System Dynamics Based Perspective to Reliability Centered Maintenance

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Abstract

This paper proposes a System Dynamics model for manufacturing system with specific focus on studying the influence of dynamic responses of machine failure on the production system. Machine failures affect adversely inventory levels, backlogs, and production costs. Simulation results in this research have depicted that a reduction in failure rate increases the production rate, decreases the work in progress, reduces the production costs, and results in a considerable decrease in the backlog levels. Even though these outcomes are obvious to some extent, the prediction on how the variance occurs is of specific interest to the manufacturers, so as to optimize the production process. Model validation has been carried out by superimposing the actual values on the predicted and the variation is well within the range. A flow chart has been developed for effective maintenance strategy based on Reliability Centered Maintenance, and also, Root Cause Analysis undertaken in this research has identified the bottlenecks of manufacturing which has lead to the suggestions for improvement.

Introduction

Globalization has necessitated the companies to reduce the costs and improve the productivity in order to ensure sustainability. Hence, there has been a remarkable change in the strategies and policies by the companies and more focus is drawn to Total Quality Management (TQM), Supply Chain Management (SCM) and Lean Manufacturing strategies. Lean manufacturing strategy is recognized as one of the most efficient and effective global operation strategy and is focused on reducing the wastes (Shah and Ward, 2007). One of the major concern in lean is the machine failure, which hinders the production process. To avert failures various maintenance polices such as preventive maintenance, condition based maintenance, total preventive maintenance, reliability centred maintenance etc. (Duffuaa et al., 1999) have been suggested. It is important to understand that these polices cannot guarantee uninterrupted production process, as complete prevention of machine failures is not achievable due to the stochastic nature of systems involved in the process. This calls for the study of behaviour of the system under machine failure, and then, adopt appropriate strategies of maintenance.

Literature Review

System dynamics has been widely used to study the dynamics of systems since the pioneering work of Forrester in industrial dynamics in 1961 (Forrester, 1961). Computer based simulation is becoming one of the most important and valuable aid for understanding the behaviour of the system. Though discrete event simulation is commonly recommended, potential of system dynamics simulation is becoming more popular in the recent past (Lin et al., 1998). One of the major works in these lines was done by Sterman, who proposed various applications of system dynamics on production management and supply chain management. Several other applications have been proposed by a group of researchers (Towill et al., 1992). System dynamics has been successfully applied in areas ranging from supply chain management to total quality management (Affeldt, 1999; Angerhufer et al 1999; CaulField, 2001; Chen et al, 2005).

In the context of lean manufacturing, a complete guide for lean manufacturing has been developed by Ramachandran (2001). A bigger picture of lean consisting of thought process behind lean, rather than just a smaller view concentrated on lean tools has been proposed by Singh and Gill (2008). They highlight the importance of five elements of lean, namely manufacturing flow, organization, process control, metrics, and logistics. Also key practice areas of lean manufacturing were highlighted by Wong and Ali (2009). Machine failure being one of the major concerns in lean manufacturing, several research have been carried out. Siddiqui and Khan (2007) have shown the behaviour of non repairable production system under failure on variables like production costs and total costs and also deviation of production level with the desired or targeted level. Also, in certain systems, machines will be in series and failure of one will affect the entire process and the quality of the products deteriorates, and hence, better maintenance strategy is required (Tsarouhas, 2011). The failure of construction plant and its criticality was addressed by the research undertaken by Mohideen et al. (2011).

Failure can be effectively handled through deploying good maintenance strategies. Several research have been carried out in this field and the importance of maintenance strategies like Reliability Centered Maintenance (RCM), Preventive Maintenance (PM) and Condition Based Monitoring (CBM) have been highlighted in these research. International Atomic Energy Agency (2007) has published their report of implementation of RCM to optimize operations in the nuclear plant. Production system under failures and its maintenance is one of the significant areas of study due to its fallouts on the production systems' objectives and key parameters (Andijani et al., 2000; Ben-Daya et al., 2000; Duffuaa et al., 1999). It directly affects factors such as backorder levels, inventory levels, actual and target production and the costs related to these factors.

Model Construction

The causal loop diagram and stock and flow diagram for manufacturing unit of the plant dealing with the production of packaging products are given in Figure 1 and Figure 2. Ahmed Deif's (2010) Computer Simulation Model to Manage Lean Manufacturing Systems forms the basis of this model.

The research is carried out in a leading global innovator and manufacturer based in India, dealing with the manufacture of a wide range of protective packaging and performance based materials essential to many consumers and industrial markets. With operations in 52 countries, with over 100 manufacturing facilities worldwide and more than 17000 employees and a revenue of $4.2 billion, it combines a unique consultative sales expertise with a global network of science and innovation to demonstrate how better packaging makes the world a better place. The types of products include: Food packaging, Protective packaging, Medical packaging, and Shrink Packaging. The purview of this research is on 'class A' category of Protective packaging products under ABC analysis, in the Jiffy Mailer machine. The market demand is modeled as a stochastic demand parameter with dependent distribution having white noise with normal distribution function.

The model is divided into five components viz., Inventory control, Ordering process, Order fulfillment, Production control, and Cost factors. The focus of this research is on studying the impact of machine failure on the production system performance and the governing equations are given in Appendix 1.

Inventory Control

The change in demand and stochastic demand are interdependent. The inventory adjustment is controlled by the gap between desired and current inventory levels. The current inventory level is influenced by the production rate, which in turn is dependent on the cycle time.

Ordering Process

Ordering is based on the minimum value of desired production start rate and minimum ordering quantity. Desired production quantity is dependent on minimum value of maximum production rate, which is the total capacity of the available machines and desired production (sum of demand forecast and adjustment to inventory).

Order Fulfillment

It is based on order shipment rate and it is the minimum value of desired shipment rate and maximum order shipment rate. The difference of order fulfillment rate and the order rate indicates the backlog, which has a direct influence on the desired shipment rate. The desired shipment rate is the ratio of backlog and shipment time. Shipment time in turn is calculated using the probability function with occurrence of three events viz. normal delay (most likely delay), quality rejection delay, and unexpected delay.

Production Process

The influencing factor of production is the production rate, which is in turn, is influenced by the work in progress (WIP) and cycle time. The cycle time refers to order fulfillment cycle time (OFCT) and it is increased when the failure rate increases. Failure time refers to the average time required to repair a machine multiplied by the average number of failure per month. Five percent of production is considered to be scrap rate which influences the waste quantity.

Cost Factors

Only the major indirect costs are considered in this analysis, which include: backorder cost, holding cost, maintenance cost, and wastage cost. The simulation parameters used for initialization are based on the actual values as observed in the industry and are given in Table 1.

Table 1: Simulation Parameters

Parameter	Values
Mean	18711 *products*
Standard deviation	12564 *products*
Time step (DT)	1 *month*
Seed	10 *Dimensionless*
Correlation time	1 *month*
Cycle time	0.8 *month*
Initial WIP	25000 *products*
Initial backlog	50000 *products*
Initial inventory	50000 *products*
Safety stock level	1 *month*
Unit backorder cost	3 *INR/unit/month*
Unit holding cost	0.2 *INR/product/month*
Wastage cost per unit	2 *INR/product*
Cost per maintenance	10000 *INR*
Unit backorder cost	3 *INR/unit/month*

(1 US $ = 50 INR)

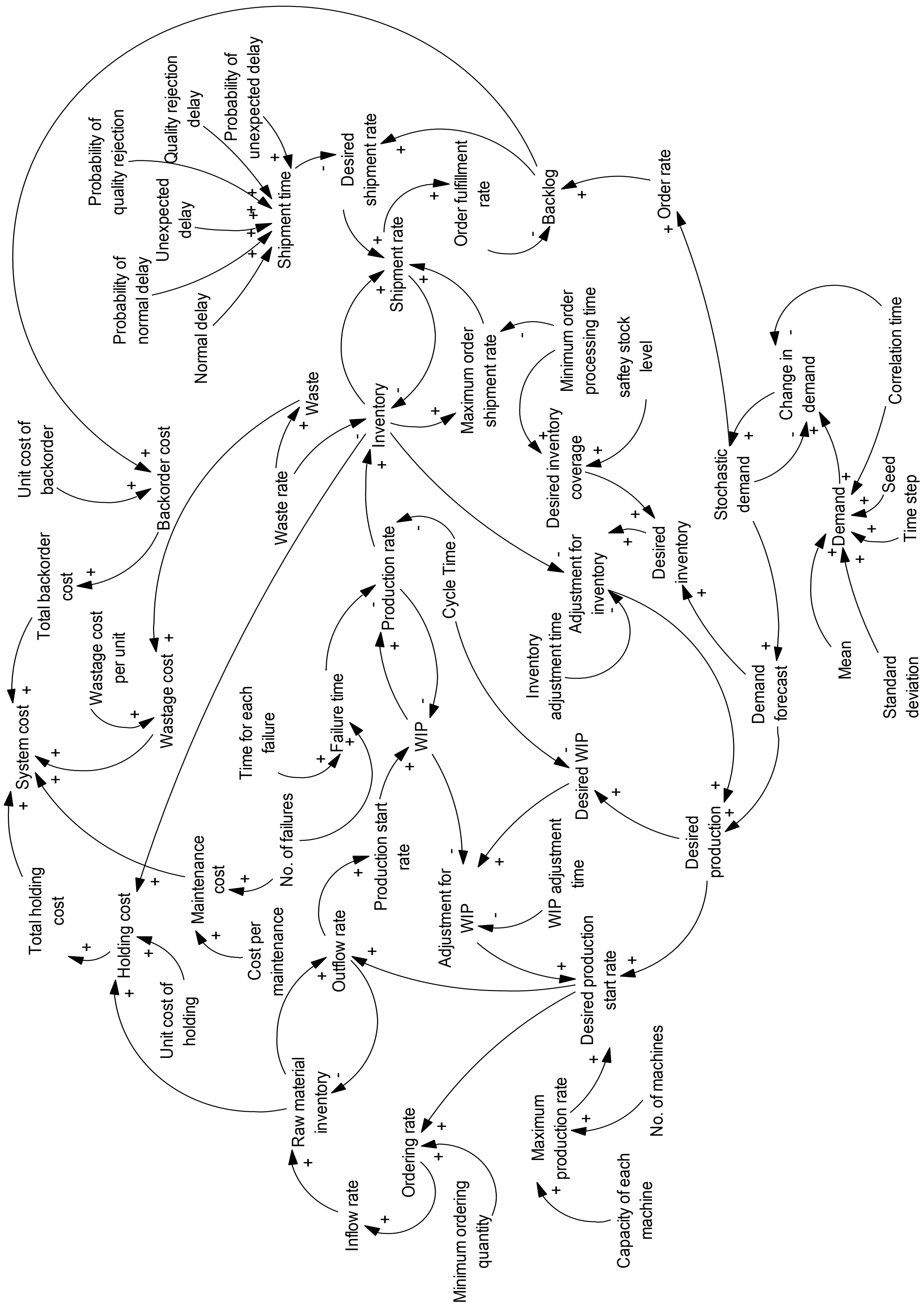

Figure 1: Causal Loop Diagram for Manufacturing System

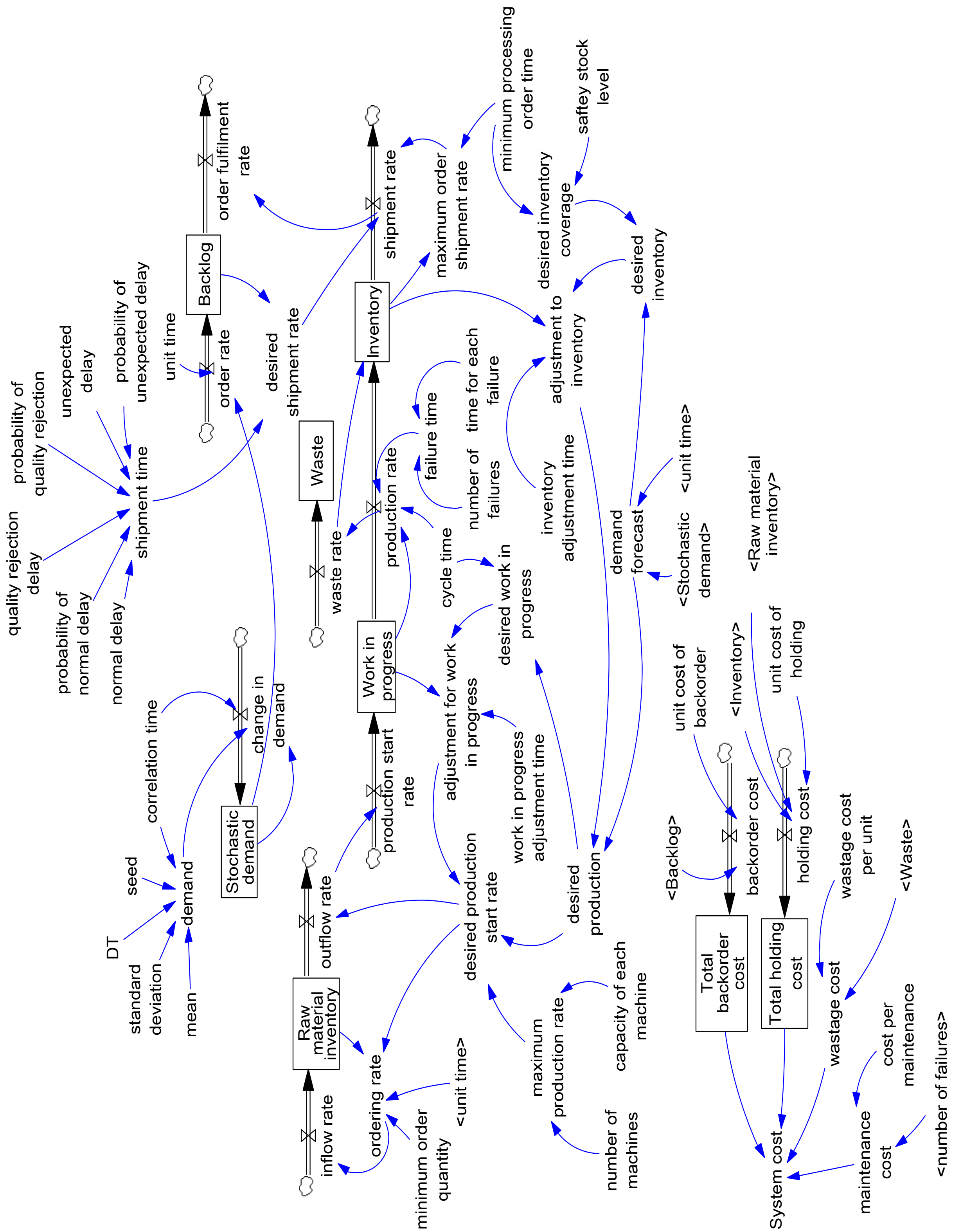

Figure 2: Stock and Flow Diagram for Manufacturing System

Simulation and Analysis

The model was simulated for 12 months and the impact of number of failures (1 to 5 per month) on inventory, work in progress, production rate, backlog, and system cost were observed. The graphs (Figures 3 to 9) imply that the work in progress decreases as the number of failure reduces from five to one and simultaneously production rate and inventory increases. It can be observed that in the first month, backlog falls considerably from 15,904 products to 11,585 products as the failure is decreased from 5 to 1 and the system takes about 4 months to stabilize. The overall cost reduces by almost 35% as the failure is decreased (from five to one) even though there is an increase in holding and wastage cost by 22% and 8% respectively.

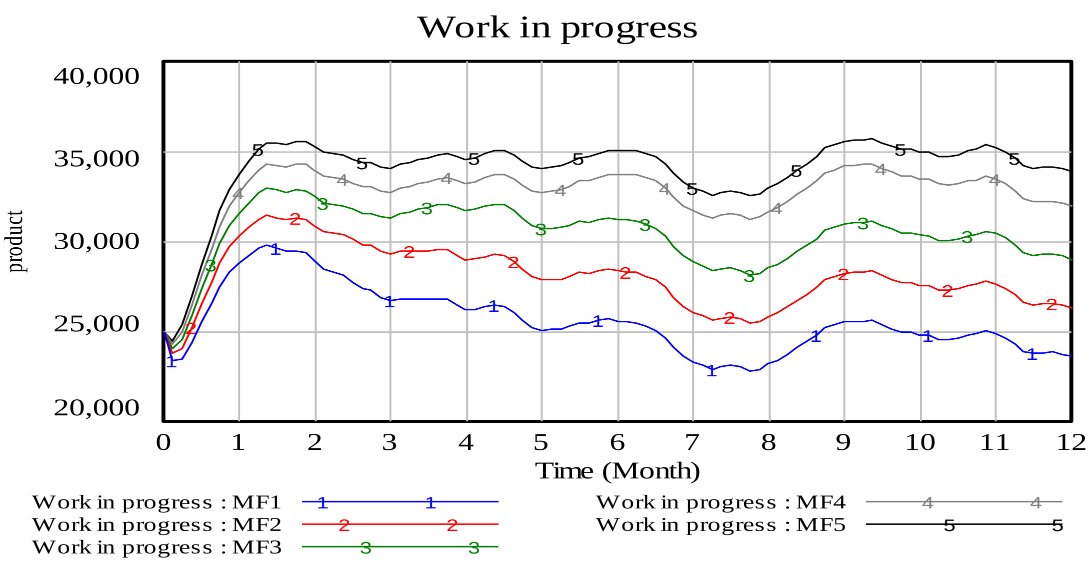

Figure 3: Behaviour of WIP for various machine failure rate.

It can be observed that even though there is an initial drop in work in progress during shipment time, it recovers within a month (Figure 3).

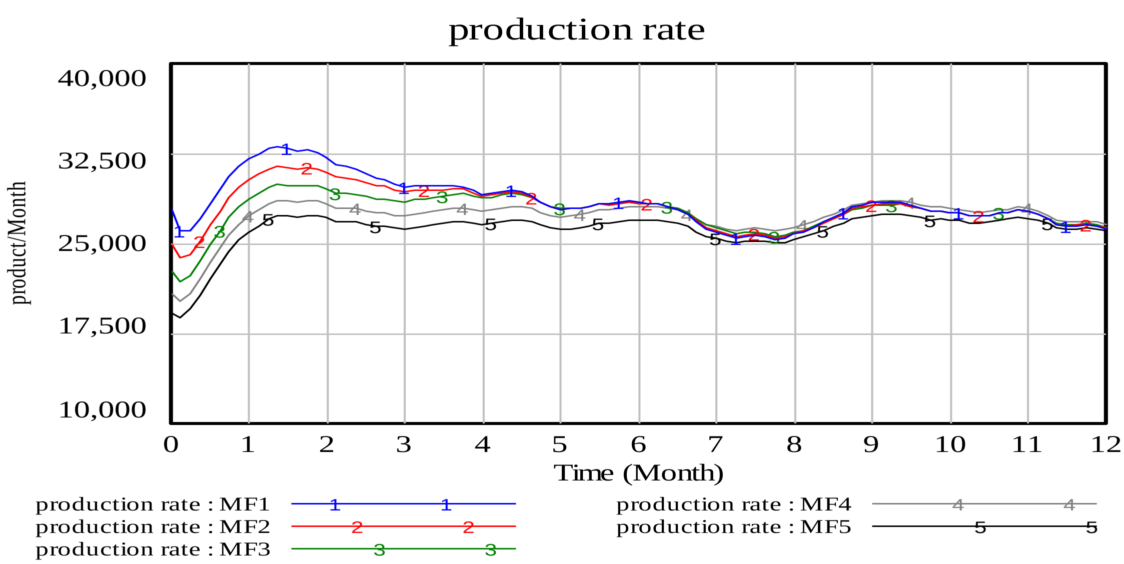

Figure 4: Behaviour of production rate

The impact of failure rate on the production is high only for the first few months, after which, it gets reduced due the adjustments being done on the production process. The production rate increases as the failure is reduced (Figure 4).

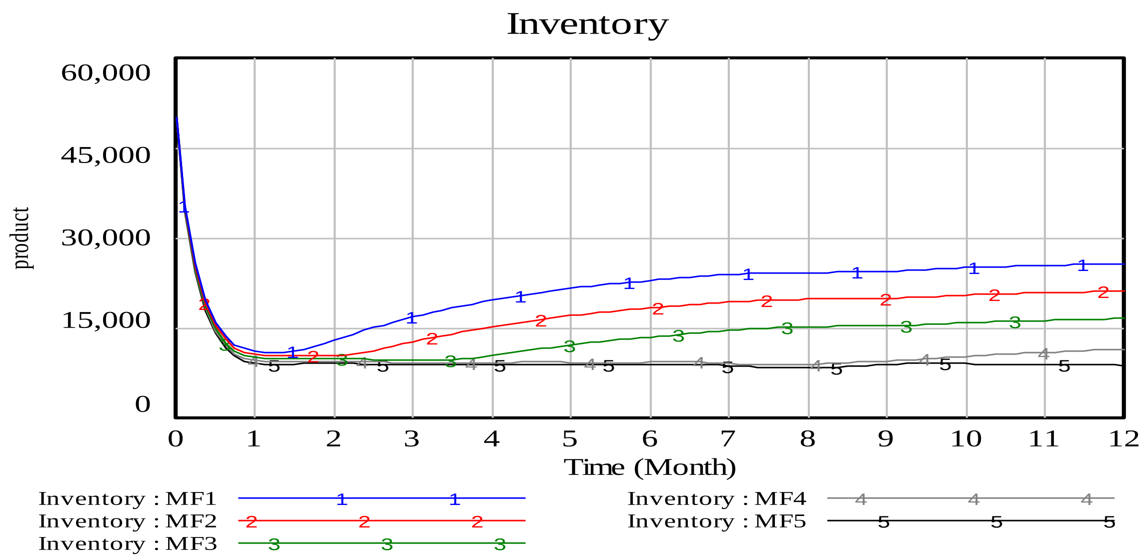

Figure 5: Behaviour of inventory

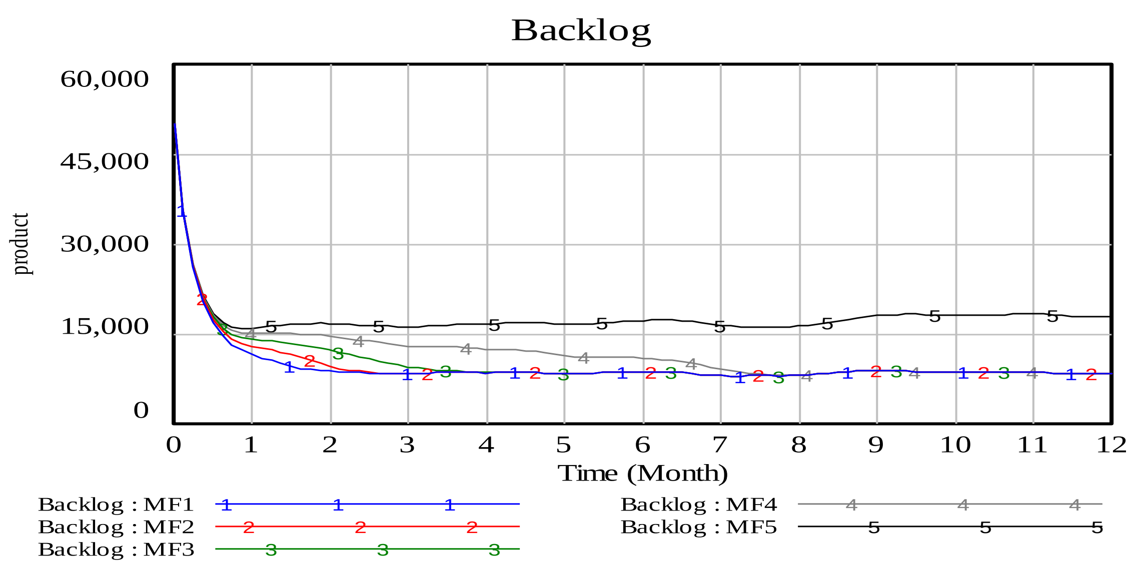

Figure 6: Behaviour of backlog

The inventory level falls down initially, after which, it regains and stabilizes (Figure 5). Further, the backlog decreases and follows close to each other for the first three simulations but for the last one (failure rate = 5) there is drastic increase in the backlog (Figure 6).

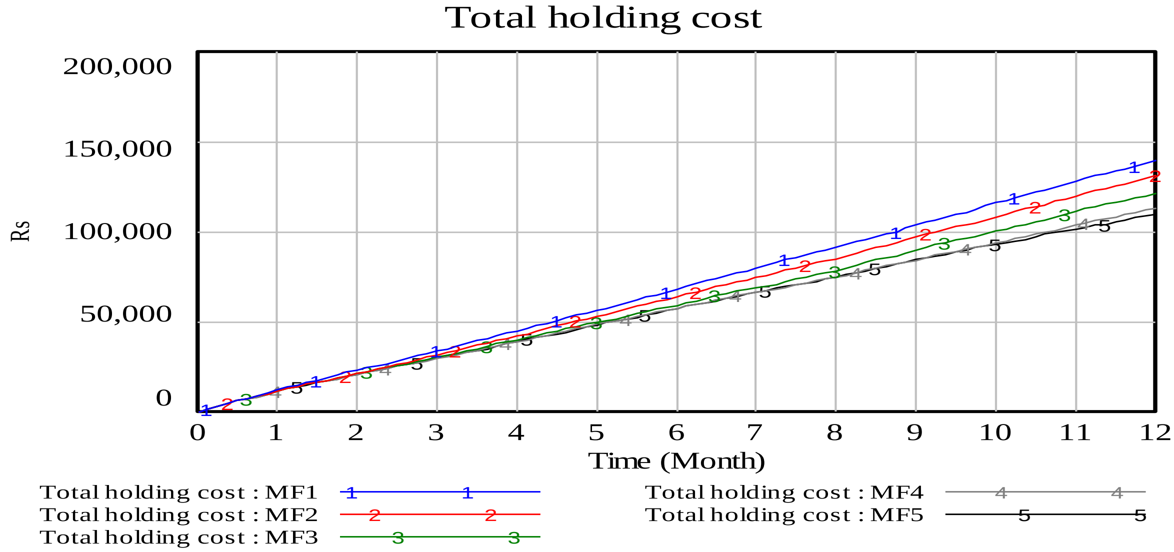

Figure 7: Behaviour of holding cost

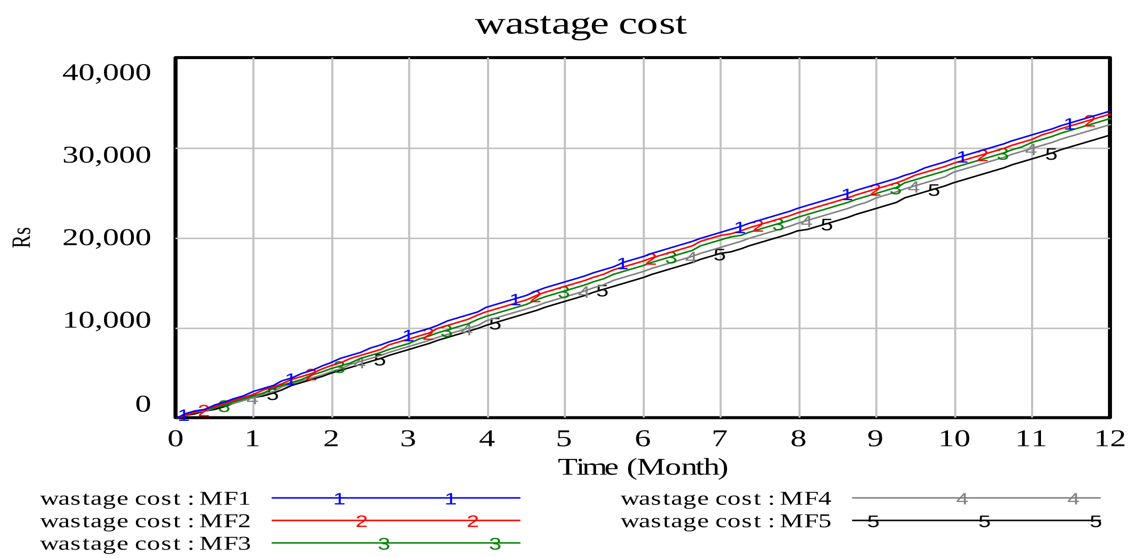

Figure 8: Behaviour of wastage cost

The holding cost increases due to the increase in the inventory level because of high production rate (Figure7). The wastage cost also increases as the production rate increases, due to the assumption that 5% of production will be waste rate (Figure 8).

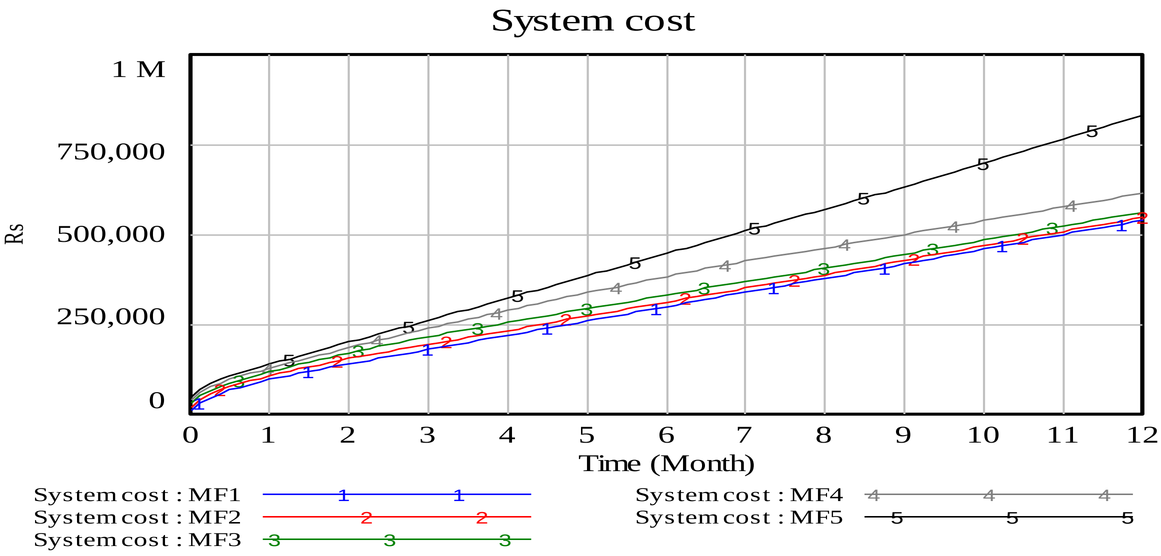

Figure 9: Behaviour of system cost

It can be observed that with the reduction in machine failure, even though the wastage cost and holding cost increases there is a considerable decrease in the system cost due to the reduction in backorder and maintenance cost (Figure 9).

Model Validation

System dynamics model is an approximation towards real life situation and there is a need to validate the same. The model presented in this paper has been subjected to a number of validation tests such as boundary adequacy test, extreme behaviour test, sensitivity test, and anomaly test and the results have been very promising. However, the most commonly used method to validate a model is to compare the actual versus simulated values. A comparison has been made between the actual sales and simulated sales value for order fulfillment rate (Figure 10). It can be observed that the model successfully follows the trend to a great extent and the percentage error observed is 2.5, which is within the margin of error and has proved predictability. The error could be due to the confounded relationship in the model simulation.

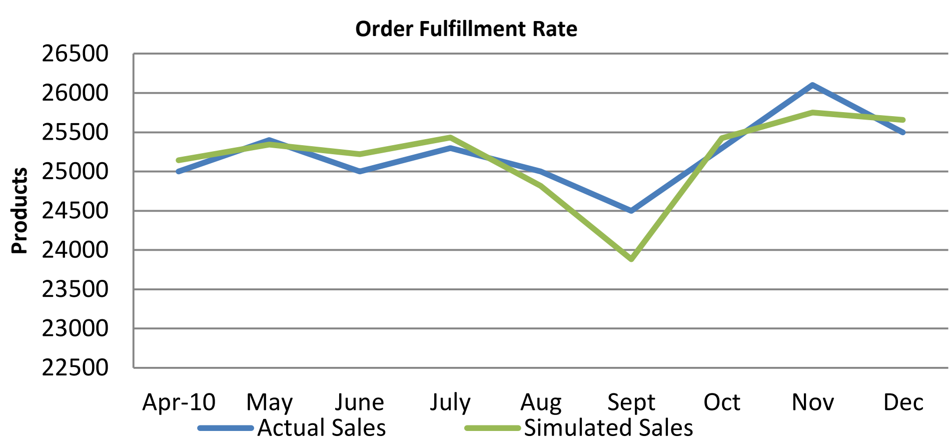

Figure 10: Actual Vs Simulated sales value

Implications

It is imperative from the study that the firm should try to reduce the failure rate to at least 3 per month in order to improve the system performance and reduce the costs. This can be clearly observed from the graph for backlog and system costs (Figure 6 and Figure 9). Reliability Centered Maintenance (RCM) methodology has been suggested to obtain the best possible maintenance strategy (Figure 11). Further, Root Cause Analysis (RCA) is undertaken which has revealed that the factors like unavailability of spares and ineffective maintenance are the causes for frequent machine failures (Figure 12). Critical components have been identified and listed along with their failure modes and effect on the process (Table 2).

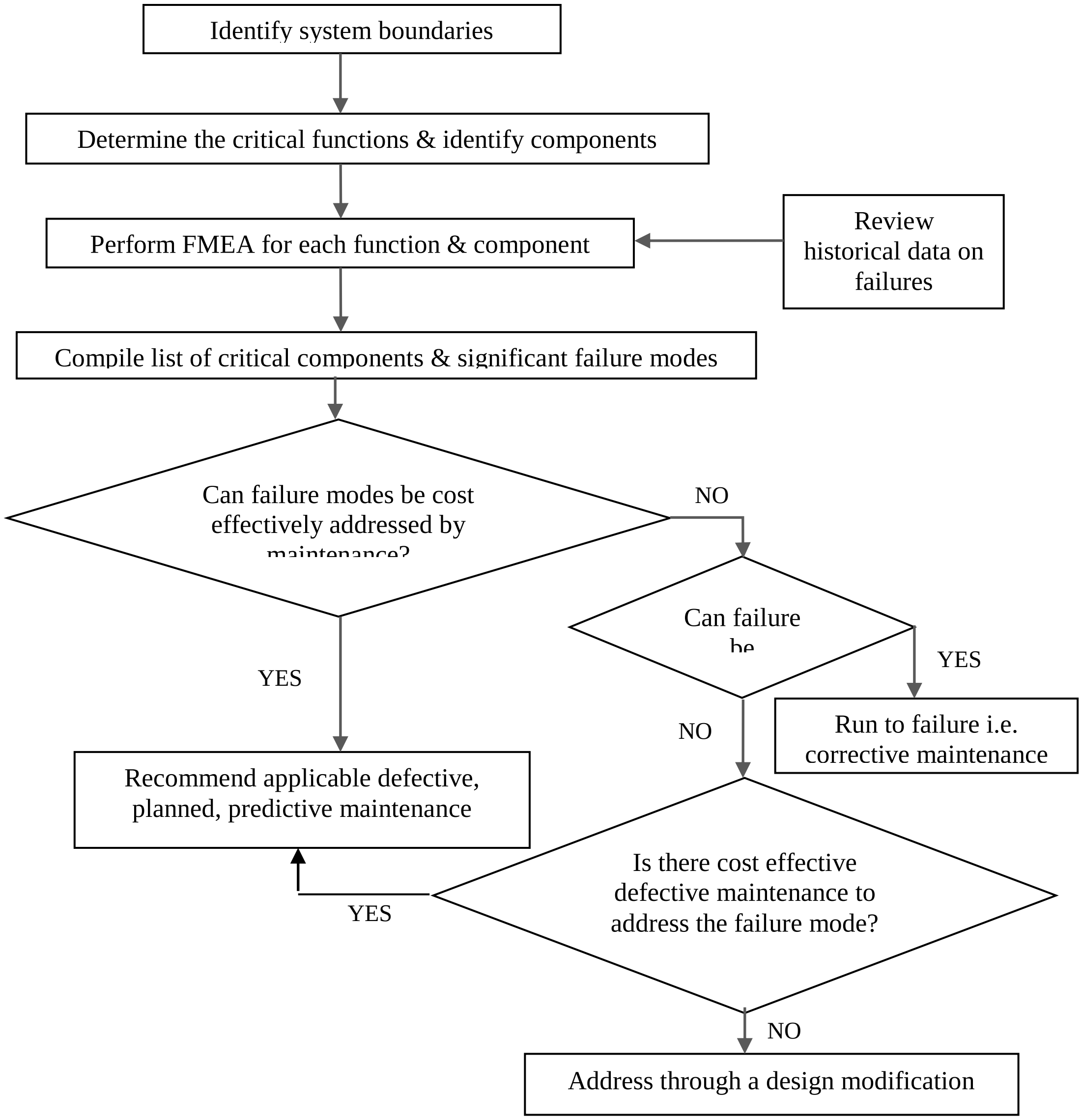

Figure 11: Flow chart for RCM process

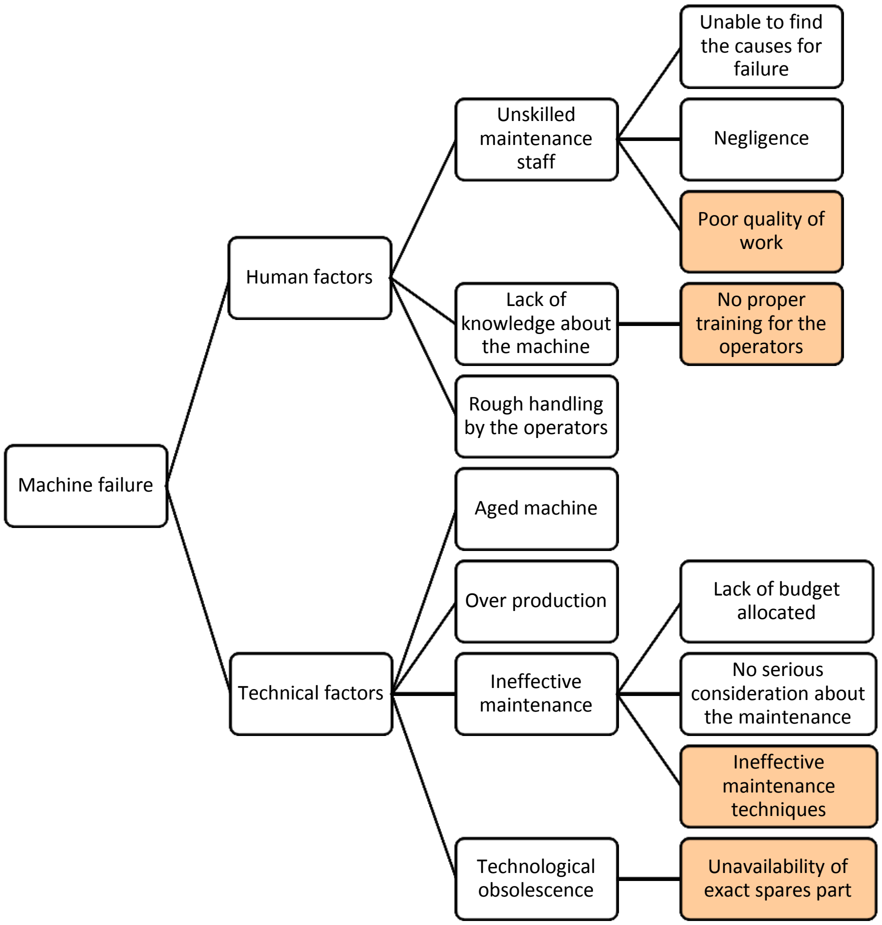

Figure 12: Root cause analysis for machine failure

Table 2: Root cause analysis for machine failure

Failure mode	Effect
Boiler • Burning of coil • Wear and tear of spares	• Stops machine performing its functions. • Quality of output products gets affected and sometimes even breakdown of machine.
Compressor • Breakdown of belts and filters • Malfunctioning or breakdown of solenoid valves	• Stops production and even quality of output is affected.
Jiffy Machine (Pouch making) • Malfunctioning of integrated circuits • Rollers and Motors breakdown	• Quality gets affected. • Stops production
Barriers Bags • Malfunctioning of thermostat • Rollers and belts breakdown	• Quality gets affected • Production stops.

Conclusions

This paper demonstrates the capability of System Dynamics as a tool to effectively solve the issue of studying the impact of machine failure on manufacturing performance. Lean manufacturing has been in practice since several decades now, and researchers have had different approaches towards it and in this research the approach is through the minimization of machine failures.

Machine failure plays an important part in the production process and has a negative impact on the system performance for every organization. Hence, it is quintessential to study the extent of impact on the system parameters like costs, productivity etc. and plan accordingly for the most effective means of overcoming it. One such means is to identify and implement the best suitable maintenance strategy as adopted in this paper. Accordingly, the importance of failure rate on the system performance is shown clearly through the system dynamics model and the reduction in the costs has also been depicted through simulation results. The minimum level to which failure has to be decreased to gain maximum advantages is also identified. Further, the reasons for the failures were identified and accordingly suggestions for the improvement were given. It was identified that the maintenance policies were the root cause for the increased number of machine failures, and hence, RCM application was suggested to identify the best maintenance technique and techniques were suggested which suits the best for the system. The acid test of any modeling and simulation exercise lies in its validation and the model has demonstrated a proved robustness and closeness to the actual with a variation within the acceptable limits of about 2.5%.

Finally, it has to be noted that this work is focused on a single independent machine and there is ample scope for extending the same methodology to the machines in series, so that their combined effect may also be analyzed. The same technique can be extended to an assembly line with slight modifications of parameters of study. In the context of lean manufacturing, it is better to ‘prepare and prevent, rather than repent and repair’, and hence, identifying the root cause of machine failure and minimizing it would be a better strategy to enhance manufacturing performance, as suggested in this research.

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Appendix I

(01) adjustment for work in progress=
(desired work in progress-Work in progress)/work in progress adjustment time
Units: product/Month

(02) adjustment to inventory=
(desired inventory-Inventory)/inventory adjustment time
Units: product/Month

(03) Backlog= INTEG (
order rate-order fulfilment rate,
50000)
Units: product

(04) backorder cost=
Backlog*unit cost of backorder
Units: Rs/Month

(05) capacity of each machine=
336000
Units: product/Month

(06) change in demand=
(Stochastic demand-demand)/correlation time

Units: product/Month

(07) correlation time=
1
Units: Month

(08) cost per maintenance=
10000
Units: Rs

(09) cycle time=
0.8
Units: Month

(10) demand=
mean+(standard deviation^2*(2-(DT/correlation time))/(DT/correlation time))^0.5*RANDOM UNIFORM(0, 1, seed)
Units: product

(11) demand forecast=
(Stochastic demand/unit time)
Units: product/Month

(12) desired inventory=
demand forecast*desired inventory coverage
Units: product

(13) desired inventory coverage=
minimum processing order time+saftey stock level
Units: Month

(14) desired production=
MAX(0, (demand forecast+adjustment to inventory))
Units: product/Month

(15) desired production start rate=
MIN(maximum production rate, (adjustment for work in progress+desired production))
Units: product/Month

(16) desired shipment rate=
Backlog/shipment time
Units: product/Month

(17) desired work in progress=
desired production*cycle time
Units: product

(18) DT=1
Units: Month

(19) failure time=number of failures*time for each failure
Units: Month

(20) FINAL TIME = 12
Units: Month
The final time for the simulation.

(21) holding cost=
(Inventory+Raw material inventory)*unit cost of holding
Units: Rs/Month

(22) inflow rate=
ordering rate
Units: product/Month

(23) INITIAL TIME = 0
Units: Month
The initial time for the simulation.

(24) Inventory= INTEG (production rate-shipment rate-waste rate, 50000)
Units: product

(25) inventory adjustment time=3
Units: Month

(26) maintenance cost=
number of failures*cost per maintenance
Units: Rs

(27) maximum order shipment rate=Inventory/minimum processing order time
Units: product/Month

(28) maximum production rate=capacity of each machine*number of machines
Units: product/Month

(29) mean=18711
Units: product

(30) minimum order quantity=200000
Units: product/Month

(31) minimum processing order time=0.35
Units: Month

(32) normal delay=0.3
Units: Month

(33) number of failures=3
Units: Dmnl

(34) number of machines=1
Units: Dmnl

(35) order fulfilment rate=shipment rate
Units: product/Month

(36) order rate=Stochastic demand/unit time
Units: product/Month

(37) ordering rate=
IF THEN ELSE((desired production start rate*unit time)<=Raw material inventory, 0,
(MAX(minimum order quantity, (desired production start rate-(Raw material inventory/unit time)))))
Units: product/Month

(38) outflow rate=
desired production start rate
Units: product/Month

(39) probability of normal delay=0.9
Units: Dmnl

(40) probability of quality rejection=0.02
Units: Dmnl

(41) probability of unexpected delay=0.08
Units: Dmnl

(42) production rate=Work in progress/(cycle time+failure time)
Units: product/Month

(43) production start rate=outflow rate
Units: product/Month

(44) quality rejection delay=0.8
Units: Month

(45) Raw material inventory= INTEG (inflow rate-outflow rate,0)
Units: product

(46) saftey stock level=1
Units: Month

(47) SAVEPER = TIME STEP
Units: Month [0,?]
The frequency with which output is stored.

(48) seed=10
Units: Dmnl

(49) shipment rate=MIN(maximum order shipment rate, desired shipment rate)
Units: product/Month

(50) shipment time=(normal delay*probability of normal delay+quality rejection delay*probability of quality rejection+unexpected delay*probability of unexpected delay)
Units: Month

(51) standard deviation=12564
Units: product

(52) Stochastic demand= INTEG (-change in demand, demand)
Units: product

(53) System cost=Total backorder cost+wastage cost+Total holding cost+maintenance cost
Units: Rs

(54) time for each failure=3/30
Units: Month

(55) TIME STEP = 0.125
Units: Month [0,?]
The time step for the simulation.

(56) Total backorder cost= INTEG (backorder cost,0)
Units: Rs

(57) Total holding cost= INTEG (holding cost,0)
Units: Rs

(58) unexpected delay=0.6
Units: Month

(59) unit cost of backorder=3
Units: Rs/product/Month

(60) unit cost of holding=0.2
Units: Rs/product/Month

(61) unit time=1
Units: Month

(62) wastage cost=Waste*wastage cost per unit
Units: Rs

(63) wastage cost per unit=2
Units: Rs/product

(64) Waste= INTEG (waste rate,0)
Units: product

(65) waste rate=0.05*production rate
Units: product/Month

(66) Work in progress= INTEG (production start rate-production rate,25000)
Units: product

(67) work in progress adjustment time=1
Units: Month