SIMULATION MODEL FOR A COMPLEX PRODUCTION/DISTRIBUTION NETWORK

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Summary

The Logistics and Budgeting Simulator (LBS)model is a generalized procedure used to simulate the material flow and cost behavior of a complex, process type manufacturing and distribution system. This model is used for corporate planning studies and for evaluating budget alternatives.

The model, representing the W.R. Grace and Co. fertilizer system, is structured as a network consisting of nodes and streams. Nodes represent production sites, inventory locations or geographical groupings of both. Streams represent material movement between nodes. Material flows within the network are determined in a logical "top-to-bottom" sequence from the network output to the network input streams. Costing is then performed by a reciprocal "bottom-to-top" procedure.

The model operates in a conversational mode using a time-shared computer system. The model is "open-ended" to provide the user the means to quickly modify the network structure and/or input parameters, thereby enabling top management to actively participate in the use of the system.

Introduction

The Agricultural Chemicals Group of W.R. Grace & Co. consists of a fully integrated mining, production, secondary processing and distribution system for agricultural fertilizers. Production facilities are located in several widely separated states and three Caribbean Islands. Wholesale and retail distribution networks include the continental United States east of the Rockies and a worldwide export marketing system.

Of the three primary fertilizer components - nitrogen, phosphate, and potash - W.R. Grace & Co. is a basic producer of the first two. Nitrogen (in the form of ammonia) is produced in continuous process plants and requires specialized handling, storage and transportation equipment. Phosphate rock is mined at a single location but conversion to plant available nutrient is done through several diverse secondary processes at numerous locations.

Production of basic fertilizer components is relatively uniform for the entire year whereas sales activity is highly cyclical and compressed into short periods of time.

Problem Statement

The number of products, manufacturing sites, transportation alternatives, possible product exchanges with co-producers and storage and warehousing constraints result in a highly complex and interrelated production and distribution system. Due to this complex environment, it is extremely difficult to provide management with the mechanism necessary for strategic planning, accurate budgeting and the evaluation of alternatives.

The primary purpose of the Logistic and Budgeting Simulator (LBS) is to provide a computerized model which represents the physical and cost behavior of the entire fertilizer network, a model which gives a transparency to the operation not previously possible.

Prior to implementation of the LBS model, a massive effort was required each year to develop the annual business plan. Manual calculations were performed to flow balance and cost a single set of sales forecasts, distribution patterns, production and inventory levels, and possible product exchanges. Once the balanced and costed system was obtained, it was impractical, because of time constraints, to manually rebalance and recost the system. Management, therefore, had no reliable and quick method for evaluating a variety of planning alternatives. Strategic studies also were restricted in the same manner.

The success of the fertilizer operation is dependent upon accurate planning since demands for individual products and their availability by location must be anticipated well in advance of requirements. Flexibility achieved through sensitivity analysis, and the ability to monitor the system impact of planning decisions is vital.

Objectives obtained with implementation of the LBS model were as follows:

A) Balancing the volumetric flow of all materials in the fertilizer network on an annual basis.

B) Costing the balanced material flows from pre-determined cost relationships and providing resultant cost and profit projections in both detailed and consolidated form.

C) Providing an information data base for planning purposes.

D) Providing the mechanism for examining the impact on the system of alternatives involving changes in volumes, distribution patterns, production costs, transportation modes/rates, inventory levels, raw material sources, and physical locations of plants/terminals/warehouses.

Why Simulation?

The W.R. Grace & Co. fertilizer system is an extremely complex and interrelated network which makes it difficult to evaluate its overall behavior and to determine how each individual part affects the total system. Therefore, it was decided to determine the physical and cost behavior of the network through simulation before developing an appropriate "optimization" model.

The reasons the simulation approach was chosen were: (1) flexibility, (2) transparency and (3) communications. The LBS model is a deterministic "what-if" simulation model which stresses basic arithmetic, uses simple modular building block construction and emphasizes the case-study method. Rather than defining the executive's thinking and value system in terms of complex objective functions, the executive can ask "what-if" questions and use his own judgment as to which alternative is best.

The LBS model represents the physical and cost behavior of the entire fertilizer system through a set of algebraic equations. It stresses simple modular structure which accurately represents the fertilizer network. The basic arithmetic manipulations at each module, can be easily verified by manual calculation. A model that the executive can quickly "see", understand and manipulate is crucial to his successful use of the model.

On the other hand, optimization techniques require a great deal of data preparation, and results are often difficult to interpret into meaningful reports at the management level for which this model was developed. In summary, simulation techniques allows the user to deal with input values and output reports which are familiar to him and which can be related to the physical operation.

Model History

The simulation model was originally devised in 1968 as a planning tool for management to rapidly compute the impact on profits of changes in sales prices and volumes. This model was a stochastic simulation program which provided for probabilistic estimates of price and volume changes. The model operated with fixed, average cost rates regardless of sales volume and plant origin of the product. This led to unacceptable cost distortions when changes in sales volume were simulated thus necessitating the redesign of the model.

The redesigned model was the immediate predecessor of the LBS model now in use. It used the same conceptual procedures as the present model. The physical system was represented by nodes and streams. The program took into account cost changes related to volume, and to a limited extent, alternate sources of materials and changes to inventory levels. Experience with this prototype in 1969 led to the development of the present LBS model.

Model Design

The LBS model represents the W. R. Grace & Co. fertilizer production and distribution system. The model is general in nature, i.e., "open-ended", so as to be readily adaptable to changes in actual physical structure, modifications of input parameters, and adjustments in operational constraints.

The model is in the form of a network consisting of nodes and streams. The nodes represent production and/or inventory locations where materials are either being converted or stored or sales regions where products are sold. The streams represent either material movements between nodes, material inflows to the system (purchases) or material outflows from the system (sales).

The LBS model is designed to calculate, from a set of predetermined sales demands and/or stream levels, those material movements and production/inventory levels which balance the network.

After the network has been flow balanced, the system is costed from given node and stream relationships. The costing procedure begins at the incoming streams and logically proceeds through the network to the outflowing streams. In the process of passing through the network, the individual node and stream costs are accumulated until the total product cost of sales is obtained.

The LBS model is designed to operate in an interactive environment. Using a CRT connected to a computer time-sharing system, the executive can quickly evaluate many alternatives and obtain results instantaneously.

Model Structure

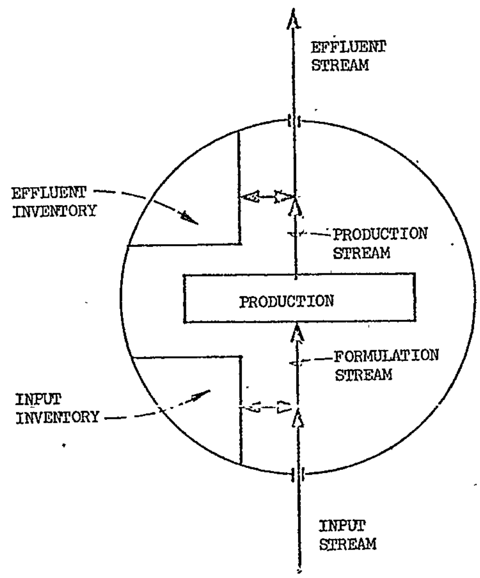
A) Basic Elements

The LBS model is modular in nature and consists of the basic building blocks of nodes and streams. Definitions and the representation of the key items as they related to nodes and streams follow:

(1) Nodes: A node is used to represent a basic operation where raw materials (flow input) are stored and/or converted, and where finished products are produced and/or stored. A node also may be used to represent a location from which finished products are sold.

A diagram of a node is shown in Figure I followed by definitions of the four streams:

Figure I



Input Stream: a raw material stream entering a node.

Formulation Stream: a stream internal to a node. This stream is one of the raw materials required for a specified formulation and is the sum of the change to the raw material inventory plus the input stream flow.

Production Stream: a stream internal to a node. This stream is the result of a transformation of raw materials via specified production formulations.

Effluent Stream: a stream leaving the node. This is the volume of product leaving the node and is the sum of the production volume modified by the change in inventory.

Each production stream at a node contains a production formulation. Two formulation options are available for each production stream at a node, either a material balance or a production recipe. The material balance option relates the sum of specified raw material streams to the sum of specified production streams; it is the volumetric pooling of specified input streams. The production recipe option relates each unit of production to specified raw materials in a pre-determined ratio. The user selects that option which correctly reflects the activity at that node.

Beginning and ending inventory levels for both raw materials and finished products may be specified at each node for a given planning period. The material balancing is performed so as to account for changes in inventory levels if so specified. However, in some situations, these changes may result in an infeasible solution. If such an impasse occurs, the LBS model adjusts inventory levels beyond specified levels in order to obtain a flow balanced network, and informs the user of the required adjustments. Minimum and/or maximum inventory levels can be imposed for any stream at any node in the network. These restrictions cannot be violated in the balancing process.

Some operations have the choice of identical raw materials from alternate sources. The user must indicate the priorities on raw materials at those nodes if he desires a specified sequence of raw material consumption.

Some operations consist of many nodes. An example is a basic production plant where the finished products from one process are raw materials for a subsequent process. In order to represent a grouping of nodes, a node set is defined. A node set represents an arbitrary collection of nodes such that production capacities can be imposed and costs allocated to individual operations within the node set.

Production capacity restrictions can be specified for any grouping of production streams at a single node and for groups of nodes within a node set. The LBS model flow balances within these predefined limits.

Equations defining added cost relationships (not necessarily linear) are defined by the user for each node and node set as a function of the levels of production streams or effluent streams within each node or node set. Costs are allocated on a volumetric, weighted basis to these pre-determined production or effluent streams. These costs may be represented either as equations defining a cost in terms of production and/or effluent stream volumes or as a series of cost versus volume grid points.

Because a stream may consist of two segments, i.e., the production stream segment and the effluent stream segment, cost definitions are divided into two classifications:

(a) those costs which are related to production streams and

(b) those costs which are related to effluent streams.

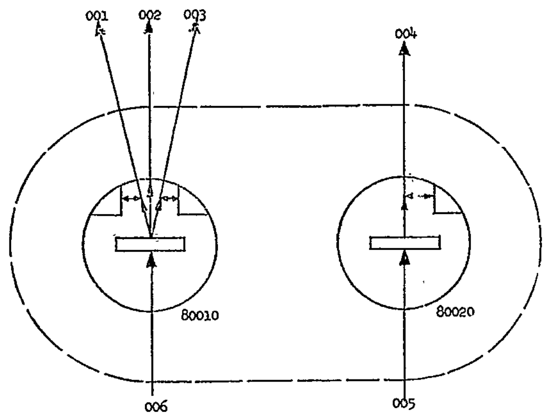
Those costs related to production streams are functions of and allocated to production streams only. The same principle applies to effluent streams. The user defines separately these two cost classifications.

Costs, whether they are related to production streams or effluent streams, must be assigned to either a node or node set. The only restriction is that, for those costs which are associated with a node, all streams contained in the cost relationship must be from the same node. If a cost relationship is a function of or allocated to streams from different nodes within a node set, the cost relationship must be a property of that node set.

Provisions are made for up to four categories of costs (fixed and/or variable) at each node and node set. These costs, when summed, will represent the total added contribution for each node/node set classified by fixed and variable costs.

The schematic on Figure II is used to illustrate the costing algorithm:

Figure II



Assume that the following cost relationship exists relative to effluent streams 001, 002 and 003 for shipping cost.

Shipping $(A_1.001, A_2.002)=B_1(001)+B_2(002)+B_3(003)$

In this equation the total shipping cost to be allocated is computed as a function of streams 001, 002, 003 where B_1, B_2, B_3 are coefficients relating volumes to costs. The resultant shipping cost is then allocated to streams 001, 002 on the basis of their volumetric weighting factors (A_1 and A_2).

Similarly, the following equation illustrates the production stream cost relationship.

Utility $(A_3.003,A_4.004)=C_1(001)+C_2(002)+C_3(003)$

In this equation the total utility expense is defined in terms of production streams 001, 003, 004 associated with two different nodes in the same node set. The resultant cost is then allocated to production streams 003 and 004 based on their weighting factors A_3 and A_4 respectively.

In addition to nodes and node sets which represent the basic operations of the physical network, nodes and node sets can be defined for reporting purposes. These nodes are not part of the simulation process but are associated with streams above the specified network effluent sales streams. Such nodes are used for consolidating product lines by sales regions to report gross profit and for applying relevant expense items in order to arrive at desired profit and loss statements. These local profit and loss statements can further be consolidated into an overall profit and loss statement for the entire fertilizer system.

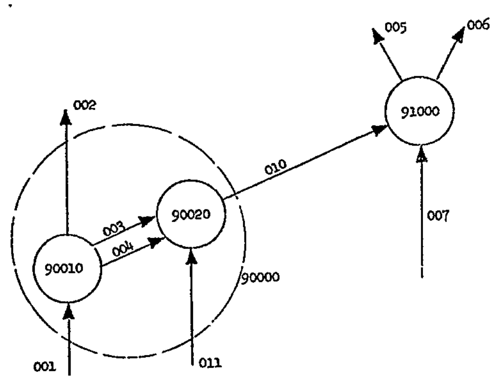
(2) Streams: Streams represent either material movements within the system from node to node, material inflows from external sources into the system (purchases), or outflows from the system (sales). Each stream if desired may have minimum/maximum flow restrictions or a specified flow level. Each stream can have up to four categories of costs (fixed and/or variable), which when summed, represent the total added costs for a given stream.

B) Network Topology

Using the basic building blocks of nodes and streams, the user can dynamically construct any desired network in order to evaluate the system impact of new facilities, elimination of existing facilities, changes in distribution patterns, introduction of new products, etc. From specified numeric identifiers on nodes and streams, together with the necessary node and stream attributes, i.e., formulations, flow demands, etc., any desired network can be constructed simply by tying these identifiers together.

A sample illustrating the network topology appears in Figure III.

Figure III



Referring to the node and stream numeric identifiers in Figure III, the following conventions are used in establishing the structure of a node/stream network:

(1) Only those nodes which have individually associated input/output streams are required in defining the network topology. If a node set contains more than one node, the topology of the set is completely defined by the individual nodes.

(2) Each node output stream is assigned a positive identifier.

(3) Each node input stream is assigned a negative identifier.

In the previous illustration, the network is represented in the following fashion:

Node	Streams
90010	- 001 002 003 004
90020	- 003-004-011 010
91000	- 010-007 005 006

Notice that the node set 90000 is not explicitly entered in the configuration specification. However, because the node set 91000 contains only a single node and has input/output streams directly associated with it, it must be entered in the configuration specification.

Using this building block technique, a network of any desired detail and complexity can be developed from a series of linked modules, each of which become a stepping stone toward a total model of a production distribution network. The operation of the LBS model is "command-driven" and not "program-driven." Each time the system structure is changed, no revisions to computer programs are required.

C) Calculational Procedure

The calculations necessary for solving a specific problem are divided into two phases - a material balancing phase and a costing phase. First, the network is flow (material) balanced from a specified set of sales and network effluent demand volumes. The resulting flows are then costed to obtain production costs, transportation costs, and product costs at any level in the network by any desired product grouping or geographical location.

Using the network representation in the LBS model, a logical procedure is used to follow flow paths through the network from "top-to-bottom", performing material balancing and adjusting inventory levels as they are encountered. Errors in input data and impasse conditions are identified by the program and are reported at the time-sharing terminal. Such conditions can thus be modified "on-line" and the simulation continued. The program and its data assure that the entire network is processed in the correct order and that all network processing rules, such as the application of priorities and the use of inventories, are carried out in the proper sequence and location.

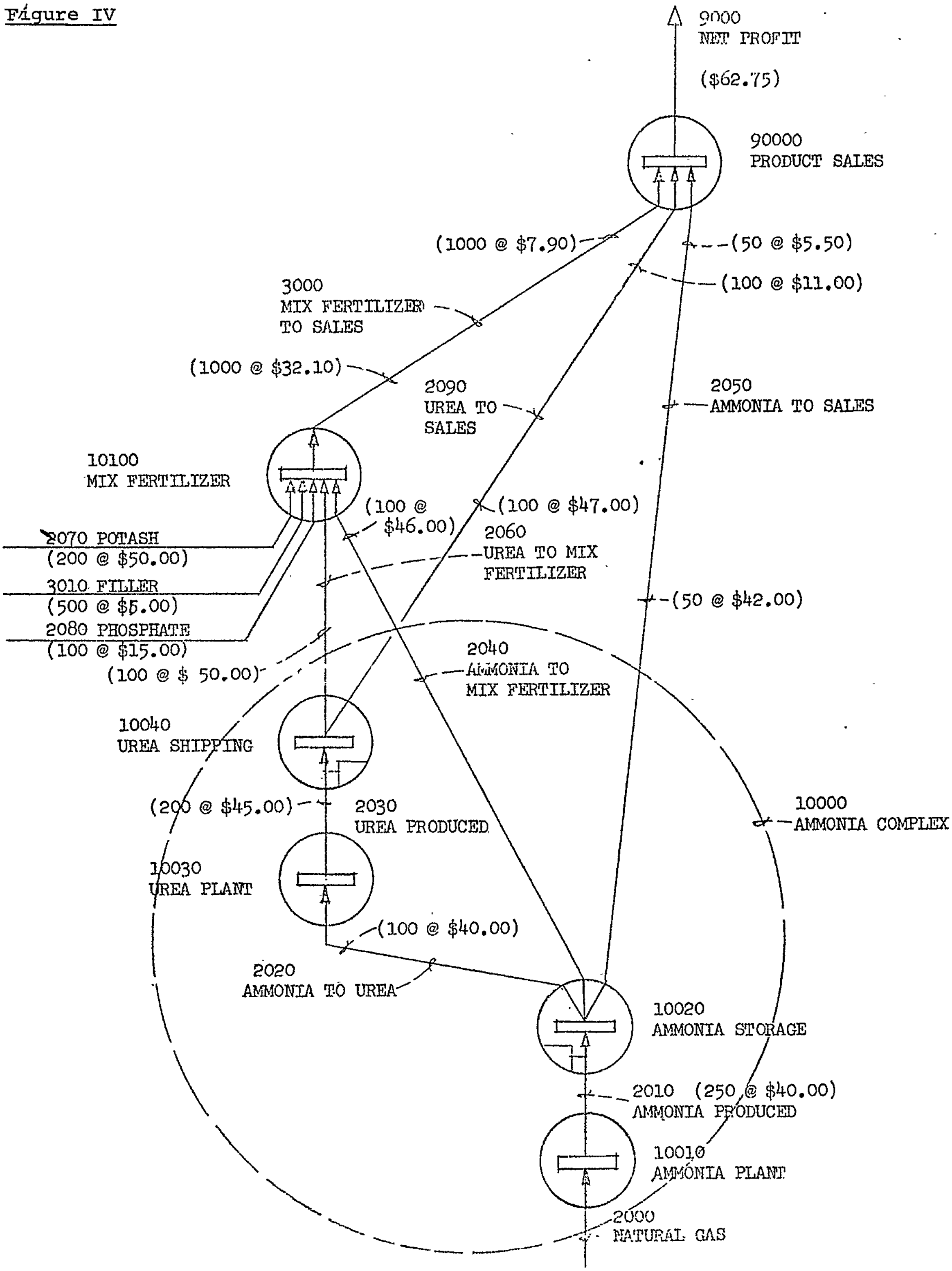
The user must specify all network product demand streams (sales); in addition, the user can also specify levels for production, intercompany transfers, product movements and raw material inputs.

After the network is flow balanced, the system is costed from given node and stream relationships. The costing procedure follows a reciprocal flow path up the network. As costs pass through the network, individual node and stream costs are accumulated until final "added" costs are obtained. These "added" costs, when summed, reflect the total cost of product at the point it leaves the network.

Physical Representation

The representation of a simplified production and distribution system which appears in Figure IV illustrates how the simulation program models a physical system. This sample involves a basic production plant for ammonia and urea. The products are both sold and used as raw material at secondary processing plants (mixed fertilizer).

Figure IV


9000
NET PROFIT
($62.75)
90000
PRODUCT SALES
(1000 @ $7.90)
(50 @ $5.50)
(100 @ $11.00)
3000
MIX FERTILIZER
TO SALES
(1000 @ $32.10)
2090
UREA TO
SALES
2050
AMMONIA TO SALES
10100
MIX FERTILIZER
(100 @
$46.00)
(100 @ $47.00)
2060
UREA TO MIX
FERTILIZER
2070 POTASH
(200 @ $50.00)
3010 FILLER
(500 @ $5.00)
2080 PHOSPHATE
(100 @ $15.00)
(50 @ $42.00)
(100 @ $ 50.00)
2040
AMMONIA TO
MIX FERTILIZER
10040
UREA SHIPPING
(200 @ $45.00)
2030
UREA PRODUCED
10000
AMMONIA COMPLEX
10030
UREA PLANT
(100 @ $40.00)
2020
AMMONIA TO UREA
10020
AMMONIA STORAGE
2010 (250 @ $40.00)
AMMONIA PRODUCED
10010
AMMONIA PLANT
2000
NATURAL GAS

(A) Sales Requirements

For flow balancing this hypothetical system from top to bottom, assume the following specified sales requirements: (capacity limitations are not reached and inventory levels remain unchanged)

1000 tons of mixed fertilizer - stream 3000 (10% ammonia, 10% urea, 10% phosphates, 20% potash, 50% filler)

100 tons of urea - stream 2090 (0.5 tons of ammonia per ton of urea produced)

50 tons of ammonia - stream 2050

(B) Material Balancing

1) Node 10100 Mixed fertilizer

Output - 1000 tons of mixed fertilizer (stream 3000)

Input - 100 tons of urea (stream 2060)

100 tons of ammonia (stream 2040)

100 tons of 100% phosphate (stream 2080)

200 tons of potash (stream 2070)

500 tons of filler (stream 3010)

2) Node 10040 Urea Shipping

Output - 100 tons urea to mixed fertilizer (stream 2060)

100 tons of urea to sales (stream 2090)

Input - 200 tons of urea (stream 2030)

3) Node 10030 Urea

Output - 200 tons of urea (stream 2030)

Input - 100 tons of ammonia (stream 2020)

4) Node 10020 Ammonia Storage

Output - 50 tons to urea (stream 2020)

100 tons to mixed fertilizer (stream 2040)

100 tons to sales (stream 2050)

Input - 250 tons produced ammonia (stream 2010)

5) Node 10010 Ammonia Plant

Output - 250 tons ammonia produced (stream 2010)

(C) System Costing

The costing of the sample system would proceed from bottom to top accumulating costs along the way.

1) Node 10010 Output ammonia - $40.00/ton

2) Node 10020 Output ammonia - $40.00/ton

3) Node 10030 Output urea -

ammonia cost	$20.00/ton
processing cost	25.00/ton
total	$45.00/ton

4) Node 10040 Output urea

urea cost	$45.00/ton
handling and shipping	2.00/ton
total	$47.00/ton

5) Node Set 10000

Fixed overhead cost of $800 to be allocated equally by volume to all products leaving the node set.

$800/400 tons = $2.00/ton

Ammonia costs from basic plant

$40.00 + $2.00 = $42.00/ton

Urea from basic plant

$45.00 + $2.00 = $47.00/ton

6) Node 10100 Mix Fertilizer

a. Raw Material Costs

Ammonia cost: $42.00 + transportation: $4.00
= $46.00 x 10% conversion = $4.60

Urea cost: $47.00 + transporation: $3.00
= $50.00 x 10% conversion = 5.00

Phosphate Cost = $15.00 x 10% conversion = 1.50

Potash cost = $50.00 x 20% conversion = 10.00

Filler cost = $ 6.00 x 50% conversion = 3.00

Total Raw Material Cost Per Ton		$24.10
b. Processing Cost	$8/ton	8.00
c. Total (Mix Fertilizer - $/ton		$32.10

7) Node 90000 Product Sales

a. Assume the following sales prices and added transportation costs, gross profits are as indicated:

	Sales Price $/Ton	Transportation Cost $/ton	Production Cost $/ton	Gross Profit $/ton	Total
Ammonia (strm 2050)	$49.00	$ 1.50	$42.00	$ 5.50	$ 275
Urea (strm 2090)	60.00	2.00	47.00	11.00	1,100
Mix Fertilizer (strm 3000)	41.00	1.00	32.10	7.90	7,900
					$9,275

8) Selling Expense for area total $3,000

less selling expense	3,000
Net profit	$6,275

Mode of Operation

The LBS Model is operated in an interactive environment using a computer time-sharing system. However, due to the large volume of data required to initially load the model, data is prepared and entered on an off-line basis.

Once the basic model has been structured and the files created, the executive, through a remote CRT terminal, is able to quickly evaluate a large number of planning alternatives merely by changing those variables that affect network configurations, input data and operational parameters relative to the particular situation.

Model Implementation and Data Collection

Validation and implementation of the LBS model proceeded in two stages. During the first stage (a technical feasibility and educational phase), the model was used to duplicate the previous year's business plan. A single solution was tested, namely the one based upon the assumptions and calculations used in manually generating the original plan. The purposes for going through this substantial exercise were the need to insure that the generalized simulation model, as designed, could cope with all the calculational aspects required in generating the business plan, and to determine the degree of detail required for an "accurate" simulation.

For the second stage, the model will be run in parallel with the manual preparation of the 1972 business plan. The areas of concern in the second stage will be more the timing, systems and personnel aspects. Answers to such questions as -

(1) How will the presence of the simulation model aid in the planning process and assist top management in selecting and evaluating alternative company strategies?

(2) What maintenance effort is required to arrive at a simulation system which can be routinely used by the appropriate people?

(3) What are the economics involved in the implementation and use of such a program?

-will be obtained during this phase.

The initial collection and preparation of input data for the LBS model involved considerable effort. The structure of the fertilizer system was designed on the basis of the network existing at the time of the 1971 Business Plan. This structure, being relatively static, will require only minor modifications as the physical structure itself changes.

Cost relationships for basic production plants were generated from detailed cost simulators developed for each plant location. These detailed cost simulators were constructed using the LBS system. These cost relationships will be periodically updated. Formulation recipes at all basic and secondary plants, externally sourced products and transportation restrictions and rates are prepared from current operational data and are continually monitored for changes.

Resources to Develop & Implement the Model

In designing and implementing the LBS model, a cautious and thorough approach was chosen to insure the proper functioning of the model.

All basic design work was performed by W. R. Grace & Co. personnel. This effort involved approximately four man-years. After the design work was completed, three management consulting organizations evaluated the design specifications to determine if they satisfied the specific objectives for which the LBS model was being developed. Based on their evaluation and critique, necessary modifications were made to the model design.

Rather than program the model "in-house", it was decided to award the programming of the model to a software consultant. The LBS model was programmed by National Computer Software Services, Inc. of Stamford, Connecticut in a period of six months.

The testing and validation of the LBS model using the 1971 Business Plan required five people for a three month period to gather and input data and verify the model results.

Communication Techniques

All data input, data retrieval and output reports for the LBS model are in a conversational type language using a combination Cathode Ray Tube/Hard Copy Unit. No knowledge or prior experience with computer languages is required.

In addition to the standard input/output reports which can be obtained on a selective basis from a remote terminal, the LBS model can provide graphic plots of the results. These network plots are created in a batch environment using a CalComp plotter. Plots can be generated in the following fashion:

Network Plot: Network plot of the entire system in which only node sets and inter-connecting streams appear.

Partial Network Plot: Any predefined portion of the network. This is displayed with the same information as a full network plot.

Node Set Plot: A plot of all nodes and streams within a specified node set. Detailed information relative to each node is displayed on this plot.

Because of the complex nature of the W.R. Grace & Co. fertilizer system, a visual display of the model nodes and interconnecting streams provides management with a clear representation of the relationships and interaction between the various segments of the fertilizer operation. From the graphic plots management can quickly determine product allocations, accumulated costs and the effects of alternative decisions on the various parts of the system.

Future Plans

In summary, the LBS model is a simulation tool which represents the cost and material behavior of the fertilizer network which is used by top management for evaluating planning alternatives.

The present model determines those material flows, inventory and production levels which balance the fertilizer network for a predefined planning or budgeting period. This balancing is performed without regard to the incremental material movements that occur over finite time intervals during the period. The possible inclusion of intermediate material balancing and inventory volume fluctuations is now being investigated since the ability to perform simulation in discrete time stages is necessary for the model to be effective as a tool for operations as well as planning.

An expanded representation of the distribution network is also being examined. Flow balancing is now started with specified volumes on streams effluent from terminals and primary warehouses. Extension of the system to final distribution points is a desired refinement of model.

Simultaneous with the above two proposals the feasibility of incorporating optimization techniques will be investigated.