October, 2007

SIMULATION-BASED ENVIRONMENT FOR MULTI-ECHELON CYCLIC PLANNING AND OPTIMISATION

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Keywords: Multi-echelon cyclic planning, optimisation, integrated approach, supply chain simulation.

ABSTRACT

The paper focuses on the development of simulation-based environment for multi-echelon cyclic planning and optimisation at the product maturity phase. It is based on integration of analytical and simulation techniques. Analytical techniques are used to obtain initial planning decisions under conditions of stochastic demand and lead time. Simulation techniques extend these conditions to backlogging and capacity constraints. Simulation-based optimization is used to analyse and improve cyclical decisions received from the analytical model. Simulation environment is built in the ProModel simulation software. Automatic generation of simulation model is provided by using the ProModel ActiveX technology and VBA programming language. An example of multi-echelon cyclic planning and optimisation using this environment is given.

INTRODUCTION

Application of the MILP analytical model (Campbell and Mabert, 1991) in multi-echelon cyclic planning is limited by assumptions of a constant demand, fixed set-up costs and lead times. These assumptions significantly decrease the complexity of the problem, but still could be considered useful for mature products.

Simulation technology provides an experimental approach to supply chain analysis and optimisation that allows the analyst easily to introduce into the multi-echelon cyclic planning procedure variability of demand, lot sizes and processes lead times, to model processes that contain nonlinearities, combinatorial relationships and uncertainties, and take into account constraints at different echelons of the supply chain.

By building a virtual reality out of small components and not requiring a rigid structure of the analytical model, a simulation model provides the great flexibility that allows in the planning procedure to estimate consequences of planning decisions in time and by echelon; to perform sensitivity analysis of parameters that influence optimality of the cyclic schedule, to define optimal planning parameters for each of supply chain nodes during the product maturity phase, and analyse stability of the optimal production schedule under conditions of uncertain demand and finite capacity.

INTEGRATING ANALYTICAL AND SIMULATION TECHNIQUES

Integrated approach to multi-echelon cyclic planning and optimisation at the product maturity phase is based on integration of analytical and simulation techniques. Analytical techniques are used to obtain initial planning decisions under conditions of stochastic demand and constant or stochastic lead time. Simulation techniques extend these conditions to backlogging and capacity constraints.

In this case, the multi-echelon cyclic planning problem is formulated as a simulation-based optimisation problem that is aimed to determine optimal parameters of cyclic schedules at different supply chain echelons. To analyse results of simulation experiments and control simulation runs, optimisation techniques are imbedded into simulation software.

NETWORK SIMULATION

The following are assumptions that define the scope of a network simulation model:

- Demand is considered to be uncertain, while predicting the demand mean value, its variations are estimated by a standard deviation of the demand per period;
- Lead times of the processes are considered to be variable and/or stochastic;
- Lot sizes of the products are variable;
- Capacities are limited, or finite;
- Demand is considered to be independent only for customised products;
- Full backlogging is allowed;

- Costs: fixed set-up and ordering costs, linear inventory holding costs are analysed;
- Multiple products;
- Multi-echelon cyclic replenishment policy is introduced;
- Planning is performed for a finite planning horizon.

The main idea of a cyclic schedule that describes a multi-stage schedule is to use fixed order intervals at each stage or echelon while synchronizing these cycles in a multi-echelon supply chain in order to keep cycle inventories and order costs low. For that, additional cyclical replenishment constraints are introduced in an optimisation algorithm that will define main cyclic policy types, i.e. *integer-ratio policy*, in which the reorder interval at any stage is the only integer.

A network simulation model itself is built as process oriented one. It models processing of parts, assembling and packing end products, storage of raw materials, semi-finished and finished products, and distribution of packed products to customer sites. The supply chain network is defined as an input in the format that allows automatically reading it within the simulation environment.

The network is supposed to have a one-directional flow of goods. It is presented by two types of atomic elements: stock points and processes. The *stock point* defines any buffer or storage where output products of the process are stored. The *processes* correspond to transformations of a set of input products to a set of output products, such as assembling, packaging and transportation operations. Stock points and processes are graphically represented by triangles and rectangles, correspondingly. Any process with a stock point connected with a directed arc defines a stage. A set of stages that belong to the same network level creates an echelon.

The supply chain generic network is constructed from basic sub-networks, such as linear, convergent and divergent (see Figure 1). The replenishment and delivery logic for sub-networks is defined. For example, in the linear sub-network (1), a stage has one predecessor and one successor (except the last echelon). The replenishment order is placed to the immediately preceding stage. If on hand stock is insufficient to fulfil this order, then the backorder is created. Orders and backorders are delivered to the immediately succeeding stage.

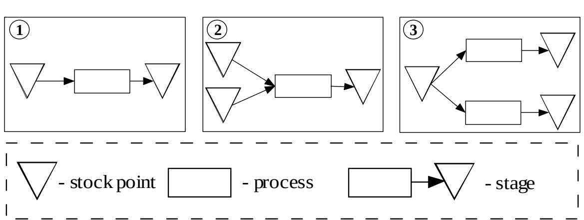

Figure 1: Basic Sub-Networks of Supply Chain

Average total cost of a cyclic schedule that includes a sum of set-up, ordering and inventory costs is defined as the main network performance indicator. However, in order to avoid unconstrained minimization of the total cost, service performance measures such as order fill rate, demand fill rate, product fill rate or cycle service level are introduced as additional performance measures to be controlled in optimisation experiments. Here, the performance measurement approach is based on a trade-off between the total cost objective and a specific service performance measure which is balanced by introducing weight coefficients and composition of a multi-term objective function.

As control parameters for multi-echelon cyclic replenishment policy, lengths of replenishment cycles and order-up-to-levels for stock points are defined. These parameters identify so called controllable variables or multiple decision variables that influence above described performance measures of a multi-echelon supply chain and have to be optimised by performing simulation-based optimisation experiments.

SIMULATION-BASED ENVIRONMENT

The simulation environment for cyclic planning and optimisation provides automatic generation of the simulation model of a generic network described in the Excel format; definition of an initial point for simulation optimization using analytical calculus, and realization of a simulation-based optimization algorithm. As an initial or starting point for optimisation in simulation based environment, an optimal solution received from MILP problem could be used as well (see Merkuryev et. al., 2007).

The simulation environment for cyclic planning and optimisation includes the following four components (Figure 2):

1. *Database component* built in the Excel format that contains network and dataset subcomponents. The dataset subcomponent includes basic data about products, costs, capacities, time steps or period in the planning horizon and customer demand.

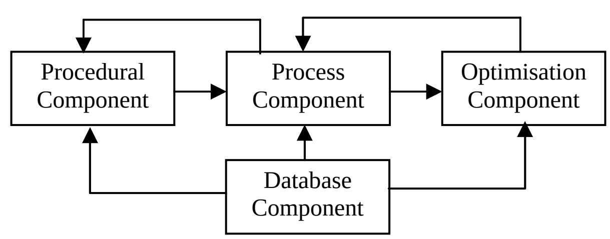

Figure 2: Basic Components of Simulation Environment

2. *Procedural component* that by using analytical calculus generates cyclic schedules for different products and contains lot sizing procedures workable under conditions of time-varying demand.
3. *Process component* where the network is built up and simulated, cyclic schedules are modelled, inventory levels are controlled, and the network performance measures are estimated.
4. *Optimisation component* to find optimal parameters of a multi-echelon cyclic schedule and optimise network simulation model performance measures.

Automatic generation of a supply chain simulation model is supported by ProModel's ActiveX Automation capability (Promodel Corp, 2007) that allows to automatically generate simulation models from external applications by using the VBA programming language. Data exchange between database, process, optimization and procedural components is illustrated in Figure 3.

Database Component

The database component consists of a network and dataset subcomponents. The network subcomponent describes a structure of the supply chain. The dataset subcomponent includes basic data about inventory control policies, costs, capacities and end-customer demand.

The database component is built in the Excel format, and includes the following six worksheets (Figure 4):

- 'Network_matrix' worksheet defines a supply chain structure by its matrix representation. Rows and columns correspond to stock points, while cells correspond to connecting them process numbers.
- 'Network_data' worksheet is automatically generated from 'Network_matrix' and is used to efficiently read matrix data more from VBA code.
- 'Stockpoint_data' worksheet defines graphical positions of stock points in the model layout, initial inventory levels, replenishment cycles, order-up-to levels and safety stocks, which are obtained from the procedural component.
- 'Process_data' worksheet contains graphical positions of processes in the model layout, as well as the average processing lead time and its standard deviation, capacity constraints.
- 'Costs_data' worksheet specifies inventory holding, setup and ordering costs.
- 'Endcustomer_demand' worksheet determines the average end-customers demand per period and its standard deviation.

Examples of database component worksheets that define a network matrix and data about stock points and processes are given in Figures 5, 6 and 7.

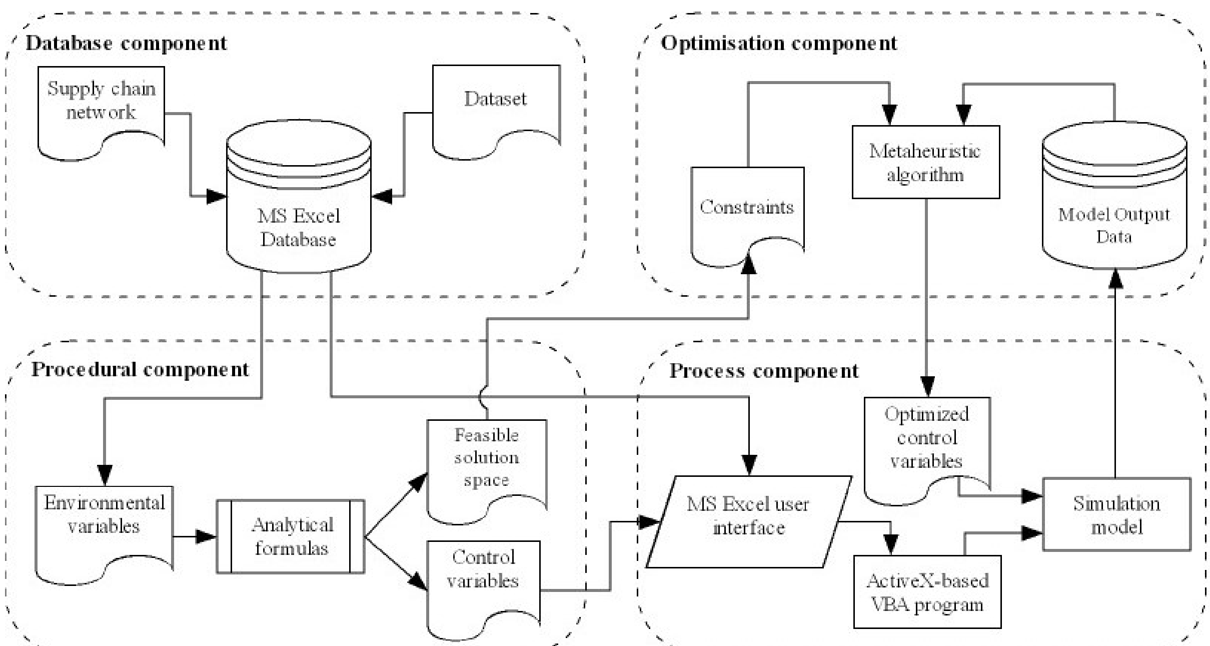

Figure 3: Architecture of Simulation-Based Environment

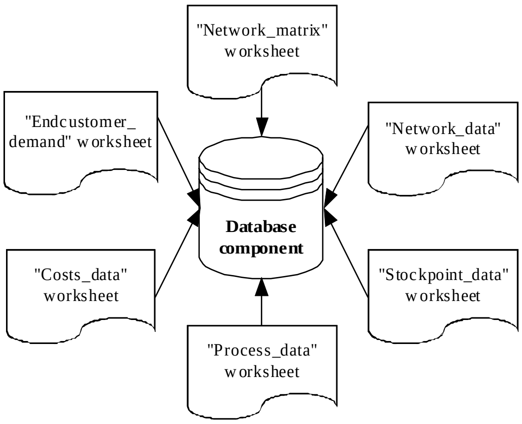

Figure 4: Structure of Database Component

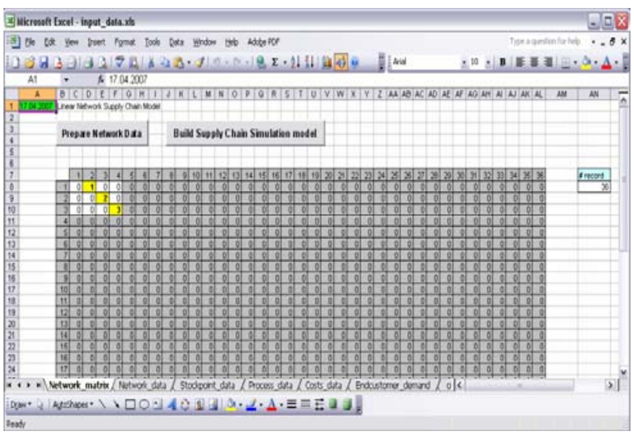

Figure 5: Network Matrix Worksheet

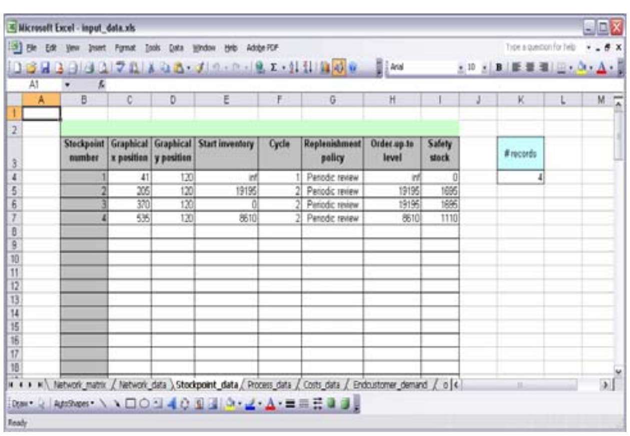

Figure 6: Stockpoint_data Worksheet

Procedural Component

The procedural component is built to generate cyclic schedules using simplified analytical calculus (Simchi-Levi et.al., 2003; Simchi-Levi & Zao, 2005). The analytical model assumes that the end-customer demand is normally distributed, lead times are constant or stochastic, process capacities are infinite, and backlogging is not allowed.

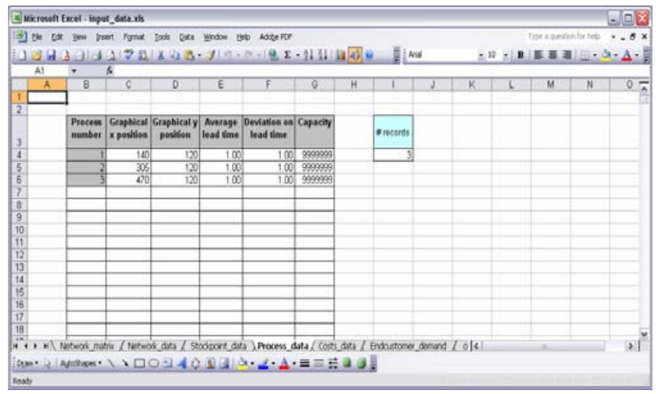

Figure 7: Process_data Worksheet

The following formulas are used in the procedural component in order to estimate replenishment control parameters that refer to the stock points immediately preceding end-customers:

$$Cy_i = \frac{\sqrt{2 * \sum_{k \in succ_i} \mu_{d_{k,i}} * Cs_i \Big/ Ch_i}}{\sum_{k \in succ_i} \mu_{d_{k,i}}}, \tag{1}$$

$$\mu_{DDLCy_{k,i}} = \mu_{d_{k,i}} * (Cy_i + \mu_{L\, j \in i}), \tag{2}$$

$$\sigma_{DDLCy_{k,i}} = \sigma_{d_{k,i}} * \sqrt{(Cy_i + \mu_{L\, j \in i})}, \tag{3}$$

$$SS_i = NORMSINV(CSL_i) * \sqrt{\sum_{k \in succ_i} \sigma^2_{DDLCy_{k,i}}}, \tag{4}$$

$$S_i = \sum_{k \in succ_i} \mu_{DDLCy_{k,i}} * SS_i, \tag{5}$$

where Cy_i is a replenishment cycle of stock point i, SS_i - safety stock of stock point i, S_i - order-up-to level of stock point i, $\mu d_{k,I}$ is an average demand of end-customer k for stock point i, $\sigma d_{k,i}$ is standard deviation of demand of end-customer k for stock point i, Cs_i - setup cost at stock point i, Ch_i - unit inventory holding cost at stock point i, μL_j is average lead time of process j, σ_{L_j} - standard deviation of lead time of process j, $\mu_{DDLCy_{k,i}}$ - average demand of end-customer k to stock point i during lead time and replenishment cycle, $\sigma_{DDLCy_{k,i}}$ - standard deviation of demand of end-customer k to stock point i during lead time and replenishment cycle, and $Succ_i$ is the set of indices of stock points immediately following the stock point i.

In formulas (1) and (4), an aggregate demand is introduced that allows multiple end-customers to be connected to the same stock point.

If a stock point is not immediately connected to end-customer(-s), then the following updates are made to formulas (2) and (3):

$$\mu_{DDLCy_{m,i}} = \mu_{d_{k,i}} * (Cy_i + \sum_{j \in i} \mu_{L_j}), \quad (6)$$

$$\sigma_{DDLCy_{m,i}} = \sigma_{d_{k,i}} * \sqrt{(Cy_i + \sum_{j \in i} \mu_{L_j})}. \quad (7)$$

In this case, replenishment orders from a current stage are used as the demand in immediately preceding stages.

Using of simplified analytical calculus allows to define initial control parameters of a multi-echelon replenishment policy that are used as a starting solution in simulation optimisation experiments. The procedural component is also used in order to specify search spaces for decision variables that are used in the optimisation component. Here, required customer service levels are introduced and are taken into account in calculations.

Process Component

The process component performs two different tasks: 1) automatic generation of a supply chain simulation model, and 2) simulation runs, i.e. simulation of cyclic schedules in a multi-echelon environment while controlling inventory levels and estimating the performance measures.

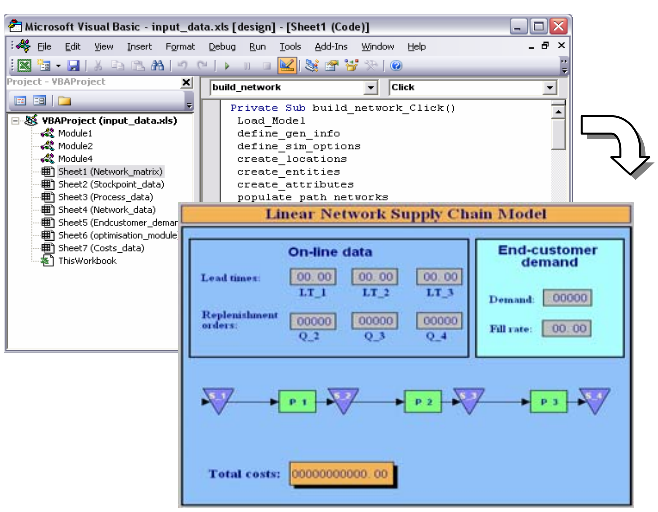

Figure 8: Automatic Generation of Simulation Model

Automatic generation of a supply chain simulation model is supported by ProModel's ActiveX Automation capability that allows to automatically generate simulation models from external applications by using the VBA programming language (Promodel Corp., 2007). Automatic generation of a simulation model by using ActiveX-based VBA programmes and data defined in the database component is illustrated in Figure 8.

Here, the ActiveX-based VBA program is developed in MS Excel and consists of subroutines. It provides Promodel operational control and allows accessing the model information, e.g. loading a blank simulation model; defining a title of the model, path to a graphical library, animation speed, simulation length and number of replications; creating entities, locations of stock points and processes, path networks used to establish links between stock and process points; creating arrays, variables, functions and procedures; definition of entities arrival schedule, sequence of processes and their operational logic (Figure 9).

In the network simulation model, the processing logic is defined for each stage in the network. It is initialised at the beginning of each period, when the end-customer demand is generated. If order arrivals are scheduled for this period, then events are processed in the following sequence:1) waiting incoming orders, 2) fulfilling backorders (if any exist), 3) fulfilling the demand. If on hand inventory is insufficient to fulfil the demand, then it is saved as a new backorder. At the end of a period, reordering decision is made according to the cyclic planning policy, and corresponding costs are calculated.

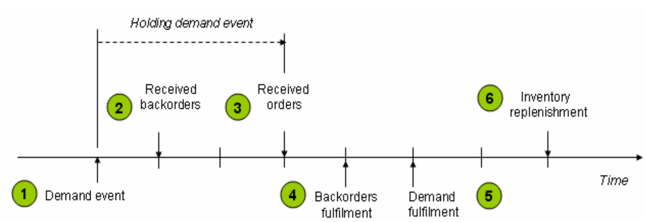

Figure 9: Processing Logic and Sequence of Events

In order to verify automatically generated network simulation models, a chart-based tracing procedure is used (Figure 10). The following are examples of main points verified while tracing the automatically generated simulation models: tracing of sent orders; checking when on hand inventory is equal to inventory position or when on hand inventory is not equal to inventory position.

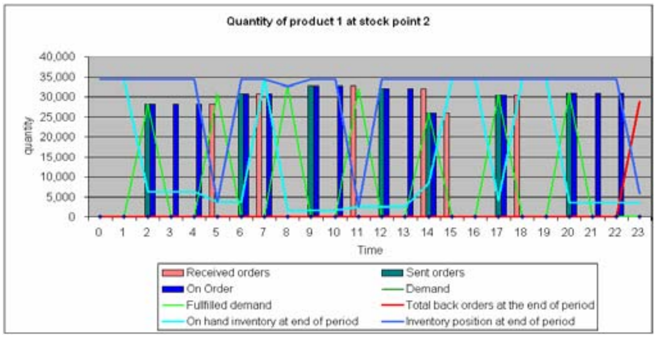

Figure 10: Example of Tracing Chart

Optimisation Component

The optimisation component aims (Merkuryev et.al., 2007) to define an optimal cyclic schedule for each of the supply chain stages during a maturity phase of the product life cycle in order to minimize the sum of inventory holding, setup and ordering costs while satisfying customer service requirements defined by a target customer service level.

Advanced simulation-based optimisation techniques apply metaheuristics and optima-seeking methods. Here, the optimization component based on the SimRunner tool (Promodel SimRunner, 2002) uses outputs from the process component and network model inputs, and on the basis of both current and past output values decides upon a new set of input values to be simulated (Figure 11).

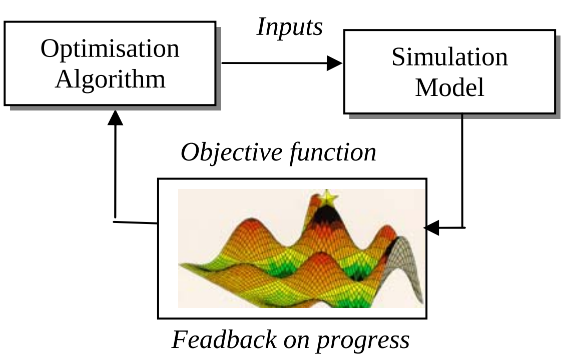

Figure 11: Objective Function Definition

SimRunner is an optimization software add-on included in the ProModel, MedModel, and ServiceModel Optimization Suites. The optimization procedure implements a genetic algorithm to explore a search space, as well as neural network-based metamodels in order to estimate an objective function without performing simulation experiments, in order to decrease time necessary to solve the optimisation problem.

The objective function (Figure 12) is defined in such a way that it minimizes total costs and does not allow stock-outs. In order to ensure that the objective function does not unintentionally favour any particular statistic, these values are weighted via assigning importance coefficients of optimization criteria.

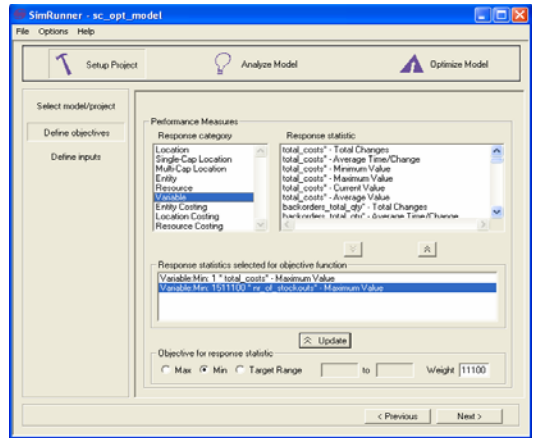

Figure 12: Objective Function Definition

Multiple decision variables are divided into two sets that include correspondingly replenishment cycles and order-up-to levels for stock points. While all decision variables are discrete, their metric scales have very different range of possible values. During simulation-based optimisation experiments, 'order up-to-level' variables are changed with a discrete step size defined by 10, 100 or 1000 product units depending on a particular case.

EXAMPLE

As an example, let us consider a three-echelon linear supply chain network (Figure 8) consisting of four stock points and three processes. The following dataset (Table 1) describes the test environment. Number of periods in the planning horizon is equal to 34.

Table 1: Input Data

Stock points / **Inputs**	**1**	**2**	**3**	**4**
Inventory holding cost (Ch_i), CU		0.09	0.02	0.06
Setup cost (Cs_j), CU		400	800	200
Ordering cost (Co_i), CU		5.00	9.15	3.15
Average lead time (μL_j), periods		2	2	1
Variability on lead time (σL_j), periods		1	1	0.2
Customer service level (CSL_i), %				90
Average demand per period ($\mu d_{k,i}$), units	10000			
Variability on demand ($\sigma d_{k,i}$), units	2000			

Initial values of decision variables received from the procedural component using analytical formulas (1) – (7) are given in Table 2.

Table 2: Initial Values of Decision Variables

Stock points / **Inputs**	**1**	**2**	**3**	**4**
Replenishment cycle (Cy_i), periods		2	4	2
Order-up-to level (S_i), periods		19195	19195	8610

In order to specify the search space, lower and upper bounds of decision variables are estimated in the procedural component by using analytical formulas. Here, lower and upper bounds for order-up-to levels are defined by 90% and 97% of CSL, correspondingly (Table 3). Search regions for replenishment cycles vary between 1 and 12 time periods.

Table 3: Search regions for order-up-to levels

Stages / Bounds	1	2	3	4
Lower		19190	19190	8610
Upper		19990	19990	9130

The optimization procedure has been completed within 431 experiments. Simulation optimization experiments searching for the optimal solution are illustrated in Figure 13. The solution set that define optimal values of decision variables is summarized in Table 4.

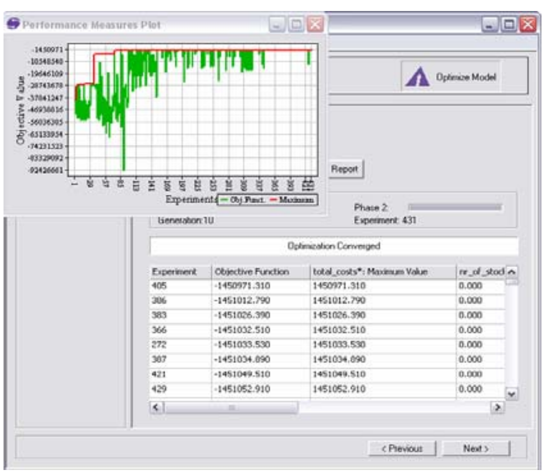

Figure 13: Simulation Optimization Experiments

Table 4: Optimal Values of Decision Variables

Stages / Variables	1	2	3	4
Replenishment cycle		5	3	2
Order-up-to level		19195	19538	8610
Total costs:	1450971			

Based on the solution set received, the optimal cyclic schedule per each stage of the supply chain is created. As a result, replenishment orders to fulfill inventories' up-to-order level are made per stage 2 in periods 2, 7, 12, per stage 3 – 2, 5, 8, etc., and for the last stage – 2, 4, 6, etc.

CONCLUSIONS

The simulation environment for cyclic planning and optimisation is proposed that includes the following components: the database that contains network and dataset subcomponents about products, costs, capacities, etc.; the procedural component that by using analytical calculus generates cyclic schedules parameters for different products under conditions of a time-varying demand; the process component where the network is built up and simulated, cyclic schedules are modelled, inventory levels are controlled, the network performance measures are estimated; and the optimisation component to find optimal parameters of cyclic schedules.

ACKNOWLEDGMENTS

The presented research is supported by the ECLIPS Specific Targeted Research Project of the European Commission "Extended Collaborative Integrated Life Cycle Supply Chain Planning System".

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BIOGRAPHIES

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