Value Analysis of Industrial Systems

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Abstract

A generalised strategy for modelling and integration of an overall system is developed for the purpose of detailed economic analysis of industrial systems. The process industries today are facing severe challenges that lye in improvement in economic competitiveness, achieving a variety of the highest quality, the lowest cost and environmentally benign products from limited supply of low quality feedstocks. In such a constrained situation, a fundamental, practical and systematic methodology for a detailed and differential economic analysis of an industrial system at any market and environmental conditions can be very useful for achieving the optimal operations. This paper deals with industrial applications of the value analysis method by Sadhukhan (2002) for such an economic analysis of complex systems, e.g. refineries, petrochemical complexes, having a number of processing networks. Economic analysis of a system (Sadhukhan et al, 2003) establishes the economic performances of individual streams and processes with respect to the current system operation, network configuration and market situation. Such differential economic analysis of streams and processes can also provide the design basis for deriving the optimum network layout that achieves the maximum economic margin for the overall system (Sadhukhan et al, 2004).

Currently, LP optimisation provides the economic value structure of systems in terms of marginal value analysis (Hartmann, 1999) of streams. However, such an analysis is based upon fixed operating conditions and therefore it needs continuous update of process models and use of optimiser to evaluate the current most marginal values. The main drawback of LP lies in the restriction of use of any non-linear correlation while dealing with blending of streams and highly non-linear process operations. On the other hand, marginal values obtained from NLP and MINLP formulations (Grossmann and Daichendt, 1996; Grossmann et al, 1999) do not provide the transparency in the optimisation procedure to arrive at these values. Furthermore, for large systems such as refineries, petrochemicals, local optimal solutions from non-convex NLP and MINLP problem formulations, the marginal values can be misleading. The above discussions show the need for a more fundamental approach to economic analysis of industrial systems. This work aims to establish a complete economic analysis of such systems without the use of optimisation. It starts with determination of economics of small components (individual streams) in a system after which the complex overall system is addressed to represent its economics as the accumulation of economics of small components. Because the problem is large and complex can benefit most from the application of graph theory (Mah, 1983) using which the underlying mechanism of a network is described at the base level as a combination of paths and trees (elements) consisting of streams and processes.

The objective is to generate more precise economic models for basic streams, their production and processing elements and the overall system in various stages. For this reason an overall integration strategy (Sadhukhan et al, 2003) is developed 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 complex systems. The various network integration issues such as multiple feeds and multiple products of processes, recycle streams, use of rigorous simulation / non-linear process models, consideration of environmental regulations and market constraints are undertaken in order to generate a complete value structure for any complex system.

Broadly, there are four major stages to thoroughly analyse the economics of a system. The first stage is to develop the models for determining economic margins of individual streams that are integrated with the process level models. The stream economic models primarily convert the qualitative information on streams obtained from process yield models into quantitative measures for streams. The purpose of integration with the process level models is to estimate operating costs and product yields of processes and co-ordinate with the stream economic models in order to capture the impact of real plant operations in a stream's economic margin. In the second stage the economic margins of basic elements (paths and trees) of production and processing of streams are expressed as the marginal contributions of process units and integrated with the streams economic models. Thus, the marginal correlations of elements also make use of the process level models. In the third stage the problem is addressed at a higher level of complexity by integrating all the processing networks in addition to the major material and utility networks in a system and the effect of overall integration is captured in the economic analysis of streams and elements. These individual economic margins of streams and elements are finally correlated with the overall system economic margin in the centralised integrated system model that represents a system operation in totality. Industrial case studies on refining are used for practical demonstration at every stage of application of the methodology.

1. Economic modelling of streams

The stream economic model is used to predict the economic margin of a stream using the value and the cost of the stream. The value of a stream is its *value on processing* (VOP) in producing end products. This is calculated from the prices of end products subtracted by operating costs of units processing the stream (Eq. 1). The cost of a stream is its *cost of production* (COP) and calculated from the prices of feedstocks added with operating costs of units producing the stream (Eq. 2). The difference between the two (VOP minus COP) provides the specific economic margin achieved by the stream.

$$(F_{e\text{-}i})_{\mathrm{VOP}} = \Big[\sum_{e' \in ED(i)} (F_{e\text{-}i\text{-}e'})_{\mathrm{VOP}} \times m^{F}_{e-i-e'} + \sum_{p \in NP(i)} P_{e\text{-}i(p)} \times m^{P}_{e-i(p)}$$

$$- \widehat{o}_i\{\mathrm{Fe\text{-}i}, (\mathrm{Fe\text{-}i\text{-}e'}, e' \in ED(i)), (\mathrm{Pe\text{-}i}(p), p \in NP(i))\} \times \sum_{e \in EU(i)} m^{F}_{e-i} \Big] \Big/ \sum_{e \in EU(i)} m^{F}_{e-i}$$

$$\forall i \in UNIT,\ e \in EU(i) \qquad \text{(Eq. 1)}$$

$$(F_{e\text{-}i\text{-}e'})_{\mathrm{COP}} = (P_{e\text{-}i(p)})_{\mathrm{COP}} = (F_{e\text{-}i})_{\mathrm{COP}} + \widehat{o}_i(\mathrm{Fe\text{-}i}, \mathrm{Fe\text{-}i\text{-}e'}, \mathrm{Pe\text{-}i(p)})$$

$$\forall i \in UNIT,\ e \in EU(i),\ e' \in ED(i),\ p \in NP(i) \qquad \text{(Eq. 2)}$$

The unit operating cost, feed and product distribution are the variables with which the economic models for predicting VOP and COP of streams are integrated with the process level model.

2. Process modelling aspects for integration with stream economic models

The process level models are required to predict operating costs, yields and properties of products in terms of flow distributions and properties of feeds as used by the stream economic models. The product properties are required to verify whether they satisfy the property specifications (process and market constraints). All these constraints must be satisfied and therefore, stream economic models indirectly make use of the product property set calculated from the process models. For each process two types of models are developed, typical lumped models based on the bulk properties and flows of the *overall* feed and the models based on the individual feed components. The former type of model is required to represent the actual operation (taken into consideration in the centralised system model) whereas the latter is to differentiate among the economic contributions from individual feed components.

Eqs. 3 and 4 are for integrating the stream economic models / process level models with the economic models of network elements given by marginal contributions of process units present in the element in which the stream belongs to. All the process units that are somehow connected to the stream or in other words participating in the stream's production and processing contribute to the economic margin of the stream. The marginal contribution of a process unit towards the margin of a stream may not be full unless the unit processes no streams other than that particular stream, in which case the profit of the unit is presented without the stream's function (Eq. 3). In case of partial contributions of processes (e.g. Eq. 4) the marginal contributions of the processes towards the margin of a stream are represented as the stream's function.

$$\sum_{u \in U(i)} \Delta_u + \Delta_i + \Delta_j + \sum_{d \in D(i)} \Delta_d$$

$$= \{(F_{e\text{-}i\text{-}j})_{\mathrm{VOP}} - (F_{e\text{-}i\text{-}j})_{\mathrm{COP}}\} \times m^{F}_{e-i-j} \qquad \forall i, j \in UNIT,\ e \in EU(i) \qquad \text{(Eq. 3)}$$

$$\sum_{u\in U(i)} \Delta_u(\mathrm{Fe\text{-}i\text{-}j}) + \Delta_i(\mathrm{Fe\text{-}i\text{-}j}) + \Delta_j(\mathrm{Fe\text{-}i\text{-}j}) + \sum_{d\in D(i)} \Delta_d(\mathrm{Fe\text{-}i\text{-}j})$$
$$= \{(F_{e\text{-}i\text{-}j})_{\mathrm{VOP}} - (F_{e\text{-}i\text{-}j})_{\mathrm{COP}}\} \times m^{F}_{e-i-j} \qquad \forall i,\, j\in UNIT,\ e\in EU(i) \qquad \text{(Eq. 4)}$$

3. Strategies for overall integration of various processing networks

A large process network system (e.g. refining industry) has a number of streams other than major material streams (liquid hydrocarbons in refineries) forming various processing networks. In order to effectively analyse a system the overall integration of a system should be considered by taking account of complex interactions among all networks (Sadhukhan et al., 2003). Two important issues have been brought out for overall integration of networks for value analysis: 1) dealing with processes that take multiple feeds, 2) recycle streams. Two situations can arise in multiple feed processing. In the first situation, the feeds need to be processed together through a process unit and the unit can not be run on one feed at a time (e.g. chemical reactions). In such a case the primary feeds are considered as material streams whereas secondary feeds can be treated as utilities (contributing to operating costs) consumed in the unit. The COP of primary feeds may differ depending on their elements of production. In such a case COP of *overall* feed is evaluated from COP of its component feeds. The VOP can be evaluated for the *overall* feed using VOP of products. In such a case though the VOP of component feeds are the same their marginal contributions are different depending upon individual COP. In the second situation the feeds can be processed separately through a unit (e.g. unit operations). In such a case the feeds can be treated either as utilities (contributing to operating costs) or as material streams (giving rise to separate processing elements) inter-changeably according to user needs.

In order to analyse process networks with recycle streams tearing of recycle streams is carried out in order to treat a recycle stream separately at the point of production from the point consumption. Such internal streams resulting from a recycle stream are treated either as utilities or as material streams in separate elements same as before. For details of mathematical proof against the concept that a material stream can be treated as it is or as a utility interchangeably without any effect in the final economic analysis of systems the readers are advised to refer to the work by Sadhukhan et al, 2003.

4. Centralised integrated system model

The objective of developing the centralised system model is to represent a system in totality. The centralised model co-ordinates with the economic models of streams to estimate the economic margin for the overall system. The integrated system model also predicts the bulk properties of *overall* streams and therefore deals with the lump models of *overall* streams.

An overall system economic margin is given by the summation of economic margins of all its basic elements (paths and trees) or that of streams across a boundary (Sadhukhan et al, 2003). A boundary of a system is drawn in such a way so that the total flow of the inlet and the outlet streams across the boundary are equal to each other (material balance) and individually equal to the net mass in or out of the system. Such expression inherently captures all the cost and the benefit effects from the networks of material, utility and all other processing networks due to the consideration of overall network interactions.

In addition to the overall system economic margin, the bulk property set of overall streams at the inlet and the outlet of every process and the blending correlations are formulated (Sadhukhan and Zhu, 2002). The process constraints are imposed on the stream property set. The blended finished products are subjected to the market constraints imposed on the property set. In addition, there are market constraints on the minimum and the maximum production of products and availability of feeds. Similarly, for utilities there are constraints on purchasing and selling. This centralised integrated system model can also be used for conventional optimisation using NLP.

5. A case study on refinery

The methodology is applied to a refinery case study in Figure 1 for economic analysis of the overall system. The system comprises of 11 process units. The various networks that are to be considered for the overall integration are hydrogen, hydrogen sulphide and light gases networks in addition to the material and the utility networks. Hydrogen is treated as a utility for value analysis, considering its internal usage as the refinery fuel gas within the existing network. As sulphur and the light gases in the existing system are derived as refining products, hydrogen sulphide and light gases are treated as the material streams to explore the potential market opportunities.

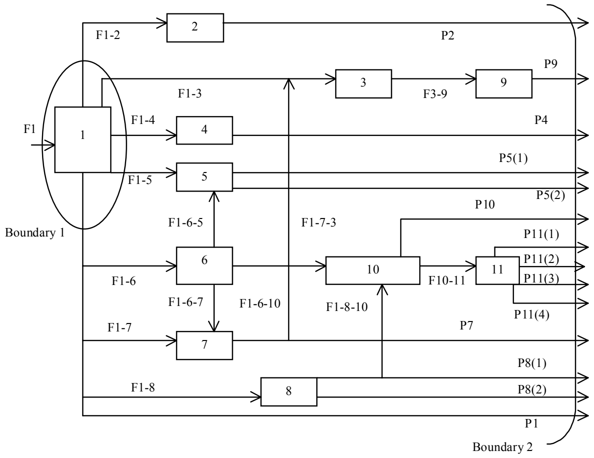

Figure 1. Refinery flowsheet under demonstration with boundaries shown.

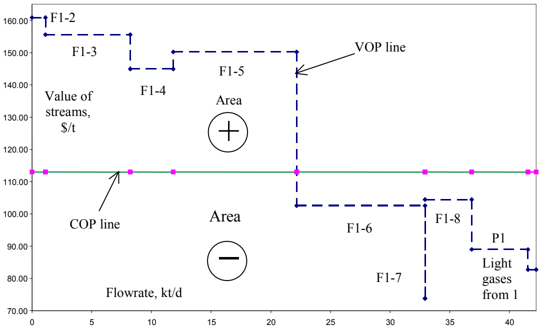

Figure 2. The network economic profile of the refinery across boundary 1 in Figure 1.

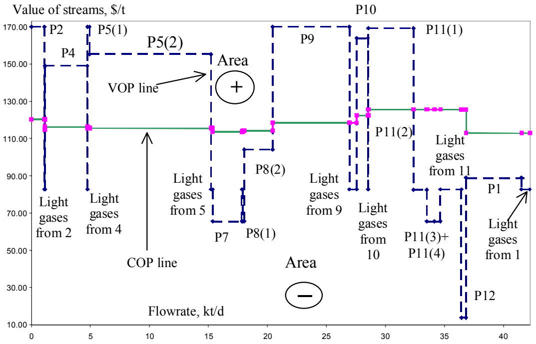

Figure 3. The network economic profile of the refinery across boundary 2 in Figure 1.

While developing marginal correlations between elements and streams, the effects of overall network interactions are captured in the marginal contributions of process units producing and processing streams. The derivation of marginal correlation of element of processing of the stream F1-6 (connecting units 1 and 6) (Eq. 5) is illustrated as follows. As the stream F1-6 is the total feed to unit 6 the entire margin of unit 6 is contributed towards the margin of its element of processing. The stream F1-6-5 is a product of the stream F1-6 from unit 6 and is one of the feeds to unit 5. Therefore, a marginal contribution from unit 5 for processing the stream F1-6-5 is present in the marginal correlation of the element of processing of the stream F1-6. Similarly, stream F1-6-10 is another product of the stream F1-6 consumed in units 10 and 11 through the streams F1-6-10 and F1-6-10-11 respectively. The remaining route of consumption of the stream F1-6 is through the product F1-6-7 to unit 7. The process units consuming this stream are 7, 3 and 9 through streams F1-6-7, F1-6-7-3 and F1-6-7-3-9 respectively.

$$\Delta_6 + \Delta_5\,(\text{F1-6-5}) + \Delta_{10}\,(\text{F1-6-10}) + \Delta_{11}\,(\text{F1-6-10-11}) + \Delta_7\,(\text{F1-6-7}) + \Delta_3\,(\text{F1-6-7-3}) + \Delta_9\,(\text{F1-6-7-3-9}) = \{(F_{1\text{-}6})_{\text{VOP}} - (F_{1\text{-}6})_{\text{COP}}\} \times m^{F}_{1-6} \qquad \text{(Eq. 5)}$$

The economic margins of various streams (calculated by multiplying the flowrate and the difference between VOP and COP of a stream) across boundaries 1 and 2 (Figure 1) are provided in Figures 2 and 3 respectively. The net positive area bounded between VOP and COP of streams in any of the Figures 2 and 3 provides the economic margin of the overall refinery. Thus, a network economic profile can be represented as collective marginal contributions of streams. The profitable streams are F1-2, F1-3, F1-4, F1-5 in Figure 2 and P2, P4, P5(1), P5(2), P9, P10, P11(1) in Figure 3. The non-profitable streams are F1-6, F1-7, F1-8, P1, light gases products in Figure 2 and P1, P7, P8(1), P8(2), P11(2), P11(3), P11(4), P12, all light gases from various units in Figure 3.

5. Conclusions

The approach for economic analysis of a system is simple and provides a transparent and complete set of economic values for all basic components and correlates these values with the overall system economic margin. The approach considers all possible effects of interactions among streams and processes and retains the overall integrity in the economic analysis. At the same time rigorous process models can be used to capture the effects of real plant operations in economic analysis. Even for complex systems such as refineries with many processing networks interacting in complicated ways, such economic analysis can be conveniently carried out by integrating the overall system while retaining the quality of models at process level. With the current optimisation techniques based on mathematical programming all these aspects are difficult to achieve.

6. Nomenclature

Process units set

$UNIT = \{i, j, k, l$ / process units$\}$

D = $\{d\ (i \in UNIT)$ / downstream process units of process unit $i\}$

U = $\{u\ (i \in UNIT)$ / downstream process units of process unit $i\}$

Elements set

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

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

End products set

$NP = \{p\ (i \in UNIT)$ / end products from process unit $i\}$

Economic margin of units

Δ_i	economic margin of process unit *i*
Δ_d	economic margin of downstream process unit $d \in D(i)$ of unit *i*
Δ_u	economic margin of upstream process unit $u \in U(i)$ of unit *i*
Δ_j	economic margin of process unit *j*

Values of streams

$(F_{e-i})_{COP}$	cost of production of feed Fe-i to unit *i* from upstream element $e \in EU(i)$
$(F_{e-i-e'})_{COP}$	cost of production of feed Fe-i-e’ to downstream element $e' \in ED(i)$ from unit *i* / element *e-i*
$(F_{e-i-j})_{COP}$	cost of production of feed Fe-i-j to unit *j* from unit *i* / element *e-i*
$(F_{e-i})_{VOP}$	value on processing of feed Fe-i to unit *i* from upstream element $e \in EU(i)$
$(F_{e-i-e'})_{VOP}$	value on processing of feed Fe-i-e’ to downstream element $e' \in ED(i)$ from unit *i* / element *e-i*
$(F_{e-i-j})_{VOP}$	value on processing of feed Fe-i-j to unit *j* from unit *i* / element *e-i*
$P_{e-i(p)}$	market price of end product Pe-i(p) from element *e-i*
$(P_{e-i(p)})_{COP}$	cost of production of end product Pe-i(p) from element *e-i*
$(P_{e-i(p)})_{VOP}$	value on processing of end product Pe-i(p) from element *e-i*

Flowrate of streams

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

$m^{F}_{e-i-e'}$	flowrate of feed Fe-i-e’ to downstream element *e’*∈*ED*(*i*) from unit *i* / element *e-i*
m^{F}_{e-i-j}	flowrate of feed Fe-i-j to unit *j* from unit *i* / element *e-i*
$m^{P}_{e-i(p)}$	flowrate of end product Pe-i(p) from element *e-i*
	Operating costs of process units
$\widehat{o}_{i}$	operating cost of process unit *i* per unit flowrate in terms of feed flow distributions and product yields

7. References

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