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Enterprise Architectural Framework for Supply-Chain Integration

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Abstract

The concept of supply-chain is about managing coordinated information and material flows, plant operations, and logistics. It provides flexibility and agility in responding to consumer demand shifts without cost overlays in resource utilization. The fundamental premise of this philosophy is; *synchronization* among multiple autonomous business entities represented in it. That is, improved coordination *within* and *between* various supply-chain members. The increased coordination can lead to reduction in lead times and costs, alignment of interdependent decision-making processes, and improvement in the overall performance of each member as well as the supply-chain network. This paper describes an architecture to create the appropriate structure, install proper controls, and implement principles of optimization to synchronize the supply-chain. A supply-chain model based on a collaborative system approach is illustrated.

Keywords: Supply-Chain, Supply-Chain Modeling, Distributed Problem-Solving, Cooperative System, Enterprise Integration.

1 Introduction

A supply-chain is a *society* (network of *Member*s, termed a *Group*) formed by autonomous business entities (and their systems) by bonding together to solve a common problem. With their collective and collaborative efforts, they sustain the progress of each Member as well as the Group. Collaboration between Members requires effective communication. In a collaborative environment, a Member may modify its norms of behavior to accommodate other Member's perspectives (Bond and Gasser, 1988; Gasser, 1991; Moulin and Chaib-Draa, 1996). We propose following guiding principles for the supply-chain framework described in this paper:

- supply-chain is a *Cooperative System*,
- supply-chain exists on *Group Dynamics* of its Members,
- *negotiation* and *compromise* are norms of operation in a supply-chain,
- supply-chain system solutions are *pareto-optimal* (*satisficing*), not optimizing, and
- *integration* in supply-chain is achieved through *synchronization*.

2 A Distributed Problem-Solving Hypothesis for a Cooperative Supply-Chain System

The system architecture of a cooperative supply-chain (CSC) is based on the distributed problem-solving approach, illustrated in Figure 1. The CSC is comprised of a Group and more than one Member. The network is arranged in the order -- flow of materials, processes, and information occurs between its Members. In the textile industry example depicted in Figure 1, consumer demand is relayed by retailer to -- apparel maker, textile manufacturer, fiber manufacturer, and ultimately to Cotton grower. Similarly, flow of material occurs in transforming -- cotton to yarn by fiber manufacturer, fabric by textile manufacturer, apparel by apparel maker, and finally a name brand garment by retailer. The interaction between Members occurs as a *consumer* and a *provider*. Thus, an apparel maker assumes the role of a provider (of apparels) in its dealings with retailer (a consumer of apparels). However, it acts as a consumer of fabric while dealing with a textile manufacturer (a provider of fabric). The CSC requires design and implementation of three primary components: structure, control, and optimization. We describe these below.

Structure. The CSC is a distributed system of collection of components and elements of autonomous business entities. In the distributed problem-solving environment, the task of solving a problem is divided among a number of modules or nodes (autonomous business entities and their systems). They cooperatively decompose and share knowledge on the problem and its evolving solutions. Interactions between Members in the form of cooperation and coordination are incorporated as problem-solving strategies for the system. Entity Group, is responsible for coordination throughout the supply-chain. Entity Member, brings specialized expert knowledge and technology to the supply-chain. The decision-making process is centralized for the Group -- common goals and policies of the supply-chain are enforced by the Group on its Members. However, decision-making at Member is decentralized -- each Member pursues its own goals, objectives, and policies, independently of the Group. A common knowledge-base supports the CSC structure. Knowledge is assimilated for an *activity* (the lowest level of information) in a specific domain and aggregated for various decision-making levels in the enterprise.

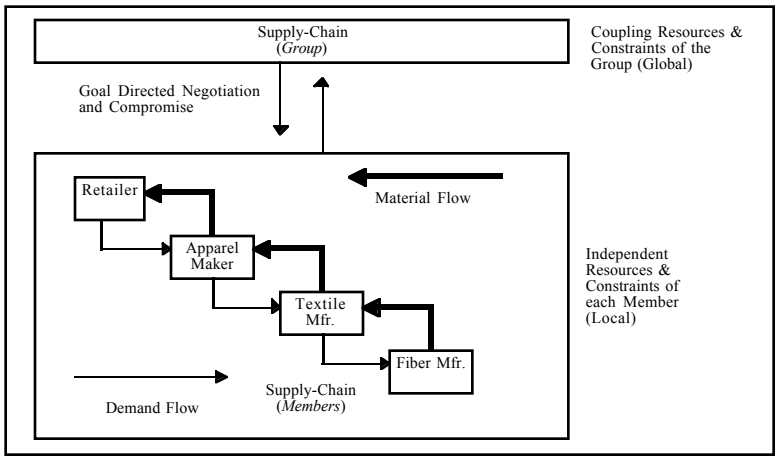

Figure 1. A Supply-Chain Enterprise Decomposition Model

Control in the CSC is maintained via goals, policies, and objectives that are synchronized along the system's decision-making hierarchy. This is accomplished by applying principles of complementarity, consistency, and constriction to these control elements, as depicted in Figure 2. A vertical arrow ( ) between two decision-making levels signifies complementarity of controls at these levels. Thus, a primary goal at the strategic level must be complementary to a secondary goal at tactical and tertiary goal at the operational levels. A horizontal arrow ( ) signifies consistency between control elements across a decision-making level. Thus, a strategic goal must be consistent with policies and objectives outlined for its implementation. A diagonal arrow ( ) denotes constriction between goals, policies and objectives between decision-making levels. Thus, a strategic *goal* will constrain *policies* to be implemented at the tactical level, which in turn will constrain *objectives* at the operational level.

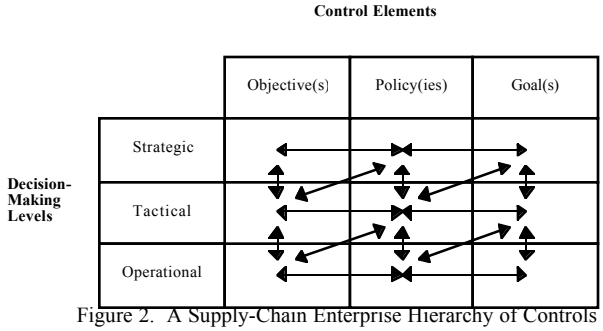

Figure 2. A Supply-Chain Enterprise Hierarchy of Controls

Optimization. The principle of optimization of the CSC system is enunciated by investigating relationships between *methods*, *standards*, and *costs* on the operation of the enterprise. Figure 3 depicts these relationships, summarized below:

- standards vs. costs,
- standards vs. productivity,
- standards vs. methods, and
- influence of methods and standards on product and process designs.

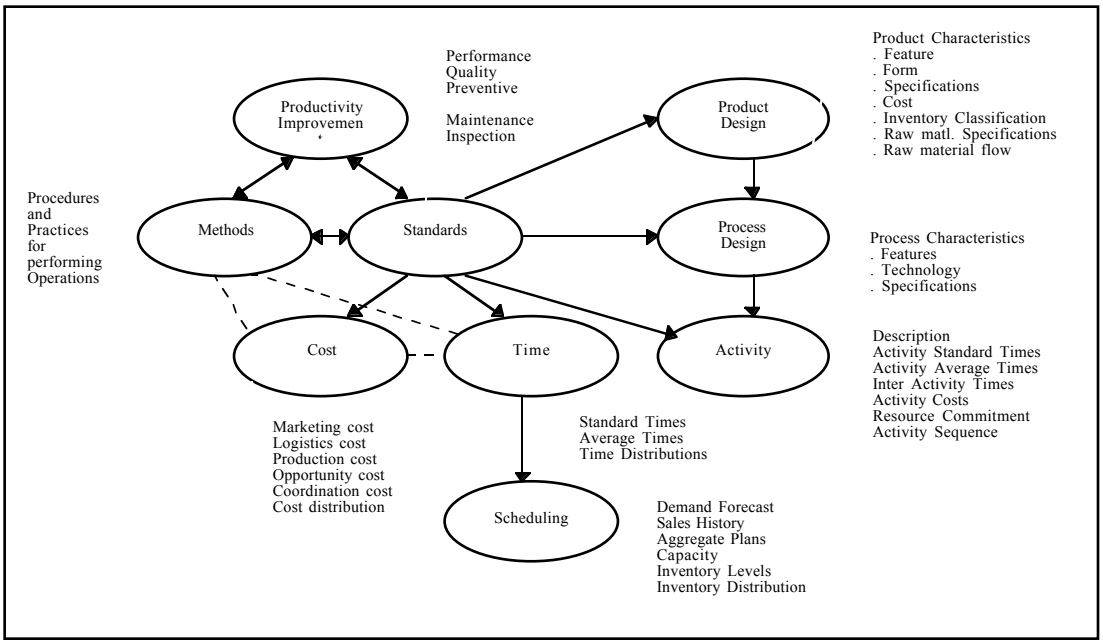

Figure 3. A Supply-Chain Enterprise Work Design and Methods Improvement Approach

These relationships are first quantified through known *work design* and *method's improvement* techniques, and then represented as joint attributes of various *decision-making levels* and *control elements*, in the CSC system model (Nadler, 1970; Niebel, 1993).

System Analysis. The analysis of a CSC system focuses on interactions between its design components. That is, analyzing interactions between Members of the supply-chain for information sharing, defining controls and specifying roles and responsibilities, while adding value to the product. This requires identifying activities in the product-life-cycle, defining strategies for their implementation, and establishing performance criteria to measure their outcome. Figure 4 illustrates a structured approach to integrate CSC design components over the product and process life-cycles.

3 Cooperative Supply-Chain System: A Member Perspective

Members of a CSC system in a distributed problem-solving architecture are *heterogeneous* (Durfee et al., 1989*)*. The degree of heterogeneity can be attributed to the implicit and explicit behaviors they portray within their internal organization, as well as in their dealings with other Members of the supply-chain. Some key factors that differentiate Members in terms of their heterogeneity are:

- rules for allocation and utilization of *resources*,
- methods and approaches utilized in *problem-solving*,
- degree of *adaptability* shown in negotiation and compromise, and
- extent of *inter* and *intra* activity interactions within the Member organization.

System analysis of a Member deals with evaluating the influence of these factors primarily on it's Member organization, and through interactions on other Members of supply-chain. This is accomplished by, (a) conducting a value analysis of primary activities as depicted in Table 1, and (b) identifying hierarchy of controls in the decision-making process as depicted in Table 2, of the Member enterprise.

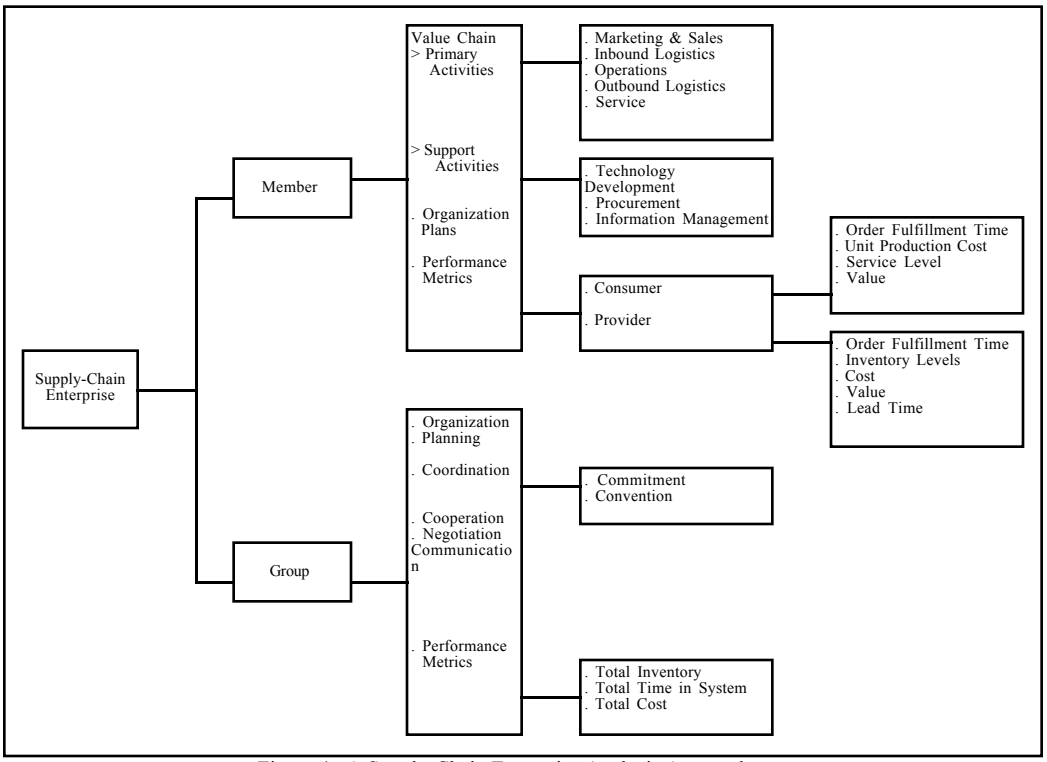

Figure 4. A Supply-Chain Enterprise Analysis Approach

Figure 5 illustrates the architecture of a CSC Member enterprise. The integration of design components described in Section 2, is evident in this diagram. Decision-making models are aggregated from the lowest (activity) to the highest (Member) component of the enterprise. The transformation of material from one stage to the next, until final product is derived, occurs at the activity level. Transformation in the order-life-cycle occurs at the business level as the order is processed by marketing & sales, order entry, product design, production planning & scheduling, manufacturing, and shipping functions, respectively. Controls are passed at both inter (between operations along the model hierarchy) and intra (within operations belonging to the same function) levels to implement independent organizational goals, policies, and objectives.

Table 1. Member Enterprise Value Analysis

	Procurement	**Technology Development**	**Information Management**	**Others**
Marketing & Sales	. Buy advertising campaigns . Buy sales promotions	. Consumer market research . Incorporate market needs in the product	. Forecast demand and sales . Sales analysis . Track product performance	. Coordinate order processing
Inbound Logistics (*Receiving, Warehousing, Inventory Control, Production Planning*)	. Procure end-products . Procure raw-material for assembly and packaging		. Receive and track raw materials and end-products	. Manage storage of raw materials and end-products
Plant Operations (*Manufacturing, Inspection, Product Assembly, Product Packaging*)				. Quality inspection of finished product . Assemble end-product . Package end-product
Outbound Logistics (*Warehousing, Inventory Control, Shipping*)	. Procure shipment modes		. Inventory control of finished product . Track and report shipments	. Select shipment and routing modes . Consolidate order for a carrier
Service (*Organization and Management*)			. Manage inventory carrying, quality, back order, and opportunity costs . Analyze cost variance	. Guarantee shipment schedules

Table 2. Member Enterprise Hierarchy of Controls

	Objective(s)	**Policy(ies)**	**Goal(s)**
Marketing	. Maximize customer service	. Implement a procure-to-stock policy	. Achieve a *x%* order-fill-rate of within *t* days order processing
Procurement Planning	. Maximize inventory turns	. Implement a JIT procurement policy	. Achieve *k* inventory turns
Warehouse Operations	. Minimize merchandising costs	. Implement a quick response shipment policy	. Achieve a *s%* shipment-fill-rate of within *t* hours of order

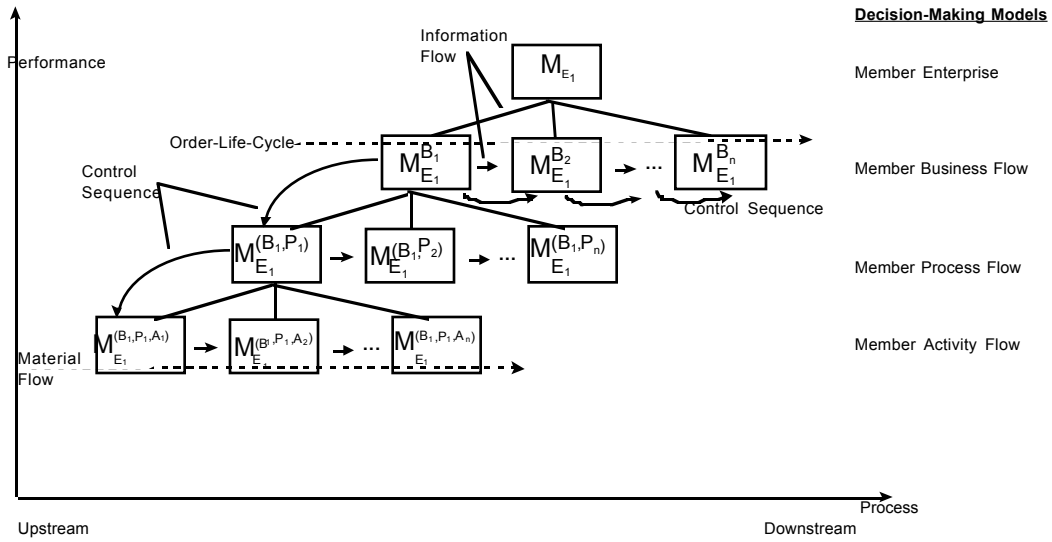

Figure 5. A Cooperative Supply-Chain Member Architecture

4 Cooperative Supply-Chain System: A Group Perspective

The organization of a Group in a CSC system is with the purpose of finding homogeneity in the heterogeneous behavior of supply-chain Members (Malone, 1990). This is accomplished by gaining mutual commitment, and converging on joint intentions of Members towards achieving common supply-chain goals. Some norms that enunciate this spirit of partnership are:

- allocation rules for sharing scarce resources in the supply-chain,
- rules for cooperation and coordination,
- adoption of a *problem-solving* approach by the Group,
- defining roles and responsibilities of each Member,
- rules for negotiation and compromise, and
- extent of *inter* and *intra* activity interactions in the Group.

System analysis of a Group deals with evaluating the influence of these factors on the Group enterprise. This is accomplished by, (a) conducting a value analysis of primary activities as depicted in Table 3, and (b) identifying hierarchy of controls in the decision-making process as depicted in Table 4, of the Group enterprise.

Table 3. Group Enterprise Value Analysis

	Commitments	**Information Management**
Marketing & Sales	. Price agreements	. Share forecast demand and sales . Share product performance . Share product cost data
Inbound Logistics (*Receiving, Warehousing, Inventory Control, Production Planning*)	. Agreement on inventory stock levels . Pre-commitments on short and long-term manufacturing capacity	. Share production forecasts and plans . Share production schedules . Share inventory status . Reserve manufacturing capacity for specific products
Plant Operations (*Manufacturing, Inspection, Product Assembly, Product Packaging*)	. Pre-shipment inspections	. Share product and process specifications
Outbound Logistics (*Warehousing, Inventory Control, Shipping*)	. Warehousing agreements on finished goods . Direct shipments from manufacturing locations	. Share inventory status . Share customer order information
Service (*Organization and Management*)	. Guarantee delivery schedules	. Share forecast demand . Share forecast production schedules

Figure 6 illustrates the architecture of a CSC Group enterprise. The integration of design components described in Section 2, is evident in this diagram. Decision-making models are aggregated from the lowest (Member business) to the highest (Group) component of the enterprise. The transformation in the order-life-cycle occurs at the Member business level as the order is processed, for example, by marketing & sales function of Member enterprises, in the sequence they add value to the

Table 4. Group Enterprise Hierarchy of Controls

	Objective(s)	Policy(ies)	Goal(s)
Marketing	. Maximize customer service	. Evaluate and implement a *Push* or *Pull* policy	. Achieve an industry benchmark of *x%* order-fill-rate of within *t* days order processing
Production Planning	. Maximize production under-runs . Maximize inventory turns	. Evaluate and implement a JIT scheduling or planned production scheduling policy	. Achieve a *y%* effective capacity utilization . Achieve inventory of *k* or above
Plant Operations	. Minimize manufacturing costs . Maximize yield per production run	. Evaluate and implement a JIT manufacturing or planned manufacturing policy	. Achieve over *z%* actual capacity utilization . Achieve less than *r%* rejects

product. Controls are passed at both inter (between common business operations of Group and a Member along the model hierarchy) and intra (within business operations belonging to the same function) levels to implement common supply-chain goals, policies, and objectives.

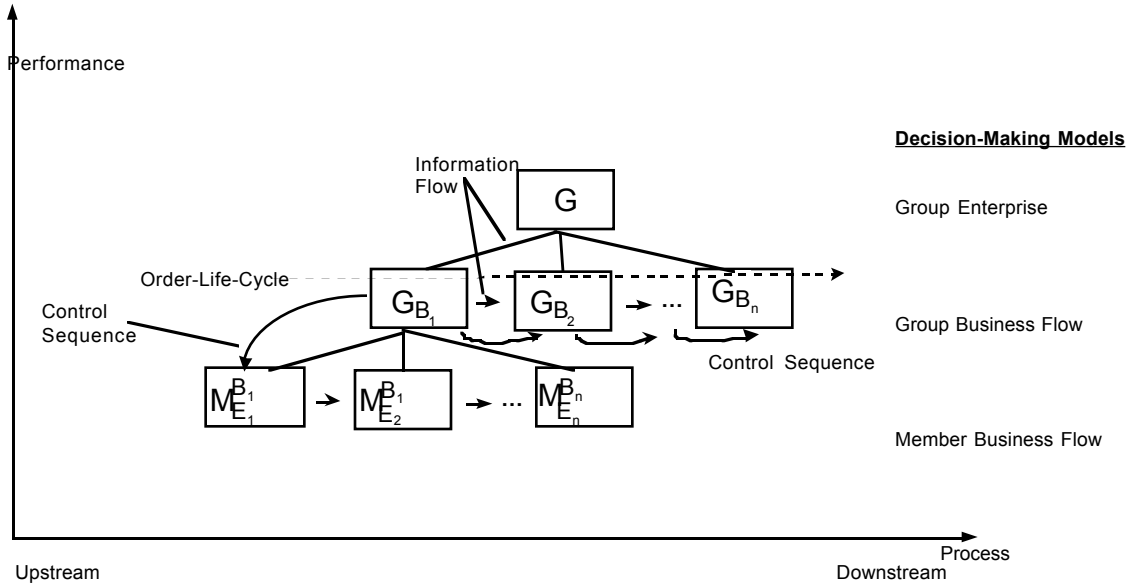

Figure 6. A Cooperative Supply-Chain Group Architecture

5 Cooperative Supply-Chain System Modeling

The main thrust of CSC modeling is based on the principle that its architecture should be domain independent, whereas its application domain specific. Such a strategy assures integration of disparate applications to a common, yet generic architecture. Some guidelines for implementing this strategy are:

1. the structure of the conceptual model of a CSC system must reflect inner workings of its global (Group) and local (Member) components,
2. the design of an application of CSC should be based on a conceptual model of the CSC architecture, but specific to decision-making relevant to that application,
3. realization of objectives of a CSC enterprise must be achieved through implementation of a highly coordinated set of strategies and policies at the global and local levels. These should be consistent with trends and directions pursued by the industry for which the supply-chain is being designed, and
4. the implementation of a CSC application model must balance the issue of scope vs. focus.

The goodness of a CSC model for a problem, is judged by the ability of solutions to the problem to satisfy necessary and sufficient conditions posed by the problem. That is,

- to satisfy *necessary conditions*, the CSC model must reflect requirements of the industry, as borne out of facts through various methods of inquiry, and
- to satisfy *sufficient conditions*, every business strategy that facilitates implementation of the CSC model, is a candidate solution to the industry supply-chain problem.

The above modeling concepts are further elaborated by two representations of a CSC system model:

I. *A Cooperative Supply-Chain System Decomposition Model* (DM) is depicted in Figure 1 with notations in the Appendix (Taha, 1987). The technology matrix D_j and corresponding resource vector b_j represent the independent *structure* of the Member. The technology matrix A_j and the objective function vector C_j denote the common structure of the Group derived from the homogeneity of Members. *Controls* embedded in the technology matrix constitute relationships between various strategies, such as identified in Table 2 (marketing, production planning, warehouse operations, etc.), in regards to their goals, policies, and objectives. These controls are propagated as constraint equations represented by the technology matrix. A similar approach is applicable for gathering Group information, per Table 4.

II. *A Cooperative Supply-Chain System Dynamic Process Flow Model* (DPFM), with notations in the Appendix (Hillier and Lieberman, 1990). The *structure* of a Member is signified by the network depicted in Figure 7. It has a source (supply) and a sink (demand) node with a transshipment node acting as an intermediary node. *Controls* in this network are implemented by modulating (managing discrepancies) inputs (activity flow rates) based on strategies identified in Table 2 (marketing, production planning, warehouse operations), to support goals, policies, and objectives. Linking of Member networks through common control strategies (Table 4), produces the *structure* for the Group.

For both models, coefficients for various decision variables in the technology matrix are derived by the application of various *optimization* techniques, such as, methods engineering and value engineering on different operations of the enterprise across the value-chain as depicted in Table 1. A similar approach is applicable for gathering Group information, per Table 3.

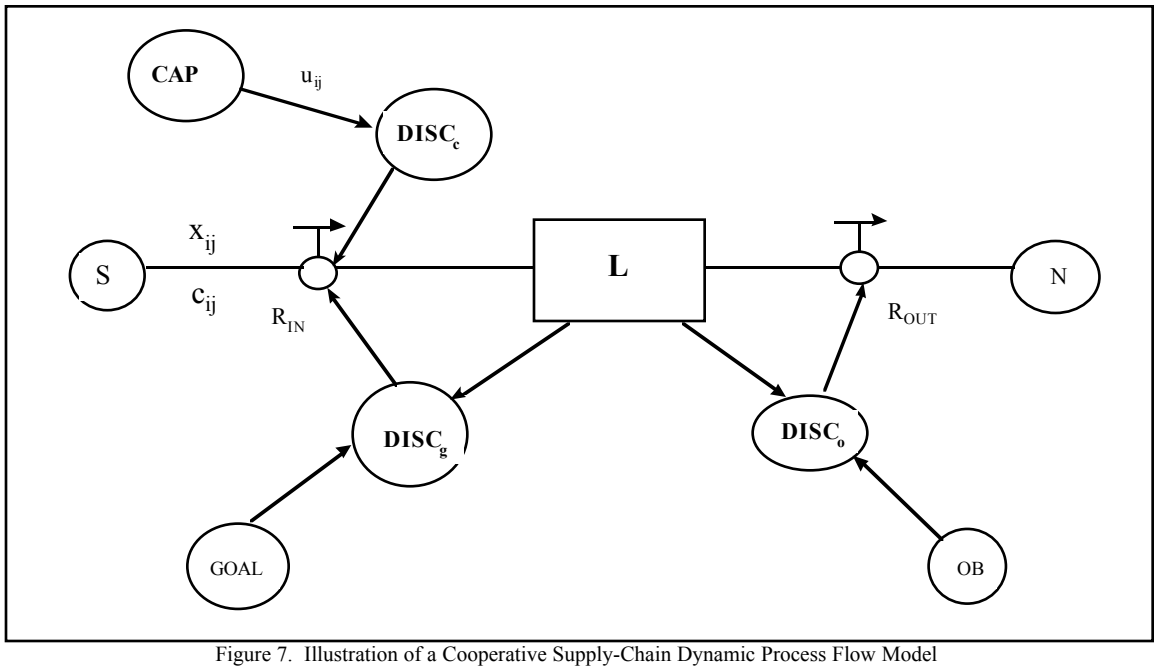

Figure 7. Illustration of a Cooperative Supply-Chain Dynamic Process Flow Model

6 Conclusions

In this paper, the problem of supply-chain design has been approached as that of a *cooperative* system design. The composition of a cooperative system as the collective behavior of it's constituents, offers a unique architectural framework for applying a distributed problem-solving approach. The decomposition process of the supply-chain enterprise leading upto identification of activities of it's Members, reveals behavior of Member entities that is useful in designing the supply-chain design problem. A cooperative supply-chain system model is presented incorporating behavioral traits of its Members. These behaviors have attributes that are essential to modeling separation of Members from their collective identity, Group, in a cooperative supply-chain system. The unique feature of a distributed problem-solving approach to represent behavior of a system through its component entities, offers opportunities to model large-scale supply-chain systems, modularly.

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Appendix

A. A Cooperative Supply-Chain System Decomposition Model

Notation:

A_j - technology matrix of the jth Member representing common constraints.
b_0 - resource vector for the jth Member w.r.t. common constraints.
D_j - technology matrix of the jth Member representing independent constraints.
b_j - resource vector for the jth Member w.r.t. independent constraints.
C_j - vector of the objective function coefficients for the jth Member.
X_j - vector of decision variables corresponding to j^{th} Member.

Problem Formulation:

Maximize, $z = C_1X_1 + C_2X_2 + \ldots + C_nX_n$ — *Common Objective*

subject to (constraints):

$A_1X_1 + A_2X_2 + \ldots + A_nX_n = b_0$ — *Common Constraints*

$$\left.\begin{array}{lll} D_1X_1 & & = b_1 \\ & D_2X_2 & = b_2 \\ & \ldots\ldots & \\ & & D_nX_n \quad = b_n \end{array}\right]$$

Independent Constraints

$X_j \geq 0, \forall j$ — *Non-negativity Constraints*

B. A Cooperative Supply-Chain System Dynamic Process Flow Model

Notation

1. *Variables*

L - Level (stock) in the transshipment node, denoted by a

R - Flow (rate) per unit of time t, denoted by a

- R_{IN} - flow rate "in" through feedback
- R_{OUT} - flow rate "out" as feedforward

t - time (period)
Δt - change at time t
x_{ij} - average flow through arc $i \rightarrow j$
c_{ij} - cost per unit flow through arc $i \rightarrow j$
u_{ij} - arc capacity for arc $i \rightarrow j$
b_i - average net flow generated at node i
$b_i > 0$, if node i is a source (supply node)
$b_i < 0$, if node i is a sink (demand node)
$b_i = 0$, if node i is a transshipment (intermediary node)

Auxiliary variables, denoted by a

GOAL - desired level
CAP - designed capacity
$DISC_c$ - discrepancy w.r.t. capacity
$DISC_g$ - discrepancy w.r.t. a goal
$DISC_o$ - discrepancy w.r.t. an objective
OB - desired objective

2. *Problem Statement:*

Set up the flow model as a minimum cost flow problem, that is,

Minimize $\sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij}\, x_{ij}$

subject to (Constraints):

$\sum_{j=1}^{n} x_{ij} - \sum_{j=1}^{n} x_{ji} = b_i$, for each node i

and $0 \leq x_{ij} \leq u_{ij}$, for each arc $i \rightarrow j$

3. *Components of a System, represented as a Flow model:*

Stocks (Levels), Rate of input / output, Source (S), Sink (N), System boundary, Feedback / Feedforward, Goals, Objectives, Policies

"Intra" flow
System boundary, Capacity, Feedback / Feedforward

"Inter" flow
System boundary, Capacity, Feedback / Feedforward

4. *Conservation Equations:*

$L(t + \Delta t) = L(t) + (R_{IN} - R_{OUT})\Delta t$, [Level (Stock) Equation]

$R_{IN}(t) = F(L(t))$, (Rate Equations)
and $R_{OUT}(t) = G(L(t))$
where, F and G are some functions.