$$\delta = \hat{X} - X = -QA^T V^{-1} r \tag{6}$$

For each measured data x_i, establish the statistic test:

$$Z_i = \delta_i W_{ii}^{-1/2} \tag{7}$$

Where, $W = QA^T V^{-1} AQ$.

2) The entire $|z_i|$ are sorted in decreasing order and S sequence is gained after ranging.

Compare max. S(1) to critical value ZC, if $S < ZC$, indicating all the $|z_i|$ are among the confidence interval, so no need to carry on gross error detection, error detection ends. If $S > ZC$, then proceed the next step.

3) The probability of containing gross error is most probable in the first several variables in S.

Supposing Pos is the set of local position of the first N variables in S.

Assumption without gross detection $H_0 = E(r) = 0$.

N alternative assumptions established for the variable in the Pos, $H_k = E(r) = bf_k$.

Where $f_k \in Ae_k, k \in Pos$, likelihood ratio is constructed: $\lambda = \sup \Pr|H_k / \Pr|H_0$, where sup is to find the upper limit, equals to the following:

$$\sup_{b, f_k}[r^T V^{-1} r - (r - bf_k)^T V^{-1} (r - bf_k)] \tag{8}$$

4) If T equals to $f_k = Ae_k, k \in Pos$, then measured data of variable x_k are most probably containing gross error. x_k may have a parallel variable x_i (namely Ae_i parallels to Ae_k).The integrated effect of x_k and its parallel variable make $E(r) = bf_k$, based on the upper or lower bound, we compensate the measured data so that the total amount of compensation as close to b as possible. Measured data compensated is:

$$X_c = X - b_{c1} e_{i1} - b_{c2} e_{i2} - \cdots \tag{9}$$

5) Replace X with X_c, and then repeat the first step.

C. Figures Components balance data reconciliation model for coal coking process

Corresponding to Figure 1, the equipment-based node-stream figure used for data reconciliation is shown as Figure 2. In the streams, methanol 1 and methanol 2 are liquid phase, all others are gas phase. The split factors of the splitter are to be estimated, flow rates of stream 1, 2, 22, 23, 24 and 27 don't have measured value, and component of stream 23 doesn't have analyzed value. V1, V2, V3 and V4 are released gas in purification section, T1, T2 and T3 are recovered gas in purification section, which will recycle to purification 2. The most important gas components are CO_2, H_2 and CO, they account for over 99 percent.

There exist one shift reaction and two synthetic reactions in reactor 1 and 2 as below:

$CO + H_2O = CO_2H_2$

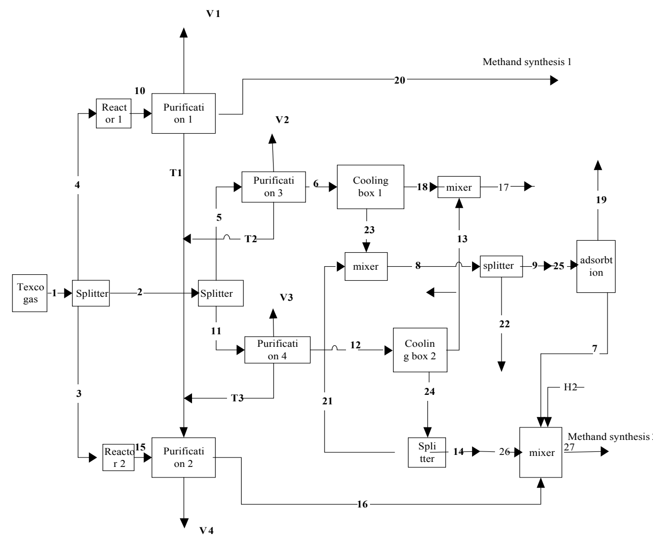

Fig. 2.Graph of Process Data Reconciliation

$CO + 2H_2 = CH_3OH$

$CO_2 + 3H_2 = CH_3OH + H_2O$

Overall process includes 19 nodes, more than 30 streams, 4 reactors and a couple of recycle streams. It is obviously not a straightforward task to proceed online data reconciliation of component balance for such a complicated process.

Based on deep analysis to the process model, a bi-linear method for data correction is adopted with some reasonable assumptions.

Due to split factors of the splitters are unknown, data reconciliation are proceeded in three steps as following:

--First, without constraints of streams which feed to or exit from splitters consisting of the same components, proceed bilinear data reconciliation and gross error detection.

--Second, according to component flow with higher redundancy (here are CO and H_2), calculate the split factors, add splitter constraints into the constraint equations, to carry out the second bilinear data reconciliation and gross error detection.

--Third, compare the above two results, modify some of measured data, reduce the variance of some data, and revise the split factors of splitter, then carry on the final data reconciliation.

One example of original data and finally reconciliation results are showed in Table 1 and Table 2.

III. The Development Of Dynamic Cost Technology

A. What is dynamic cost

From cost accounting and cost control point of view, there exists major difference between discrete manufacturing and continuous process. Generally speaking the former one has an exhaustive and accurate detail list, namely BOM (Bill of Material) formbut the latter can only provide a rough range of the consumption index. The consumption of utilities and material, or the cost in another word, in process industry is actually a continual variable. The variance of cost is strongly related to operating conditions such as temperature, pressure, reaction degree and reflux ratio, etc. Very naturally the cost value behaves all characteristics of complex systems, such as interactions of variables, nonlinearity, time-varying and so on. In 1996, the concept of ERP/MES/PLC structures in process industry was presented by America AMR (Advanced Manufacturing Research), and successfully applied in steel enterprises. After that, how to realize the online cost calculation, analysis, prediction, and feedback in the information integration environment, and to dynamic control the cost, have become an important topic in process industry.

TABLE I
MEASURED DATA AND RECONCILED DATA OF FLOWS

Stream No	Measured	Reconciled
1		8.96E+05
2		2.44E+05
3	3.10E+05	2.85E+05
4	3.48E+05	3.67E+05
5	1.13E+05	1.13E+05
6	9.10E+04	9.10E+04
7	1.78E+04	1.97E+04
8	8.34E+04	6.06E+04
9	4.73E+04	4.48E+04
10	4.34E+05	4.44E+05
11	1.31E+05	1.32E+05
12	1.06E+05	1.06E+05
13	5.37E+04	5.60E+04
14	3.59E+04	3.36E+04
15	3.60E+05	3.46E+05
16	2.43E+05	2.45E+05
17	8.39E+04	1.03E+05
18	4.29E+04	4.72E+04
19	2.37E+04	2.51E+04
20	3.11E+05	3.06E+05
21	1.74E+04	1.69E+04
22		1.58E+04
23		4.38E+04
24		5.05E+04
25	4.66E+04	4.48E+04
26	3.41E+04	3.36E+04
27		2.98E+05

TABLE II
MEASURED DATA AND RECONCILED DATA OF COMPONENTS

Stream No	Measured			Reconciled		
	CO_2	CO	H_2	CO_2	CO	H_2
1,2,3,4,5,11	17.28	45.72	36.47	17.62	47.25	35.13
6	0.1	54.9	44.79	0	56.88	43.12
7	0	19.97	79.24	0	22.94	77.06
8,9,22,25	0	9.41	90.32	0	10.09	89.91
10	33.11	21.25	45.35	31.84	21.82	46.33
12	0.1	56.8	42.79	0	56.86	43.14
13	0	99.19	0.13	0	99.88	0.117
14,21,24,26	0	8.75	90.35	0	9.084	90.92
15	32.84	23.67	42.99	32.26	21.08	46.66
16	2.36	32.28	65.03	2.337	30.9	66.76
17	0	99.21	0.099	0	99.92	0.084
18	0	99.24	0.06	0	99.95	0.046
19	0	0	99.9	0	0	100
20	2.33	31.92	62.25	2.373	30.88	66.75
23				0	10.48	89.52
27	1.9	24.4	72.5	1.919	27.91	70.17

B. The calculation of dynamic cost

Let A represent the direct consumption matrix of varies product to internal material (intermediate product).

B represents the direct consumption matrix of varies product to exterior materials (outsourcing product).

X represents the column vector of totally output of varies products.

Y represents the column vector of commodity amount of varies products.

Z represents the column vector of consumption of the varies products' outsourcing materials.

For the factory module of process industry with complicated topological structure, it can be expressed as follows:

$$AX + Y = X \tag{10}$$

$$BX = Z \tag{11}$$

From (10):

$$(I - A)^{-1} Y = RY = X \tag{12}$$

Equation (11) was substituted:

$$B(I - A)^{-1} Y = QY = Z \tag{13}$$

Where $R = (I - A)^{-1}$ is the complete consumption matrix of varies product to internal materials.

$Q = B(I - A)^{-1}$ is the complete consumption matrix of varies product to external materials.

The dynamic cost of varies product was given in the price form of external materials (such as water, electricity, gas, coal and so on) and the matrix Q.

Fixed cost including overhead, manpower, equipment deprecation, repair expenditure and other manufacture expenses can be updated and read by ERP system monthly or annually.

The advantage of matrix method to calculate cost is that the complete consumption coefficient of utilities and varies products to raw materials can be directly given by real-time data which is calculated by matrix operation.

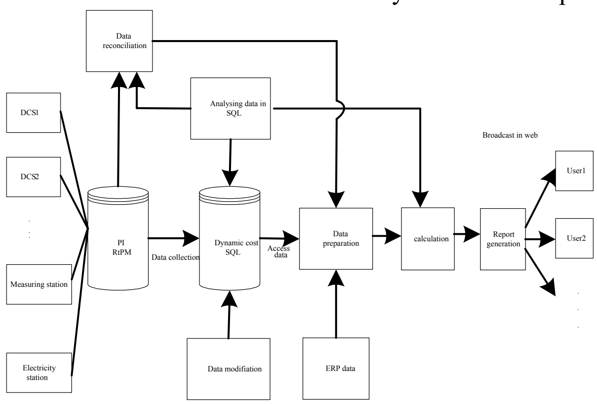

Fig. 3. Information flow chart of dynamic cost

Therefore it is convenient to realize automatic calculation procedure and compile the constraint conditions and the objective function for optimization purposes.

C. Realization of MES dynamic cost in coal-coking and chemical plant

The flow chart of dynamic cost is shown in Figure 3. Data reconciliation is applied to all major process variables in DCS including material flows and consumption of utilities in order to create real-time database. In the environment of MES information bus, process data such as flow rate in real-time database and finance data (like expenditure of depreciation, manpower, maintenance, management and the external material price) can be accessed by dynamic cost system in specified time interval (in shift, daily, monthly, yearly etc).The dynamic costs of products are automatically calculated and output. Some functions such as query, analyzing and comparing can be arbitrarily carried out in the system.

IV. CONCLUSIONS

This project has developed a new Gross error detection and bilinear data reconciliation method which has been implemented in a coal-coking and chemical plant. For the chemical processes, the measured data is often unbalanced, so the adjustment and apportion made are inevitable. After the data reconciliation, balanced and complete logistics data will provide a solid and creditable base for production planning and scheduling, cost accounting, process optimization and management.

The reconciliation-based online dynamical cost model with the completed consumption matrix is obviously important to calculate cost dynamically by which the complete consumption coefficients of utilities and varies products to varies raw materials can be obtained directly. All of the information about the manufacturing cost, which required great efforts to capture from real processes in the past, is now all automatically presented in front of people by means of integrated information bus.

The data reconciliation and calculation of dynamic cost are of course not our final purpose. Once the MES platform is adopted in industry, the real-time data of material consumption and cost could be used in more advanced applications to achieve maximum benefit through projects of process optimization. We can feel more timely and more keenly than ever that the change of material and energy consumption brought by slight adjustment of the operation conditions. For example, to schedule the load distribution of the two methanol units, adjust the volume of transfer hydrogen-enriched flow from 600# to 300#, optimize inserts concentration in the synthetic section with membrane separation units, adjust shifting depth of 400#, regulate the gas flow of cooling box on the three pressure grades, and so on, all of these actions can certainly generate huge benefits. In this kind of meaning, dynamic cost in MES is like a "sensor" in production scheduling and process optimization. The importance of the project is significant for new project scope, management decision and engineering implementation.

REFERENCES

[1] Ajit C.Tamhane, Richard S.H.Mah., Data Reconciliation and Gross Error Detection in Chemical Process Networks, *Technometrics*, vol. 27, 1985, pp 409-421.

[2] S.Narasimhan,R.S.H.Mah, Generalized Likelihood Ratio Method for Gross Error Identification, AIChE Journal, vol. 33, 1987, pp 1514-1587.

[3] Chetam P M, Niranian R P., Cost model for a steel-reheating operation, Industrial Heating, vol. 72, 2002, pp 67-70.

[4] Kellermaye K H., Integrated computer systems in the Donawitzsteel mill, Control Engineering Practice, vol. 1, 1993, pp 827-833.

[5] In Won Kim, Mun Sik Kang, Sunwon Park and Thomas F. Eddgar., Robust data reconciliation and gross error detection: the modified MIMT using NLP, Computers chemical engineering, vol. 21, 1997, pp 775-782.

[6] Chen,J.,Bandoni,A. and Romagnoli, J.A, Robust estimator of measurements error variance/ covariance from process sampling data, Computers chemical engineering, vol. 21, 1997, pp 593-600.

[7] Keller, J.Y., M. Zasadzinski, and M. Darouach., Analytical estimator of measurement error variances in data reconciliation, Computers chemical engineering, vol. 16, 1992, pp 185-188.

[8] Rao, R.R., and S. Narasimhan., Comparison of techniques for data reconciliation of multi-component processes, Ind. & Eng. Chem.Res, vol. 35, 1996, pp 1362-1368.