

Planning a Supply Chain with Risk and Environmental Objectives

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Abstract—The main objective of the current work is to introduce sustainability factors in optimizing the supply chain model for process industries. The supply chain models are normally based on purely economic considerations related to costs and profits. To account for sustainability, two additional factors have been introduced; environment and risk. A supply chain for an entire petroleum organization has been considered for implementing and testing the proposed optimization models. The environmental and risk factors were introduced as indicators reflecting the anticipated impact of the optimal production scenarios on sustainability. The aggregation method used in extending the single objective function to multi-objective function is proven to be quite effective in balancing the contribution of each objective term. The results indicate that introducing sustainability factor would slightly reduce the economic benefit while improving the environmental and risk reduction performances of the process industries.

Keywords—Supply chain, optimization, LP models, risk, environmental indicators, multi-objective.

I. INTRODUCTION

CRUDE oil is the basic valuable feedstock a large number of petroleum fractions and products that have added value caused by manufacturing and energy costs. Such products can be categorized as refinery, petrochemical, and chemical products. Refinery products range from light gases and naphtha to gasoline, diesel, and heavy fuel oils. Selected refinery feedstocks are then utilized to produce a variety of downstream chemicals and consumer products. Chemicals can be the standard industrial chemicals such as ammonia, acetone, ethylene, glycerol, etc., or specialty chemicals such as plastics, detergents, sulfates, pesticides, and so on. The structure of the upstream oil and gas industry together with the midstream refining industry and downstream chemical and petrochemical industries can be visualized as a supply chain (SC) of chemical conversion processes connecting the basic feedstock chemicals to the desired final products.

Mathematical models are effectively used in decision-making and planning the SC to deal with processing interactions. Their main objective is to select the optimal strategy for producing demanded products with minimum cost and best utilization of resources. Such models are purely economic in nature and ignore important factors such as environmental impacts and risk. However, incorporating these factors in planning models is not an easy task due to the

difficulties encountered in defining and quantifying the anticipated impacts.

In the current work, we propose a methodology for introducing environmental, economic, and risk factors in SC models. The method is based on defining a set of indicators that are commonly monitored by process industries. A multilayer SC model of a petroleum organization will be used in studying the effect of the newly introduced factors on the optimum production plans of the chain.

II. SC OF A PETROLEUM ORGANIZATION

The SC network that will be considered in this work is the one originally proposed by Al-Othman et al. [1]. It includes all upstream, midstream, and downstream components of a petroleum organization in an oil producing country. The SC, shown schematically in Fig. 1, starts from oil well production, spans to refining and petrochemical industry, and terminates at the markets and demand sources.

Crude oils produced from different locations are preprocessed, to stabilize them and remove associated gas and water, to meet the quality required for downstream operations. Produced crude may be categorized into different grades based on its “lightness” (based on specific gravity or API) and “sweetness” (based on amounts of impurities, mainly sulfur). Each grade has specific processing requirements and market demands. Part of the produced crude oil is exported to the international markets, while some quantities are processed in local refineries.

In the refineries, specific mixes of different grades of crude oil are processed in successive unit operations to produce demanded product slates. Typical refinery products include light components, naphtha, gasoline, kerosene, gasoil, and fuel oil. Light components such as ethylene and propylene are streamed to the petrochemical industry, while other refinery products are either exported or used locally. In turn, petrochemical plants are chemical processes that convert basic chemicals into industrial products that are used in further downstream industries to produce configured customer products. For instance, ethylene and propylene are produced from light hydrocarbons, which are further converted to polyethylene, polypropylene, poly-vinyl-chloride (PVC), and other products. Furthermore, naphtha from the refinery is used to produce a range of aromatics that are essential for a number of customer products such as detergents, paints, and textiles.

For the SC case study shown in Fig. 1, crude is gathered from ten locations (C_1 to C_{10}), categorized into three grades: light, medium, and heavy (P_{C1} , P_{C2} , and P_{C3}), exported to four crude demand sources (M_{C1} to M_{C4}), or processed in three

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local refineries (R_1 , R_2 , and R_3). The product slate of the refineries includes six refinery products (P_{R1} to P_{R6}), which are supplied to eleven demand sources (M_{R1} to M_{R11}). Furthermore, the proposed SC (Fig. 1) comprises two petrochemical plants (P_1 and P_2) and one downstream industry (D_1). The main feedstock of P_1 and P_2 are refinery products P_{R2} and P_{R6} , respectively. Two products are produced by from P_1 (P_{P1} and P_{P2}), and one product is produced by P_2 (P_{P3}). P_{P3} is forwarded to the downstream industry (D_1) to produce P_{D1} . Products of the petrochemical and downstream sectors are

demanded by three sources, M_{P1} to M_{P3} and M_{D1} to M_{D3} , respectively.

III. SUSTAINABILITY INDICATORS

Global developments focus on sustainability as an explicit goal. But, the concept has to be translated into the practical dimension of the real world to make it operational. Arnette et al. [2] provided an extensive review and analysis on the application of sustainability on SCs with its three dimensions; economics, environment, and society. Indicators for each one of these dimensions are defined in the following sections.

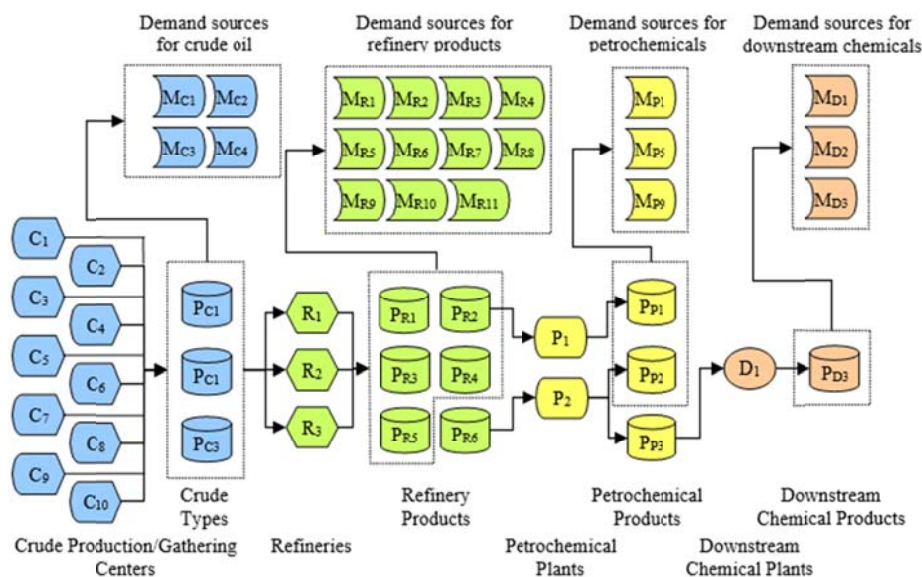


Fig. 1 SC network for a Petroleum Organization – case study [1]

A. Environmental Indicators

Environmental aspects include potential damage to local regional environment including humans. Over the last 30 years, there has been a very rapid growth in environmentally related legislation affecting the oil industry. The relation between the industry performance and the environment is complex and not fully understood; however, environmental regulations and indicators are widely used. Regulations now cover many aspects such as products, air and water quality, waste disposal, soil reclamation, noise abatement, and related matters. Environmental indicators cover global warming, photochemical oxidation potential, and ozone.

For the industry, the highly complex nature of environmental effects makes it difficult to link environmental and design calculations with either sufficient scope or detail. Also, the balance of recourse use as well as benefit is an individual and social judgment and is clearly difficult to quantify [3]. Some studies used the environmental concept in the design stage of a single process with relatively complex indicators (design stage of a single process with relatively complex indicators) [4]. Environmental life cycle assessment and indicators were reported by a number of researchers [5]-[10].

Environmental indicators are very useful to evaluate the impact of industrial activities. However, most of reported indicators are applicable for the specific industry and operating conditions for which they were defined. Hence, their generalization for other industries is difficult and not practical. For SC models, it is preferable that the indicators are as simple as possible and reflect the main activities and emissions related to the group of industries involved. Examples of simple indicators that can be used are CO_2 emission, total energy consumption, and weight waste per weight product [3], [11].

For the current study, the concept of introducing environmental indicators in SC models will be demonstrated using the CO_2 emission indicator as explained below.

B. Risk Indicators

Safety aspects include accidental risk causing major damage to humans or plant. Risk studies have to protect the people and the environment, as far as possible, from the dangers that can arise from an industrial plant. On the other hand, the application of risk concepts must avoid restricting production or increasing costs of these plants. Most of the chemical industries spend substantial budgets to ensure a healthy and safe working environment for their personnel.

Their efforts in this respect are regularly reported and in most cases in terms of quantitative indicators such as number of days without accidents or day lost work.

Safety and risk are usually included in the three components of sustainable development (environmental, economic, and social). For instance, human toxicity is considered in environmental indicators, expenditure on health is economical, and work satisfaction is included social aspects. Hutchins and Sutherland [12] considered safety as a representative social indicator together with labor equity, health care, and philanthropy. However, for a decision in industrial planning, safety or risk indicators should dominate over other social indicators.

The primary hazard in the oil industry is in the chemical inventory and usage. They may be considered as hazardous and present a primary risk whether they are in the form of raw materials, intermediates, or finished products [13]. Risk is basically the product of the incident probability and the magnitude of the harmful effects. Based on this definition, Al-Sharrah et al. [14] developed a simple risk index that can be applied to chemical plants. The index uses the properties of major chemicals associated with the production, and defined as:

$$K = Freq \times Haz \times Inv \times Size \quad (1)$$

where, $Freq$ = Frequency of accidents, number of accidents per process per year, Haz = Hazardous effect of a chemical, people affected per ton of released chemical, Inv = Inventory of chemical released, ton per accident, $Size$ = Size of plant, number of major processes in plant. Thus, the overall unit of the index K is people affected per year. The plant is assumed to have major processes in which chemicals are being treated, and an accident in any part of the plant may cause, in an extreme case, the release of the plant inventory. The proposed index was applied for risk analysis in a petrochemical plant [15]. Frequency of accidents ($Freq$) was derived from the historical chemical accidents database, and the hazardous effect (Haz) was correlated with the lethal dose of chemicals.

IV. SC OPTIMIZATION MODEL

The SC optimization model used in this work is the one developed by Al-Othman et al. [1]. The optimization model is a multi-period deterministic planning model developed for the entire SC of a petroleum organization. The SC consists of all activities related to crude oil production, processing, and distribution. Detailed description of the mathematical model is given in Al-Othman et al. [1].

The objective function is basically defined to maximize sales revenue and minimize total production and logistics costs, and penalize lost demands and backlogs.

$$Z_{eco} = \min \{C^C + C^R + C^P + C^{DSP}\} \quad (2)$$

Equation (2) consists of four cost categories; C^C , C^R , C^P , and C^{DSP} , corresponding to the four sectors of the petroleum

SC shown in Fig. 1. These sectors are: (a) crude oil production and distribution, (b) refining, (c) petrochemicals, and (d) down-stream petrochemicals, respectively.

A. Environmental and Risk Terms

A number of modifications have been introduced on the SC optimization model. Constraints were introduced to limit the minimum production rates of refining and petrochemical products. The constraints are necessary to prevent the model from recommending the closure of a plant when market prices are low, because it is unrealistic and not practical to shutdown re-operate chemical plants especially in short-time periods. Another modification is that the objective function (2) has been extended to multi-objective after adding environmental and risk indicators to present sustainability. Input data and economic parameters are the same as those used by Al-Othman et al. [1].

The environmental term added to the objective function account for CO₂ emissions from four sectors of the SC. Emissions are mainly from fuel consumption in the plants as well as shipping of end products to demand sources (downstream industries, different markets, and end users). Data for CO₂ emissions related to energy consumption have been obtained from two sources; EIA [16] and de Beer et al. [17]. Two parameters were defined; E_{m1} and E_{m2} to account for CO₂ emitted per production of refining and petrochemical products, respectively. Data related to amount of CO₂ emitted (in Kg) per distance to destination have been estimated as reported in Prpic-Orsic and Faltinsen [18].

The risk term has been introduced to the objective function in terms of people affected by chemical accidents, as represented by (1). Data needed for evaluating the risk term are mainly the number of people affected per tonne of specific chemical, and the inventories of chemicals at different stages of the SC [14].

Formulations of the environmental and risk terms which are defined in (3) and (4) are similar to the economic objective function defined in (2).

$$Z_{env} = \min \{E^C + E^R + E^P + E^{DSP}\} \quad (3)$$

$$Z_{risk} = \min \{R^C + R^R + R^P + R^{DSP}\} \quad (4)$$

where the components of (3) and (4) are defined as follows in (5) and (6):

$$E^C = \sum_{t \in T} \sum_{i \in PC} \sum_{j \in MC} \{F_{i,j,t}^C FCO2_j^C\} \quad (5a)$$

$$E^R = \sum_{t \in T} \sum_{k \in RF} \left\{ \sum_{h \in PC} CV_k^R VC_{h,k,t}^R Em_1 + \sum_{j \in MR} \sum_{i \in PR} \left\{ F_{i,j,k,t}^R FCO2_j^R \frac{1}{cap} \right\} \right\} \quad (5b)$$

$$E^P = \sum_{t \in T} \sum_{i \in PP} \left\{ \sum_{j \in MP} \left\{ V_{i,t}^P Em_2 \left\{ F_{i,j,t}^P FCO2_j^P \frac{1}{cap} \right\} \right\} \right\} \quad (5c)$$

$$E^{DSP} = \sum_{t \in T} \sum_{i \in DSP} \left\{ \sum_{j \in MDSP} \left\{ V_{i,t}^{DSP} Em_2 \left\{ F_{i,j,t}^{DSP} FCO2_j^{DSP} \frac{1}{cap} \right\} \right\} \right\} \quad (5d)$$

$$R^C = \sum_{t \in T} \sum_{i \in PC} S_{i,t}^C AP_i^C \quad (6a)$$

$$R^R = \sum_{t \in T} \sum_{k \in RF} \sum_{i \in PR} S_{i,k,t}^R AP_i^R \quad (6b)$$

$$R^P = \sum_{t \in T} \sum_{i \in PP} S_{i,t}^P AP_i^P \quad (6c)$$

$$R^{DSP} = \sum_{t \in T} \sum_{i \in DSP} S_{i,t}^{DSP} AP_i^{DSP} \quad (6d)$$

It is clear that the formulations of environmental and risk contributions to the objective function (3) and (4) have different level of details that makes the proposed model more realistic and overcome the shortcomings of other models.

The remaining task is aggregating the three objectives in a multi-objective optimization model that accounts for the contribution of each of the three terms, i.e. economic, environmental and risk. The weighted objective method was used in defining the sustainability objective function as:

$$Z_{sustainability} = \left\{ \frac{Z_{eco}}{f_{eco}^*} + \frac{Z_{env}}{f_{env}^*} + \frac{Z_{risk}}{f_{risk}^*} \right\} \quad (7)$$

In (7), the contribution of each objective is divided by a normalizing factors f_i^* . As shown below, the three normalizing factors are determined by individual solution of the single objective functions represented by (2)-(4).

V. RESULTS AND DISCUSSION

The SC optimization model is a linear programming model (LP) that consists of 2,969 equations and 8,681 variables. The model was solved using the General Algebraic Modeling System (GAMS) optimization package [20]. Optimal solutions were obtained at two levels. First single objective (SO) function models were solved to get the industry bounding structure. For the second level, the multi-objective (MO) model was solved in which the three cost terms, economic, environment and risk, were included.

To determine the normalizing factors, f_i^* , the three SO models were solved individually. The SO economic objective (2) resulted in an optimum cost of 10.55 billion USD per year,

which is considered comparable to values reported in similar studies [21]. The SO environmental objective (3) estimated environmental emission as 142.1-ton CO₂ per year, which is also comparable with results reported by Mallidis et al. [19]. The SO risk objective (4) was solved for two extreme cases. The first case assumed ideal SC where all products are either consumed in the downstream sectors or shipped. Obviously, for this case resulted in zero affected persons per year. On the other hand, for the second risk case assumed storage of all products before distribution to their final demands. The result was 128 people affected per year.

Results obtained from solving the MO problem (7) are now compared with those of the three SO models in Table I. When environmental and risk issues are considered, the economics reduced profit by 46% and 13%, respectively, but it resulted in 43% reduction in CO₂ emissions, and 100% less affected people. The results also show that the highest CO₂ emission is obtained for the SO risk case because storage of products is restricted, and shipments are the highest. The contrary is shown for the SO environmental objective because shipments are restricted while storages are encouraged, hence risk issues increased (Table I).

TABLE I
 COMPARING RESULTS OF THE SO AND MO OBJECTIVE FUNCTIONS

	SO		SO Risk	MO
	Economic	Environmental		
Profit (billion USD/yr)	10.55	5.73	9.19	8.05
Emission (tonCO ₂ /yr)	252.6	143.3	259.9	187.7
Affected People	9	65	0	3

Profitability contribution of each sector of the SC is compared in Table II. It is evident that the crude oil sector has the highest contribution to the overall profitability of the organization, for the results obtained from solving the SO models as well as the MO model. The contributions of the refining sector come second, while the rest two petrochemical sectors share similar minor contributions.

TABLE II
 COMPARING THE PERCENT PROFITABILITY CONTRIBUTION RESULTS OF DIFFERENT SC SECTORS

	SO		SO Risk	MO
	Economic	SO Environmental		
Crude oil	67.7%	75.0%	63.1%	72.1%
Refinery	29.2%	22.1%	35.5%	25.2%
Petrochemicals	1.7%	1.0%	1.0%	1.1%
DS Petrochemicals	1.4%	1.9%	0.4%	1.6%
Total profit (billion USD/yr)	10.55	6.08	9.19	8.02

Introducing environmental and risk factors affects also the planning results related to shipments and demands. The ratio of shipped products to their demanded quantities is shown in Fig. 2 for the four sectors. The plots illustrate that demands are not usually satisfied (ratio less than one), with the highest for the crude oil, followed by the refining products, while the petrochemical products which are very low meet the demanded amounts. It is clearly shown in Fig. 2 that the SO economic model resulted in the best fulfillment of demands

for all four sectors except for the refinery sector where the SO risk objective gave a higher fulfillment. The reason behind these results is that the refining sector has the highest number of products, which should be distributed directly to end demands to reduce storage and achieve optimum risk reductions. This observation demonstrates the strength of the proposed mathematical models and proves the effectiveness of the aggregation method used.

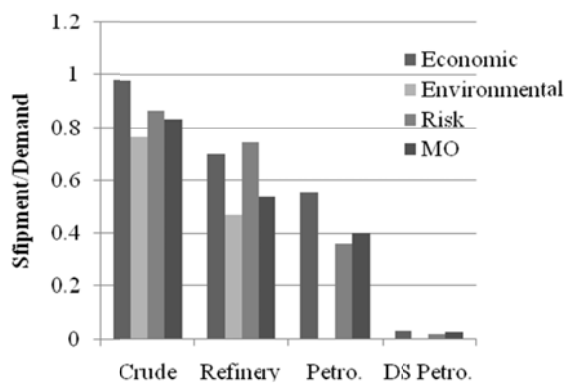


Fig. 2 Comparing shipment to demand ratio for different objectives

VI. CONCLUSIONS

Sustainability is increasingly becoming an important issue and concern that should be considered by process industries and particularly by the oil and gas industries. To respond to the challenges, industry must be able to measure its progress towards sustainable development. The indicators for sustainable development proposed in this work could be used for assessing the level of sustainability of a chemical SC and to support decision making. Decision making is concerned with the implementation of the optimal strategy for the overall performance taking into account the three aspects of the industry performance, namely economic, environmental, and risk. In proposing the indicators, the aim was to present relatively simple, informative and easily applied indicators with relevance to different aspects of sustainable development.

The selection of appropriate measures of economic, environmental, or risk performance for a process will depend on the level of the concerns, the type and quantity of information available and the degree of accuracy required in the representation with the possibility of combining simple with complex indicators. Data required for each index are different, and the produced results may vary. Different indicators are suitable for different stages of process development, design, and operation.

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