Supply Chain Risk Identification Using a HAZOP-Based Approach

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Risk management has become imperative for today's complex supply chains. Most approaches reported in the literature have been ad-hoc and specific to certain risks; a general and comprehensive approach is lacking. To address this, we present a structured methodology for risk identification. Supply chain networks are in many ways similar to chemical plants, therefore well-established methods and concepts from chemical process risk management can be adapted to supply chains. Drawing from this analogy, we propose to represent supply chain structure and operations using flow and workflow diagrams, equivalent to process flow diagrams (PFDs) and operating procedures. Following the HAZard and OPerability (HAZOP) analysis method common in process safety, risk identification can be performed by systematically generating deviations in different supply chain parameters and identifying their possible causes, consequences, safeguards, and mitigating actions. The application and benefits of the proposed approach are demonstrated using a refinery supply chain case study. © 2009 American Institute of Chemical Engineers *AIChE J,* 55: 1447–1463, 2009
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Introduction

A supply chain comprises all the entities and activities required to deliver final products to end-customers—encompassing procurement, transportation, storage, conversion, packaging, etc. A broad range of supporting services, such as sourcing, contracting, planning, scheduling, monitoring, and financing, are necessary to ensure that the supply chain performs smoothly and optimally—these are termed supply chain management. In a global survey of companies in both discrete and process industries, the median supply chain management cost was reported to be 10% of revenue[1]; however, the cost in the process-based industries could be as high as 30%.[2]

In recent years, due to increasing competition and tightening profit margins, companies have adopted a number of strategies to operate more efficiently and reduce supply chain costs. This is also reflected by the increased interest in the

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Table 1. Parallel Features of Chemical Plant and Supply Chain

Feature	Chemical Plant	Supply Chain
Entity	Unit operations: reactor, heat exchanger, storage tank, etc	Enterprises/business units: Supplier, manufacturer, logistics, etc
Flow	Material, energy	Material, information, finance
Input	Raw materials, energy, etc	Raw materials, finance, order, etc
Output	Products, waste, energy, etc	Products, finance, data, etc
Process	Reaction, separation, heat exchange, etc	Sourcing, production, sales, marketing, etc
Controller	Control systems: measurement, valve, etc	Supply chain entities: sales, storage, etc
Performance measures	Cycle time, throughput, capacity, quality, yield, flexibility, etc	Cycle time, capacity, costs, customer satisfaction, flexibility, etc

supply chain optimization area in literature.[3,4] In general, lower cost and higher efficiencies are accomplished through a globalized supply chain, higher capacity utilization, lower inventories, and just-in-time activities. However, there is a trade-off between efficiency and vulnerability. For instance, a survey by the Procurement Strategy Council reveals that 40% of large businesses rely on a single supplier.[5] Single sourcing decreases cost, but production continuity hinges upon the single supplier. Similarly, outsourcing leads to a more complex supply chain with more links exposed to a greater variety of disruptions. Sourcing from and distributing to other countries in other continents result in a globalized supply chain with exposure to new risks including political, cultural, and security risks. Just-in-time production and inventory reduction eliminate buffers which could be critical for business continuity when an unexpected strikes. Hence, there is a clear need for enterprises to manage supply chain risk and reduce vulnerability so that they can respond and recover from disruptions promptly and efficiently. However, a recent survey reveals that only 42% of businesses have corporate standards and practices for overseeing the mitigation of supply chain risk.[6]

A variety of adverse events, such as SARS, avian flu, terrorist attacks, tsunami, and Hurricane Katrina, have recently beleaguered organizations around the world. Risks arise because of the consequent uncertainties. Measures can be taken to reduce uncertainties but it is not possible to eliminate them altogether from the supply chain as they cannot be controlled by any one entity. Risk is defined as the potential negative impact that may arise from an adverse situation. In our context, the adverse situation is disruption to supply chain operations. This definition of risk includes, but is not limited to, financial risk, where it primarily refers to investment loss. Jüttner et al.[7] classify supply chain risk sources into three categories: environmental, network-related, and organizational. Environmental risk sources comprise any uncertainties arising from the supply chain–environment interaction, e.g., accidents, socio-political actions, and natural disasters. Network-related risk sources arise from interactions between organizations within the supply chain, e.g., outsourcing risks, distorted information, and lack of responsiveness to changing market signals. Organizational risk sources lie within the boundaries of the supply chain parties, e.g., labor strikes, machine failures, and IT-system disruptions. All these risk sources could lead to disruptions in the supply chain.

Disruption is defined as any event or situation that causes deviation from normal or planned supply chain operations. Disruptions bring about adverse effects such as blockage of material and information flow, loss of ability to deliver the right quantity of the right product to the right place and at the right time, inability to meet quality requirements, loss of cost efficiency, under- or over-supply, and process shutdown. All of these translate into financial losses, directly or indirectly. Hurricane Katrina disrupted operations of Chevron Oronite's lube additive plant in Belle Chasse, La. and tipped the marine lubricants industry into a crisis. In 2000, there was a fire accident at a Philips' chip plant in Albuquerque, New Mexico, disrupting supply of radio frequency chips to Ericsson. Slow in managing the supply disruption and securing alternate supplies, Ericsson consequently lost significant market share and eventually left the mobile handset market. It is reported that supply chain glitches negatively impacted stock prices by nearly 20%.[8] Another study reported that when chief financial officers (CFOs) and risk managers were asked what would cause the most disruption to the business, supply chain matters came second only to labor issues.[5] All of the above motivate the development of simulation models and decision support systems for managing risks and disruptions in the supply chain.

Risk management and disruption management are closely related. Risks are often measured in two dimensions–frequency and severity. Risk management aims to reduce either or both to acceptable levels by having proper safeguards and mitigating procedures which protect against the risks. Disruption management aims to minimize the impact of disruptions as they occur and restore the supply chain to normal operation as soon as possible. Having a reliable disruption management system will reduce the severity of the disruption when it strikes. Hence, disruption management can be viewed as a part of risk management, which is the subject of this article.

It is observed that supply chain operation shares common basic features with chemical process operation. Both are structured as a network of entities with flows among them. Both take in some input of raw materials and result in some output of products. Both operations should be optimized, controlled, and monitored continuously or continually. Table 1 maps several parallel features between a chemical process and a supply chain operation. Making use of this similarity, this article proposes to adapt methods from chemical process safety, hazard evaluation, and risk management to the supply chain domain. The former is a well-established area and many of the methods are widely-practiced and well-tested with much success. At the outset, this approach looks promising as one can easily see that, for example, having back-up pumps and dual sourcing share the same idea of redundancy. To study the efficacy of this idea, this article explores the feasibility of adopting the method of Hazard and Operability (HAZOP) study to supply chain risk identification.

Briefly, the supply chain risk management framework proposed in this article consists of the following steps in sequence: risk identification, consequence analysis, risk estimation, risk mitigation, risk assessment, and risk monitoring. This article focuses on the risk identification step. There are a number of methods commonly used for hazard identification in process plants, e.g., checklist, what-if analysis, concept hazard analysis, HAZOP, scenario-based, hazard index, etc. The HAZOP method is selected here because it is one of the most widely-used, structured, and comprehensive hazard identification techniques. The HAZOP study is done using a set of guidewords in combination with system parameters to seek deviations from design or planned intention. HAZOP has also been extended for environmental study (ENVOP).[9] A literature survey on supply chain risk and disruption management is presented next, followed by a discussion on the proposed risk management framework in the subsequent section. The application of HAZOP to supply chain risk identification is discussed in the next major section and illustrated by a refinery supply chain example in the following section.

Literature Review

Supply chain risk is one aspect of enterprise risk management, which can be broadly classified into market, credit, and operational risks.[10] Supply chain risk falls under operational risk. The methods for managing financial (market and credit) risks are not applicable to operational risks as the former are specific while the latter cover a diverse type with a wide scope. Operational risk mitigation begins with risk identification.[8] Two of the tools used in risk identification are risk checklist and risk taxonomy.[11] Risk checklist is a list of risks that were identified on previous projects, and often developed from managers' past in-house experience. The risk taxonomy provides a structure to organize the checklist of known enterprise risks into general classes. For example, enterprise risks are divided into internal processes and business environment. Each can be further classified, for instance, internal processes can be divided into financial, operational, and technological risks. Risk identification is performed by going through each item in the checklists and taxonomies and evaluating their applicability and implications in the situation at hand. The key strength of these methods is their flexibility, which makes them applicable to diverse situations. Two shortcomings arise from application of these methods to supply chain risk identification. First, they are rather ad-hoc and not systematic. Second, they are not tailored to supply chain and thus do not consider the complexity which arises from the interconnections among supply chain entities. Both of these lead to "blind spots" and unidentified risks.

The complex interactions among the constituent entities make the supply chain inherently vulnerable to disruptions. A disruption in the production side of a supplier can have implications for the web of transportation and logistics services that move material from one plant to another, and eventually propagate to final products delivered to customers. Similarly, disruptions in the information and communication technologies that support the supply chain operation can simultaneously propagate across the entire network rapidly. Such disruptions occur not only from disasters but also due to "normal" dynamics, such as limited capacity in a fast-growing industry, demand changes due to new competitors, or sudden loss of customer confidence. Supply chain risk management is therefore a growing research area[12] and continues to attract more attention, especially in the operations research, supply chain management, and logistics communities.[13]

Chopra and Sodhi[14] grouped supply chain risks into nine categories: disruptions, delays, systems, forecast, intellectual property, procurement, receivables, inventory, and capacity. Disruptions can be caused by terrorist attacks, natural disasters, and other physical events such as industrial accidents and labor strikes[15] or chemical, biological, radiological, and cyber events.[16] Management of low-probability, high-severity risks has also been termed as business continuity or disaster management.[17] Motivated by the events of September 11, 2001, Uygun et al.[18] developed tools to identify possible security problems in a chemical plant. Besides disruptions, which are more extreme, risks could also arise from day-to-day variability and uncertainties in the other eight categories above.

Risk identification could be done through "stress testing," i.e., identifying key suppliers, customers, plant capacity, distribution centers and shipping lanes, and asking "what if" questions to probe potential sources of risk and assess possible supply chain impacts.[14] Role-playing or "red-blue teaming" is a similar approach commonly used in the military.[19] In this approach, a Red Team generates a set of scenarios that they believe can lead to serious disruptions. The Blue Team attempts to provide mitigation or countermeasures against the scenarios. These methods suffer the same shortcomings of checklists and taxonomies, they are ad-hoc and not systematic.

There is some work on designing strategies to manage specific supply chain risks. Sheffi[20] proposes various strategies that companies can take to lower their vulnerability to disruptions and increase resilience. The limited ability to estimate the likelihood of specific disruptions means that significant management attention should be focused on general redundancy and flexibility measures. The author discusses how companies can reduce redundancy without increasing vulnerability by having inherently flexible supply chain designs that are demand-responsive. Reducing the number of parts and product variants allows aggregate forecasting, which is more accurate and creates inherent flexibility–inventory can be deployed to serve multiple products and markets. Other measures to build flexibility include interchangeability, postponement, and supplier and customer relations management. Elkins et al.[21] recommend best practices to enhance supply chain resiliency and risk management. These best practices derived from surveys of global companies cover four areas: strategic sourcing and advanced procurement, supply-base management, real-time operations management, and enterprise risk management/strategic supply

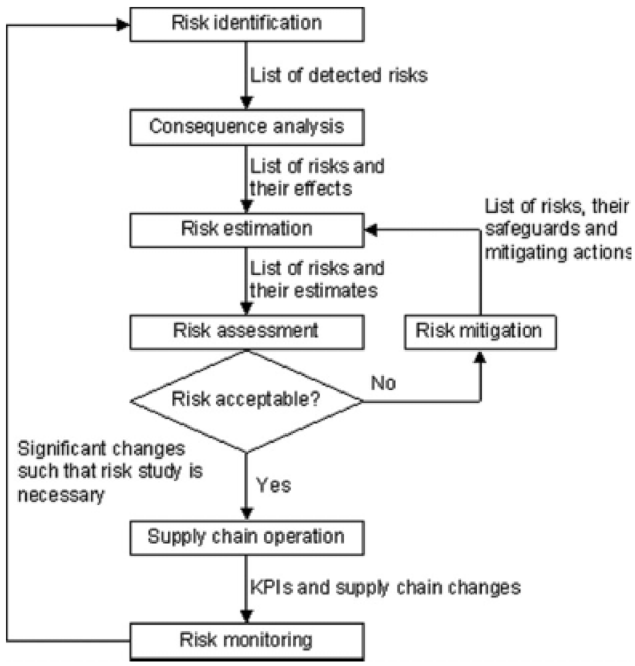

Figure 1. Proposed framework for supply chain risk management.

chain design. Kleindorfer and Van Wassenhove[19] propose strategies for coordinating supply and demand in the face of uncertainties. Uncertainties in production, transportation, and other variables could propagate through the supply chain leading to a lack of confidence in its overall operation. Christopher and Lee[22] suggest that this can be managed by improving visibility and control. The key to improved visibility is shared information among supply chain members which translates to less ‘‘just-in-case’’ safety stock. Control of supply chain operations is essential for improved confidence as information is useful only if necessary actions can be taken accordingly, for example, if a flexible production line can efficiently handle order changes once the information arrives. For such situations, analytical approaches, such as methods based on control theory, have also been proposed for dealing with demand uncertainty.[23,24]

From the above discussion, it is clear that numerous risks commonly bedevil supply chains. The existing literature does not provide a way to systematically identify risks. In this work, we propose a structured methodology based on a unified representation and cause-and-effect analysis.

Framework for Supply Chain Risk Management

The proposed framework for supply chain risk management is illustrated in Figure 1 and follows a structure similar to that for chemical plant risk management.[25,26] The study is best conducted by a team comprising of people from the different entities and functions involved in the supply chain. This ensures a more complete picture of the supply chain risks as seen from the different perspectives. The major steps to be conducted are:

1. *Risk identification*: The first step is to recognize uncertainties and possible sources of disruption to the supply chain operation, both internal and external. With globalization and increased outsourcing practices, the number of parties involved in the supply chain and the links connecting them have increased significantly. Hence, some risks may not be obvious and it is important to have a structured method for risk identification. The next section presents one such method.

2. *Consequence analysis*: Once the risks have been identified, their consequences have to be analyzed using an appropriate model of supply chain operations. The disruptions due to one particular risk or a combination can be simulated and consequences propagated through the supply chain model to identify all likely effects. In a complex supply chain, there could be important domino effects. These should be explicitly considered in the analysis.

3. *Risk estimation:* Risk is usually quantified in financial terms and/or ranked according to some pre-defined criteria. Two different dimensions need to be considered: its frequency/probability and its severity/consequence, taking into account the effects of mitigating actions and safeguards, if any. Methods from chemical process risk management can also be adopted here.

4. *Risk assessment:* The risk management team decides whether the risk quantified in the previous step is acceptable based on experience, industry standards, benchmarks, or business targets. If not, additional mitigation actions or safeguards are required.

5. *Risk mitigation:* Mitigating actions and safeguards such as emergency procedures and redundancies have to be developed, based on both the supply chain model and inputs from the risk management team or relevant supply chain personnel. Two types of mitigating action can be differentiated– preventive and responsive. Once the risks have been reduced to an acceptable level with the appropriate safeguards and mitigating actions in place, supply chain operations can proceed.

6. *Risk monitoring:* The supply chain structure and operation do not remain stationary but change regularly, for example due to changes in suppliers, regulations, operating policies, products, etc. The risk management team should continually monitor the supply chain for new risks. The entire analysis could be repeated when new risks arise from these changes.

This framework is comparable to the risk management process in Hallikas et al.[27] and Jüttner et al.[7] This article focuses on the risk identification step.

HAZOP-Based Method for Supply Chain Risk Identification

A variety of methods are used for hazard identification in process plants including checklists, what-if analysis, Failure Modes and Effects Analysis, scenario-based hazard identification, and HAZOP analysis. While it is possible to draw parallels of any of these to the supply chain context, this article takes HAZOP analysis as a starting point as it is the most widely used in the chemical industry.

A HAZOP study is a structured analysis of a system, process, or operation carried out by a multi-disciplinary team.[25,26] It is conducted when a detailed process description and a full design are available. Within the process industries, these come in the form of process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs), and plot plans. The team performs a line-by-line or stage-by-stage examination of the process using a set of guidewords (e.g., ''high,'' ''low,'' ''no'') in combination with the system parameters (e.g., ''temperature,'' ''flow,'' ''pressure'') to seek deviations from the design intention (e.g., ''high temperature in reactor A''). In a well-designed system, hazards arise only if there is a deviation from the design intent. Deviations can occur in either a component of the system or an interaction between the components. When a potential hazard or operability problem is found, the team uses their experience to study the possible causes and consequences. They then identify existing safeguards in the system which protect against the identified hazard and decide whether they are adequate. Design or operational changes may be triggered, if necessary, to eliminate the hazard or minimize its risk.

The advantages of HAZOP are apparent from the above description. The systematic procedure imbues completeness because the deviations studied are generated using predefined guidewords and pertinent system parameters. It is structured around a representation of the whole process in the form of PFDs or P&IDs. This contrasts with other methods such as checklists or ad-hoc scenario analysis that are based on experience. HAZOP is also a versatile approach, applicable in both the design stage and the operation stage of the system. It is best started at the earliest possible stage and can be repeatedly applied throughout the lifecycle. Because of these advantages, HAZOP is widely used not only for chemical processes but also for non-process systems such as software.[28] We therefore seek to extend HAZOP analysis to supply chain systems here.

The broad similarities between the structure and operation of supply chains and chemical plants that motivate this work can be best understood in the context of an example.

Example: Refinery supply chain operations

The refinery supply chain has many sub-processes such as crude procurement, planning, scheduling, oil trading, logistics, etc. At the center of this supply chain lies the refinery. Refining is a complex process which involves a number of operations to transform crude oil into valuable products. The refinery supply chain begins from the oil reservoirs, found most abundantly in the Middle East region, and tapped via both ground fields and offshore platforms. Transportation of the crude to various processing plants/refineries around the world is carried out mostly by large ships called Very Large Crude Carriers (VLCCs) or pipelines. Even with extensive networks and carefully planned schedules, transportation times are relatively long; it takes 4–6 weeks for a VLCC carrying crude oil from the Middle East to reach refineries in Asia. Such long periods make crude supplies easily susceptible to disruptions, leading to failure to meet customers' demands or a crude stock-out. This is a critical problem as it would compel unit shutdowns and result in large losses. A single crude mix allows numerous products and their variants to be produced through a suitable alteration of processing conditions. Accordingly, refineries must adapt their operations to the different crude batches to maintain the required product specifications, resulting in differing operating costs. Further, since crude oil prices, product demands and prices fluctuate highly, optimization needs to be done frequently. Other key features of the refinery supply chain are large inventories, need for safety-first, sensitivity to socio-political uncertainties, environmental regulations, and extensive trading. Hence, there is clearly a need for risk management in the refinery supply chain.

The supply chain operations considered in this example are crude procurement, delivery, storage, and refining in the refinery supply chain as presented in Julka et al.[29] These involve internal departments of the refinery, i.e., procurement, sales, operations, storage, and logistics, and external parties, i.e., oil exchange, oil suppliers, and 3PLs. Crude procurement is a complex activity involving multiple entities. The procurement department plays the key role in this process and liaises with the other departments: the sales department provides forecasted demand data; the operations department ensures operational constraints; the logistics department arranges the transportation of the crude with the 3PLs. Crude delivery and storage involve the logistics department, the 3PLs, and the storage department. Crude refining is primarily managed by the operations department, which interacts with the sales department and the storage department. For a more detailed description of the role that each entity plays and the exact steps of each process, the reader is referred to Julka et al.[29] We use this example to illustrate the proposed supply chain HAZOP approach. The starting point in any HAZOP study is a detailed and well-defined system description analogous to the PFD of the chemical plant. However, human action and decision-making also play a large part in the operation of supply chain. Thus, as in the batch process case, operating procedures also have to be considered. There are also elements that play the role of instrumentation, control, and supervision. Schemes for capturing and depicting the various elements in the supply chain and their interactions have therefore been developed as described in the next sections.

Supply chain representations

Like flows of material and energy in chemical processes, supply chains comprise at least three types of flows: material, information, and finance. Supply chain flows are often intermittent and not continuous. Also, supply chain entities usually perform multiple functions (e.g., taking orders, forecasting, negotiating, etc.). A supply chain is therefore more like a batch process than a continuous one. There are often multiple interactions among the same supply chain entities; hence there are more loops (especially in information flow) in supply chain operations. Asynchronous transfers with time delays and event-driven activities are other significant characteristics. To capture these complex interactions among the supply chain entities, this article proposes two interrelated representation schemes: (1) the *supply chain flow diagram* to represent structure, and (2) the *supply chain work-flow diagram* to represent operations. The former is the supply chain equivalent of a PFD and the latter of operating procedures. Each of these is described in detail next.

Supply chain flow diagram

The supply chain flow diagram (SCFD) provides a visual depiction of the *topology* of the supply chain. The diagram

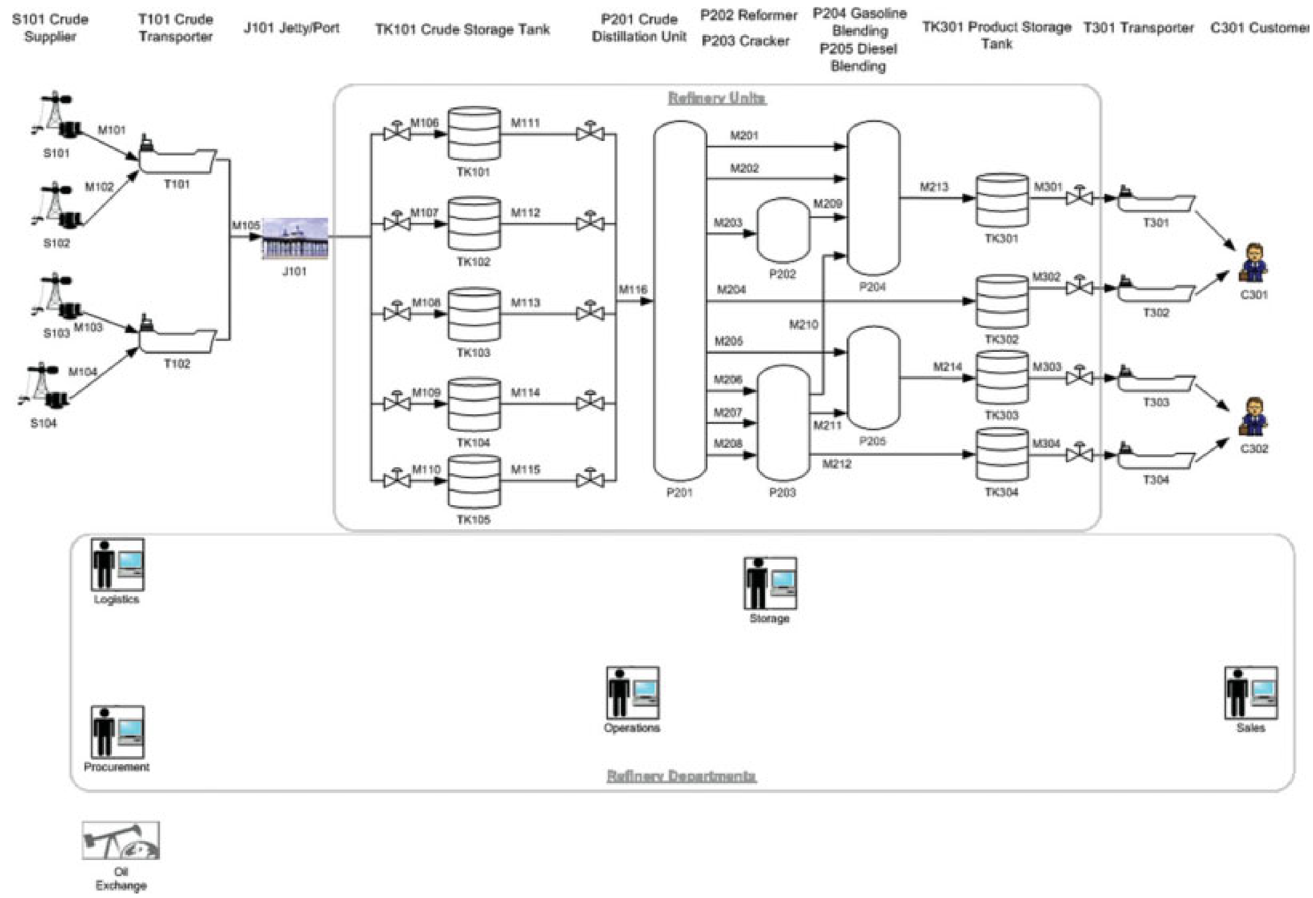

Figure 2. Entities and material flows in refinery supply chain flow diagram.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

shows the major *entities* participating in the supply chain and the connections (*flows*) between them. Figure 2 shows the entities and the *material flows* in the refinery SCFD. The structure of the refinery supply chain shown in Figure 2 includes entities such as suppliers, shippers, jetty, refinery, customers, and oil exchange. There are two types of entities in the SCFD: the *physical facilities*, which are used to physically store, transport, or transform material, and the *functional departments*, which manage the facilities and the flows. The former deal primarily with material flows whereas the latter with *information flows*. Entities which belong to the former are grouped together as refinery units and the latter as refinery departments. The refinery comprises three groups of physical equipment entities (crude storage, processing units, and product storage) and five functional departments (sales, procurement, logistics, operations, and storage). In this example, the SCFD is developed from the viewpoint of the refinery. The supplier, transporter, jetty, and customer are therefore shown as external entities. In reality, these external entities would also have different physical facilities and functional departments as sub-entities. However, these underlying sub-entities are not under the refinery's purview. Therefore, in this example, every external entity is abstracted into a single element dealing with both material and information flows.

In the SCFD, an entity is represented symbolically by ''icons'' that identify specific supply chain operations. External and physical equipment entities are identified by a number on the diagram, whereas functional department entities are labeled directly. A brief descriptive name for a corresponding entity number is included along the top of the diagram, roughly in the same horizontal location as the entity. The convention for numbering the entities is given in Table 2. As an example, consider the entity S101: **S**101 identifies the entity as a supplier, S101 indicates that this entity is dealing with raw material (crude), S101 means that

Table 2. Convention Used for Identifying Entity in Supply Chain Flow Diagram

General format XXYZZ	
XX are the identification letters for the entity type	
S	Supplier
T	Transporter
J	Jetty/port
TK	Storage tank
P	Processing unit
C	Customer
Y is the identification number for the material type the entity is dealing with	
1	Raw material
2	Intermediate
3	Product
ZZ is the number designation for each entity in the same group XXY	

Table 3. Parameters for Supply Chain Entities

Entity	Parameters
Supplier	Raw material type, Capacity, Lead time, Location, and Cost
Shipper	Capacity, Transportation time, Allowable waiting time, Allowable material type, Material type, and Cost
Jetty	Capacity, Transfer rate, and Cost
Storage	Capacity, Allowable material type, Material type, and Cost
Processing units	Capacity, Material input, Material output, Processing time, and Cost
Customer	Product type, Demand, Location, Due date, and Price
Functional departments	Policy type and Policy parameters

Table 4. Examples of Entity Summary Tables for (a) Supplier, (b) Storage tank, and (c) Procurement Department

(a) Supplier	
Entity ID	S101
Description	Supplier
Raw material type	Crude [C1 C2]
Supply capacity	[400 500] kbbl/week
Lead time	1 day
Transportation time	14 days
Cost	[65 68] $/bbl
(b) Storage Tank	
Entity ID	TK101
Description	Storage tank
Allowable material type	C1, C2, and C3
Material type	C1
Capacity	500 kbbl
Maintenance cost	$1/day
(c) Procurement Department	
Entity ID	Procurement
Policy type	Safety stock
Crude safety stock	100 kbbl

this entity is the first in the group of crude supplier entities. Each entity is further described by a number of important parameters, as summarized in Table 3. For example, a supplier is characterized by parameters such as raw material type, capacity, lead time, and cost. The detailed information on each entity in terms of these parameters is given in an *entity summary table*, such as Table 4.

Like a PFD, the SCFD also contains two types of supply chain flows: material and information, as shown in Figure 3. The former is depicted by a solid arrow and the latter a

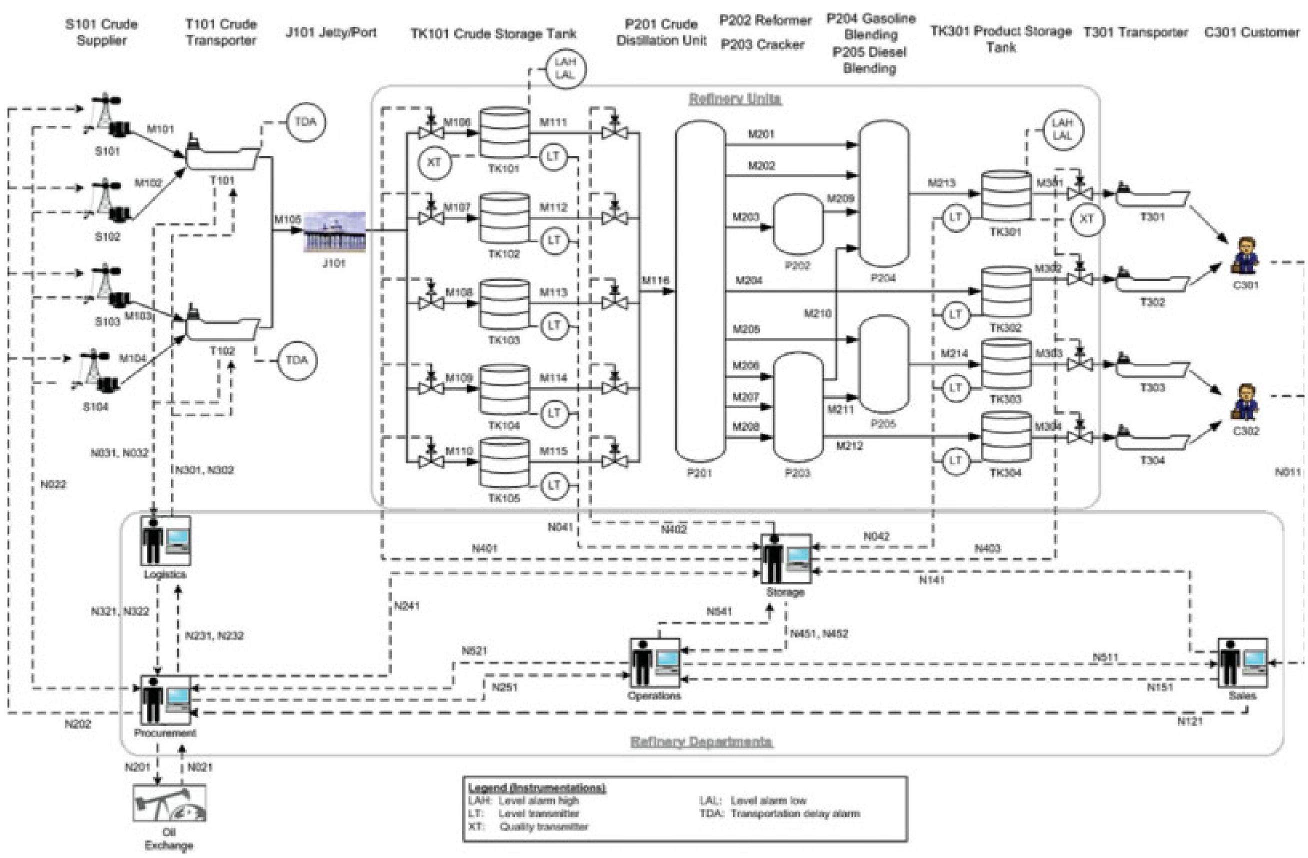

Figure 3. Refinery supply chain flow diagram with information flows.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Table 5. Convention Used for Identifying Flow in Supply Chain Flow Diagram

General format XYZZ for material flow and XYQZ for information flow	
X is the identification letter for the flow type	
M	Material
N	Information
Material flow XYZZ	
Y is the identification number for the material type	
1	Raw material
2	Intermediate
3	Product
ZZ is the number designation for each flow in the same group XY	
Information flow XYQZ	
Y and Q are the identification numbers for the source and destination of the flow, respectively	
1	Sales department
2	Procurement department
3	Logistics department
4	Storage department
5	Operations department
0	Others
Z is the number designation for each flow in the same group XYQ	

broken arrow. The arrow indicates the direction of the flow. Each flow is numbered using the convention in Table 5. For example, M110 identifies a specific flow of crude (material) and N121 identifies an information flow (from sales to procurement). The characteristics of the flows such as quality and quantity can be detailed in a *flow summary table*, indexed using the flow number. Table 6 shows examples of flow summary table.

The information flows control the material flows and capture the interactions among the functional departments. Analogous to control loops in the process, the amount of material flow from an entity is determined based on certain information, denoted by a controlled valve with a setpoint provided by an information flow. This setpoint variable is calculated based on a policy by the respective functional department, which may in turn require one or more measured variables as input. Measurements thus serve as inputs to policies; their causal flow is represented through information flows in the SCFD. Such information flows usually form the basis for control of material flows. For example, the storage department measures crude inventory levels (N041) and product inventory levels (N042). Both measurements are transferred to the operations department (N451, N452), which uses these along with production targets from the sales department (N151) to determine the operating throughput. An appropriate crude release request is subsequently sent to the storage department (N541) to release the corresponding crudes (N402). This is hence analogous to a flow control loop in a chemical plant, with the level transmitter LT equivalent to the sensor, the operations department as the controller, and the storage department as the final control element.

Based on the above discussion, the steps to derive the SCFD are as follows:

1. Identify and label the entities: external entities, physical facilities, functional departments
2. Identify and label the materials that flow between the entities
3. Identify and label the information flows which control the material flows and the interactions among the functional departments
4. Identify measurements and alarms
5. Fill in the detailed specifications of the entities and flows in the summary tables
6. When changes occur in the supply chain structure or operations, update the entity and flow summary tables to reflect the new situation, e.g., additional storage capacity, new policy parameter, new crude types, etc.

In summary, the SCFD comprises three components: supply chain topology, entity information, and flow information. It shows how the supply chain moves material from suppliers to customers, converting raw materials to products in the process and the controls involved. The advantage of the SCFD is that it allows us to get a complete picture of the supply chain structure and the entity interactions. While the SCFD shows the overall supply chain structure and overview of the material and information flows, the dynamics of the supply chain operations can be understood only when the activities of the functional departments are also considered in detail.

Supply chain work-flow diagram

The work-flow diagram (WFD) describes the sequence of tasks performed by a functional entity. An entity can perform one or more activities, each of which comprises one or more tasks. Different activities are represented in different threads in the WFD. Each entity involved in the supply chain operations has its own WFD. Figure 4 shows the work-flow of an entity which has two major activities, represented by the two threads. An activity is performed when

Table 6. Examples of Flow Summary Table for (a) Raw Material, (b) Product Material, and (c) Information

(a) Raw Material	
Flow Number	M101
Type	Material
Content	Crude C1
Quantity	200 kbbl
Quality	Specific Gravity = 1.2576 Sulfur = 0.0020 Viscosity = 71.7767
Source	S101
Destination	T101
(b) Product Material	
Flow Number	M301
Type	Material
Content	Gasoline
Quantity	300 kbbl
Quality	Octane Number = 95.1 Specific Gravity = 0.719 Reid Vapor Pressure = 6.0 psi
Source	TK301
Destination	T301
(c) Information	
Flow Number	N121
Type	Information
Content	Demand forecast
Quantity	[600 140 420 270] kbbl
Due date	Day 28
Source	Sales
Destination	Procurement

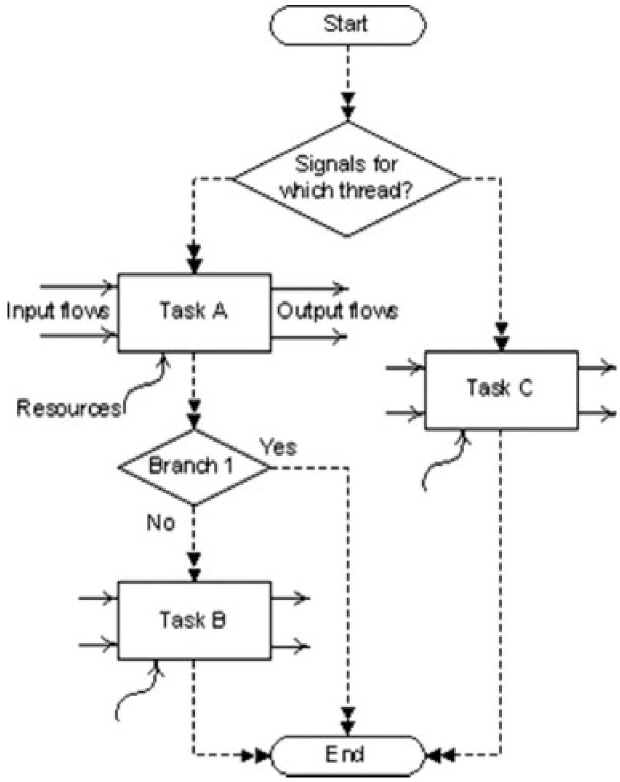

Figure 4. Structure of a work-flow diagram.

the entity receives a signal corresponding to the thread of that activity. The first activity involves Task A and, if the condition in Branch 1 is not satisfied, Task B; the second activity involves only Task C. Each task requires some resources, could take in some input flows and result in some output flows. In contrast to flows, resources reside in the entities for longer time scales, e.g., manpower, equipment, etc. For example, a task of receiving and recording order takes in the order data (customer name, product type, amount, date, etc.) as input flow from a customer, requires an order management system as resource, and provides order receipt confirmation as output flow to the same customer.

WFDs of different entities are interconnected by the input and output flows across tasks of different entities or by common resources used by multiple entities. The connection between the SCFD and the WFDs is established through the flows which are identified by the same labels in both diagrams. The level of detail required in the WFD depends on the purpose at hand. The WFDs can be validated by tracing the exchange of flows and the common resources. They should be consistent with the overall material and information flow in the supply chain, which are captured in the SCFD.

The steps to derive the WFD are as follows:

1. Identify activities performed by each entity
2. Identify sequence of tasks in each activity
3. Identify input flows (and their corresponding source) required in each task
4. Identify resources required in each task
5. Identify resulting output flows (and their corresponding destination) from each task

Figures 5 to 9 show the WFDs of the sales, procurement, logistics, storage, and operations departments in the refinery, respectively. The sales department (Figure 5) performs three activities as represented by the three threads, each with its own signal. The first thread is related to forecasting demand, the second to setting daily production targets, and the third to updating product database. The second task in the first thread, ‘‘Send forecasted prices and demands,’’ provides market data as an output information flow to the procurement department. This becomes an input flow to the first task in the first thread of the procurement department (Figure 6), ‘‘Receive market data.’’ Similarly, the second task in the second thread, ‘‘Send production targets,’’ provides an output flow to the operations department (Figure 9). The interconnections across different entities are thus explicitly captured in the WFDs. Such interconnections across WFDs of different entities underscore the complexity of the supply chain operation.

Supply chain HAZOP analysis

Once the SCFD and WFDs are available for a supply chain, risks can be systematically identified using a HAZOP-study-like structure. The *SC-HAZOP* should be conducted by a team ideally comprising members from the various entities and led by a risk specialist. The SC-HAZOP study can be performed on the SCFD, comparable to HAZOP analysis for continuous plants,[25,26] and on the WFDs, comparable to the analysis for batch processes.[30,31] Risk identification is performed by systematically generating deviations in different supply chain parameters, and identifying their possible causes, consequences, safeguards, and mitigating actions. The study begins by taking one part of the SCFD, selecting a particular entity or flow, and a particular parameter from the entity or flow summary table. The parameter to be studied can also come from a particular entity’s WFD in the form of tasks, flows, or resources. The deviations are generated using a set of guidewords in combination with these parameters. Tables 7 and 8 give a list of guidewords and parameters. The guidewords are combined with the parameters to seek deviations from the design intent or normal operation. For example, the guideword ‘‘High’’ can be combined with the parameter ‘‘quantity’’ of the material flow M105 (crude flow from ship to jetty in Figure 3) to get ‘‘High quantity of crude flow from ship to jetty’’ or ‘‘High crude unloading’’ in short. In the WFD, the guideword ‘‘No’’ can be combined with a resource to result in the deviation ‘‘No order management system.’’ Similarly, the guideword ‘‘Late’’ can be combined with a task to result in the deviation ‘‘Late in sending products to customer.’’

After generating the deviation, the team proceeds to identify its possible causes, consequences, existing safeguards, and propose possible mitigating actions. Causes and consequences can be identified by tracing the flows in the SCFD, or the sequence of tasks and the exchange of flows between tasks across different departments’ WFD. In general, possible causes are identified by tracing backward and possible consequences by tracing forward, as far as the extent of the diagrams allows. In some cases, it is possible to have the consequence upstream from the cause, for example high inventory in a crude tank resulting in a longer waiting time for

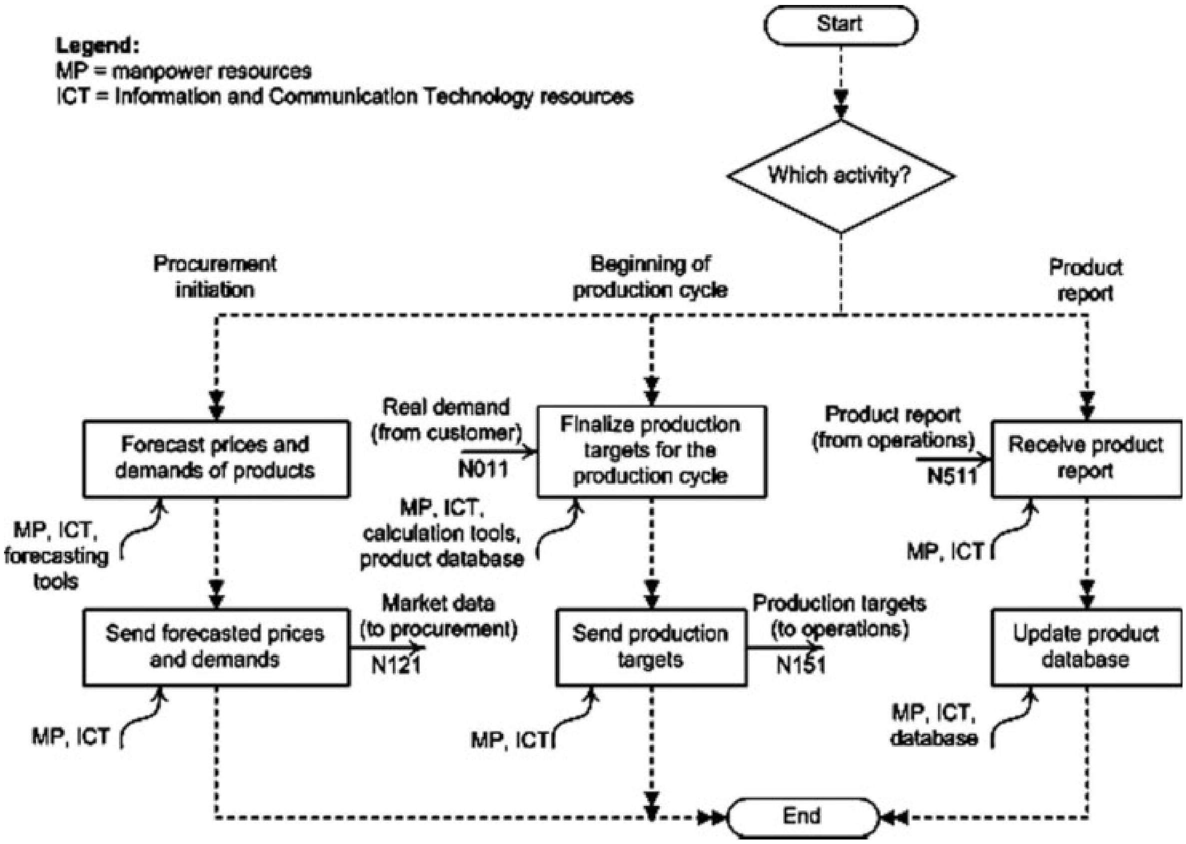

Figure 5. Work-flow diagram of the sales department during crude procurement, delivery, storage, and processing.

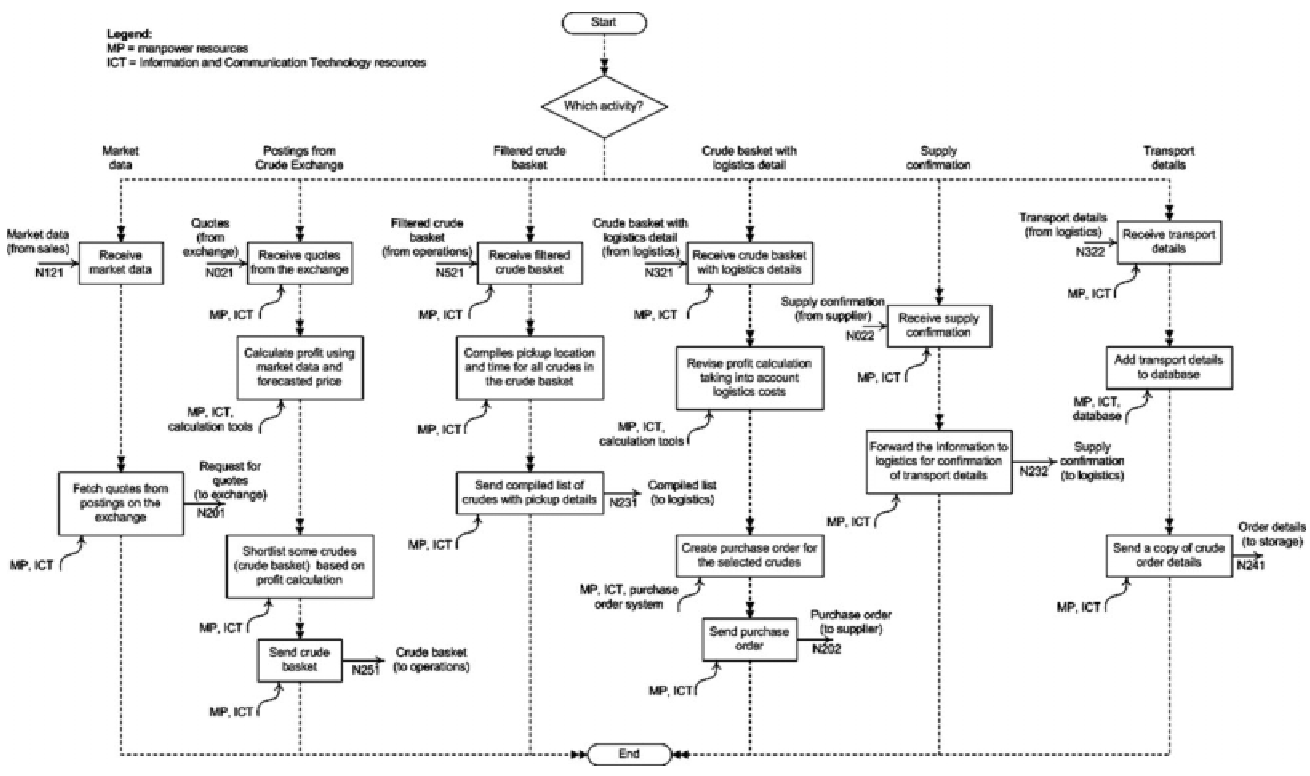

Figure 6. Work-flow diagram of the procurement department during crude procurement, delivery, storage, and processing.

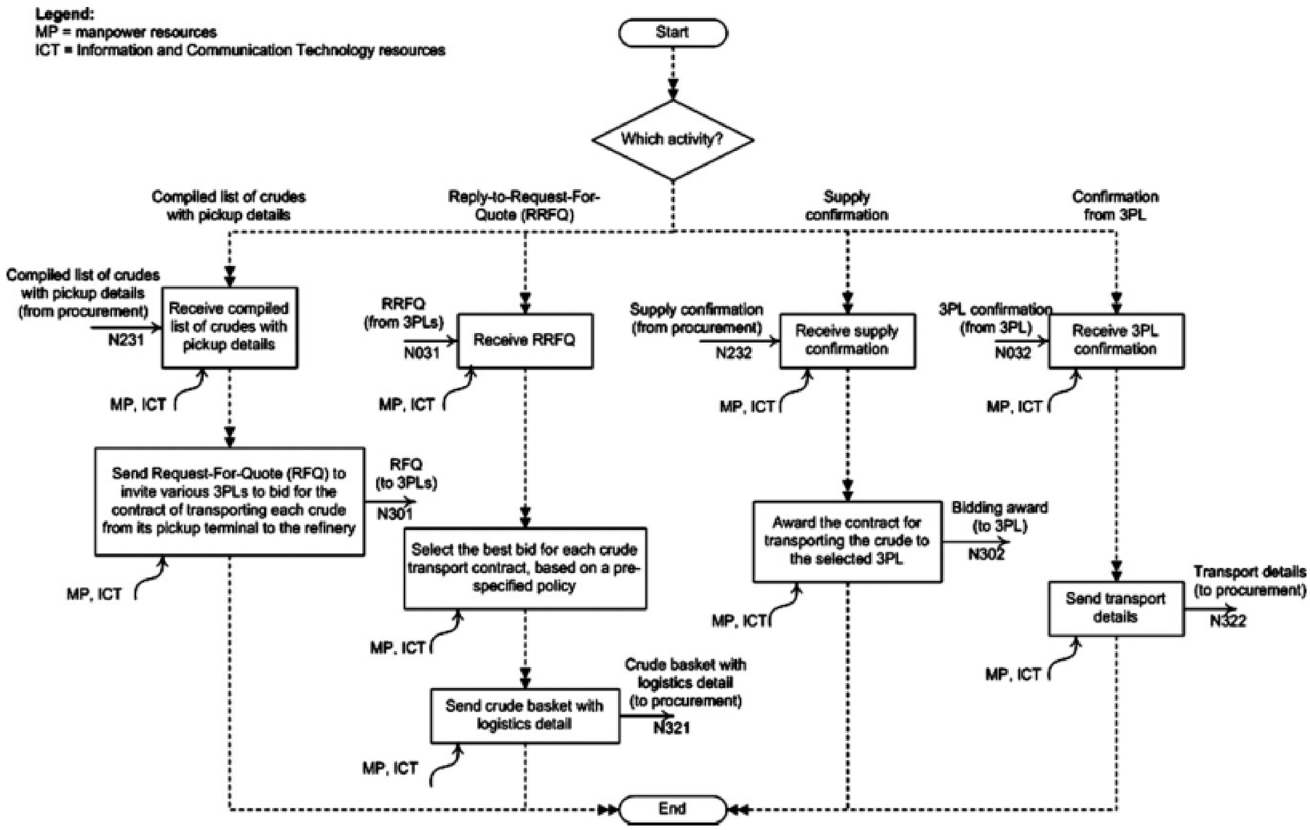

Figure 7. Work-flow diagram of the logistics department during crude procurement, delivery, storage, and processing.

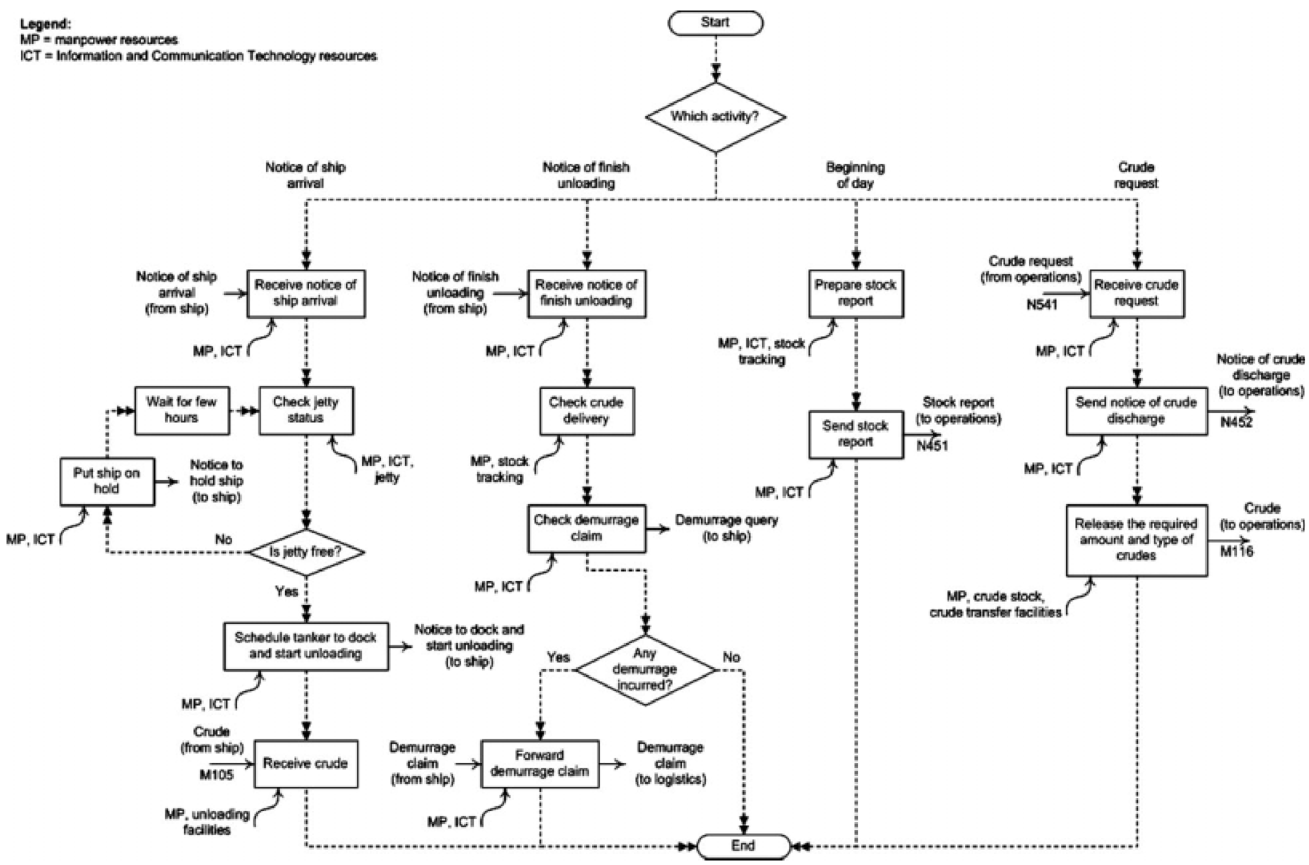

Figure 8. Work-flow diagram of the storage department during crude procurement, delivery, storage, and processing.

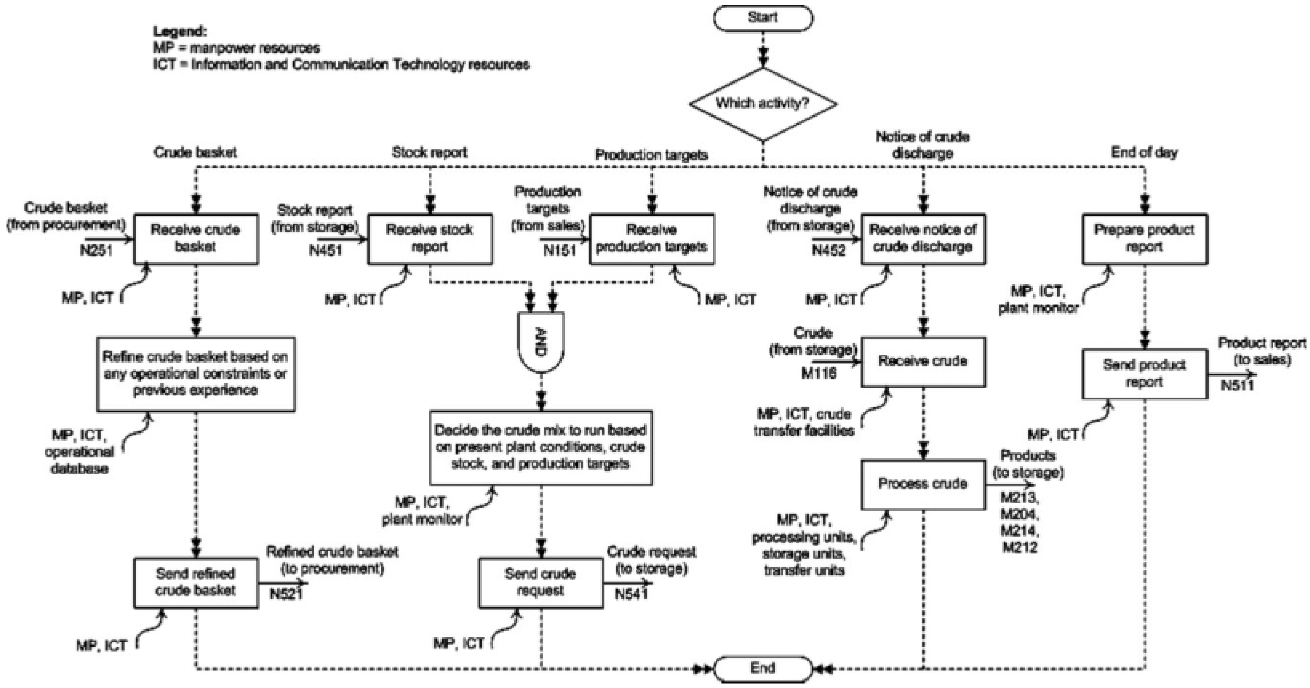

Figure 9. Work-flow diagram of the operations department during crude procurement, delivery, storage, and processing.

a ship (that is upstream of the tank) until sufficient ullage is available for unloading. A deviation can lead to further deviations downstream, thus multiple deviations can have common causes and consequences.

Safeguards are any items or procedures which help to protect against a particular deviation. It could protect against the deviation before it occurs, i.e., reducing the frequency, or help to recover quickly and minimize impact after it occurs, i.e., reducing the severity. An example of the former is safety stock, which protects against demand uncertainty; an example of the latter is insurance, which compensates for the damage suffered from a disruption. Mitigating actions are additional items or procedures on top of any existing safeguards which are deemed necessary to manage the deviation. These may include adding safeguards to reduce the risk and preparing response strategies should the risk materialize. For managing risk, it is useful to think of safeguards and mitigating actions in three categories: hardware, software, and humanware. Hardware means the engineering and technical equipment and tools, software includes the systems and procedures, and humanware refers to the risk culture of the people. Comprehensive risk management strategies should include all three categories.

Once the team has identified the causes, consequences, safeguards, and mitigating actions for the current deviation, they proceed to the next deviation. After all deviations from that part of the SCFD have been looked into, they continue to another part of the SCFD or another WFD. Thus, we can clearly see the strengths of the SC-HAZOP method for risk identification. It is exhaustive since any deviation can be captured as long as they are contained within the diagrams. It is also systematic and structured as the study follows a well-defined procedure involving predefined guidewords, system parameters, and cause-effect relationships implicit in the diagrams. We illustrate the proposed scheme in the next section using the refinery supply chain example.

Table 7. Typical Guidewords for SC-HAZOP Risk Identification (Adapted From Crawley and Tyler)[26]

Guide Word	Meaning
No	None of the design intent is achieved
High	Quantitative increase in a parameter
Low	Quantitative decrease in a parameter
As well as	An additional activity occurs
Part of	Only some of the design intention is achieved
Other than	Complete substitution, different from design intent
Before/after	The step is effected out of sequence
Early/late	The timing is different from the intention
Faster/slower	The step is not done at the right rate

Table 8. Sample Parameters for SC-HAZOP Risk Identification

Class	Example
Material flow	Raw material, side product, energy, utility, etc
Information flow	Order, quote, forecast, message, signal for action, etc
Finance flow	Cash, credit, share, receivables, pledge, contract, etc
Resource	Equipment, manpower, etc
Task	Putting order, monitoring, transporting, reporting, etc

Table 9. SC-HAZOP Results for Material Flow M105 "Crude Unloading"

Deviation	Causes	Consequences	Safeguards	Mitigating Actions
No crude unloading [M105]	Supplier stock-out; Shipper disruption; Jetty unavailability; Problem with unloading facilities; No ullage in crude tank	Low crude stock, out-of-crude; Operations disrupted; Low product inventory; Demand unfulfilled	Emergency suppliers; Transportation delay alarm [TDA]; Crude tank low level alarm [LAL]; Crude safety stock; Product safety stock	Frequent check with supplier /logistics about ship arrival time; More reliable shipper; Regular maintenance of unloading facilities; Rescheduling of operations
Low crude unloading [M105]	Miscommunication with supplier; Low crude loaded into ship; Leak from ship during sailing; Problem with unloading facilities; No ullage in crude tank	Low crude stock, out-of-crude; Operations disrupted; Low product inventory; Demand unfulfilled	Emergency suppliers; Crude tank low level alarm [LAL]; Crude safety stock; Product safety stock	Regular maintenance of unloading facilities; Rescheduling of operations; Add "Final check with supplier before delivery" to work-flow of procurement
High crude unloading [M105]	Miscommunication with supplier; High crude loaded into ship	High crude stock; No ullage, next ship has to wait; Demurrage incurred	Tank capacity; Crude tank high level alarm [LAH]	Add "Final check with supplier before delivery" to work-flow of procurement
Early crude unloading [M105]	Miscommunication with supplier/shipper; Shipper's problem; Early ship arrival	No ullage, ship has to wait	Tank capacity; Crude tank high level alarm [LAH]	Add "Final check with supplier before delivery" to work-flow of procurement; Add "Final check with shipper" to work-flow of logistics
Late crude unloading [M105]	Supplier stock-out; Shipper disruption; Jetty unavailability; Problem with unloading facilities; No ullage in crude tank	Low crude stock, out-of-crude; Operations disrupted; Low product inventory; Demand unfulfilled	Emergency suppliers; Transportation delay alarm [TDA]; Crude tank low level alarm [LAL]; Crude safety stock; Product safety stock	Frequent check with supplier /logistics about ship arrival time; More reliable shipper; Rescheduling of operations
Wrong crude unloading (other than) [M105]	Supplier's mistake; Miscommunication with supplier; Water get in during travel	Crude storage problem; Plant operation disrupted	Crude tank quality transmitter [XT] (i.e., laboratory check)	Add "Final check with supplier before delivery" to work-flow of procurement

Case Study: Risk Identification in a Refinery Supply Chain

The SCFD for the refinery SC is given in Figure 3 and the WFDs for the five refinery departments are shown in Figures 5–9. The team is currently studying the part around the jetty in the SCFD. They are considering the crude unloading flow, which is the material flow from the ship to the jetty (M105) in Figure 3. Combining the quantity parameter of this flow with the guideword "No" derives the deviation "No crude unloading." One possible cause of this deviation is the jetty or the unloading facilities are unavailable. To study other possible causes, they trace backward from the crude unloading flow and find the shipper and supplier entities. "No crude unloading" could also be caused by shipper unreliability or supplier stock-out. As previously mentioned, it is also possible to have causes upstream. Tracing forward from the crude unloading flow, "No crude unloading" could be caused by unavailability of ullage in the crude tank. The possible consequences can be examined by tracing forward from the crude unloading flow, from which they identify low inventory in the crude tanks, possible out-of-crude situation which leads to operation being disrupted, low inventory in the product tanks, low product shipment to customers, and unfulfilled demand.

The safeguards for this deviation are the availability of emergency suppliers in case of supplier stock-out, transportation delay alarm that could notify plant personnel of any ship arrival delay as soon as it becomes known, crude tank low level alarm that gives a warning when crude inventory is low, crude safety stock, and product safety stock. Because shipper unreliability is one possible cause, a suitable mitigating action could be to consider engaging a more reliable shipper. Other mitigating actions include establishing better communication and transparency with suppliers and shippers for timely notice of any delay, regular maintenance of unloading facilities, and rescheduling to avoid shutdown by reducing throughput until the crude arrives.

The team then proceeds to the next guideword "Low" and studies the deviation "Low crude unloading." Again tracing

Table 10. Illustrative Results of SC-HAZOP Study Conducted Using the Work-Flow Diagram

No	Task	Deviation	Causess	Consequences	Safeguards	Mitigating Actions
1	Sales: Provides present and forecasted product prices and demands.					
1.1	Send production targets	High production target [N151]	Miscalculation; High demand	High crude request; High product inventory; Unfulfilled demand; Lost opportunity; Unsatisfied customer	CDU capacity; Crude safety stock; Product safety stock	Double-check calculations; Add CDU capacity, add units; Negotiate delivery date, prioritize customer
1.2	Forecast prices and demands of products	Rush order (early) [N011]	–	High production target; Unfulfilled demand; Lost opportunity; Unsatisfied customer	CDU capacity; Crude safety stock; Product safety stock	Emergency supplier; Come up with new business process for rush order (<3 days to fulfil)
2	Procurement: Coordinates the crude procurement process.					
2.1	Receive market data	No ICT for task "Receive notice of arrival"	Hardware/software problem	Procurement process delayed, higher forecast inaccuracy	Backup ICT facilities	Regular maintenance of ICT facilities and backups
3	Logistics: Arranges the transport of crude from the oil supplier terminal to the refinery.					
3.1	Any	No manpower	Employee callsin sick	Tasks cannot be performed or performed insufficiently	–	Review standby policy; Train backup personnel
4	Storage: Manages the tank farm and schedule the jetties.					
4.1	Receive crude	High crude delivery from ship [M105]	Supplier's mistake; Miscommunication with supplier	No storage space, ship has to wait; Demurrage incurred	Tank capacity; Crude tank high level alarm [LAH]	Add "Final check with supplier before delivery" to work-flow of procurement
4.2	Release crude	Other crude type discharge to operations [M116]	Wrong report of crude type; Human error	Plant operation disrupted; Product inventory problem	Crude tank quality transmitter [XT]	Check crude type before connecting; More frequent lab sampling
4.3	Check jetty status	Before check jetty status, schedule ship to dock	Human error	If jetty is not free, unloading delayed and demurrage incurred	Clear operating procedures	Training of personnel
5	Operations: decides which crudes, how much to process, and various operating conditions for the daily refining process.					
5.1	Process crude	No transfer facilities [M116]	Pump problem	Plant operation disrupted	Backup pump	Backup equipment
5.2	Process crude	Product off-spec (other than)	Process control problem	Product returned by customer; Product inventory problem	Product tank quality transmitter [XT]	Downgrading, reprocessing
5.3	Send product report	Wrong product report (other than)	Human error	Delivery ship has to wait, demurrage incurred; Customer unhappy	–	Double-checking procedure in generating product report

backward to the shipper and supplier entities, possible causes are miscommunication with supplier such that less crude was loaded into the ship, crude leaking out during transportation, and problems with the unloading facilities. Like the previous deviation, "Low crude unloading" could also be caused by unavailability of ullage in the crude tank. The consequences of "Low crude unloading" are found to be similar to those of "No crude unloading," as the latter can be considered as an extreme case of the former. The safeguards and mitigating actions are also similar to those of "No crude unloading," except that those related to ship arrival time are not applicable to "Low crude unloading." An additional mitigating action is adding "Final check with supplier before delivery" to the work-flow of the procurement department, to prevent or minimize miscommunication with supplier. Other guidewords "High," "Early," "Late," and "Other than" combined with the same parameter "Crude unloading" have also been analyzed and these results are summarized in Table 9. The corresponding flows in the SCFD and WFDs, where applicable, are denoted in square brackets.

The SC-HAZOP study has also been performed using the WFDs in Figures 5–9. Illustrative results are given in Table 10. As described above, the team looks at a particular WFD and starts identifying deviations by combining suitable guidewords with flows, tasks, or resources in the diagram. For example, Item 1.1 studies the deviation ''High production target,'' which is the combination of the guideword ''High'' and the output flow ''Production target'' during the task ''Send production targets'' in the second thread of the sales department work-flow (Figure 5). The team discusses the possible causes and consequences and identifies safeguards and mitigating actions with the aid of the WFDs and knowledge of their supply chain.

To find the possible causes for the deviation ''High production target,'' the team traces backward from the task ''Send production targets'' and finds the task ''Finalize production targets for the production cycle,'' which takes in ''Real demand'' from customer as input flow (Figure 5). Hence, a possible cause for high production target is high demand from customer. To examine the consequences, the team traces the flow ''Production target'' forward to the task ''Receive production target'' in the WFD of the operations department (Figure 9). Based on the production target, the stock report (from the storage department), and the CDU capacities, the operations department decides the crude mix to run and request the storage department to release the corresponding crude. High production target leads to high crude request. If there is not enough crude stock or CDU capacity, the production target could not be met and this could lead to unfulfilled demand, lost opportunity, and unsatisfied customer. Hence, safeguards to this deviation could be in the form of safety stock or additional CDU capacity. The team proposes mitigating actions if the current safeguards are deemed insufficient (Table 10 Item 1.1).

After identifying the risks qualitatively, a quantitative consequence analysis could be necessary. Risks can be quantified in two dimensions: probability/frequency and severity/consequence. Quantification of the latter, i.e., consequence analysis, can be done through simulation. We have developed a dynamic simulation model of the refinery supply chain, called Integrated Refinery In-Silico (IRIS).[32] The model explicitly considers the various supply chain activities such as crude oil supply and transportation, along with intra-refinery activities such as procurement planning, scheduling, and operations management. Stochastic variations in transportation, yields, prices, and operational problems can be introduced and consequences on the operations evaluated based on profit and customer satisfaction. In the following, two examples of quantitative consequence analysis of a particular risk or deviation through IRIS simulation are presented.

Example 1: No crude unloading

This example focuses on the deviation ''No crude unloading'' (Table 9), particularly caused by shipper disruption which results in arrival delay. In this case, the refinery would like to evaluate the benefits of engaging a more reliable shipper. The existing shipper has a 10% probability of late crude delivery while the new shipper is more reliable with a 5% probability of delay. However, the new shipper on average costs $30million more than the existing one. The refinery also considers having a safeguard in the form of safety stock. Hence, four cases are evaluated: with and without safety stock for each shipper option, under stochastic demand. To get a more representative performance measure, 100 IRIS simulation runs of 120-day horizon are carried out for each case. The resulting average profit and customer satisfaction for each case are shown in Table 11. Safety stock can increase customer satisfaction to 95% despite low existing shipper reliability. However, profit suffers a lot from low shipper reliability due to high shutdown costs. Demand backlog can be satisfied in the next cycle; hence customer satisfaction does not suffer much from shutdown. Safety stock cannot make up for poor performance of shipper. In both cases (with and without safety stock), the new shipper increases the profit by more than $50 million. Since the increase in profit is more than the increase in cost, it is recommended to switch to the new shipper. Further, safety stock is also recommended as it increases both customer satisfaction and profit.

Table 11. Consequence Analysis Results for "No Crude Unloading" Scenario

		Average Customer Satisfaction (%)		Average Profit ($, million)	
		Shipper		Shipper	
		Existing	New	Existing	New
Safety Stock	Yes	95	98	38	93
	No	91	95	27	83

Example 2: High demand

This example focuses on the deviation ''High production target.'' One possible cause for this deviation is high demand (Table 10 Item 1.1), which could be a sudden increase in demand or an urgent order. The consequence is unfulfilled demand and missed opportunity. One of the safeguards identified is safety stock. The refinery can hold safety stock for both crude and product. Crude safety stock is defined as the minimum amount of crude that should be available in the refinery at all time. Product safety stock is the amount of additional production on top of the actual demand, defined in terms of a percentage of the actual demand to keep in line with the changing market demand. A case with high demand in three procurement cycles is simulated in IRIS.

To study the benefit of safety stock as a safeguard against the risk of high demand, different safety stock levels are used in two simulation runs. The first uses safety stock levels of 250 kbbl for crude and 10% for product, while in the second, higher safety stock levels of 1250 kbbl for crude and 50% for product are used. Figure 10 shows the demand fulfillment (%) and the ratio of actual demand to forecast demand for the two runs. In each of Procurement Cycles 5, 6, and 7, the actual demand is around 80% higher than the forecast demand. The actual demands are in the range of 1500 kbbl per cycle, but shoots up to around 2700 kbbl in Cycles 5, 6, and 7. Using a safety stock of 250 kbbl and 10%, demand fulfillment falls to around 61% and 80% in Cycles 6 and 7, respectively. In the second run with

Figure 10. Demand fulfillment for two different safety stock levels in high demand scenario.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

1250 kbbl and 50% safety stock, demand fulfillment can be maintained at a respectable level of around 90% despite the sharp demand increase. This demonstrates the protection safety stock provides against the risk of high demand. However, the safety stock comes with a cost, so the trade-off between risk protection and cost efficiency has to be evaluated considering the stochastic environment.[33]

The case study demonstrates that risk identification could be done in a structured and systematic way using the proposed method. Furthermore, the method is elaborate and detailed such that there is high probability of identifying most of the important risks, i.e., risk transparency. Benefits of the study have been illustrated using two scenarios. The proposed risk identification method is not specific to refinery supply chains and can be applied to any supply chain.

Concluding Remarks

Risks are increasingly prevalent in globalized supply chains. In addition to disruptions within each supply chain entity, the maze of interactions necessary for smooth supply chain operation can also be the origin for disruptions. Currently, there are no systematic methods to identify supply chain risks. In this work, we propose a structured approach for supply chain risk. The central thesis is that methods from chemical process safety, a mature field with a variety of specialized approaches, can be adapted to the supply chain arena as well. Here, we have tailored the common HAZOP analysis approach to supply chain risk identification. In order to perform HAZOP analysis, a unified representation of the system is required. Analogous to the process flow diagram (PFD), we have developed a supply chain flow diagram which depicts pictorially all the elements in the supply chain and their interactions in the form of material and information flows. Measurement, control, and monitoring elements are also explicitly depicted there. Essential to supply chain operation is the role of human activities and decision making. These are flows of information but are instrumental in the flows of materials; these are analogous to the operating procedures in batch processes. Such activities are captured in the supply chain work-flow diagram. The two diagrams provide a unified representation of the diverse elements and their interactions. Comprehensive risk identification can be performed by considering the various deviations that can occur in each element through a HAZOP-analysis-like guideword and variable/parameter combination. In the proposed SC-HAZOP methodology, the causes, consequences, and safeguards for each deviation are identified by following the flows using the diagrams.

The proposed approach has been illustrated using a refinery supply chain comprising of crude procurement, processing, and product delivery. Possible deviations in the supply chain were considered and their causes and consequences identified. The existing safeguards were located and new ones proposed if necessary. Quantitative consequence analysis using a dynamic simulator has been performed to provide a detailed cost-benefit analysis for the safeguards. The proposed method can be easily applied to any level of supply chain of any industry.

The main advantage of the proposed method is that it enables a structured and systematic risk identification and evaluation. Also, existing safeguards can be located and new ones proposed if necessary. Various strategies for risk management such as the agent-based disruption management decision support system of Mishra et al.[34,35] and Bansal et al.[36] or the rescheduling strategies of Adhitya et al.[37,38] can therefore be seamlessly considered in the analysis. Additionally, while constructing the supply chain flow and activity diagrams, the team gains a better understanding of how the supply chain operates; this would help them identify and correct inefficiencies along the way. These benefits come with some costs; typically information about the supply chain is not available centrally in many enterprises today. Therefore gathering all the requisite information for constructing the diagrams would involve significant effort. We have designed the representations to exploit related resources to the extent possible. Specifically, the proposed work-flow diagram shares some similarities to the swim diagram used in the Supply Chain Operations Reference (SCOR) level 3 processes.[39] Supply Chain Operations Reference-model (SCOR-model) is a cross-industry standard diagnostic tool for supply chain management.[40,41] Many enterprises today have adopted the SCOR-model. In such cases, given the compatibility with the SCOR-model, preparing the work-flow diagram will require minimum effort if SCOR models are already available.

The entire SC-HAZOP life cycle requires considerable effort and resources, from developing the diagrams, analyzing deviations, identifying safeguards and mitigating actions, to documenting the results. This motivates the development of computer aids and tools that can provide some automation to the process as future work. There have been considerable works on automating HAZOP analysis for both batch[30,31] and continuous plants,[42] employing techniques such as signed digraphs, Petri nets, and expert system. These help save time and effort on the more ''routine'' aspects of the study. Similarly, it is possible to develop computer tools to aid in generating the SCFD and WFD, performing the SC-HAZOP analysis, and recording the results. While fully automated analysis may miss out on aspects that are not covered in the knowledge base, these tools can still serve as a means to make manual analysis more efficient so that the experts can focus on the special cases that are not amenable to automation. On the other hand, if the whole process is automated, the benefit of SC-HAZOP that it strengthens understanding of the SC structure and operation will not accrue.

This work also provides a platform for further extensions of other process hazard evaluation techniques, both qualitative and quantitative, to the supply chain arena. Examples of this are techniques for quantifying effects or consequences such as Event Tree Analysis, and those for quantifying probabilities of events such as Fault Tree Analysis and Human Reliability Analysis along with cost-benefit analysis and risk optimization strategies.

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