Analytical Optimisation of Industrial Systems and Applications to Refineries, Petrochemicals

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Abstract

A new method for optimising process networks is presented in this paper. The method uses economic analysis of existing systems based on the value analysis method derived by Sadhukhan (2002) as the basis to derive the optimum network design. Optimising a large scale industrial system (e.g. refineries, petrochemicals) where multiple processes, many material streams and a number of supporting systems (e.g. energy) are involved, is a difficult task to achieve. For such a case, a fundamental, practical and systematic methodology for detailed differential economic analysis (Sadhukhan et al, 2003) of an industrial system at any market and environmental condition can be very useful for achieving its optimal operation.

Application of the non-linear discrete / continuous mathematical programming techniques (Grossmann and Daichendt, 1996; Grossmann et al, 1999) for process network optimisation does not provide a clear and transparent economic value structure of individual components (streams and processes) in a network. Overcoming this drawback is the sole driving force of this work that aims to develop a novel optimisation technique called analytical optimisation, for process industries (Sadhukhan et al, 2004). The essence of integration and optimisation of process networks is the evaluation and differential analysis of the economic performance of individual streams and processes. It builds from graph theory by representing any production network as a graph that consists of arcs (streams) and nodes (processes), interconnected to form paths and trees (Mah, 1983). Every stream in a process network can be characterized by a *value on processing* and a *cost of production*. Once they are evaluated for a stream the difference between them provides the specific economic margin achieved from the stream. The profit margins of individual paths and trees and finally the entire network are predicted from the economic margins of streams. Using this new value analysis method an overall integration strategy is developed by Sadhukhan et al (2003) so as to capture the impacts of real plant operations (no fixed operating conditions) and the effects of network interactions in the detailed economic analysis of a complex system.

The analytical optimisation procedure by Sadhukhan et al (2004) is designed based on comprehensive economic analysis of process networks discussed above for maximising the overall system economics. The economic analysis of systems helps to identify the weakest links and their integration opportunities existing in a network configuration. Thus, an optimum network flowsheet can be derived using the existing processes and also including new process technologies as necessary.

The analytical optimisation of a process network comprises of three steps. Market integration is the first step that fully exploits the available market opportunities for selling and purchasing streams based on individual marginal contributions from productions and processing of streams. This activity does not incur any capital investment and is an easy and straight – forward way for achieving quick benefits. The second step deals with optimisation of network flowsheet / connections. The economic margins of various paths of network are used to determine the weaker paths and their corresponding stronger paths where the loads of weaker paths can be shifted. This load shifting among paths leads up to the overall benefits of a system. In general, this stage involves minor capital investment for piping, rerouting of streams etc. At the core of the analysis there is the opportunity to perform a detailed process level optimisation for improvement of non-profitable / less profitable process units. Thus it deals with optimisation of individual processes in order to improve their marginal contributions in the overall economics. Optimisation of processes can incur significant capital investment if integration of new process technologies is considered. For all the three considerations the methodology has been further extended to determine the achievable marginal benefit from every modification suggested. Thus, using such a technique the more economically profitable projects can be readily screened for further evaluation. All the above three aspects of analytical optimisation have been illustrated with the help of refinery case studies (Sadhukhan et al, 2003 and 2004). The effectiveness of the methodology has also been demonstrated in design and scheduling of petrochemical complexes in changing economic scenarios.

1. Market integration of process networks

Sadhukhan et al (2003) has developed marginal correlations for elements (trees and paths) of production and processing of a stream in terms of its market price, *cost of production* (COP) (Eq. 1) and *value on processing* (VOP), market price (Eq. 2) respectively.

$$\sum_{u \in US\_UNIT(i)} \Delta_u(F_{e\text{-}i}) = \{(F_{e\text{-}i})_{MP} - (F_{e\text{-}i})_{COP}\} \times m^F_{e-i} \qquad \forall i \in UNIT,\ e \in EU(i) \qquad \text{(Eq. 1)}$$

$$\sum_{d \in DS\_UNIT(i)} \Delta_d(F_{e\text{-}i}) + \Delta_i(F_{e\text{-}i}) = \{(F_{e\text{-}i})_{VOP} - (F_{e\text{-}i})_{MP}\} \times m^F_{e-i} \qquad \forall i \in UNIT,\ e \in EU(i) \qquad \text{(Eq. 2)}$$

Summation of the two expressions provides the economic margin of the entire element where the stream belongs to (Eq. 3).

$$\sum_{u \in US\_UNIT(i)} \Delta_u(F_{e\text{-}i}) + \sum_{d \in DS\_UNIT(i)} \Delta_d(F_{e\text{-}i}) + \Delta_i(F_{e\text{-}i}) = \{(F_{e\text{-}i})_{VOP} - (F_{e\text{-}i})_{COP}\} \times m^F_{e-i} \qquad \forall i \in UNIT,\ e \in EU(i) \qquad \text{(Eq. 3)}$$

These marginal correlations (Eqs. 1-3) are used to demonstrate how the various market integration opportunities can be fully exploited in a process network. There are 3! arrangements possible among the three values of a stream, VOP, COP and market price (VOP > COP > market price; VOP > market price > COP; market price > VOP > COP; and so on) based on which various market integration strategies are developed. In an ideal situation, the market price of a stream is in between its VOP and COP $\{(F_{e\text{-}i})_{VOP} \geq (F_{e\text{-}i})_{MP} \geq (F_{e\text{-}i})_{COP}\}$. The margins incurred from both the elements of processing and production of the stream are positive (Eqs. 1-2) and so is the overall economic margin of the stream. No market strategy is required to improve the economics. However, if production of a stream is non-profitable (market price of the stream is less than its COP), an improvement in the stream's economic margin can be achieved by reducing production of the stream and instead increasing purchasing of the stream. The difference between the COP and the market price is the *scope for value improvement* of the stream per unit flowrate. The marginal improvement achievable from the stream is determined by multiplying the *scope for value improvement* with the *purchasing potential* of the stream given by the difference between the current flowrate and the minimum production requirement of the stream.

2. Optimisation of network connections

The steps for optimising network connections at site level are as follows.

(1) The streams in an existing network system are evaluated for VOP and COP (Sadhukhan et al, 2003). Using Eqs. 1-3 economic margins of elements (paths) are determined.

(2) The weaker or less efficient paths (with negative / lower economic margins) are screened based on individual economic margins (Eqs. 1-3) and organised in the ascending order of economic margins at any design stage k.

(3) For the current weakest path with the least economic margin the stronger optional paths with better economic margins in the current system at any design stage k are identified where the loads of the current weakest path can be shifted. If no optional path is identified the next weakest path and its set of stronger optional paths are taken into consideration at the design stage k.

(4) The load from the current weakest path is shifted to an identified stronger optional path at any design stage k. Thus a new link is set up between the current weakest path and the stronger optional path.

(5) The maximum marginal benefit achievable from every such new link set up is determined. If the marginal benefit achieved is justified the network is updated with the new link and a new flowsheet is obtained for optimisation in the next design stage $k + 1$.

(6) The procedure from step 1 is followed until no integration opportunity is identified. $k = k + 1$.

The various steps of analytical optimisation of network connections are presented in Figure 1. Due to load shifting from the weaker paths to the stronger paths, the weaker paths receive a share of the stronger economics. The net result is optimisation of overall network connections resulting from integration between weaker and stronger paths.

2.1 Correlations of marginal benefits from new links set up

The marginal benefit achieved from a load shifting is calculated from improvement in economic margin of the shifted load (Sadhukhan et al, 2004). In case the COP remains the same for the shifted load, the marginal benefit is equal to the improvement in VOP multiplied by the flowrate of the shifted load.

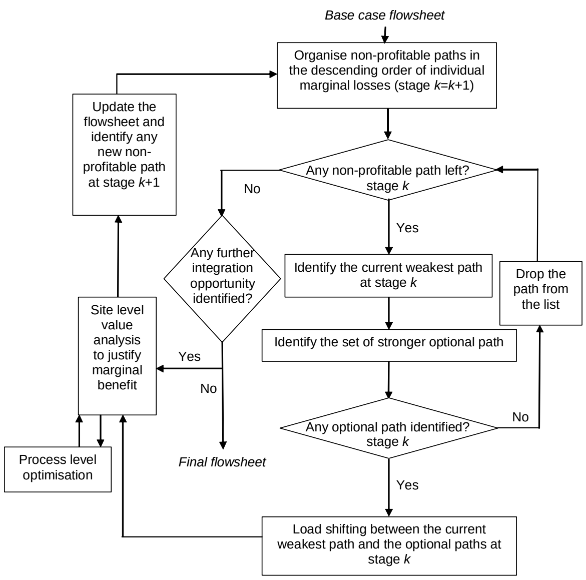

Figure 1. Analytical optimisation procedure for network connections.

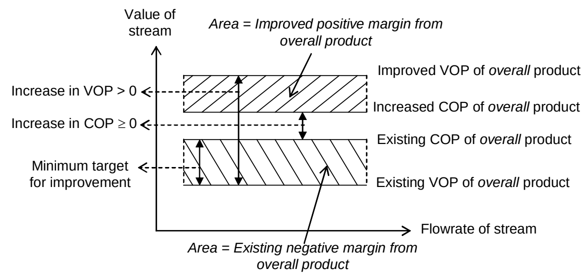

Figure 2. Illustration of system optimisation through improvement of existing processes.

2.2 Determination of optimal load shifting in new links set up

For every new link set up the optimum amount of load shifting is determined in order to predict the maximum marginal benefit achievable from a new link set up. The marginal benefit achievable from a new link set up is a variable depending on the amount and VOP, COP of the load to be shifted. The amount of load to be shifted is a decision variable whereas VOP and COP of the load are dependent on process operating conditions. There are two levels of models to be used to determine the optimal load shifting and thus the maximum marginal benefit from a new link set up, site level and process level models (Figure 1). The site level model predicts VOP, COP of streams (Sadhukhan et al, 2003) and marginal benefit (Sadhukhan et al, 2004) for a given amount of load shifting through a link. The process level model (Sadhukhan et al, 2004; Sadhukhan and Zhu, 2002) provides the process operating conditions (operating costs, yields and properties of streams) as the input to the site level model. Thus, the site level and the process level models co-ordinate with each other to generate a relationship between the marginal benefit and the amount of load shifting through a new link set up. This relationship is finally used to determine the optimal load shifting for which the marginal benefit is the maximum.

3. System optimisation through improvement of existing processes

In this section the non / less profitable processes are investigated to identify the modifications required in order to improve the overall margin. The economic analysis of systems employs two factors, operating costs of process units and values of products, to determine marginal contributions of processes. Therefore, to improve the marginal contribution of a process, the attempts should be made either to reduce the operating cost of processes or to improve the values / qualities of products from processes or both if possible. A more realistic case is when the VOP of products is enhanced through quality improvements at the expense of additional operating costs that increase COP as well. The *stream economic profile* in such a case is more likely to be as in Figure 2. The existing *overall* product is non-profitable. The VOP of the stream is targeted for a minimum increment equal to the existing difference between the COP and the VOP. Some additional process operating costs can be incurred thereby increasing the COP of the stream. This increment in COP should be kept to the minimum possible. The modification should be such that the new VOP is greater than the new COP as indicated in the figure. The marginal improvement can be calculated from the total shaded areas of the existing margin and the new margin in Figure 2.

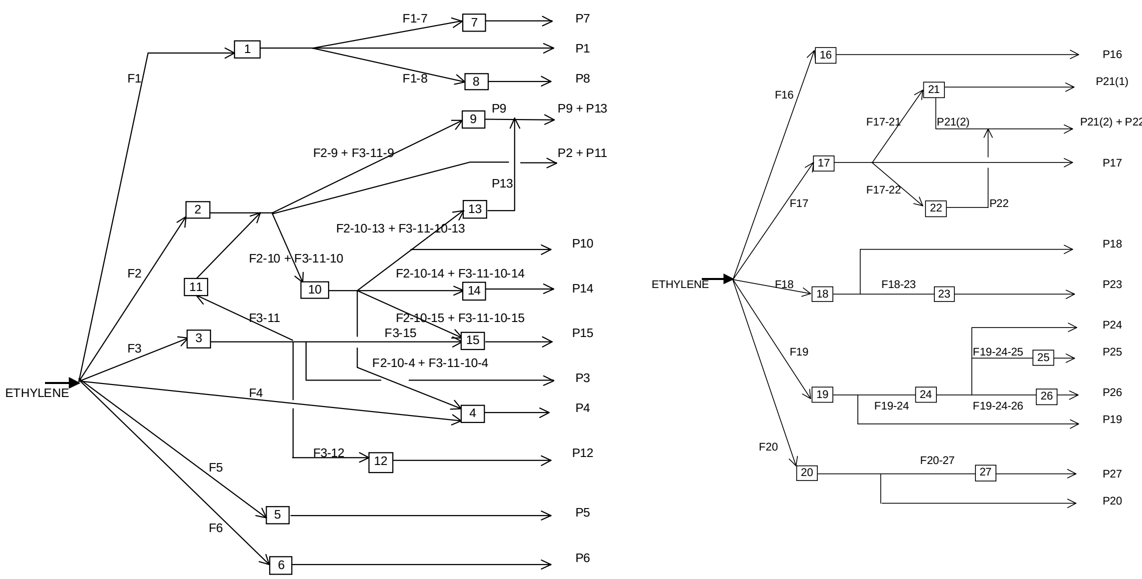

Figure 3. The flowsheet of ethylene derivative complex.

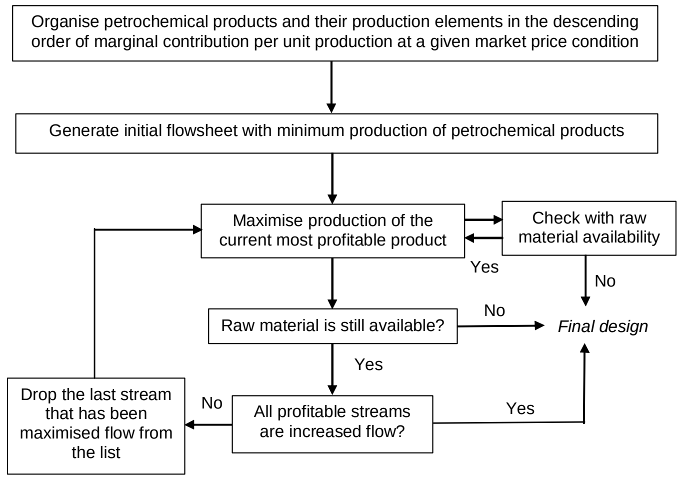

Figure 4. Optimisation of flowsheet distribution for petrochemical complexes.

4. Generalised optimisation methodology for petrochemical complexes

A petrochemical complex is a typical example of multiperiod plant for which supply, demand and prices vary with time period. In this example of ethylene derivative complex (Figure 3), the concepts of analytical optimisation are extended to such an application for determining the optimum operations in varying economic scenarios. The maximum and the minimum prices of the raw materials and the corresponding prices of the petrochemical products over a ten-year period are noted (petrochemical industries generally go through a ten-year cycle in terms of market price variation) in order to derive the most profitable flowsheets in these two market scenarios and thereby covering the entire range of price variation. A generalised step by step procedure (Figure 4) is developed for optimising any petrochemical complex.

Following the procedure, the initial flowsheet distribution is determined where the minimum production requirements of all products set by the market demands are met. The production elements of individual products are then identified and throughput through one by one such element producing profitable products is maximised utilising the existing facilities to the maximum extent. While maximising the production rate of the current most profitable product the market constraint on the source feed availability / supply is verified. The new total flow of ethylene consisting of streams F1 to F6 and F16 to F20 should be less than equal to its market availability in order to proceed to the next stage. At any stage when the constraint on ethylene availability is not satisfied the design stops. For the non-profitable products, the productions are retained to their minimum market demands as in the initial flowsheet. Thus in the end of the analysis the more profitable products have maximum productions and less / non-profitable products have minimum productions ensuring the optimal operation of the system at any market condition. The same procedure is followed for optimal network flowsheet in case of maximum market price scenario. The common features in both the scenarios are captured in the generalised flowsheet. For example, the appropriate design decisions are made for the streams that are always profitable or non-profitable at any market condition. The streams that are uncertain in terms of positive or negative profitability are determined for the market scenarios at which the individual stream becomes profitable to non-profitable or vice versa. Based on this the most appropriate production strategy for such streams is decided.

5. Conclusions

A systematic step-by-step analytical optimisation procedure has been proposed for conceptual optimisation of process networks. The methodology is conceived in consideration to exploit opportunities existing in both the market as well as in the site to the fullest extent. All such optimisation issues for large systems can give rise to highly complex non-linear discrete problems, beyond the solution capabilities of the currently available software. Instead, the proposed optimisation procedure uses analytical insights to integrate and optimise process networks. The procedure is built upon economic analysis at the basic stream and process level. First, a market integration strategy is employed that utilises all the available market opportunities for buying and purchasing of streams. Next, the network connections and processes are thoroughly analysed for process integration. The resulting network flowsheet includes the profitable connections and gets rid of the non-profitable connections. The opportunities in the existing infrastructure are fully exploited to result in an overall network integration.

6. Nomenclature

Process units set

$UNIT = \{i$ / process units$\}$

$DS\_UNIT = \{d\ (i \in UNIT)$ / downstream process units; $DS\_UNIT \subset UNIT\}$

$US\_UNIT = \{u\ (i \in UNIT)$ / upstream process units; $US\_UNIT \subset UNIT\}$

Elements set

$ED = \{e\ (i \in UNIT)$ / downstream elements of process unit $i\}$

$EU = \{e\ (i \in UNIT)$ / upstream elements to process unit $i\}$

Economic margin of units

Δ_i economic margin of process unit i

Δ_d economic margin of downstream process unit $d \in UNIT$ of unit i

Δ_u economic margin of upstream process unit $u \in UNIT$ of unit i

Flowrate of feeds

m^F_{e-i} flowrate of feed F_{e-i} to unit i from upstream element $e \in EU(i)$

Values of feeds

$(F_{e-i})_{COP}$ cost of production of feed F_{e-i} to unit i from upstream element $e \in EU(i)$

$(F_{e-i})_{MP}$ market price of feed F_{e-i} to unit i from upstream element $e \in EU(i)$

$(F_{e-i})_{VOP}$ value on processing of feed F_{e-i} to unit i from upstream element $e \in EU(i)$

7. References

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