Discrete Event Simulation using WITNESS

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ABSTRACT

Discrete event simulation is the modelling of a system in which the state variable changes at a discrete set of points in time. It helps in investigating and experimenting complex systems with interaction process between internal variables. Stochastic models having random variables can be designed in software WITNESS 12 Performance Manufacturing Edition. Manufacturing plant has been modelled using WITNESS. Analysing the statistics of internal variables and carrying out scenario manager wizard in WITNESS, performance of the production plant has been optimized to achieve maximum revenue. Investigation for effect on daily production as a result breakdown of elements has been carried out. Maximum revenue in terms of given budget is obtained using optimization tool in WITNESS. Daily production has been increased. Discrete event simulation helps in answering wide variety of 'what if' questions to a real world system and gives an estimation of the impact caused in performance of the system.

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1. INTRODUCTION

1.1 Simulation

"A simulation is the imitation of the operation of a real-world process or system over time" [Banks, et al., 2010]. Simulation involves creation of an artificial data of a system and the examination of that data to deduce an opinion regarding the operational characteristics of real world system.

The behaviour of a system over a period of time is studied by generating a simulation model. This involves in consideration of set of assumptions with respect to the real operation of the system. The assumptions are formulated in symbolic, logical and mathematical relation between entities of the system. The investigation of variety of questions like 'what if' about the real world scenario is possible after the validation of the model. Simulation of system is carried out by making potential changes and its impact on performance of the system is analysed. It can also be used as a design tool to study a conceptual system prior to creation and its behaviour under varying circumstances in order to predict its performance.

Simulation mimics the real world scenario and hence attracts many clients as output in simulation corresponds to that recorded in real world system. Insight about the interaction of various variables and its effect on the performance of the system can be obtained from simulation model. In contrast, results of simulation can be arduous to interpret. Analysis and modelling can be expensive and time consuming.

Areas of application for simulation include Manufacturing, Business processing, Construction engineering, Project management, Logistic, Transportation, Distribution, Military applications, Health care and many more.

Table 1 lists examples of entities, attributes, activities, events and state variables of several systems [Banks, et al., 2010].

Table 1. Examples of Systems and their components

System	Entities	Attributes	Activities	Events	State Variables
Banking	Customers	Checking account balance	Making deposits	Arrival ; departure	No. of customers waiting; No. of busy tellers.
Production	Machines	Capacity; speed; breakdown rate	Stamping; welding	Breakdown	Status of machine (busy, idle or down)
Communications	Messages	Destination; length	Transmitting	Arrival at destination	No. waiting to be transmitted
Inventory	Warehouse	Capacity	Withdrawing	Demand	Levels of inventory; back-logged demands

1.2 Discrete and Continuous System

A system can be classified as discrete or continuous. The system, in which state variable(s) vary only at a discrete set of points in time, is defined as a discrete system. As an example, in a bank, the state variable, i.e., no. of customers varies in accordance with their arrival or completion of service.

In continuous system, the state variable varies continuously with respect to time. The head of water behind the dam is an example of continuous system. During or after rain, the water flows into the lake behind the dam. Water is drawn to produce electricity or to control flood and evaporation also causes reduction in water level. Thus, the state variable water head changes continuously over a period of time.

1.3 Types of Model

A model is a representation of the system. The areas of system that affect the problem are considered in most of the models. Thus, it is simplification of the model in order to be able to study the system effectively.

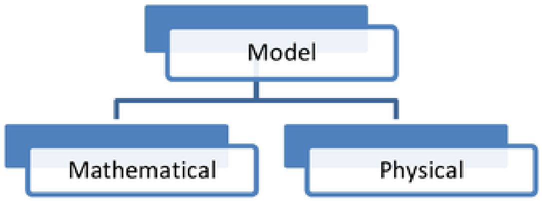

Fig 1. Types of model

A model can be categorized as mathematical or physical. A mathematical model uses mathematical relations and symbolic representation for a system. Physical model is either small or large scale version of an object such as scaled-down model of solar system. Simulation model is particularly a mathematical model of the system. Simulation model can be further categorized as static or dynamic, deterministic or stochastic and discrete or continuous.

Stochastic models have one or more random variables as inputs. Random input generates random outputs and as a result they can only be considered as estimation of the true characteristics of the system. The simulation of a restaurant usually involves random inter-arrival and service times. Thus in stochastic modelling, the measures – number of customers waiting, average waiting time, group of customers arriving, serving time – determines statistical estimates of the true characteristics of the system.

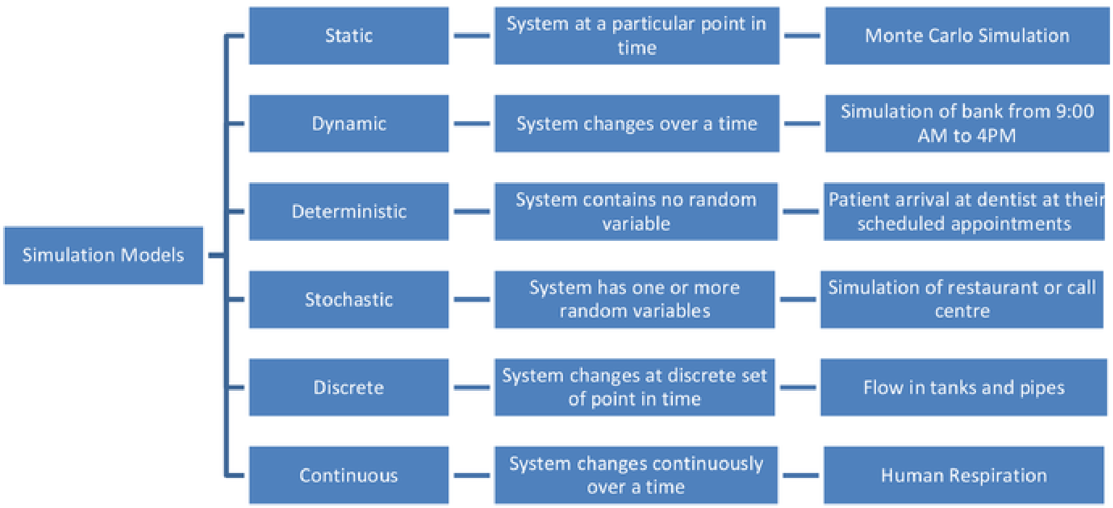

Fig 2. Types of Simulation Models

1.4 Discrete Event Simulation

Discrete-event simulation is the modelling of the systems in which the state variable varies at a discrete set of points in time. The discrete-event simulation models are solved by numerical approach rather than analytical methods. Analytical methods emphasize deductive mathematical reasoning to solve the problem. Numerical methods employ computational approach to solve models. The models are rather run then solved using numerical approach. The artificial data of the system is generated from the assumptions in model and observations are stored in order to analyse and estimate the performance of the system. Real world simulation models are run with aid of computer as they are large and amount of data collected is huge.

1.5 Simulation Methods

Random number generation forms the basic element for almost all discrete systems. In many computer languages, random numbers are generated by a function or subroutine. They are used to generate random variables and event times in simulation. Several effective algorithms provide means to achieve this end.

1.5.1 Linear Congruential Method

Linear congruential method is most widely used technique for generating random numbers. Lehmer proposed linear congruential method to produce a sequence of integers, $X_1, X_2, \ldots$ between zero and m-1 by following a recursive relationship :

$X_{i+1} = (aX_i + c) mod\ m, \quad i = 0, 1, 2, \ldots$[Banks, et al., 2010].

Initial value X_0 is called the seed, *a* is called the multiplier, *c* is the increment, and m is the modulus. In above equation, if $c \neq 0$, then it is known as mixed congruential method and if $c = 0$, it is called multiplicative congruential method. The cycle length and the statistical properties are drastically effected by the values selected for *a, c, m* and X_0. The equation generates only random integers. In order to generate random numbers R_i having value between 0 and 1, the equation should be set as

$R_i = \frac{X_i}{m}, \quad i = 1, 2, \ldots$ [Banks, et al., 2010].

1.5.2 Convolution Method

Convolution Method is used to generate non-uniform random variables. It defines an algorithm for stochastic generator. Consider a random variable X which is sum of n other independent and identically distributed (IID) random variables $X_1, X_2, \ldots, \; X_n$. If X_i has a density function $f_i(x)$ for $i = 1, 2, \ldots, n$, the density function $f(x)$ of X is the convolution of each of n basic density functions then, it can be expressed as

$X = \sum_{k=1}^{n} X_k$, then $f(x) = f_1(x) \times f_2(x) \times \ldots \times f_n(x)$,

where $\times$ is the convolution operator defined by $f_1(x) \times f_2(x) = \int_{-\infty}^{\infty} f_1(\lambda) f_2(x - \lambda) d\lambda$ [Severance 2001].

1.6 Discrete-event Simulation Software

1.6.1 ProModel

ProModel Corporation founded ProModel in 1988. It serves as a simulation and animation tool which focuses primarily on modelling of manufacturing systems. Company also offers similar products MedModel for healthcare simulation and ServiceModel for service system simulation.

ProModel has a plug-in to Microsoft Visio which is called Process Simulator through which process charts, facility layouts and value stream maps can be simulated for any industry. It also has plug-in Microsoft Projects in order to model projects having shared resources and variable task times. It has interface with Microsoft Excel and other database programmes available commercially. It provides platform for 2D and 3D animation. It offers graphical interface to construct a model and elements like conveyor belt, operator, cranes, fork trucks, pumps and tanks can be designed. ProModel can track cost based on labour, equipment cost and material. It can also export output data to minitab and excel for more extensive analysis. It allows user to define multiple scenario as an experiment and compares it side by side.

1.6.2 WITNESS 12

WITNESS 12 is founded by Lanner Group. It can simulate complex business problems with the use of professional tools. Witness offers easy and accessible ways to create different scenarios for an industry which can be tested and verified in a risk-free way.

WITNESS provides unique range of elements and comprehensive set of control options and logic rules though which enables rapid production of a model. It allows manipulating, cloning and reusing existing models. It has interface with Microsoft Excel, XML and CAD. Witness offers quick 3D environment. It uses cutting edge algorithms to provide best possible solution for optimization. WITNESS can analyse cost and revenue for the models and sustainability factors such as carbon emission, energy consumption, etc. WITNESS represents a real world process in a dynamic animated computer model and allows us to observe the operation process as time advances.

1.7 Introduction to Problem

Simulation package Witness 12 Manufacturing Performance Edition is used to carry out analysis of a manufacturing plant whose layout can be seen in figure 3. Gears are manufactured in a separate plant and arrived by following distribution shown in Appendix 1. Gears are kept on a conveyor belt which feeds an assembly area. Castings are drawn from stock and loaded into CNC workstation by operator for additional machining and boring. Every 20th machined gearbox from CNC is passed on to inspection bench and rest to a buffer (bin). If the dimensions of machined gearbox are above tolerance limit, then it is sent to scrap and the tools in CNC are changed. Working gearbox is produced at assembly station by joining two gears, two bearings and one machined gearbox. The output is then sent to test bench for testing. Most of them are passed and are sent for shipment. Failed gearbox is sent to disassembly station where gears are loaded back to conveyor belt and others to scrap. The plant operates in 8 hours shift.

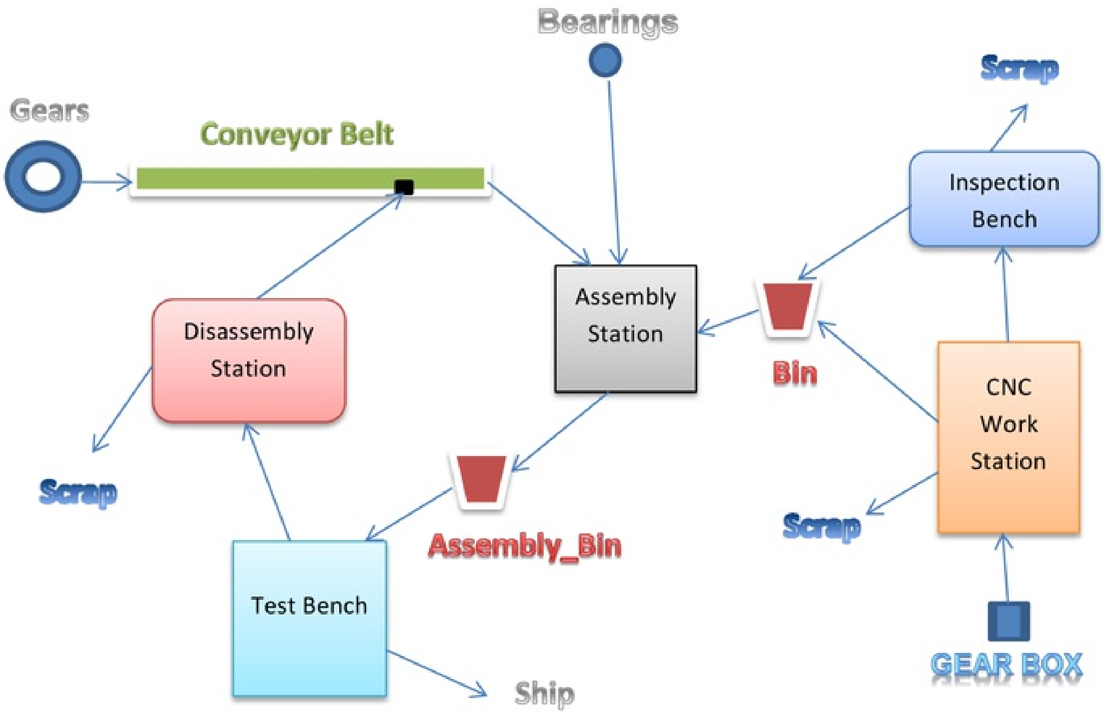

Fig 3. Layout of plant

The plant is simulated for 10 days with an appropriate warm-up period. The model is analysed and optimized with an object of achieving maximum revenue in terms of available budget. Current report focuses on generation of model in WITNESS 12 and discuss varies factors affecting the scenario by investigating several 'what if' questions. It aims to achieve best possible solution for the model to enhance system performance.

2. METHODS

Current problem states that there is 78% chance in every 20 machined gearbox inspected at inspection bench that it would cross upper tolerance limit. And in that case, tools in CNC machine need to be replaced. This would affect the state of other entities of the system. The state variable (status of machine), for example CNC, changes at a set of point in time (after 20 inspections). Therefore, it is a discrete-event system.

Test bench can take up to 5 working gearbox at a time which is a random variable. The model has other random variables such as, cycle time for machine, no of operator, priority allocated to machine, arrival of gears. Model has many random variables and hence it is a stochastic model.

Stochastic model of given discrete event system is created in WITNESS 12 Manufacturing Performance edition as shown in figure 4.

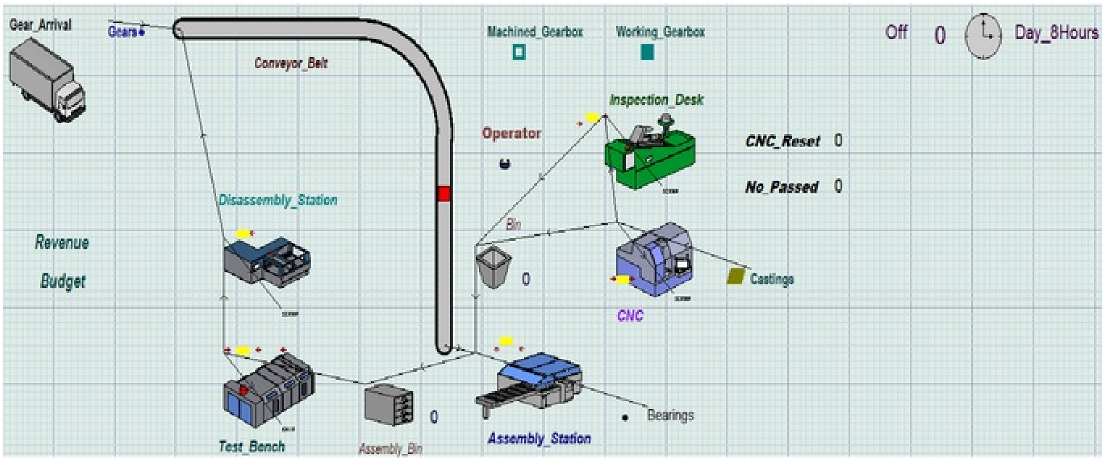

Fig 4. WITNESS model

Gears are arrived on conveyor belt and feed to an assembly station where it gets assembled with two bearings and machined gearbox. Castings are machined in CNC to produce machined gearbox and few are also sent to inspection desk. Working gearbox is obtained from an assembly station and sent to test bench via buffer. Most of them are shipped and failed ones are sent to disassembly station. Gears are separated from the whole assembly and are kept on conveyor belt. Rest are scrapped. Process of generation of current model is described in brief along with logic rules.

2.1 Witness Structure

A WITNESS model uses combination of parts, people, machines and other simulation devices, called modelling elements, in order to simulate the operation.

2.1.1 Discrete Elements

These are displayed as dynamic icons and represent tangible elements in the real-life situation.

- *Parts* – flow through the model. They can represent products, product batches, calls in telephone exchange, tiny electronic components or whole computers. Parts are characterized by particular set of attributes (for example width, length, and colour) either fixed or variable. It can be handled in different ways.
- *Buffers* – are places where parts can be held. For example, parts waiting for an operation, people in queue. Parts can be arranged according to different ordering methods (for example, first-in-first-out). It can be tied directly to machine and can hold parts for specified maximum or minimum time.
- *Machines* – are powerful elements which are used to represent anything that takes part from somewhere, processes them and sent them out to next destination. For example, lathe or a press. Machine can be of seven types with different ways of handling. It can model factors such as multiple set ups, multiple cycles, breakdown time, repair time as well as labour for these events.
- *Labour* – can be used to model physical resources and human. It can be required by other elements for processing, setting up, repair, cleaning and so on. Labour can be controlled by allocating complex rules so that it gives preference to more important task for another element.
- *Conveyor* – are used to move parts from one point to other point in model over time. Belt and roller conveyors can be represented. They are of two types, i.e., fixed conveyor and queuing conveyor. Fixed conveyor maintains a

constant distance between the parts while queuing type allows parts to accumulate.

- *Paths* – represents the physical route of a real life journey in model.

2.1.2 Logical Elements and Modules

These represent data and reporting aspect of model. They allow handling data easily, customizing reports and building more complex logic into WITNESS model.

- *Attributes* – are characteristics of specific part or labour unit. It can hold an integer, a real number or a string.
- *Variables* – are values which can be accessed from anywhere in model. It can hold an integer, a real number or a string. It can be set to equal to an expression involving attributes, to constant value or a sample from distribution. It displays its name and value on screen.
- *Files* – allows taking values that are relevant to simulation and load them into a WITNESS model.
- *Distributions* – allow building variability into a model by including data collected from real world. It can be integer, real, continuous or discrete.
- *Functions* – are used to build intelligence into the logic of the model. Built in functions include reporting and status functions and random sampling functions.

  NFREE – current free capacity of the element.

  NQTY – returns the quantity defined of the element.

  NSHIP – returns the number of parts that have been shipped.
- *Shifts* – is used to simulate shift pattern in effect to sequence of working and non-working periods.

2.1.3 Graphical and Reporting Elements

These are graphical representation of what is happening to the model as run proceeds.

- *Pie Charts* – allows to present simulation results on screen in standard pie chart format. It is useful to represent percentage of time that an element spends in certain state.

- *Histograms* – allows to present simulation results on the screen in the form of a bar chart. It is useful to determine range of values observed for some parameter of simulation.

2.1.4 Manipulating Elements

- *Rules* – Parts are transferred between elements according to input and output rules on the detail dialog box for those elements.
  IF – used for applying a condition to the model.
- *Actions* – gives specific instructions about logic of the model. It allows to model calculations and formulae which underpin decision in real life situation. It can be used to introduce interaction between the model and the person using it. It can be used to set initial conditions of the model or at any stage during the running of the model. It can be used at key stages in element's operation.
  Change – changes from one part to another part.
  Return – returns the value generated by the variable.

2.2 Generating a Model in Witness

Model is generated in WITNESS by combination of various discrete elements, logical and manipulating elements according to real world scenario.

2.2.1 Defining Parts

Gears, *Bearings*, *Castings*, *Machined Gearbox* and *Working Gearbox* are represented graphically as parts. They are the elements which flow through the model.

Gears are arriving according to distribution (*Gear_Arrival*) as shown in Appendix 1 and kept on a conveyor belt. As a result gears are considered to be *active* with *inter-arrival time* denoted by *Gear_Arrival ()*. *Gear_Arrival* is real distribution (allowing decimal digits) of the data collected from the real world. *Gears* have footprints of length 0.08m, width 0.08m and height 0.1m and are specified in *Actions on Create*. *Gears* are then pushed to *Conveyor Belt* with output rule *PUSH to Conveyor_Belt(1) at Rear.*

Castings and *Bearings* are drawn from stock and as a result are *passive* parts. *Castings* are pulled out of world by *CNC* which is then processed and converted to *Machined Gearbox*. *Bearings* are pulled out of world in quantity of two by *Assembly Station*. *Assembly Station* assembles two *Gears*, two *Bearings* and one *Machined Gearbox* and the output product is called *Working Gearbox*. Therefore, *Machined Gearbox* and *Working Gearbox* are passive parts as they are produced in the plant.

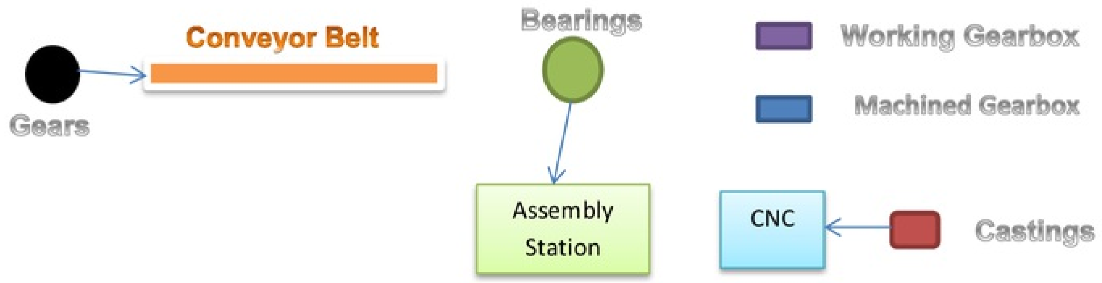

Fig 5. Construction of parts.

2.2.2 Defining Buffers

Bin and *Assembly* Bin has a *maximum capacity* to withhold *50* parts. They act as buffers in model. *Machined Gearbox* is pushed from *CNC* and *Inspection Desk* to *Bin*. *Working Gearbox* is pushed from *Assembly Station* to *Assembly Bin*.

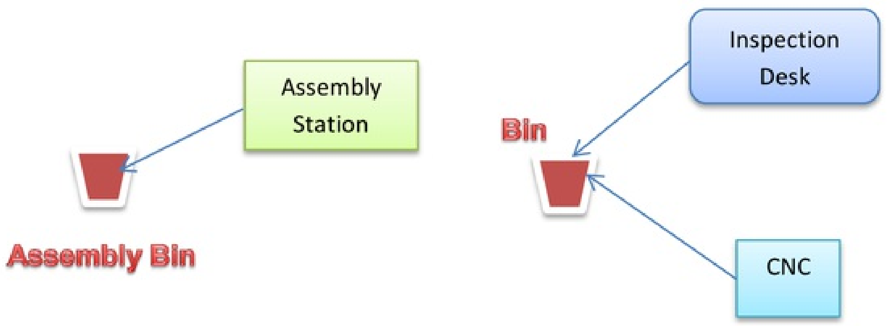

Fig 6. Construction of buffers.

2.2.3 Defining Conveyor

Conveyor Belt sends Gears from one point to another point in plant and as a result it works as a conveyor. The length is defined as 20 meters and it has maximum capacity of 180. Conveyor is of belt type and so parts are kept at a distance preventing queuing at front. Therefore, it is defined as *continuous fixed* with a speed of 5 m/min and spacing of 0.1 m between adjacent parts. *Conveyor Belt* feeds two *Gears* to *Assembly Station* for the operation. Sensor is defined at 5m distance from the front where gears are replaced from *Disassembly Station*.

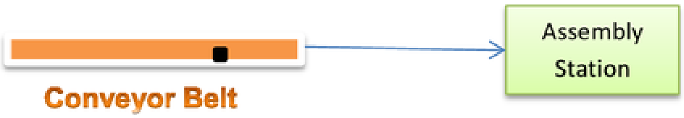

Fig 7. Construction of conveyor

2.2.4 Defining Machines

CNC, *Inspection Desk*, *Assembly Station*, *Test Bench* and *Disassembly Station* process different parts by pulling from somewhere and pushing to different destination. They act as machines.

CNC has to perform various processes in the model such as loading, unloading, machining and boring of *Castings*. It performs different tasks in cycle and as a result it is a multi-cycle machine. Loading and unloading time is uniformly distributed on interval and is represented by function *Uniform (0.5, 0.9)*. Machining and boring time is 2.3 minutes. *Operator* loads and unloads *CNC* and output is *Machined Gearbox*. It is defined at *Actions on Finish* as *CHANGE Castings to Machined Gearbox*. Every 20^{th} *Machined Gearbox* goes to *Inspection Desk* for inspection and rest to *Bin*.

Inspection Desk performs single task of inspecting one *Machined Gearbox* and outputs the same. It acts as single machine and cycle time is triangularly distributed which is represented as *Triangle (0.8, 1.1, 2.2)*. According to analysis, it is concluded that after inspection of 20 parts, there is 78% chance that critical dimensions of bearings are at upper tolerance limit. In this case, tools in *CNC* need to be replaced and machine to be cleaned following set up time *Triangle (2.5, 3.2, 3.7)*. Failed parts are to be scrapped.

In order to form logic between *CNC* and *Inspection Desk* in WITNESS, two integer variables (parts don't flow in proportions) *CNC Reset* and *No Passed* are created. Logic is defined at *Actions on Finish* at *Inspection Desk* as

```
IF Binomial (0.78,20) < No_Passed
        CNC_Reset = 1
        No_Passed = 0
ELSE
        No_Passed = No_Passed + 1
ENDIF
```

According to logic, variable *No Passed* records the value of parts passed to *Inspection Desk*. When the peak of binomial distribution falls then the number of parts, the value of *CNC Reset* is reset to 1 and *No Passed* to 0. In contrast, No Passed increments the value and carry on counts.

These two variables are the integral part for implementing logic to different discrete elements. When *CNC Reset* will be set to 1, *CNC* will stop and carry out replacing operations. This set up mode in *CNC* can be triggered by mode – value change and writing expression as *CNC Reset*. The value should be reset after the completion of task in order to carry on defined sequence and this can be applied by defining *CNC Reset* = 0 in *Actions on Finish* in setup of *CNC*.

In the event of failure in inspection, the failed product at *Inspection Desk* and part machined in *CNC* needs to be scrapped. This can be defined in output rule:

For CNC

```
IF CNC_Reset = 1
        PUSH Machined_Gearbox to SCRAP
ELSE
        SEQUENCE /Wait Machined_Gearbox to Bin(1)#(19),
        Machined_Gearbox to Inspection_Desk(1)#(1)
ENDIF
```

FOR INSPECTION_DESK

```
IF CNC_Reset = 0
        IF NFree (Bin) > 0
                PUSH Machined_Gearbox to Bin
        ELSE
                PUSH Machined_Gearbox to SCRAP
        ENDIF
ELSE
        PUSH Machined_Gearbox to SCRAP
```

ENDIF

In *CNC*, when the value of *CNC Reset* sets to 1 according to logic defined in *Inspection Desk*, the part which is not processed inside the machine will be scrapped. In contrast, the parts will flow following a normal sequence sending every 20th part to *Inspection Desk*.

In *Inspection Desk*, if *CNC Reset* =0 and there is space available in Bin, then the part will be sent to Bin. In all other conditions including *CNC Reset* = 1, the parts would be scrapped.

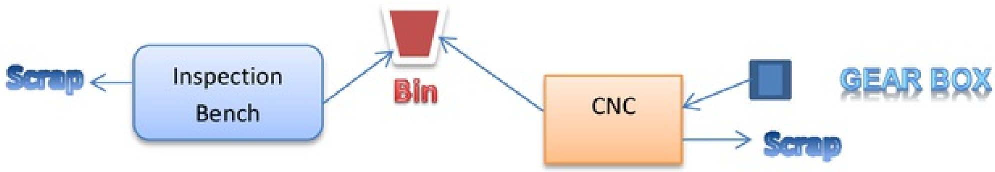

Fig 8. Construction of CNC and Inspection Desk

Assembly Station takes two *Gears* from the front of conveyor, two *Bearings* out of world and one *Machined Gearbox* out of *Bin* and assembles it into *Working Gearbox*. It takes many inputs and processes into a single input and hence it serves as an assembly machine. *Assembly Station* follows cycle time in truncated normal distribution which is represented as *TNormal (3, 0.7, 2.2, 5)*. The input rule for machine is defined as

SEQUENCE/WAIT Machined_Gearbox Bin(1)#(1), Bearings out of WORLD#(2), Gears Conveyor_Belt(1)#(2)

and output rule as

PUSH Working_Gearbox to Assembly_Bin(1)

The output part is assembled into one by an operator and it is called *Working_Gearbox* which can be defined in *Actions on Finish* as

CHANGE Machined Gearbox to Working Gearbox.

Assembly machine push the finish part to *Assembly Bin* and pulled in by *Test Bench*. *Operator* loads the *Working Gearbox* on the test points, further which testing is carried out by machine in 10 minutes. *Test Bench* can process up to 5 parts at a time and so it is called a batch machine. Loading and unloading is done by operator in time *Uniform (0.2,0.4)*. This is defined in Setup dialog of *Test Bench*. Working parts are shipped which in this case is 93 % and rest of them are sent to *Disassembly Station* for splitting out parts. The input rule is defined as

PULL Working_Gearbox Assembly_Bin(1)

And output rule as

PERCENT Working_Gearbox SHIP 93.00, Working_Gearbox Disassembly_Station 7.00

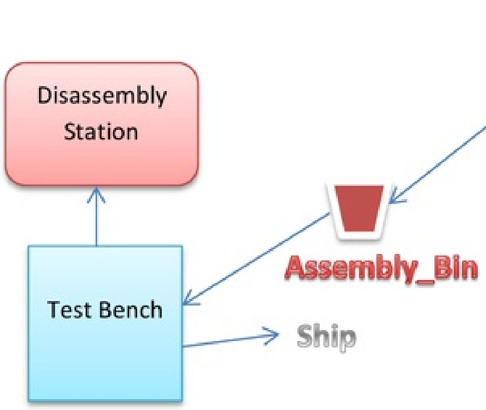

Fig 9. Construction of assembly station and test bench

Disassembly Station splits out the failed parts out of *Working Gearbox* which is a single part. Hence, it acts as production machine which produces parts from first part. An *operator* disassembles the parts in duration defined as *TNormal (2.3, 0.4, 1.7, 3.5)* and scrap out *Bearings* and *Machined Gearbox*. *Gears* are further fed to *Conveyor Belt* at a position 5m (at sensor (1)) from the front and is defined by output rule

PUSH Working_Gearbox SCRAP, Bearings SCRAP, Gears Conveyor_Belt(1) at (1).

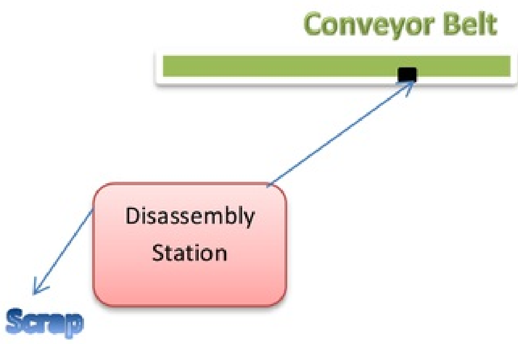

Fig 10. Construction of disassembly station.

2.2.5 Defining Labour

Labour is defined in *labour rule* as *Operator*.

2.2.6 Defining Shifts

Plant operates on 8 hour shift in day which is defined from designer elements. Shifts can be selected in various active elements by selecting the dialog box shifts.

2.2.7 Defining Revenue

Working gearbox is sold at cost of 80 pounds per unit. Costs of *CNC* machine has to be recovered in three years and other elements in one year. Cost of all machines is calculated per hour. Considering 50 weeks in a year and plant running on 8 hour shifts, total hours in a year is rounded to 2000.

CNC workstation = £ 72000/ 3 years = 12£ / hour

Assembly stations or Disassembly Station = £1800/2000 hours = 0.9 £/hour

Bins = £200/2000 hours = 0.1 £/hour

Test bench / Inspection Bench space per gearbox = £2200/ 2000 hours = 1.1 £/hour

Fixed cost for hiring an operator (advertising, training etc.): £1500/ 2000 hours = 0.75 £/hour + £15.60 (Operator hourly rate including on-costs) = 16.35 £/hour.

Plant needs to be run for 10 days and it works on 8 hour shift.

Simulation Time = T = 80 hours.

Revenue function calculates the profit gained from selling parts after deducting the cost incurred on elements (machine, labour, etc.).

Revenue function is defined as:

*RETURN NShip (Working_Gearbox) * 80{Selling Cost} - NQty (CNC) * 12 * 80{Simulation Time} - NQty (Bin) * 0.1 * 80 - NQty (Assembly_Bin) * 0.1 * 80 - NQty*

*(Assembly_Station) * 0.9 * 80 - NQty (Disassembly_Station) * 0.9 * 80 – 2 * NQty (Test_Bench) * 1.1 * 80 - NQty (Inspection_Desk) * 1.1 * 80.*

2.2.8 Defining Budget

Budget gives an estimate of income for buying different components in plant. Budget is the total expense on machines and components. Maximum Budget is 15000. Budget is the expression of quantity of machine multiplied by its cost. CNC and conveyor belt are purchased already and hence opted out from calculation. Budget is defined as

*RETURN NQty (Assembly_Station) * 1800 + NQty (Disassembly_Station) * 1800 + NQty (Bin) * 200 + NQty (Assembly_Bin) * 200 + 2 * NQty (Test_Bench) * 2200 + NQty (Inspection_Desk) * 2200 + NQty (Operator) * 1500*

Note: *Test_Bench* is multiplied by 2 in budget and revenue function.2 is the maximum quantity for batch. Reason would be explained in section 2.3.

2.3 Optimising a Model

Cost of all necessary components is calculated as follows:

Total cost = Cost of (Assembly Station + Inspection Desk + Bin + Assembly Bin + Test Bench with space of 2 gearbox (Batch Max = 2) + Disassembly Station + Operator = 1800 + 2200 + 200 + 200 + 2200*2 + 1800 + 1500 = £12100.

Remaining Budget = 15000 – 12100 = £ 2900.

The plant is run for a cycle time of 10 days with a warm-up period of single day. Plant is set to 8 hour day shift. The statistics of machines are listed in Table 2.

Table 2. Machine Statistics obtained in WITNESS

Name	% Idle	% Busy	% Blocked	% Cycle Wait Labor	% Setup	% Setup Wait Labor	No. Of Operations
Inspection_Desk	98.26	1.19	0	0.55	0	0	41
CNC	0	62.41	0	37.21	0.25	0.14	801
Assembly_Station	42.41	51.82	0	5.77	0	0	783
Test_Bench	0	81.37	0.1	0	4.92	13.61	391
Disassembly_Station	94.55	2.74	1.2	1.51	0	0	56

As seen from statistics, it can be concluded that Inspection Desk and Disassembly Station are least busy as well as cycle wait labour and set up wait labour is minimum. Hence no more extra quantity of that machine needs to be purchased and the priority should be lowest compare to others.

Assembly station is busy only round about half of the time and as a result its current quantity is sufficient. Cost of CNC is out of budget in current scenario and so it cannot be purchased. Test bench is sufficiently busy with batch max 2.

Cycle wait labour for CNC and setup wait labour for Test bench is highest and it needs to be decreased by allocating priorities to machines. Assembly station shows cycle wait labour to 5%.

Statistics for buffer is shown in Table 3.

Table 3. Buffer Statistics obtained in WITNESS

Name	Total In	Total Out	Now In	Max	Min	Avg Size	Avg Time	Min Time	Max Time
Bin	802	783	19	20	0	4.85	87.01	0	939.44
Assembly_Bin	790	782	8	21	5	13.33	242.95	35.94	1001.8

Buffers have maximum quantity of 50 and average size is around to 13. It can be concluded from the statistics that the number of bin in current model is sufficient.

Statistics of Operator, conveyor belt and shipment are shown in Table 4.

Table 4. Statistics of different elements

(a) Operator Statistics obtained in WITNESS

Name	% Busy	% Idle	Quantity	No. Of Jobs Started	No. Of Jobs Ended	No. Of Jobs Now	No. Of Jobs Pre-empted	Avg Job Time
Operator	84.92	15.08	1	3305	3305	0	0	1.23

(b) Conveyor belt Statistics obtained in WITNESS

Name	% Empty	% Move	% Blocked	% Queue	% Broken Down	Now On	Total On	Avg Size	Avg Time
Conveyor_Belt	41.75	30.63	27.62	0	0	4	1571	2.21	6.56

(c) Shipment statistics obtained in WITNESS

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Working_Gearbox	792	726	56	0	0	10	15.35	279.05	2.97

Operator is seen quite busy from the statistics. Conveyor belt is seen to be moved and blocked for one-third of total cycle time. Increasing the speed might show difference in statistics. Number of shipped parts (Working Gearbox) is found to be 726 without optimization.

With the current statistics, most appropriate solution with respect to quantity would be either increase an operator or buy an extra space for gearbox on Test Bench. In accordance with remaining budget £2900 only one of them can be purchased.

Scenario manager wizard was carried out in order to investigate the most optimum solution. Two cases were considered where taking Batch Max to be 2 and 3. In both cases, priorities for CNC, Test Bench and Assembly Station are investigated from 1 to 3 with step size of 1. Also, speed for conveyor in range of 5 to 10 was investigated. The best 5 results with maximum revenue obtained from scenario manager with Batch Max = 2 and Batch Max = 3 are listed in Table 7 and Table 8 respectively.

Table 5. Statistics from scenario manager with Batch Max = 2

Scenario	Assembly_Station.Priority	Operator.Quantity	CNC.Priority	Conveyor_Belt.Speed	Test_Bench.Priority	Budget()	Revenue()
115	1	2	1	5	2	13600	58802.667
223	1	2	1	5	3	13600	58802.667
235	1	2	2	5	3	13600	58802.667
271	2	2	2	5	3	13600	58802.667
151	2	2	1	5	2	13600	58776

Table 6. Statistics from scenario manager with Batch Max = 3

Scenario	Assembly_Station.Priority	Operator.Quantity	CNC.Priority	Conveyor_Belt.Speed	Test_Bench.Priority	Budget()	Revenue()
187	3	2	1	5	2	15800	58661.333
151	2	2	1	5	2	15800	58608
234	1	1	2	10	3	14300	57701.333
229	1	1	2	5	3	14300	57541.333
114	1	1	1	10	2	14300	57434.667

From the results of scenario manager it can be concluded that revenue is optimum with batch max = 2 and speed of conveyor set to 5 m/min. Therefore, Test Bench with space of 2 gear box has been selected. This is the reason for multiplying Test Bench with value 2 in revenue and budget function.

Using these methods and concept for optimization through scenario manager, optimization of the model has been carried out. The important parameters have been selected through analysis of statistics of model and scenario manager. Optimization has been carried out with following variables:

- Assembly Station Priority from 1 to 3
- CNC Priority from 1 to 3
- Operator quantity from 1 to 2
- Test bench priority from 1 to 3

Model in optimization has been run for cycle length of 10 days (14400 minutes) with warm up period of single day (1440 minutes). Runs per evaluation have been set to 3 for optimum results and algorithm to Adaptive Thermostatistical SA. Objective for optimization is to obtain maximum revenue along with side by side tracking of budget and revenue in order to ensure that the value of budget obtained is within limit defined.

3. RESULTS

Scenario Manager played effective role in setting up variables for the model. Operation of plant over 10 days with appropriate warm up time of single day has been optimized. The results obtained from optimization are listed in Table 9.

Table 7. Results of optimization

Evaluation	Revenue	Assembly_Station .Priority	CNC .Priority	Operator Quantity	Test_Bench .Priority	Budget
4	58802.7	1	1	2	2	13600
11	58802.7	1	2	2	3	13600
29	58802.7	2	2	2	3	13600
22	58776	2	1	2	2	13600
40	58776	3	1	2	2	13600

Table 10 shows the results for parameter analysis obtained from optimized model.

Table 8. Parameter analysis

Variable	Value	ObjFnAvg	% Benefit
Assembly_Station.Priority	1	57836	222.7
Assembly_Station.Priority	2	55331	208.72
Assembly_Station.Priority	3	57449	220.54
CNC.Priority	1	55113	207.5
CNC.Priority	2	57664	221.74
CNC.Priority	3	57656	221.69
Operator.Shift:Day_8Hours.Quantity	1	54660	204.98
Operator.Shift:Day_8Hours.Quantity	2	58706	227.55
Test_Bench.Priority	1	57772	222.34
Test_Bench.Priority	2	57587	221.31
Test_Bench.Priority	3	54892	206.27

Objective graph for maximum revenue in current optimization can be shown in figure 11.

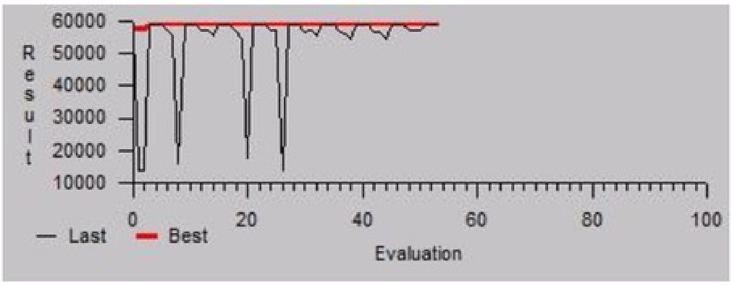

Fig 11. Objective Graph

Result analysis shows that maximum revenue of around about £ 58800 can be obtained with hiring two operators and setting up priorities for CNC, Assembly Station and Test Bench to be 1, 1 and 2 respectively.

These results were applied to the basic model. Priorities for both Inspection Bench and Disassembly Station are set up to 3 (hardly busy). Model has been run again to 10 days with 8 hour shift and warm up time of 1440 minutes. Statistics of model has been analysed again which are listed in Table 11.

Table 9. Statistics from optimised model in WITNESS

(a) Machine Statistics

Name	% Idle	% Busy	% Blocked	% Cycle Wait Labor	% Setup	% Setup Wait Labor	No. Of Operations
Inspection_Desk	98.3	1.21	0	0.48	0	0	41
CNC	0	64.36	35.13	0.26	0.25	0	826
Assembly_Station	46.39	53.47	0	0.14	0	0	808
Test_Bench	0.25	93.97	0.09	0	4.84	0.85	452
Disassembly_Station	96.33	2.8	0.16	0.7	0	0	57

(b) Shipment Statistics

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.
Working_Gearbox	813	753	57	0	0	3	3.3

(c) Buffer Statistics

Name	Total In	Total Out	Now In	Max	Min	Avg Size	Avg Time	Min Time	Max Time
Bin	858	808	50	50	48	49.86	836.82	294.58	1280.29
Assembly_Bin	811	811	0	6	0	1.47	26.07	0	892.79

(d) Conveyor Statistics

Name	% Empty	% Move	% Blocked	% Queue	% Broken Down	Now On	Total On	Avg Size	Avg Time
Conveyor_Belt	46.28	34.15	19.57	0	0	2	1618	1.87	5.57

Results shows major improvement in decreasing cycle and setup wait labour time in machine statistics. Flow of parts to the buffer has been increased and blocked duration of conveyor belt has been decrease. Parts shipped are increased from 726 to 753 giving up more revenue with incurring small cost on hiring an additional operator. Plant generates revenue of £58800 over 10 days.

4. DISCUSSION

Model created in WITNESS signifies an estimation of production performance in a plant. Another investigation has been done on the scenario in which each of CNC and conveyor belt breakdowns for 90 minutes. The effect on daily production rate has been analysed by running the model for a single day. Table 10 and 11 shows comparison on statistics with breakdown and normal operating condition respectively.

Table 10. Statistics obtained under breakdown of each CNC and Conveyor for 90 minutes in a single day

(a) Machine Statistics

Name	% Idle	% Busy	% Blocked	% Cycle Wait Labor	% Setup	% Setup Wait Labor	% Broken Down	No. Of Operations
Inspection_Desk	98.31	0.88	0	0.8	0	0	0	4
CNC	0	58.94	21.67	0.64	0	0	18.75	75
Assembly_Station	50.99	48.96	0	0.05	0	0	0	74
Test_Bench	14.71	79	0	0	4.29	2	0	38
Disassembly_Station	95.38	3.44	0.05	1.13	0	0	0	7

(b) Shipment Statistics

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time
Working_Gearbox	79	64	7	0	0	8	5.06	92.28

(c) Conveyor belt Statistics

Name	% Empty	% Move	% Blocked	% Queue	% Broken Down	Now On	Total On	Avg Size	Avg Time
Conveyor_Belt	33.27	28.18	19.81	0	18.75	1	149	1.48	7.02

Table 11. Statistics obtained under normal operation for a single day

(a) Machine Statistics

Name	% Idle	% Busy	% Blocked	% Cycle Wait Labor	% Setup	% Setup Wait Labor	% Broken Down	No. Of Operations
Inspection_Desk	98.69	0.88	0	0.43	0	0	0	4
CNC	0	71.71	27.89	0.4	0	0	0	92
Assembly_Station	41.71	58.02	0	0.27	0	0	0	87
Test_Bench	0	93.62	0	0	4.94	1.44	0	45
Disassembly_Station	94.21	4.45	0.36	0.97	0	0	0	9

(b) Shipment Statistics

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Working_Gearbox	92	77	9	0	0	6	4.72	73.95	2.76

(c) Conveyor belt Statistics

Name	% Empty	% Move	% Blocked	% Queue	% Broken Down	Now On	Total On	Avg Size	Avg Time
Conveyor_Belt	42.59	32.15	25.26	0	0	1	176	1.5	6.08

Breakdown of each of CNC and conveyor belt for 90 minutes shows decrement in shipment value by 13. This would incur loss of around £1000 /day. Investigation with various ‘what if’ question can be analysed by creating a model. Estimate of various factors can be possible from simulation.

Various direct and indirect cost incurring on production site are not taken into consideration for the current model. Plant can be affected by variety of other factors (delay in arrival of gear, failure in power source, etc.) which are not investigated in the report.

5. CONCLUSION

Simulating a model can help in preventing various losses occurred due to unexpected scenario. Real world condition cannot be created inside the model. Discrete event simulation generates a random value and randomness increases with number of random inputs. As a result, the model gives only estimation on performance on the production unit. Simulation results can be difficult to interpret if they have more random variables. Simulation should not be performed if the direct cost of implementation is less as sometimes it can be time consuming as well as expensive. Simulation should not be performed to areas of common sense. Hypotheses can be tested in model for feasibility. Insight can be obtained on importance of variables with respect to the performance of system and also about the interaction between variables. Model can perform bottleneck analysis in order to investigate areas (process, materials and information) of delay in work. Model shows an individual the operation of the system and not how system operates according to thought of individual. Model helps in designing new system by answering various 'what if' questions.

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APPENDIX 1

Gear arrival distribution

0.0	0
0.5	0
1.0	0
1.5	0
2.0	1272
2.5	1300
3.0	1338
3.5	1388
4.0	1332
4.5	60
5.0	67
5.5	104
6.0	111
6.5	115
7.0	84
7.5	74
8.0	49
8.5	25
9.0	18
9.5	21
10.0	17
10.5	11
11.0	11
11.5	6
12.0	10
12.5	6
13.0	2
13.5	0
14.0	0
14.5	1
15.0	2
15.5	2
16.0	0
16.5	1
17.0	0
17.5	0
18.0	1