Integration Optimization of Production and Utility System for Refinery-wide Planning

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Abstract: Traditional optimization of production system and utility system is carried out separately which cannot ensure that the entire refinery system is optimized globally. In this paper, a novel integrated approach is proposed to optimize process production planning and utility system operation simultaneously. A refinery-wide mixed integer nonlinear programming model is proposed and the traditional method and improved integrated method are compared. A real industrial example is conducted to demonstrate the effect of the proposed mathematical model. The results suggest that the integrated approach can provide not only significant benefits but also better energy utilization.

Keywords: production, utility system, integration, process optimization, refinery

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1. INTRODUCTION

During the recent years, the industrialization in developing countries encounters an increasing demand of energy resources annually. Oil refining industries account for an important part of global energy consumption. A main part of the energy of oil refining is utilities generation. The utility consists of various forms of different grade pressure steams, electricity, hot water/air and so on.

Refineries are generally composed of production systems and utility systems. For a given refinery, refinery production system not only produce gasoline, diesel and so on by consuming energy from the utility system, but also produce some by-products. The by-products provide utility system as fuel resources which can be in forms of fuel oil and fuel gas. Respectively, in a oil refinery, the utility system needs to provide consistent steam and electricity causing operation cost and fuel material costs to all production plants. Therefore, for efficient energy utilization and economic profit improvement, the interactions between production systems and utility systems have to be taken into consideration.

The traditional optimization method to these two systems is a sequential hierarchical approach. As shown in Fig. 1, in the primary stage, the objective is to obtain optimal allocation of products and process flows to gain efficient use of raw material. In the second stage, base on the production planning results, the total energy demands for the processing plants are calculated. Attaining the utility demands, in the final stage, the utility system is optimized to operate the utility equipment not only to meet the different utility demands of the processing plants but also to minimize the fuel resource costs(Agha et al., 2010). The relation of the production systems and the utility system is separated in the traditional method. The relationship is rather 'master and slave' than united equally(Adonyi et al., 2003). A noticeable drawback of the sequential method is missing opportunities for improving the economic margin due to individual optimization of each system. As a result, energy provided by utility system is also not fully utilized.

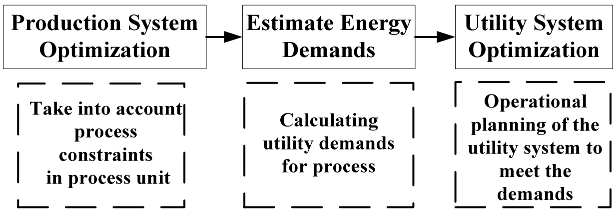

Fig. 1. Sequential procedure of refinery optimization

Therefore, there is a need for the effective integration optimization of the two systems in refinery complex. Some research has been done on incorporating production and the utility system on planning and operational scheduling recently by developing integrated models. Kim proposed a multi-period mathematical model to optimize energy supply units which deals with the varying demands of energy from processing unit and price uncertainty (Kim et al., 2003). Moita developed a dynamic model of salt crystallization process (Moita et al., 2005). A specific frame to integrate heat and power is proposed to get more optimization space in batch and semi-continuous machining processes (Puigjaner, 2007). A MILP model is proposed to optimize the material flow of a refinery along with the steam power system which restricted to the liner yields model of production and cogeneration units (Zhang and Hua, 2007). A multi-agent systems for the production planning of continuous processes is developed and applied based on the Artificial Gas Lift method (Martínez et al., 2011). Though limited to unit operation, Zhang presented a new approach to integrate the operation condition of distillation and heat recovery effect in a crude oil distillation unit (Zhang et al., 2013). Alhajri presented a proposed model integrating the hydrogen management, CO2 management, and production planning

(Alhajri et al., 2013). An integration scheme for the process plants and the utility system on the site-scale steam integration is proposed to attain energy utilization efficiencies (Zhang et al., 2013).

The main purpose of this paper is to develop an mathematical method which integrate the refinery production planning and the utility system and optimized them simultaneously. Section two gives a definition of the problem. Section three presents a detailed formulation of integrated mathematical model. The application of the proposed model as well as the comparison of the two approaches is discussed in section four. Finally, the results are summarized and conclusions are given.

2. PROBLEM STATEMENT

As shown in Fig. 2, in a general refinery, utility systems rely on the fuel resource supplied by production system to generate different grades steam including high pressure steam (HPS) and medium pressure steam (MPS). Since the production process involves in not only energy consumption but also steam generation (for example, steam from fluid catalytic cracking process), the steam can be supplemented from the utility system once the utility generated by the production system cannot meet itself demand and the extra steam can be transported to the utility system once self demand is met. Boilers of the utility system are used to generated high pressure steam and medium pressure steam by consuming fuel oil or fuel gas. The extra steam generated by boilers and production system can be used to drive the turbine to generate electricity and pass turbine to extract low pressure steam which can supply the production system as heat resource. The electricity can be purchased from a power company to maintain the power balance between demand and supply.

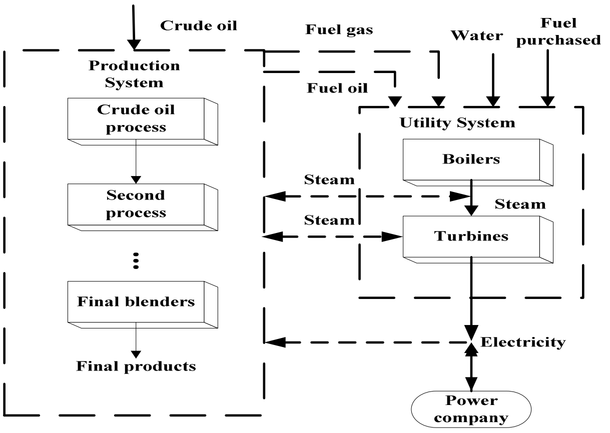

Fig. 2. Simplified framework of refinery energy system

The refinery shown above consists of two subsystems defined as fuel sinks of utility system consuming fuel oil or fuel gas and fuel source of production system producing fuel oil or fuel gas as well as the interaction between them.

The objective of the energy system is to optimize the fuel oil and gas use, steam and electricity generation and the steam network distribution as well as energy resource(fuel oil or electricity) purchase. The objective of the production system is to optimize the flow rate of the products, unit loads, unit mode selection and intermediate product output as well as material purchase to minimize the total cost. These two systems optimization target are considered simultaneously in this paper. Due to the complexity of the integrated model proposed in this paper, we use the solution of branch-and-bound to solve the MINLP model.

3. MATHEMATICAL MODEL

The mathematical model are provided by defining the traditional production planning models, the utility system model and the correlation model between them. At last, the tradition model of sequential approach and the integrated model of proposed method are formulated by selecting the basic model provided along with objective function respectively.

3.1 Production planning model

3.1.1 Process units model

To integrate the operational variable (fractions cut point) in the column crude oil distillation (CDU), we introduced the swing cut model of the CDU as (1) and (2). The product yield of other process units is related to the feed throughput, properties, and operating condition parameters (e.g., API and conversion for the fluid catalytic cracker unit) in (3).

$$\sum y_{cdu,n} = \sum_{r=0}^{3} a_r \times T_n \quad \forall n \in N \tag{1}$$

$$T_{n,IBP} \le T_n \le T_{n,EP} \tag{2}$$

$$y_{u,n} = a_{u,n} + b_{p,u,n} PP_{u,n} + c_{u,n} X_{u,n} \tag{3}$$

Where $y_{cdu,n}$ is the fraction ratio of the CDU, T_n is the cut point temperature for *n* sideline, $T_{n,IBP}$ and $T_{n,EP}$ is the lower bound and upper bound of the cut point respectively.

3.1.2 Blending constraints

Mass balance and the product quality constraints are considered in blending process as (4)-(5). To make the blending process linear, product qualities such as pour point, and octane number are simplified as corresponding quality indices.

$$\sum (FI_{u,n,i} PP_{u,n,i}) \ge \sum FI_{u,n,i} LB_{q,i} \qquad \forall u \in blend, n \in N, i \tag{4}$$

$$\sum (FI_{u,n,i} PP_{u,n,i}) \le \sum FI_{u,n,i} UB_{q,i} \qquad \forall u \in blend, n \in N, i \tag{5}$$

3.1.3 Market constraints

Market constraints are also taken into account (6)-(8) which (6) and (7) for purchased oil material and final products.

Equation (8) is for electricity purchased limited to the contact between refinery and power company.

$$Q_m^{low} \le Q_m \le Q_m^{up} \quad \forall m \tag{6}$$

$$D_i^{low} \le D_i \le D_i^{up} \quad \forall i \tag{7}$$

$$Ele_{net} \le Ele^{up} \tag{8}$$

3.1.4 Material balance

The material balance of each sideline of unit feed and output is modelled in (9-11). Equation (9) and (10) are the mass balance of each product sideline. Equation (11) is the feed balance on each processing unit.

$$FI_{u,n} = \sum FO_{u',n',u,n} \forall u,u' \in U, n,n' \in N \tag{9}$$

$$FO_{u,n} = \sum FI_{u,n,u',n'} \ \forall u,u' \in U, n,n' \in N \tag{10}$$

$$R_u = \sum FI_{n,u} \ \forall u \in U, Blender, n \in N \tag{11}$$

3.1.5 Capacity constraints

The process throughput limitation is represented as below.

$$LB_u \le R_u \le UB_u \ \ \forall u \in U \tag{12}$$

3.2 Utility system model

A typical utility system consists of boilers producing steams with fuel consumption, steam turbines generating electricity consuming steams, and steam and power network.

3.2.1 Steam boilers

A boiler can be modelled as (13) which associates fuel oil and fuel gas consumption with steam production (Shang and Kokossis, 2004).

$$\begin{aligned} & F_{fuel,eq',boiler} H_{fuel} \ = (C_p(T_{out}^{sat} - T_{in}) + q) \\ & (aF_{boiler}^{\max} y_{boiler} + (1+b) F_{stm,boiler,eq\_d}) \end{aligned} \tag{13}$$

Where $F_{stm,boiler,eq\_d}$ is the steam flowrate generated by the boiler, $F_{boiler}^{\max}$ is the boiler operation capacity, *a* and *b* are the regression parameters, y_{boiler} is binary variable for the boiler, y_{boiler} equals to 1 if the boiler operates, y_{boiler} equals to 0 otherwise.

3.2.2 Turbines

Tthe relationship between the power generation and steam feed input of the turbine is modelled as (14) which indicates that electricity generation is a linear function of the steam consumption (Shang and Kokossis, 2005).

$$\begin{aligned} & E_{turb} = 6 \times (\Delta H_{turb} - a / F_{stm,eq,turb}^{\max}) \\ & (F_{stm,eq,turb} - F_{stm,eq,turb}^{\max} y_{turb} / 6) / 5b \end{aligned} \tag{14}$$

Where $F_{stm,eq,turb}$ is the steam flowrate passing the turbine to generate electricity, y_{boiler} is binary variable of the turbine's operation condition.

3.2.3 Material balance

For different utilities in utility system (e.g., water, steam etc), the material balance can be demonstrated as (15).

$$\begin{aligned} & \sum_{eq \in EF_{eq\_d}} F_{ut,eq,eq\_d} = \sum_{eq \in ER_{eq\_d}} F_{ut',eq\_d,eq} \\ & ut \in UC_{eq\_d},\ ut' \in UP_{ut,eq\_d} \end{aligned} \tag{15}$$

3.2.4 Energy balance

The energy balance can be represented using (16).

$$\begin{aligned} & \sum_{eq \in ER_{eq\_d}} F_{ut',eq\_d,eq} H_{ut'} = \sum_{eq \in EF_{eq\_d}} F_{ut,eq,eq\_d} H_{ut} \\ & + Q_{eq} \quad ut \in UC_{eq\_d},\ ut' \in UP_{ut,eq\_d} \end{aligned} \tag{16}$$

3.2.5 Capacity constraints

The utility capacity constraints is represented by limiting the utility system unit throughput.

$$\begin{aligned} & F_{eq\_d}^{L} y_{eq\_d} \le F_{ut,eq,eq\_d} \le F_{eq\_d}^{U} y_{eq\_d} \\ & ut \in UC_{eq\_d} \end{aligned} \tag{17}$$

3.2.6 Demand constraints

Equation (18) represents that the steam generated by utility system should fully meet the demands from process. Equation (19) represents that electricity generated by utility system and purchased from power company should meet the demands from process.

$$\sum_{eq\_d} \sum_{eq \in EF_{eq\_d}} F_{ut,eq,eq\_d} \ge D_{ut} \ \ \forall ut \tag{18}$$

$$\sum_{turb \in EleP} Ele_{turb} + Ele_{net} \ge D_{Ele} \tag{19}$$

3.3 Correlation of process system and utility system

As mention in section two, processing units not only produce intermediate product as fuel resource but also consuming different types of utilities. Thus the utility distribution links the the two systems. The steam generation by processes can be represented by (20). The total utility consumption can be represented by (21) and (22). Both utility consumption and generation of processing units are related to the unit throughput, operating conditions and feed properties.

$$FS(W) = aF + \sum_{p} b_p PF_p + \sum_{j} c_j PR_j \quad (20)$$

$$D_{ut} = \sum_{h} c_h FS_h \quad (21)$$

$$D_{ut} = aF + \sum_{p} b_p PF_p + \sum_{j} c_j PR_j \quad (22)$$

3.4 Formulation of sequential and integrated models

3.4.1 Sequential model

The traditional sequential approach for optimizing the whole refinery is showed as steps below:

1) Building a production planning model incorporating the production constraints as ((1)–(12)). The objective of the model is to maximize the profit of products producing considering material purchase , represented by (23).

$$Pr = \sum_{i} D_i * s_i - \sum_{m} Q_m * v_m - \sum_{\forall u \in U} R_{u,m} * C \quad (23)$$

2) According to the production planning plan, different types of utility (steam and electricity) demand can be calculated by (20), (21), and (22).

3) Finally, based on the utility demands, the operational planning optimization for the utility system is implemented as ((13)–(19)). The objective for this model is to minimize the operational costs including fuel resource cost, water purchased cost, and electricity purchase cost, represented by (24).

$$Cost = \sum_{boiler} \sum_{fuel} F_{fuel,boiler} C_{fuel} + \sum_{boiler} F_{wat,boiler} C_{wat} + Ele_{net} C_{ele} \quad (24)$$

3.4.2 Integrated model

The disadvantage of optimization in the sequential model is overcome in the integrated model. The production units and the utility system units are taken as a united model to optimized by solving(1)–(22) rather than separately in the sequential model. The objective of the integrated model is to maximize the total refinery profit which involves the sale profit from final products and the total costs of raw material purchase (e.g. crude oil, MTBE and fuel resource) and fixed unit operating costs as represented by (25).

$$P = \sum_{i} D_i * s_i - \sum_{m} Q_m * v_m - \sum_{\forall u \in U} R_{u,m} * C - \sum_{boiler} \sum_{fuel} F_{fuel,boiler} C_{fuel} - \sum_{boiler} F_{wat,boiler} C_{wat} - Ele_{net} C_{ele} \quad (25)$$

This ends the so-called master-slave relationship between the two systems and helps get more optimum operational plan.

4. CASE STUDY

An industrial refinery in China is investigated in this case.

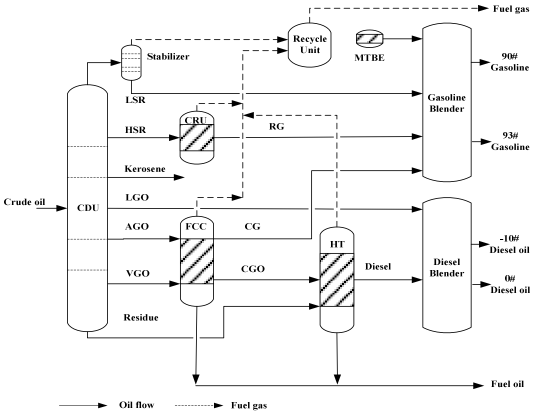

Fig. 3. Oil refinery flow chart

The refinery flow chart is shown in Fig. 3. The crude oil is divided into some straight-run fractions including light straight-run naphtha (LSR), heavy straight-run naphtha (HSR), kerosene (KER), light gas oil (LGO), atmospheric gas oil (AGO), vacuum gas oil (VGO) and residues (RED) after being separated in the crude distillation unit (CDU),. LSR is sent to the catalytic reforming unit (CRU) to produce reformer gasoline (RG). AGO, VGO and RED are sent to the secondary processes including the fluid catalytic cracker (FCC) and the hydrotreating unit (HT) to increase the crack gasoline (CG), crack gas oil (CGO)and diesel yields. LSR, RG and CG are then blended with MTBE as product gasoline in the gasoline blender. Respectively, LGO and Diesel are blended as product diesel in the diesel blender. The fuel gas and fuel oil produced by unit as byproduct are collected separately. The final products include two kinds of gasoline (90# gasoline and 93# gasoline), KER, and two kinds of diesel (-10# diesel and 0# diesel).

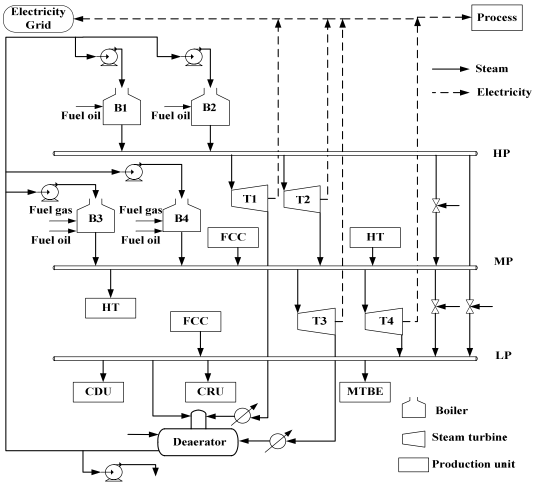

Fig. 4. The utility system in refinery

The utility system is shown in Fig. 4. It consists of four boilers and four turbines. B1 and B2 are supposed to consume only fuel oil to generate high pressure steam. B3 and B4 are supposed to consume either fuel oil or fuel gas. Some steams are condensed by cooling water, then recycled to the deaerator, and finally reused as boiler feed water once the steam supply exceed the processing demands.

The mathematical model developed in section three is investigated in the case of overall daily planning and implemented in an Intel Core i5 3.20 GHz personal computer. The CONOPT2 solver in the GAMS environment is used to solve the problem (Rosenthal, 2004). The execution time of the integrated approach is 0.048 s, a solution time that is practical for the MINLP model.

A comparison between these two approaches is made by applying them to solve this problem separately. The result shows that the total refinery profit is 15.23 million CNY/day with energy cost of 0.75 million CNY/day in the integrated model compared with the profit of 15.00 million CNY/day with energy cost of 1.75 million CNY/day in the sequential model, which results in about 0.2 million CNY/day more profit. The reason for lower energy cost in integrated model is that fuel resource for utility system is optimized simultaneously with the production system. Results for material process are shown in Table 1.

Table 1. Optimal result of raw materials and products

Raw Material (Ton/Day)	Crude oil	MTBE	Water	Power (MW)
Sequential	4428.5	1549.7	1436.5	279.8
Integrated	4535.9	1524.7	1421.5	252.0
Product (Ton/Day)	90# Gasoline	93# Gasoline	-10# Diesel	0# Diesel
Sequential	1200	1500	1332.2	700
Integrated	1200	1500	1411.8	700
Product (Ton/Day)	Kerosene	Fuel Oil	Fuel Gas	
Sequential	544.4	106.2	43.6	
Integrated	530.5	106.8	45.9	

We can see that different material mass is balanced in the refinery site except electricity which can be purchased from power company. Results of steam from process and utility system and electricity power are shown in Table 2.

Table 2. Result of steam and power of process (Ton/Day)

		HPS	MPS	LPS	Power (MW/day)
Process demand	Sequential	0	510	1312.2	569.0
	Integrated	0	510	1317.4	579.3
Process produced	Sequential	0	223.2	162.6	
	Integrated	0	236.6	169.3	

Utility equipments operation results are shown in Table 3.

Table 3. Optimal result of utility equipments (Ton/Day)

		B1	B2	B3	B4
Fuel oil	Sequential	90.2	66.2	0	0
	Integrated	90.2	79.2	0	0
Fuel gas	Sequential	0	0	33.9	16.1
	Integrated	0	0	33.9	14.8
Steam flow	Sequential	1200	876.2	400	182.1
	Integrated	1200	1051.4	400	167.3
		T1	T2	T3	T4
Steam flow	Sequential	876.2	1200	400	400
	Integrated	1051	1200	400	400
Power (MW/day)	Sequential	146.8	46.6	80.1	15.7
	Integrated	184.9	46.6	80.1	15.7

Comparing with the sequential approach in table 1 and table 2, it can be seen that, as the utility (steam and electricity) demands increased in the production system, more fuel oil/gas are produced to meet the energy demands in the utility system to produce more utilities. As s result, less Kerosene is produced due to the CDU capacity limit and less electricity power is purchased due to the more steam used by the turbine. The total operational loads of the boilers and the turbines nearly reach their maximum capacities. At the same time, more steam and electricity are generated due to the fully utilization of boilers and steam turbines in the utility system. Hence, the utility system allows a larger operational capacity as the thorough integration is carried between the process units and energy system units.

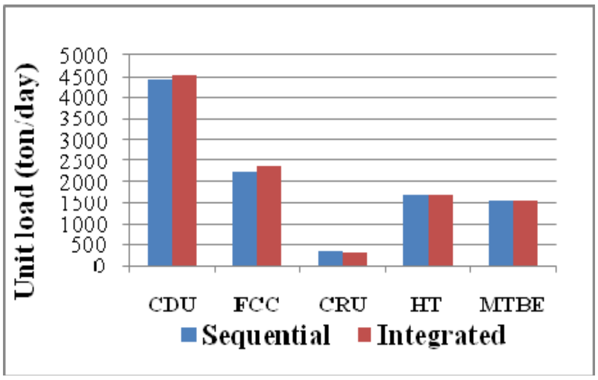

Fig. 5. Production unit processing loads

The processing load for each process unit is shown in Fig. 5. The CDU and FCC throughput increased to produce more byproducts (fuel oil and fuel gas) whereas the CRU throughput is decreased. This is partly because of the fraction yields changes in CDU shown in Fig. 6 where more gas oil other than the naphtha are produced (the HSR and KER fraction yields are reduced, whereas LGO and AGO increased). The HT remains unchanged due to its capacity limits.

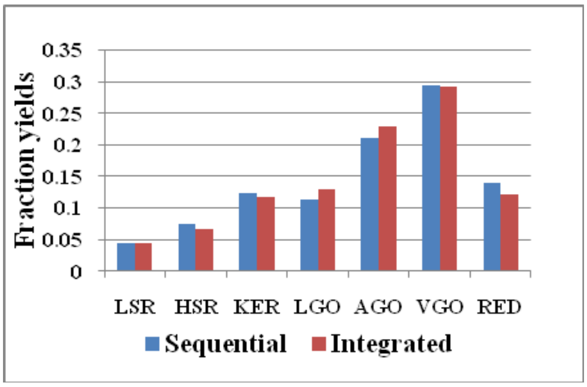

Fig. 6. The fraction yields of CDU

Moreover, we can notice that the integrated optimization method does not aims to reduce the energy consumption to reduce the utility system operating costs. On the contrary, the utility system units are fully taken use to generate more steam and electricity which in turn helps improving the products producing in production system. This is the underlying difference between the sequential method target and the integrated method target.

Above all, the utility system operation should rather be optimized as a part of the whole system of refinery simultaneously with other processes than separately as in the traditional method of refinery.

5. CONCLUSIONS

A new approach of integrating production planning and energy system for petrochemical refinery complex was developed to determine the optimal unit loads and modes and energy generation to meet the varying process energy demand aiming at maximizing the total refinery profit. In the case study, 226386 CNY/day extra profits (1.5% improvement) of a real industrial refinery can be attained using the integrated method compared with the sequential method. The reason is that the intermediate products of energy resources are fully utilized and production units have more processing capacity in the proposed approach. The integrated approach leads to a better conformity between the production unit and the utility system units as shown in results.

We can conclude that the improved model can be exploited to integrate production system and utility system and help oil refining industries to achieve profitable energy costs. The integrated method can also expand the operational ability of the utility system and yields increases in utilities generation and efficiently utilization of the self-produced fuel gas in refinery-wide planning.

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REFERENCES

Adonyi, R., Romero, J., Puigjaner, L. & Friedler, F. 2003. Incorporating heat integration in batch process scheduling. Applied Thermal Engineering, 23, 1743-1762.

Agha, M. H., Thery, R., Hetreux, G., Hait, A. & Le Lann, J. M. 2010. Integrated production and utility system approach for optimizing industrial unit operations. Energy, 35, 611-627.

Alhajri, I., Saif, Y., Elkamel, A. & Almansoori, A. 2013. Overall Integration of the Management of H2 and CO2 within Refinery Planning Using Rigorous Process Models. Chemical Engineering Communications, 200, 139-161.

Kim, J., Yi, H., Han, C., Park, C. & Kim, Y. 2003. Plant-wide multiperiod optimal energy resource distribution and byproduct gas holder level control in the iron and steel making process under varying energy demands. Computer Aided Chemical Engineering, 15, 882-887.

Mart Nez, F., Aguilar, J. & Bravo, C. 2011. Multiagent systems for production planning in automation. *Holonic and Multi-Agent Systems for Manufacturing*. Springer.

Moita, R. D., Matos, H. A., Fernandes, C., Nunes, C. P. & Prior, J. M. 2005. Dynamic modelling and simulation of a cogeneration system integrated with a salt recrystallization process. Computers & chemical engineering, 29, 1491-1505.

Puigjaner, L. 2007. Extended modeling framework for heat and power integration in batch and semi-continuous processes. Chemical Product and Process Modeling, 2.

Rosenthal, R. E. 2004. GAMS--a user's guide.

Shang, Z. & Kokossis, A. 2004. A transhipment model for the optimisation of steam levels of total site utility system for multiperiod operation. Computers & chemical engineering, 28, 1673-1688.

Shang, Z. & Kokossis, A. 2005. A systematic approach to the synthesis and design of flexible site utility systems. Chemical engineering science, 60, 4431-4451.

Zhang, B. & Hua, B. 2007. Effective MILP model for oil refinery-wide production planning and better energy utilization. Journal of Cleaner Production, 15, 439-448.

Zhang, B., Luo, X., Chen, X. & Chen, Q. 2013. Coupling process plants and utility systems for site scale steam integration. Industrial & Engineering Chemistry Research.

Zhang, N., Smith, R., Bulatov, I. & Klemeš, J. J. 2013. Sustaining high energy efficiency in existing processes with advanced process integration technology. Applied Energy, 101, 26-32.