Demand Chain Management Model Validation and Testing: A System Dynamics Approach

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***Abstract* – The Demand Chain Management (DCM) system consists of many closed loop feedback relations and thus reinforces the need for a dynamic modeling. A System Dynamics (SD) model for DCM is developed with the help of expert opinion, in consistence with the standard procedure of system dynamics modeling. This work presents the validation and testing of the DCM model according to System Dynamics methodology.**

***Keywords* – System Dynamics (SD), Demand Chain Management (DCM), Closed Loop Feedback Relationships.**

I. INTRODUCTION

In DCM system the close integration of operations between manufacturers, suppliers, and customers by synchronization of various activities and flow of information, to fulfill customers demand on a real-time basis increases complexity and adds dynamics. In such complex systems perturbations in one factor impacts other factor which in turn may impact some other factor until they form a structure of closed loops to influence the factor which started the perturbation. Therefore, the efforts directed at resolving one problem is not separated from other issues that form part of system or influence it. In many cases, adjustments made in one factor through some decision is not limited to the factors within the system but outside it as well, such as is seen in the changes in demand due to some decision by Government or because of change in geographic location or entry of a new competitor. It is these impacts that need to be assessed and incorporated in to the modeling framework for more realistic assessment of demand. Closed loop interactions constrain the outcome of any decision, which may not be obvious to the decision maker or manager and may not be directly subjected to manipulation by them. Therefore, to have a realistic assessment of demand it is essential that interrelatedness between various factors and their closed loop interactions is understood and clearly represented. This necessitates the need for a dynamic model of DCM.

Validation of system dynamics model is necessitated to establish sufficient confidence in the model (Sahay *et al*., 1996). Forrester and Senge, (1980) state that validity is fundamentally determined by the extent to which the model fulfils the purpose for which it is built. A systematic validation process first tries to establish the structural validity of the model with respect to the modeling purpose. This is crucial because the purpose of a system dynamics model is to evaluate its behavior to alternative structures (strategies, policies) (Saysel *et al*., 2002). The second step involves accessing the accuracy of model behavior, which is meaningful only if there is sufficient confidence in the model structure. As a consequence, tests for model behavior are typically performed after structural validation. A typical set of model structure validation tests may involve the use of parameter verification, extreme conditions tests, boundary adequacy test and dimensional consistency test. In behavior validity tests, emphasis is mainly on pattern prediction rather than on point prediction, primarily due to the long term orientation of the models (Barlas, 1996). These tests involve behavior reproduction tests, dimensional consistency test, boundary adequacy test, behavior sensitivity tests and extreme condition tests. The validation scheme for the proposed model follows the steps suggested by Mohapatra *et al*., (1994). It is interesting to note that there is a broad agreement amongst those who have dealt with the issue of validation of system dynamics mode1, that there is no such thing as absolute validity, only a degree of confidence can be established, which becomes greater as more and more tests are passed.

This work presents a System Dynamic (SD) model of Demand Chain Management (DCM) through literature review, expert's opinion through NGT and the framework of SD methodology. This model is further validated and tested according to the SD procedure.

II. LITERATURE REVIEW

Literature review for System dynamics methodology reveals a wide range of application of SD method in dynamic and complex situations. The use of SD modeling in supply chain was mostly limited to the work in demand amplification; some important contributions are Forrester, 1958; Burbidge, 1961; Saporito, 1994; Lee *et al.*, 1997; McGuffog, 1997; Taylor, 2000; Holweg *et al.*, 2005. Recently, it has gained popularity due to the complexity involved in supply chain. The dynamic nature of supply chain systems and their behavior depends on the uncertainties of customers' demand, suppliers, logistics routes, and alternative inventory methods. In fact uncertainty rules the supply chain therefore it is natural to apply SD simulation (Ashayeri and Lemmes, 2006).

System dynamics presupposes that the behavior of any system is essentially dependent upon its structure and inter relationship between the system components (Richardson and Pugh, 1989). It is particularly well suited for problems whose behavior is governed by feedback relationships (Vennix, 1996). DCM is one such system, which is dynamic, multi-loop, and has non-linear character of feedback system along with flows and stocks of the inventories and time delays associated with fulfillment of demand and its impact. For effectiveness of DCM a clear understanding of structure is required. The process of creating simulation model helps to clarify the system structures and makes modelers assumptions of how system works explicit. Once the model is built it can be used to simulate the effect of proposed actions on the problem and the system as a whole (Stave, 2003). The following features of system dynamics make it a desirable methodology to analyze DCM. These are its ability (Mahapatra *et al.*, 1994) to:

a. Dynamically model complex, nonlinear relationships of large number of variables. This enables one to consider many related aspects of a problem, resulting in holistic approach.
b. Explicitly model qualitative factors.
c. Experiment with alternatives.
d. Generate alternative scenarios.
e. Incorporate time delays in decision-making and implementation.
f. Test the efficacy of alternatives in a simulated environment before being implemented.

III. METHODOLOGY

SD simulation model for DCM involves following steps (Mahapatra *et al.*, 1994)

1. Define the problem
2. Define the model boundary and build model aggregate
3. Build the detailed model
4. Test and validate the model
5. Analyze the model and evaluate the policy alternatives
6. Recommend the most viable policy

System Dynamics model is developed using simulation software, 'Powersim Constructor' version 10. The building blocks of the Powersim Constructor are shown in Table-3.1.

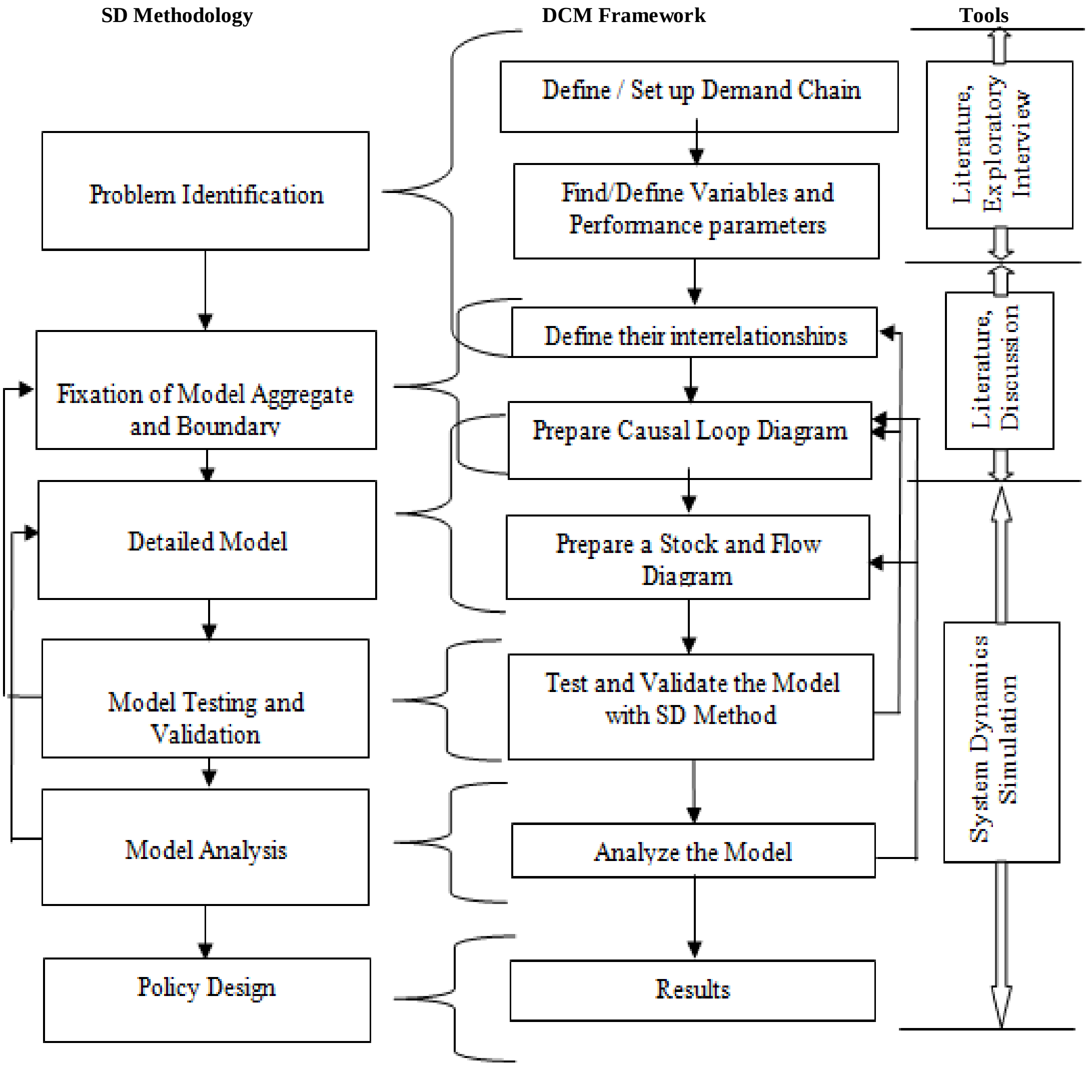


Fig. 3.1. System Dynamics-DCM Framework.

Application of SD methodology for DCM is shown by a diagram in Fig 3.1. The framework shows the integration of SD methodology and DCM along with the corresponding tools used. Literature review, exploratory interviews and NGT have helped in problem identification, defining model boundaries and developing interrelationships with model variables. A causal loop diagram is developed based on the interrelationships taken from literature and validated by experts through NGT (Fig 3.2), which depicts the feedback relationships in DCM.

3.1. *Causal Loop Diagram*

Causal loop diagram (Fig 3.2) is visual representation of cause-effect relationship among the elements of a system, forming a structure of feedback loops.

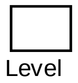
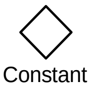
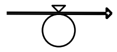
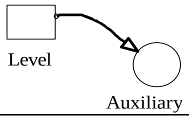
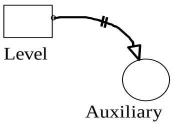
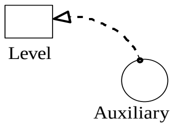
Fig. 3.2. Causal loop diagram for DCM.

The causal relationships represent the possible cause-effect relationship among the variables established with the consideration of conservation, direct observation and accepted theories. DCM's holistic view requires consideration of internal as well as environmental variables, thus the system consists of a large number of variables. While developing System Dynamics model of DCM these variables are suitably converted in appropriate stock, flow and information variables, to facilitate formulation of mathematical relationships among them.

3.2. *System Dynamics Model (Stock and Flow Diagram)*

In the next stage with the help of causal loop diagram a System dynamics model is developed. A Model (represented through Stocks and flows) consists of a set of interrelated components, called variables.

Table 3.1. Description of important system dynamics building blocks Source (Powersim, 2010) 4.

S. No.	Variable Name	Symbol	Description
1.	Level		It accumulates changes and is influenced by flows
2.	Auxiliary		A variable type, which contains calculations based on other variables
3.	Constant		Contains fixed values that are used in calculations of auxiliary variables or flows
4.	Flow with rate		It influences levels. The flow is controlled by the connected rate variable, normally an auxiliary variable
5.	Information link		Gives information to auxiliary variables about the value of other variables
6.	Delayed info-link		Used only when the auxiliary variable contains special delay functions
7.	Initializa--tion link		Gives start-up information to level variables about the value of other variables
8.	Cloud		Undefined source or outlet for a flow to, or from a Level.
9.	Dynamic Data Exchange Link		It is used to exchange data with an Excel spreadsheet, where it can be manipulated further.

It is constructed by defining these variables and the relationships between them. A brief description of the symbols used for defining system dynamics variables is given. These variables are connected using links and flows. Each link represents a relationship between the variables connected by the link. The exact definition of the relationship is defined as an equation in the system dynamics language. The use of stock (level) and flow in system dynamics model presents the power of mathematical integration in an intuitive and straightforward ways, which even a non-mathematician, can understand.

3.3. *Validation and Testing of SD Model*

The System dynamics model thus developed with the help of constructors presented in Table 3.1 is tested and validated. Validation of system dynamics model is necessitated to establish sufficient confidence in the model (Sahay et al., 1996). Forrester and Senge, (1980) state that validity is fundamentally determined by the extent to which the model fulfils the purpose for which it is built. A systematic validation process first tries to establish the structural validity of the model with respect to the modelling purpose. This is crucial because the purpose of a system dynamics model is to evaluate its behaviour to alternative structures (strategies, policies) (Saysel et al., 2002). The next step involves accessing the accuracy of model behaviour, which is meaningful only if there is sufficient confidence in the model structure. As a consequence tests for model behaviour are typically performed after structural validation. A typical set of model structure validation tests may involve the use of parameter verification, extreme conditions tests, boundary adequacy test and dimensional consistency test. In behaviour validity tests, emphasis is mainly on pattern prediction rather than on point prediction (Barlas, 1996). These tests involve behaviour reproduction tests, dimensional consistency test, boundary adequacy test, behaviour sensitivity tests and extreme condition tests. The validation scheme for the proposed model follows the steps suggested by Mohapatra et al., (1994). It is interesting to note that there is a broad agreement amongst those who have dealt with the issue of validation of system dynamics mode1, that there is nothing like absolute validity, only a degree of confidence can be established, which becomes greater as more and more tests are passed.

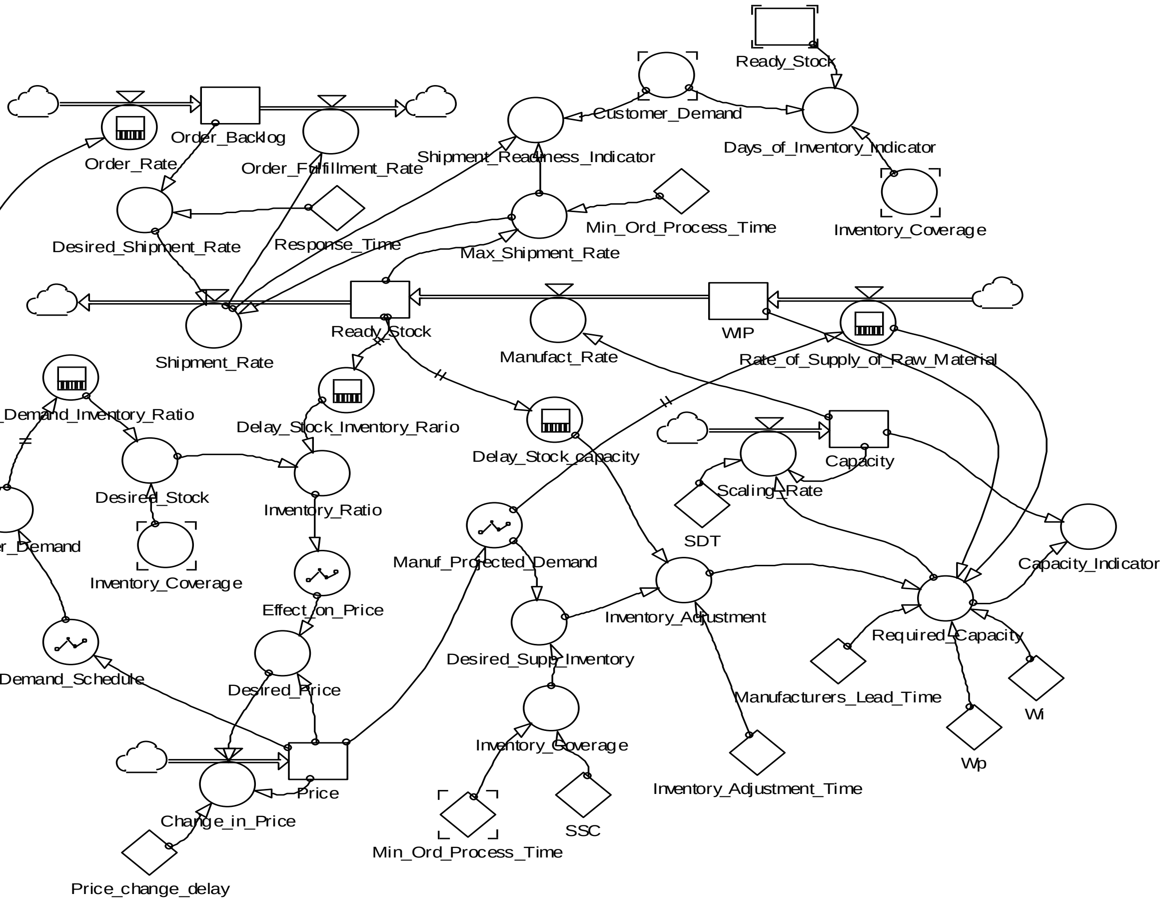


Fig. 3.3. Stock and Flow diagram for DCM.

3.3.1 *Base Case Scenario*

Results of the baseline run of the model are presented before the model validation exercise is taken up. This will give a clear picture of the structure and behaviour of the model and also help in comprehending different validation tests. The base case run of the model shows the response of manufacturing system to a demand fluctuation till the equilibrium value is reached. The values of operating parameters of manufacturing system such as, setup time, inventory adjustment time, manufacturing lead time etc. affect the duration of time in which this equilibrium value can be reached. The results shown in Fig-3.4 to Fig-3.6 are presented for the base case operating parameters presented in Table 3.2.

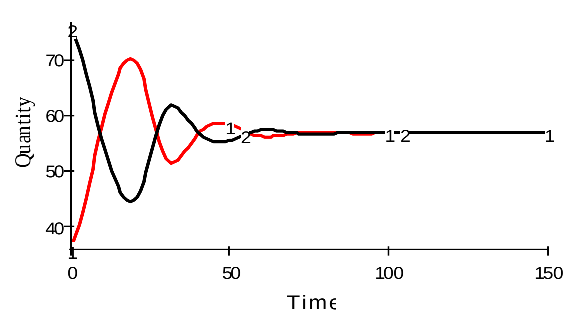


Fig. 3.4. Supply-Demand reaching equilibrium point.

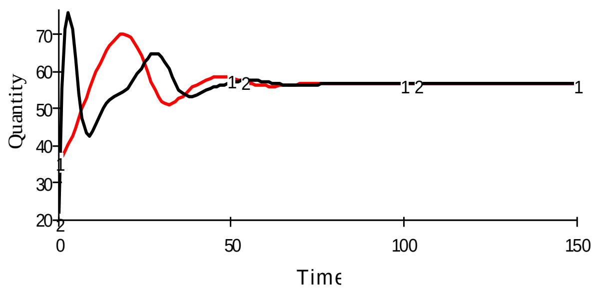


Fig. 3.5. Capacity matches demand.

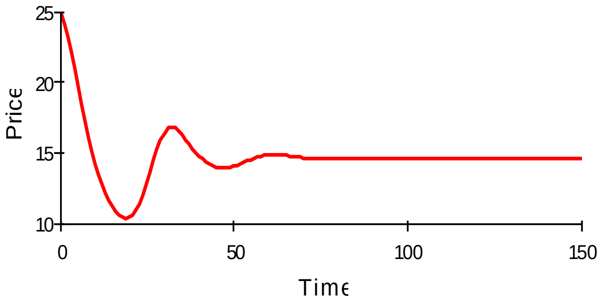


Fig. 3.6. Obtaining equilibrium value of price.

Table 3.2. Operating parameters for base case run.

Parameter	Value	Unit	Parameter	Value	Unit
MLT	1	Time Units	Demand weight	0.5	---
IAT	1.5	Time Units	Inventory weight	0.3	---
SSC	2	Time Units	WIP weight	0.2	---
Responsiveness Time	1	Time Units	MOPT	1	Time Units
SDT	1.5	Time Units	PCD	14	Time Units

3.3.2. *Tests of Model Structure*

These tests help in establishing confidence in the model structure but do not examine relationship between the structure and behaviour.

3.3.2.1. *Model Structure Verification Test*

The nature of input data necessitated that the structural validation tests are applied at every stage of model building process to detect any structural flaw; therefore these tests were done simultaneously all through the model building process. The model represents the market place in terms of demand-price and supply-price relationship, which is also called the demand and supply curve. The final value of demand-supply (matched) also called equilibrium value is the point of intersection of these curves, which is also obtained in actual run of the model. So for a set of defined demand-supply curve, always the same equilibrium point is achieved. If the demand-supply curves are changed, then the new equilibrium is achieved, this also is verified. The movement of demand along the demand curve and that of supply along the supply curve and achievement of equilibrium point in each simulation run shows the verification of model structure. (Fig. 3.7 and Fig. 3.8).

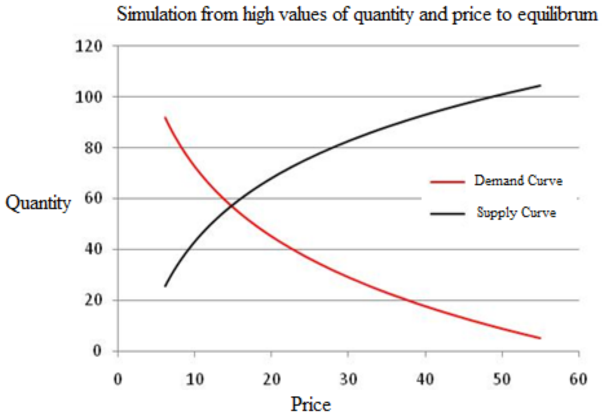


Fig. 3.7. Demand supply curve showing maximum values of price supply and demand.

Similarly, for operations module the capacity of the plant is so adjusted that it should match the equilibrium quantity depicted by demand-supply curve, it is verified during different stages of model development (Fig. 3.4 and 3.5). The days of inventory to be maintained as a safety stock is also governed by inventory coverage, is also verified. Thus all the operating parameters result in the expected values, thus validate the structure of the model.

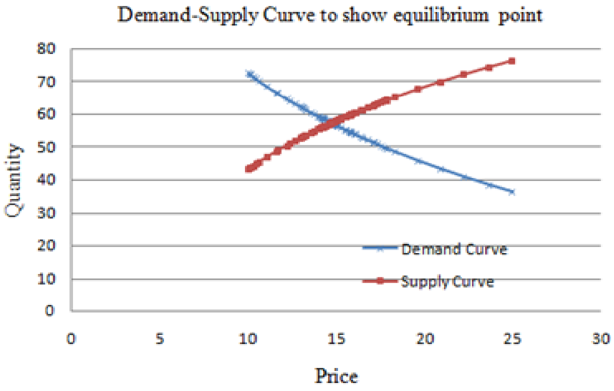


Fig. 3.8. Demand supply curve showing equilibrium values of price.

3.3.2.2. *Parameter Verification Test*

The model parameters comprise of demand, price, supply, plant capacity, inventory, work in process inventory, order backlog etc are verified from either the initial settings (for demand, supply and price the pre designed demand supply curves dictate the values) or from the modeling relations taken for planning/operations decisions, e.g. inventory coverage, response time, manufacturing lead time, price change delays etc.

3.3.2.3. *Extreme Condition Test*

These tests involve assigning extreme values to selected model parameters so as to be sure that model equations remain meaningful under extreme conditions (Richardson and Pugh, 1989). Ensuring the conformity with model equations, first the extreme values for parameters are ascertained. It is necessary, as any physical facility can have only a finite limit like manufacturing lead time, setup time, inventory, WIP etc. Some of the parameters are governed by relationship with interacting parameters; these interactions fix the minimum and maximum limit to their values e.g. demand-price and supply-price relation--ships. Some other parameters are processing parameters which govern the rate at which a certain change in the process can be incorporated; these parameters also depend upon physical facilities, flow of information etc. Some of these parameters are price change delay, inventory adjustment time, setup time (SDT), response time etc. Initially, the relationship governed parameters are put to test. The method of testing is by observing the reproduction of behavior from maximum to minimum limit, if it is as per the designed values and patterns, then the test is ok. This method is adopted for demand-price, supply-price combinations, manufacturing lead times, setup times etc, and result is found to comply with the designed extreme values and behaviors. The Fig-3.9 and Fig. 3.10 shows the achievement of equilibrium point for MLT = 1 and that for very high level of MLT they cannot match.

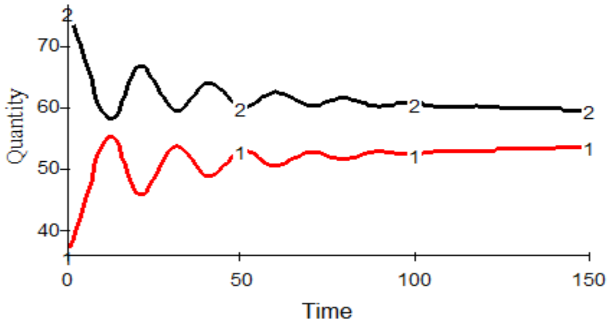


Fig. 3.9. Demand-Supply do not match at a very high value of MLT.

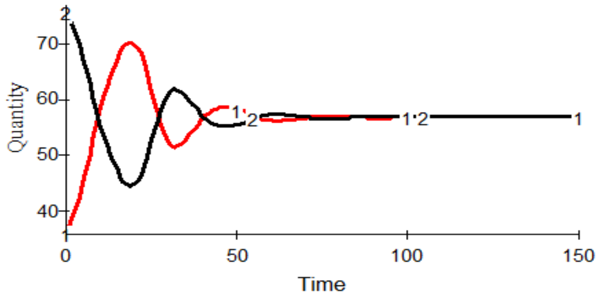


Fig. 3.10. Supply matches demand at MLT = 1.

3.3.3 *Model Behavior Test*

The reproduction of previous behaviour is one of the important tests to be carried out for model validation. In behaviour validity tests, emphasis is given to pattern prediction rather than the point prediction (Barlas, 1996). Fig-3.11 and Fig-3.12 demonstrate the reproduction of demand and supply curve.

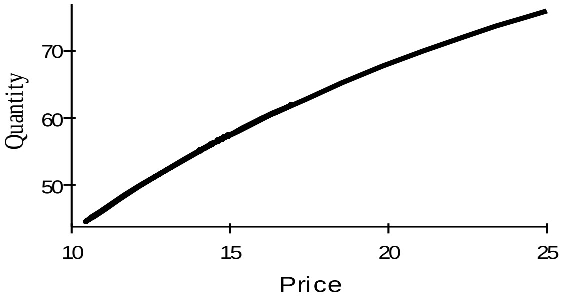


Fig. 3.11. Reproduction of Supply-Price relationship.

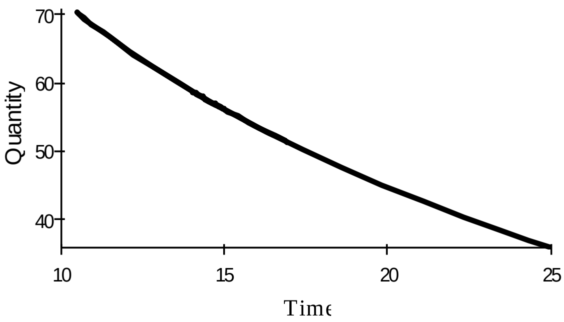


Fig. 3.12. Reproduction of demand-price relationship.

3.3.3.1. *Dimensional Consistency*

Forrester (1961) has pointed out that the behavior of graphs of selected variables is no guarantee of validity as “an endless variety of invalid components (equation forms) can exist to give the same apparent system behavior”. He therefore insists on dimensional consistency checks of model equations. These checks were applied simultaneously while writing the model equations for the present model. It is observed that the dimensional consistency is maintained throughout and the dimensions of each variable have been properly balanced.

3.3.3.2. *Boundary Adequacy Test (Face Value Test)*

Selection of model boundary is also very crucial in determining the extent to which the model fulfils its purpose. Forrester and Senge (1980) have emphasized on proper selection of model boundary, stating that a model is a simplification and that the boundary between what has been included and what has not is a significant determina--nt of models validity. The purpose of the model is to assess the duration required for matching the supply-demand and capacity-demand. The factors considered to model DCM system seem to be adequate in fulfilling the basic objective of the model i.e. assessing the responsive--ness of the system. Examination of causal loop and flow diagram further corroborates it. Hence looking to the purpose, the boundary is adequate.

3.3.3.3. *Behavior Sensitivity Test*

The test is conducted by determining those parameters to which the model is highly sensitive and asking if the real system is also sensitive to those set of parameters. The results of the test for parameters setup time, manufacturing lead time are in agreement with the real life values.

3.3.3.4. *Family Member Test*

The model is generic in nature, though the model in its present form has been developed keeping in view the reconfigurable capacity manufacturing system mainly to accommodate short term dynamics (operational level decisions), but it can also consider other types of manufacturing systems and can be modeled for long term dynamics.

3.3.4. *Sensitivity Analysis*

Sensitivity analysis has been carried out to assess how sensitive the model results are to the assumptions about the values of the parameters and to changes in the way people are assumed to make decisions. Parameter sensitivity has been performed as a series of tests in which sets of different parameter values have been used to see how a change in the parameter causes change in the dynamic behavior of the stocks. One common method to assess it is to define best and worst case scenarios. In the present analysis parameters that seem to be uncertain and influential in the final policy analysis and relationships that represent the way people are assumed to make decisions and are difficult, or even impossible to measure with accuracy in the real world have been selected for the sensitivity analysis. Best/Worst case scenario is termed as Optimistic/Pessimistic scenario in the present analysis. Table 3.3 gives the optimistic operating parameters and Table 3.4 pessimistic operating parameters, with the demand-supply response as shown in Fig. 3.13 and Fig. 3.14 respectively.

Table 3.3. Operating parameters for optimistic scenario (Fig. 3.13).

Parameter	Value	Unit	Parameter	Value	Unit
MLT	1	Time Units	Demand weight	0.5	---
IAT	1	Time Units	Inventory weight	0.3	---
SSC	2	Time Units	WIP weight	0.2	---
Response Time	1	Time Units	MOPT	1	Time Units
SDT	1.5	Time Units	PCD	14	Time Units
Initial Value of ready stock	100	Nos	Initial value of WIP	50	Nos
Initial value of capacity	20	Nos per Week	Initial value of Price	15	Rs

Table 3.4. Operating parameters for pessimistic scenario (Fig. 3.14).

Parameter	Value	Unit	Parameter	Value	Unit
MLT	20	Time Units	Demand weight	0.3	---
IAT	1	Time Units	Inventory weight	0.5	---
SSC	2	Time Units	WIP weight	0.2	---
Response Time	1	Time Units	MOPT	1	Time Units
SDT	1.5	Time Units	PCD	14	Time Units
Initial Value of ready stock	100	Nos	Initial value of WIP	50	Nos
Initial value of capacity	20	Nos per Week	Initial value of Price	15	Rs

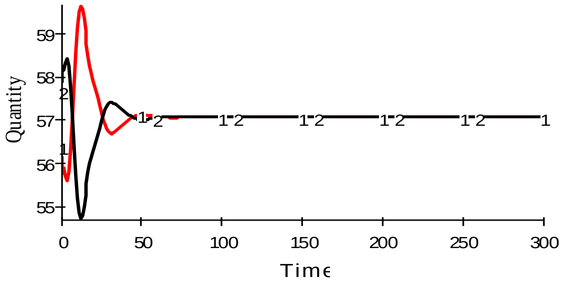


Fig. 3.13. Demand-Supply for an optimistic scenario.

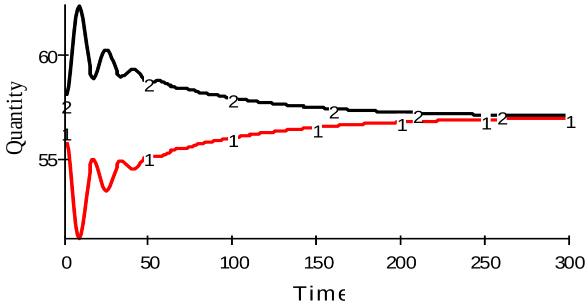


Fig. 3.14. Demand-supply for a pessimistic scenario.

IV. CONCLUSION

Validation tests are required to enhance the confidence in the model results. Several tests were carried out to test model structure and modal behaviour under different conditions. To begin with, base case run of the model was presented to get a clear picture of the structure and behavior of the model, which helps in comprehending different validation tests that follow. The importance of the model objective was stated in the next section so that the validity of model can be assessed in relation to the purpose for which it is built. A set of model structure tests was then carried out to ascertain if the model behaviour is like that of the real system and fulfills the purpose for which it is built. The model reproduced the system behaviour, and results were found to be plausible and explainable under various conditions of changes in policies and parameters. A thorough sensitivity analysis was carried out to assess the impact of variations in model parameters on responsiveness. Various dimensional consistency checks were also done and it was found that the equations in the model are dimensionally consistent and the constants in the model are defined and their dimensions stated. Due care was taken to include parameters needed to fulfill the proposed objectives of the research.

The model of DCM can be subjected to experiments to find out the impact of DCM on performance of manufacturing industries. The set of experiments can be designed to include the most important DCM drivers/activities and then its impact for finding out the performance in terms of effectiveness/responsiveness of DCM.

APPENDIX A

Basic Model Nomenclature:

C = Capacity level at time t.
B = Backlog level at time t.
I = Inventory level at time t.
WIP = WIP level at time t.
PR = Production rate at time t.
PSR = Production start rate at time t.
AD = Average demand.
SD = Standard deviation for the normal demand distribution.
DT = Time step.
OR = Order rate at time t.
ShR = Shipment rate at time t. 18
OFR = Order fulfillment rate at time t.
TRT = Target responsiveness time.
DSR = Desired shipment rate at time t.
MSR = Maximum shipment rate at time t.
MOPT = Minimum order processing time.
SSC = Safety stock coverage time.
DIC = Desired inventory coverage time.
IAT = Inventory adjustment time.
I = Desired inventory level at time t.
AI = Adjustment for inventory rate at time t.
U = Utilization level of the available capacity.
RC = Required capacity at time t.
SDT = Scalability delay time.
SR = Scalability rate at time t.
MLT = Manufacturing lead time.
MUT = Manufacturing unit time.
Wi = The relative weight of inventory consideration in capacity scalability decision.
Wp = The relative weight of demand consideration in capacity scalability decision.

init Capacity = 20
flow Capacity = +dt*Scaling_Rate
init Order_Backlog = 0
flow Order_Backlog = -dt*Order_Fulfillment_Rate +dt*Order_Rate
init Price = 10
flow Price = +dt*Change_in_Price
init Ready_Stock = 100
flow Ready_Stock = +dt*Manufact_Rate -dt*Shipment_Rate
init WIP = 50
flow WIP = +dt*Rate_of_Supply_of_Raw_Material -dt*Manufact_Rate
aux Change_in_Price = (Desired_Price-Price)/ Price_change_delay
aux Manufact_Rate = Capacity
aux Order_Fulfillment_Rate = Shipment_Rate
aux Order_Rate = DELAYPPL(Customer_Demand, 0, 0)
aux Rate_of_Supply_of_Raw_Material = DELAYPPL (Manuf_Projected_Demand, 0, 0)
aux Scaling_Rate = (Required_Capacity-Capacity)/ SDT
aux Shipment_Rate = MIN(Desired_Shipment_Rate, Max_Shipment_Rate)
aux Capacity_Indicator = IF(Required_Capacity/ Capacity>1, 2-(Required_Capacity/Capacity), Required_Capacity/Capacity)*10
aux Customer_Demand = Demand_Schedule
aux Days_of_Inventory_Indicator = (Ready_Stock* 10/Customer_Demand)/Inventory_Coverage
aux Delay_Demand_Inventory_Ratio = DELAYINF (Customer_Demand, 0, 0, 20)
aux Delay_Stock_capacity = DELAYINF (Ready_Stock, 0, 0, 50)
aux Delay_Stock_Inventory_Rario = DELAYINF (Ready_Stock, 0, 0, 50)
aux Demand_Schedule = GRAPH(Price,5,5,[100,73, 57,45,35,28,22,18,14,10"Min:5;Max:100"])
aux Desired_Price = Effect_on_Price*Price
aux Desired_Shipment_Rate = Order_Backlog/ Response_Time
aux Desired_Stock = Delay_Demand_Inventory_Ratio*Inventory_Coverage
aux Desired_Supp_Inventory_Coverage = Manuf_Projected_Demand*Inventory_Coverage
aux Effect_on_Price = GRAPH(Inventory_Ratio, 0.5, 0.1, [2,1.8,1.55,1.35,1.15,1.0,0.875,0.75,0.65, 0.55,0.5" Min:0.5;Max:2"])
aux Inventory_Adjustment = (Desired_Supp_Inventory_Coverage-Delay_Stock_capacity)/ Inventory_Adjustment_Time
aux Inventory_Coverage = Min_Ord_Process_Time+ SSC
aux Inventory_Ratio = Delay_Stock_Inventory_Rario /Desired_Stock
aux Manuf_Projected_Demand = GRAPH(Price, 0, 5, [0,0,40,57,68,77,84,89,94,97,100" Min: 0; Max:100"])
aux Max_Shipment_Rate = Ready_Stock/ Min_Ord_Process_Time
aux Required_Capacity = (Wp*Rate_of_Supply_of_Raw_Material+Wi*Inventory_Adjustment+(1-Wp-Wi)*WIP/Manufacturers_Lead_Time)
aux Shipment_Readiness_Indicator = (Max_Shipment_Rate-Shipment_Rate)/Customer_Demand
const Inventory_Adjustment_Time = 1
const Manufacturers_Lead_Time = 1
const Min_Ord_Process_Time = 1
const Price_change_delay = 14
const Response_Time = 1
const SDT = 1.5
const SSC = 2
const Wi = 0.3
const Wp = 0.5

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