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A customised discrete event simulation tool to evaluate engineering product service strategies

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Abstract

This paper examines simulation of the provision of a service through engineered products. Current trends in business show that manufacturers of technology intensive, complex engineering products are delivering their products as a 'bundle' comprising of a product offering with associated service solutions. Researchers and organisations are trying to identify a set of information, their complex inter-relationships and the ways in which they can be synergised to enhance the effectiveness of support service strategies in engineering contexts. So far, applications of Discrete Event Simulation (DES) tools have mainly focussed on either manufacturing or service operations. The work demonstrates the application of DES to support services in an engineering environment to develop a customised Witness simulation tool for modelling these support services. The tool addresses reactive, diagnostic and prognostic service scenarios and level of Integrated Vehicle Health Management (IVHM) technology involved. It would seem logical that receiving increasing product performance information would enable higher levels of service performance to be achieved. This work shows how performance can be improved as well as conditions when it is not.

Introduction

There is a paradigm shift in the methods of conducting business these days. There is an evident change in philosophy from the sale of a 'product' to the sale of the 'use of a product'. The emerging concept of providing a product along with associated services delivered as a 'bundle' has been coined as a Product-Service system (PSS) or "Servitisation" (Baines et. al., 2009).

Various commercial Discrete Event Simulation (DES) solution providers such as Witness from the Lanner group, Arena from Rockwell Automation, Simul8 Corporation etc. have so far focussed on simulating either manufacturing or service operations. There are various non-commercial research simulation tools, which address similar aspects. However while simulating support services for an engineering environment such software have shortcomings. Simulating support services in an engineering environment is a complex and time consuming activity. In addition to this, there was a need to measure the impact of increasing level of IVHM (Integrated Vehicle Health Management) technology on support services.

This work aimed to develop a customised DES tool for modelling support services in an engineering environment. The developed tool enables the user to build models within the environment of Witness for support services in a very short span of time; owing to its rapid prototyping capability.

At the outset, the software tool entails three support service scenarios (reactive, diagnostic and prognostic) (Cuthbert et al., 2011) in an engineering environment, which are based on increasing levels of involvement of IVHM technology. These have been featured in the form of three separate Witness models.

Literature Review

Literature review was undertaken on the concepts of Product-Service Systems (PSS), servitisation, simulation tools, service contracts and the use of IVHM technology in support services for an engineering context.

Mathieu, (2001) states that manufacturers typically saw services as a harmful necessity. Traditionally services were seen as extra costs that could be reduced or were thought to be "someone else's headache". Now focus has shifted to such an extent that manufactured products are seen as incidental (Ward and Graves, 2007) and services are seen as intrinsic in the product offering. Such practices are now coined as Product Service Systems (PSS).

In a PSS, the service provider and asset operator share costs throughout the life-cycle of the asset. The bundling concept here is the delivery of the product and associated services (Maintenance, spares supply etc.) as a package. Contracts capture the understanding between the parties (service provider and service operator) and typically run into years detailing deliverables, Key Performance Indicators (KPIs), remuneration and penalties.

As per Federal Acquisition regulation, contract type vary according to the degree and timing of the responsibility assumed by the contractor for the costs of performance, the amount and the nature of the profit incentive offered to the contractor for achieving or exceeding specified standards or goals. According to Roy and Cheruvu (2009), the types of contracts can be broadly classified as follows:

1) **Fixed Price Contract**: This is the method of contracting in which the contracting party pays a firm price or in appropriate cases, an adjustable price for specific deliverables regardless of the expenditure incurred by the contractor. The contractor bears the full responsibility and risk during implementation of the project and amount of contract price does not depend upon the resources or time extended.

2) **Cost plus Contract**: This is also called cost reimbursement contract. In this contract, contractor is paid all its expenditure to a set limit plus an additional amount as profit with some risk share. This type of contract is applicable where cost cannot be appropriately defined at the time of contract due to high level of uncertainty in predicting the cost or data is not enough to estimate the cost.

3) **Time and Material Contracts**: In this type of Contract, contracting party does not pay for a specified outcome; instead they purchase the contractors' direct labour. In this type of contract, deliverable is skilled labour at a negotiated price that can perform the required job.

4) **Incentive Contracts**: In this type of contract, contracting party and contractor agree for a tentative target price and maximum price with an option of price adjustment after execution of the project; based on the actual cost incurred by the contractor plus a fee (profit) which is inversely propositional to the cost. However, in any case this should not exceed the maximum contract price. The risk in this case is shared equally by contracting party and contractor. The two emerging contracts within incentive contracts are as follows:

- **Availability Contracting**: Contractors are paid according to the time that an asset is available and is fulfilling a specific target.
- **Capability contracting**: Contractors are responsible for providing a capability and outputs to agreed performance standards.

IVHM (Integrated Vehicle Health Management) is a technology platform which receives sensory input from a network to provide a corresponding output. The output indicates 'health' of systems or sub-systems of complex engineering products. In addition to this, it has prognostic capabilities whereby it can detect number of hours or number of cycles to failure.

The power of IVHM is through the valuable asset information provision and hence serves as a robust decision support tool. Companies formulate inventory/production strategies based on information obtained from the technology. For example, if it is predicted that a particular sub-system is going to fail, then service provider can make that sub-system readily available so that it can be replaced at an appropriate time. It will help in ensuring that the asset is not under breakdown for a long time. It would be useful here to think in terms of contracts whereby the provider is penalised for increased down time of asset.

Simulation models help to capture the behaviour of a system over the passage of time. There are two types of dynamic models:
- **Discrete event simulation** which captures the dynamic behaviour of a system as a change caused by the happenings of discrete events in the space of time.
- **System dynamics** which depends wholly on aggregate process flow (non discrete events) which means that no two events occur simultaneously.

The concept of discrete event simulation can act as a very powerful decision making aid in various facets of business. A thorough review of available commercial DES software was done to identify which was best suited to this type of work. Komoto and Tomiyama, (2008) discuss the integration of service CAD and Life Cycle Simulator (LCS) to form an Integrated Service CAD and Lifecycle Simulator. While the CAD provides the architecture for the service offering, the Life Cycle Simulator assesses product life and its economic and environmental repercussions. Shimomura et al. (2008) discuss the inclusion of QFD (Quality Function Deployment) for modelling. They argue that taking the concurrent customer voice right from the inception of the PSS modelling is essential for its effective performance. Hara et al. (2009) propose a design method to understand total value delivery and to design associated activities. They lay emphasis on the parallel design of product and associated service; this means that right from when the product is in the design. Based on availability, Witness was chosen as the environment for tool development and building.

Commercial and non-commercial DES tools available have so far either focused on manufacturing or services. Also, there is no tool available that addresses the impact of increasing level of IVHM technology on support services in an engineering environment. Moreover simulating support services in an engineering environment is a complex and time consuming task. Current commercial and non-commercial DES tools do not provide the feature that enables the user to build complex models quickly.

This work is on the novel development of a DES tool for rapid model building for quick assessment of support services in an engineering environment and the impact of IVHM

technology on such support services using the prototype work on bespoke modeling from Ball et al. (2010) and Cuthbert et al. (2011) as a foundation.

Tool development

The tool is developed within the Witness (manufacturing edition) environment; a commercial discrete event simulation developed by Lanner Group Inc. A model can be built with ease, owing to the user friendly interface. The underlying objectives are to develop a DES tool possessing rapid prototyping capability through development of specification, build architecture and tool development for different support services followed by experimentation to test the tool.

The approach followed for development and testing of tool consists of following four steps:
- Specification development (including input and parameters)
- Architecture development (including conceptual and pilot)
- Tool development (including interactive logic functionality)
- Experimentation

The first step was to formulate the tool specification, in the form of input and output parameters (see table 1). These parameters were developed through literature review on the different contracts in support services in an engineering environment based on different terms and conditions as well as the level of support service requirement. Validation of these parameters was through review with researchers at Cranfield University and experts at the IVHM Centre at Cranfield.

Table 1. Input and output parameters developed

Input parameters	Output parameters
Contract duration	Fleet and asset utilisation
Total no. of assets within fleet	Maintenance group utilisation
Required service level based on avg availability	Total number spares replaced in the fleet
Required service level based on size of fleet	Current spare stock in store for all spares
Total demand (total customers to be served)	Number of customers waiting to be served (lost)
Cycle time of asset	Average availability of fleet (operational availability)
Mean Time To Repair (MTTR)	Total assets below KPI
Mean Time Between Failure (MTBF)	Total assets above KPI
Time Between Overhaul (TBO)	Total penalties based on availability of the asset
Time To Overhaul (TTO)	Total incentives based on availability of the asset
Diagnosis time	Total penalty given avg avail below service level
Number of maintenance staff	Net penalty/incentives based on point availability
Number of reasons for failures	Total cost of spares supplied
Travel time of maintenance staff	Total labour cost
Inventory lead time	Inventory holding cost
Order lot size for inventory	Total fixed cost of asset
Safety stock level of each inventory	Total cost incurred
Penalties/Incentives based on availability	Difference of contract price and total cost incurred
Penalty based on avg avail below service level	
Unit asset cost	
Cost of inventory required for each failure	
Contract price	
Man hour rate	
Inventory holding cost as % of total inventory cost	

After formulation of tool specification, tool architecture was created to visualise the conceptual building blocks. As the context of tool building is the support services in an engineering environment, the support services were classified into three different functions namely: Operations, Maintenance and Inventory Management. The interactive logic between these three function forms the basis for building different models for three service scenarios in the Witness environment. Three different levels of IVHM technology were modelled: reactive, diagnostic and prognostic, see Figure 1.

The interactive logic within Witness was coded in such a way that the user has the flexibility to change the values of input parameters in input table in Microsoft Excel spreadsheet. As soon as user saves the Excel file, the values of input parameters are imported into Witness through an Excel interface. Model is build based on these inputs and the in-built logic functionality and user can run the model for contract duration. The different output parameters provide freedom to concerned stakeholders for further decision making based on their requirement.
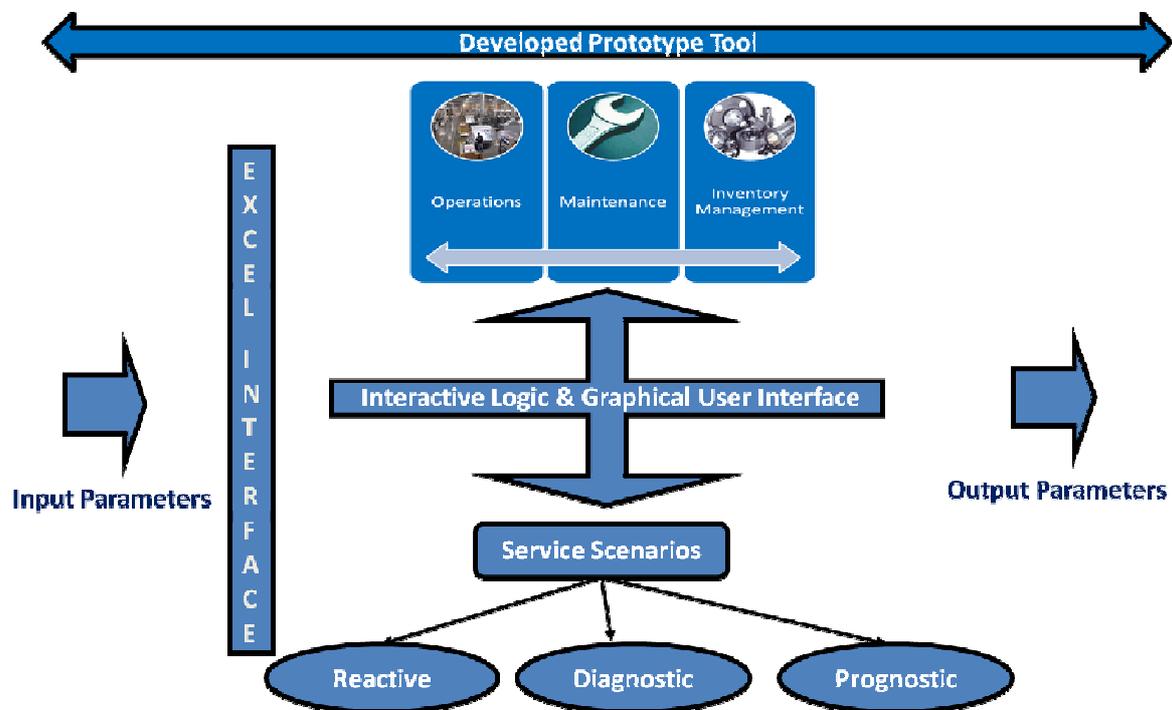

Figure 1. Tool architecture

As part of tool development, the different support service scenarios are based on the type of service level and Integrated Vehicle Health Management (IVHM) technology involved and build three models based on the three different scenario defined below:

Service Scenario 1: Reactive
Service Scenario 1 in the tool represents a reactive kind of services in engineering environment. There is no IVHM technology involved in this scenario. The sequence of events in this scenario is as follows:
a. Asset randomly breaks down after according to MTBF data for each sub-system.
b. Available maintenance staff go to diagnose (variable time) the faulty asset sub-system.
c. Maintenance staff check inventory, if it is available, acquire it, travel to asset and fix.

d. Safety stock (ordering characterised by lot size and lead time) is maintained.

This scenario differs from others as follows:
- Diagnosis time has been considered because of absence of IVHM technology.
- Safety stock level for each spare.
- If the operational availability goes below the agreed KPI then penalties are incurred.
- There is no incentive for the provider for better services above desired service level.

Service Scenario 2: Diagnostic
Here, an intermediate level of IVHM technology is used to support the service provision. Sensing enable assets to self diagnose faults on failure, i.e. when the asset fails, it ascertains which particular sub-system has failed. There is no need of manual diagnosis as in first scenario. Perfect diagnosis is assumed. The sequence of the events in this scenario is explained as follows:
a. Asset breaks down.
b. Asset diagnoses the failed sub-system by itself owing to self diagnostics capability.
c. If particular inventory is available, staff acquire inventory, travel to asset and fix.
d. If no inventory is available an order is placed. Once stock arrives the above is carried out.

This scenario differs from scenario1 (Reactive) on the basis of following aspects:
- Asset possesses self-diagnostics capability of failed sub-system.
- Diagnosis time is not considered.
- Stock orders can be triggered and batching can be specified.
- No target safety stock is maintained.
- Incentives exist for the supplier to exceed the basic agreed service level.
- Penalties are based upon the point availability rather than average operational availability.

Service Scenario 3 - Prognostic
Here a more advance level of IVHM technology is used than the previous two scenarios. The prognostic scenario represents the involvement of IVHM technology to extent of predictive maintenance in support services in engineering environment by enabling the asset to predict the failure. The sequence of activities in this scenario is as follows:
a. Asset is operational.
b. During the use, asset predicts next failure (when and which sub-system).
c. At the point of sensing of failure, a check is made for available spares inventory.
d. If inventory is available, staff collect, go to asset and replaces prior to actual failure.
e. If no inventory is available an order is triggered. Replacement is made once available that may be before or after the actual failure.
f. No Safety stock for spares is maintained in this scenario.
g. Penalties and incentives are based upon point availability.

This scenario is similar to service diagnostic scenario, with the following two differences that relate to the IVHM technology used:
- The asset predicts the failure before actually it happens rather than after it happens.
- Spares orders are triggered at failure sensing point rather than at point of failure.

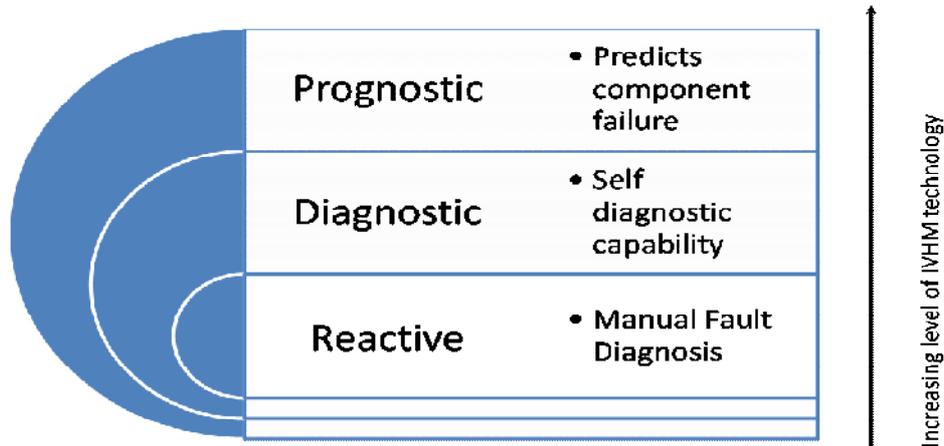The three scenarios are differentiated in Figure 3.

Figure 3. Scenarios differentiation

Model Building

The simulation model interface entails basic manufacturing entities in Witness which include machines, parts, labor and buffer; connected by interactive coding logic. Witness essentially helps analyse model behaviour over the simulation run as it captures the interactive behaviour of discrete events as a function of time. The work models support services and simulate it over contract duration to understand how discrete events (operations, maintenance etc.) interact with each other to affect the system as a whole. Each model consists of four main building blocks: Operations, Maintenance, Inventory Management and Costing.

- Operations refer to the actual performance of the engineering product (or asset) in the field. In the model, the asset has been shown as an aircraft and the group of aircrafts as fleet. Model has icons to indicate that the asset is functioning (i.e. running, down, under repair, idle) and graphics provide the summary performance.
- On-site stores and spare parts supplier form the inventory management. Spare parts arrive, are stored and then used for asset repair. Arrival is characterised by batch size and lead time as well as cost. Again graphical summary information is shown on the display.
- Maintenance staff provide support to ensure the assets are repaired in a timely manner. They are responsible for fault diagnosis, asset repair and transport of spares from store to asset. They have been modelled to follow a path for their all movements.
- Costing involves some basic assets and resources cost. These are calculated on the basis of input values provided by the user in the Excel sheet.

Experimentation

Subsequent to tool development, experimentation was carried out to test the tool and analyse the results. Out of all input parameters, 11 input parameters are identified which have a significant impact on the performance of support services under the test scenario. Similarly, there are 16 parameters to be recorded as the outcome of model run. The value for each input parameter is varied while keeping all others at constant value. The model is run for a period of equivalent of 5 year time duration and value of output parameters was recorded. The experimentation is followed for all three service scenarios with same variation in numerical values of input parameters. Whilst the results will be different for a different given scenario, showing these results demonstrates the capabilities of the tool created. The results show the effectiveness of support services from 'Reactive' to 'Diagnostic' and 'Prognostic'. This is

due to the increasing level of IVHM technology level associated with these scenarios. Some of the results are shown in figure 3.

Assets availability Vs Number of assets

Assets wait repair Vs Number of maint. staff

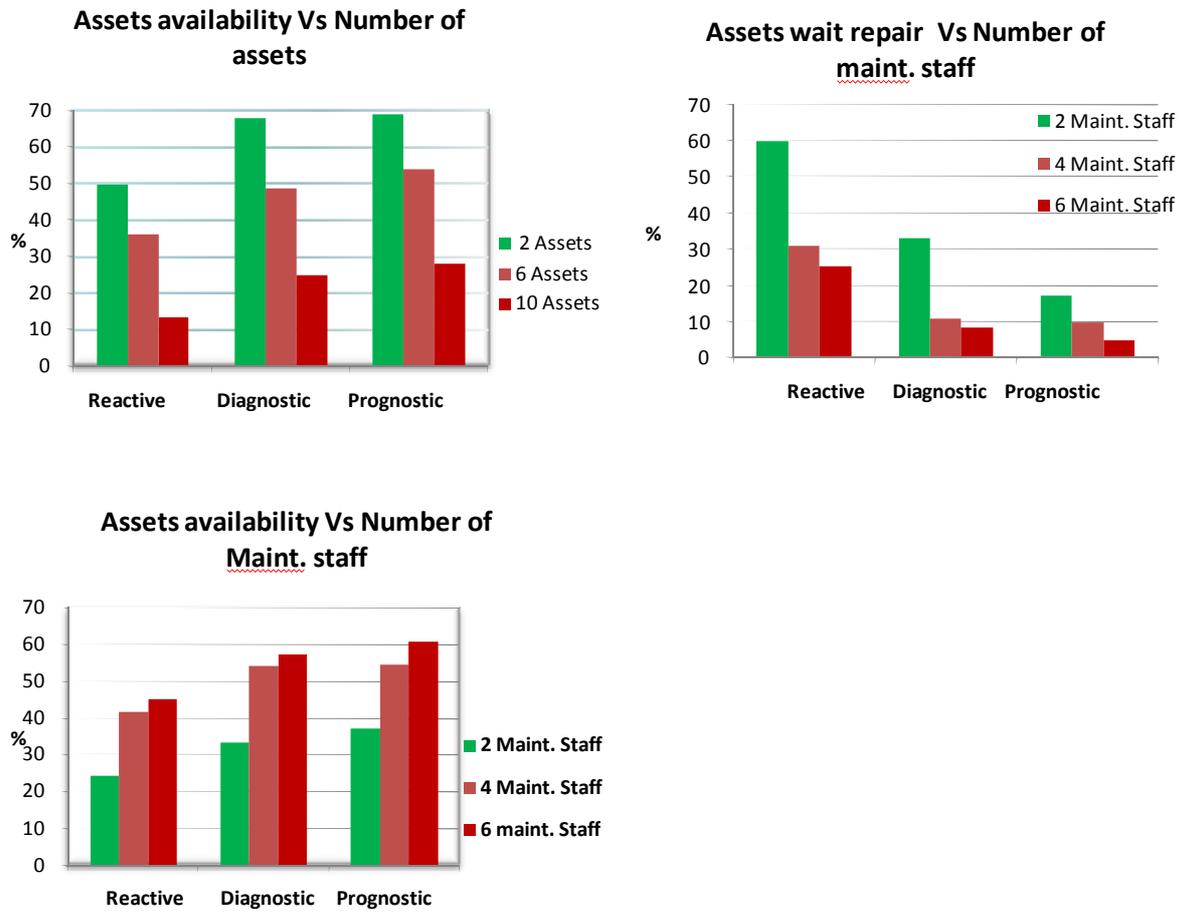**Assets availability Vs Number of Maint. staff**

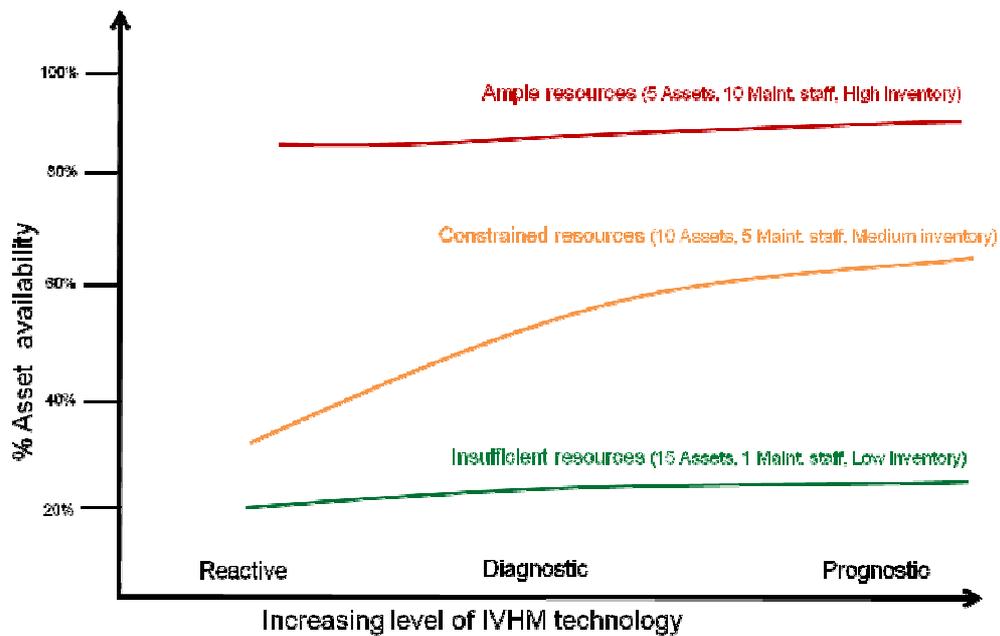Figure 3 results from test scenario of the DES tool

Figure 4. Effect of IVHM technology with varying system capacity levels

An important observation emerged during the experimentation was that IVHM technology was not significant when there are insufficient support service resources, i.e. the constraint is not the asset availability but the availability of inventory or that the asset is not heavily used to fast repair is not significant to performance. The impact of IVHM technology is more significant when the constraints are balanced throughout the system. See summary results in Figure 4.

Discussion
The tool was developed in a discrete event simulation environment to assess the impact of sub-system performance on the overall effectiveness of support services for engineering product offerings. In addition to this the tool, addresses limitations with existing DES software packages to address modelling of integrated product-service offerings. The architecture of the tool was developed based on literature survey and support from IVHM experts.

Throughout the length of its build time, the architecture was subject to a number of modifications. It was apparent that support service contracts had a direct bearing on the effectiveness of support services. Discrete events within these contracts were then identified and the architecture of the tool was built on those findings. Interactive logic (within software environment) between these events would differ on the basis of the contract types, the modelling choice of which was provided to the user.

To incorporate differing service levels, the architecture was modified to incorporate 'service scenarios'. Each scenario would differ based on increasing proliferation of information owing to increasing IVHM technology. It was first discussed that 'modules' within the same Witness model would address each service scenario. Coding difficulty with this approach led to the building of three separate models with Excel interfacing being an incorporated aspect in each of the three scenarios.

Depending upon the terms and conditions of contract regarding the associated risks, financial implications and agreed level of service to be provided; the service provider can decide over which service scenario is best suited for service support. Similarly, the customer can investigate the type of contract to use depending on the required service level.

The developed tool has the capability of rapidly building the models for the support services in an engineering environment. Without using a tool such as this, building models for support services in an engineering environment would be complex and time consuming for experienced as well as inexperienced modeller. Using such a tool will enable experienced and inexperienced modellers to build the models for support services quickly and more easily using spreadsheet interfacing with simulation software.

Conclusion
This work was concerned with the development a customised discrete event simulator within Witness software for modelling support services in an engineering environment. The tool developed addresses three different service scenarios based on IVHM technology involved to enable a user to build the model for these service scenarios quickly. At the same time, it offers flexibility of the input parameters and to obtain data to support decision making. The tool can act as a platform for modelling support services as per specific business requirements

and it opens the avenues for further work on rapid prototyping capability in simulation as well as ascertaining the most valuable conditions in which to implement IVHM support.

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