Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 11 (2013) 213 – 218

www.elsevier.com/locate/procedia

2nd International Through-life Engineering Services Conference

Warrior Vehicle Fleet Sustainment using Intelligent Agent Simulation

Ip-Shing Fan*[a], Ian K Jennions[a], Fadi Matar[a], Malcolm Bridgeford[b], Steve Osborn[b], Gary Vickers[b]

[a]*IVHM Centre, Cranfield University, Cranfield, Bedford, MK43 0AL, United Kingdom*
[b]*Aerogility, Smithfield Business Centre, 5 St John's Lane, London, EC1M 4BH, United Kingdom*

* Corresponding author. Tel.: +44 1234 750111; fax: +44 1234 758331. *E-mail address:* i.s.fan@cranfield.ac.uk

Abstract

The Warrior Infantry Fighting Vehicle(IFV) is one of the key tracked combat vehicles in the UK Army. It was first introduced in 1988. A modernisation programme is currently underway to enhance 643 vehicles to serve to 2040 and beyond. The Warrior is typical of military assets that have to be acquired, maintained, supported and deployed. Effective materials and logistics support for the life of the asset is necessary to give the army a capability to defend the country and keep world peace. In the military world, events are uncertain. An asset can be used relatively lightly in peace time for training and readiness preparation. When it is deployed, it is used intensely and probably in situations not foreseen in the original design specification. Compared with a commercial vehicle that is designed to be continuously heavily used, military uncertainties make the planning for spares and repairs very difficult. Responding to the dynamics of military logistics, inventory planners have to make decisions on how many spares to order from the manufacturer and when, where to store the spares, and when to send them to the units. Maintenance decisions are also made by military engineers to pull vehicles into depots for scheduled maintenance, deal with unexpected repairs, and make sure all people, equipment and spares are coordinated for the maintenance work. Planning for the worst case scenarios provides enhanced resilience to military needs, but is likely to be unnecessarily costly. Compared with an inventory management problem that has steady demand and supply, optimal military logistics could be better served by adapting the behaviour of the planners to suit the dynamics of the deployment scenarios. This paper reports on a military logistics sustainment model built using an agent based simulation platform, with the Warrior vehicle fleet as the case study. The model proves an effective tool to help military planners evaluate different spares inventory policies to match deployment demands.

Selection and peer-review under responsibility of the International Scientific Committee of the "2nd International Through-life Engineering Services Conference" and the Programme Chair – Ashutosh Tiwari

"Keywords: Military logistics; sustainment; inventory management; scenario planning; simulation"

1. Introduction

Defense activities around the world face different challenges: political, social, and environmental; but ultimately economic because of the high cost of running activities in more than one location. Managing the effective cost of running the military operations in multiple sites requires the use of an efficient logistics management system. Military logistics is one of the most complex type of logistics as it requires a high level of coordination between different streams of operational and strategic decisions. Its main objectives are to reduce the risks of spare parts unavailability in theatre and to manage the operational cost.

Intelligent agent simulation is a powerful tool used to simulate the complexity of different real world situations and to support and identify intelligent decisions. Simulation modelling is a powerful and effective tool to imitate a real-world logistics scenario, by observing the behaviour and analysing the results and identifying the best practise. The main advantage of simulation is to compress time and study the consequences of events. Agent model representation gives the flexibility to customise the scenario parameters to

Selection and peer-review under responsibility of the International Scientific Committee of the "2nd International Through-life Engineering Services Conference" and the Programme Chair – Ashutosh Tiwari
doi:10.1016/j.procir.2013.07.047

implement a high level of realism, and simulate a number of experiments without affecting the real world system.

The work of this project was to develop a proof-of-concept intelligent agent model to simulate the operation life for a population of Warrior Infantry Fighting Vehicles for their 25 year life, combining different roles in training and theatre missions. The paper presents the different stages of the project, starting by identifying the fleet life and model design, followed by the description of different vehicle operation scenarios; findings; discussions; and conclusion.

2. Literature background

Military logistics has developed over many centuries, Ostrowski et al.[1] categorised these stages starting from the stone ages before inventing the wheel through The Romans, World War 1 and World War 2, until the Gulf war. Through these eras the transportation types developed from using manpower or beasts to wagons, ships/boats, and later, railways, truck, aeroplanes, etc.

While the fundamentals between military logistics and commercial logistics are not significantly different, studies showed that military logistics seldom consider the just in time (JIT) method for the supply chain because of the high risk of unavailability during wartime. In addition, when deployed in theatre availability is more important than the logistics cost to ensure mission success.

"A simulation is the imitation of the operation of a real-world process or system over time. Whether done by hand or computer, simulation involves the generation of an artificial history of a system and the observation of the artificial history to draw inferences concerning the operating characteristics of the real system"[2].

Simulation has been a recognised tool to solve problems arising from design and operational process; it is a technique to abstract the key information from the real system, build a logical model mimicking the real system, and describe the interactions and the inter-relationship among the agents. Furthermore, experiments on real systems are costly and might cause unrecoverable damages to the system. Hence as a technique, simulation is the best solution which allows us to collect the information, execute the experiments and conclude intelligent decisions without interrupting the real system.

There are different types of simulation models:

- Static Simulation Models: steady state or particular time, such as Monte Carlo simulation.
- Dynamic Simulation Models: track events over time but no probabilistic components.
- Stochastic Simulation Models: at least one random input component.
- Continuous Simulation Models: usually in process industry
- Discrete Simulation Models.

"Discrete Event Simulation utilizes a mathematical/logical model of a physical system that portrays state changes at precise points in simulated time. Both the nature of the state change and the time at which the change occurs, it mandates precise description. Customers waiting for service, the management of parts inventory of military combat are typical domains of discrete event simulation."[3] In other words, it simulates an operation with a sequence of different events in different phases of time.

A powerful paradigm to programme a simulation environment is the use of Multi-Agent Systems. "A multi-agent environment is one in which there is more than one agent, where they interact with one another, and further, where there are constraints on that environment such that agents may not at any given time know everything about the world that other agents know (including the internal states of the other agents themselves)"[4].

Multi Agent System is recognised as both abstraction and effective technologies for modelling and building complex distributed applications. However, it is not easy to design because when large number of autonomous components interact it is very difficult for the emergent organisational structure to fit into the system goals or that the desired functionalities to be fulfilled[5].

Successful modelling of multi-agent simulation requires both detail and representative concepts of the real world, as well as an efficient software platform to model these concepts as agents.

3. Warrior Fleet

This scenario simulates the sustainment logistics of the assets and spare parts of UK MOD Infinity Fighting Vehicle (IFV) Warrior through 25 years of asset life.

3.1. Warrior IFV

The Warrior is one of the British armoured vehicles. The main role of the Armoured Personnel Carrier/Infantry Fighting Vehicle (APC/IFV) is to carry troops under protection to the objective and then give firepower support when they have disembarked[6]. An upgrade programme for 643 Warriors has been commissioned by the British Army to extend their service life to 2040 and beyond[7]. 449 vehicles will also be fitted with a new turret and weapon system under the Warrior Fightability Lethality Improvement Program (WFLIP) [8].

Based on the programme information, the simulation will include a fleet of 400 Warriors and an asset life of 25 years.

3.2. Fleet life plan

Figure 1 illustrates the division of 400 IFV Warriors into 4 fleets, 100 Warriors each, through the period of 25 years (from 2012 till 2037), the scenario includes different stages of training and theatres in various regions. This scenario was developed and validated with the military experts.

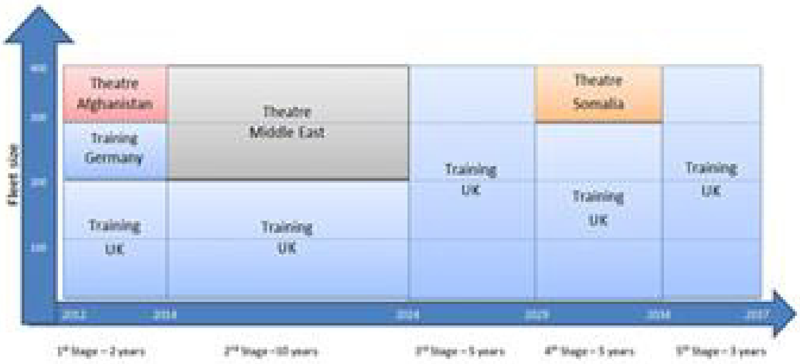

Fig. 1. Warrior fleet life plan.

At the start of the simulation period, one fleet of Warriors is in the Afghanistan theatre. When the fleets are deployed overseas, all the supporting facilities (maintenance, warehouse...etc.) move together with the assets.

4. Model Development

The model is built with the Aerogility platform. Aerogility is a software solution for global aerospace and defense organisations delivering complex aftermarket and through-life support services. Its customers include leading military aircraft and defense solution manufacturers in USA and Europe.

Aerogility has a three tiered architecture with the simulation application and database functions running on a server; and users interact with the system through a web interface, allowing multi-user deployment across a network.

Aerogility uses an intelligent agent paradigm to model the objects of scenario simulation. The agents are software objects where the characteristic and behaviours are defined. Aerogility has a rich library of agents that covers most of the features in the aftermarket and through life support business. The rich agents library makes modelling with Aerogility very efficient, as most of the simulation attributes and rules could be reused from the library agents. The following briefly describes the modeling concepts and agents used in the Warrior model.

4.1. Assets

The asset view is the engineering view of the asset under consideration. It can be an aircraft, a ship and in this case the Warrior IFV.

An **Asset** has an identity and life in the simulation, being deployed on missions and has its maintenance needs. An asset is made up of different sub-systems and parts, each having their own failure and maintenance characteristics.

Master Parts could be understood as the engineering Bill of Material(BOM) of the assets. These are the subsystems and parts that build up an asset. The generic part may have multiple variants, for example an engine could be supplied by different suppliers, or have earlier and later variants. The different part versions can have different deterioration and repair characteristics; and different costs. The Warrior model defines multiple lines of maintenance: base, workshop, depot and manufacturer. Each part is defined with its wear and tear life, maintenance time and cost and other related characteristics.

Only four master parts are defined for this simplified Warrior model: engine, transmission, turret and track. There are two variants for each of engine, transmission and turret.

Configuration represents the make up of a batch of assets from the set of Master Parts. In long life assets, there could be multiple asset configurations in the fleet population. For example the population may have some vehicles with the original engines, and others with more fuel efficient new engines.

Fleet represents the deployment unit of the assets. A fleet could have assets of different configurations.

The simulation model tracks the life of each individual asset, while it may be deployed as part of a fleet and has a specific engineering configuration.

4.2. Operations

The asset fulfills its purpose in operation. In commercial operation, this could be represented as earning income. In real life military deployment, non-availability for operation could lead to mission failure, resulting in failure in military objectives and even loss of life. There are various ways to avoid failure by building in redundancy or deployment alternative assets. These are represented as penalty costs for unavailability in the simulation.

From the engineering viewpoint of an asset, operation consumes life and may cause unscheduled part failures, creating maintenance and spares requirements.

Mission in the Warrior model represents the high level concept the operation activity and geographic location.

Operation defines the criticality of unavailability, the tempo of use and maintenance regime, eg training or in theatre.

Region defines the environmental factors that accelerate wear and tear. In the model, the regions are defined as UK, Germany, Middle East, Afghanistan and Somalia.

4.3. Logistics

Logistics covers the maintenance of the assets and the management of the spares inventory.

Operation Base is the location of operation related to the regions defined above. Rules are defined to specify the preference of maintenance facility and warehouse to support each operation base, and the associated cost and time parameters.

Maintenance Facility is the location where certain types of maintenance could be carried out. Each maintenance facility has its capability characteristics defined, like working day pattern, skills, equipment, cost and quality. If the facility is too busy, the asset may be passed to other facilities according to a set of rules. Transport cost and time are incurred and defined according to the movement between regions. Maintenance job allocation rules are managed and can be set up as different maintenance policies. Spares are drawn from warehouses to support the maintenance. Rules are defined to specify the preference order of warehouses where spares are drawn.

Warehouse is the location where spares are kept. Each warehouse may keep different parts. Parts in warehouses incur inventory costs, in addition to its acquisition cost. The inventory planner move spares between different warehouses and re-order spares according to the inventory level in the warehouses. Transport cost and time are incurred if the spares move between warehouses. These rules are managed as inventory policy.

In the Warrior simulation, the UK Army practice of having integrated maintenance and warehouse support to operation is represented. Thus associated with each operation base, there is a maintenance facility and a warehouse. The capabilities of these vary according to deployment mission.

Manufacturer is the provider of spares in the Warrior simulation, as no more new vehicles are to be built. Different manufacturers for different parts could be set up within Aerogility, but this simulation simplifies to using only one manufacturer for all the spares defined.

Shipping is the cost and time to move assets and parts between regions. Shipping can be sent through standard method or express, with express costing more and arriving faster.

Inventory Manager is the agent that manages the rules for ordering new parts from manufacturer, moving parts between warehouses and maintenance facilities. This agent has a complex set of triggers for considering decisions based on the inventory levels in each warehouse, the maintenance demand for spares and the cost of parts. The decision rules can be as simple and complex as required. The set of scenario rules used in the Warrior simulation is reported in Section 4.

4.4. Key Performance Indicators(KPIs)

Aerogility captures all the details in the execution of the simulation and can generate a wide range of reports and charts. The KPIs represent the business performance measures of the logistics problem being investigated. For the military logistics of Warrior, the following are used:

- Asset availability
- Parts availability rate
- Stocking cost
- Spare turn rate
- Part unavailability count
- Emergency shipments
- Part manufacture cost
- Total cost
- Unavailability Cost

The Warrior model has over 2000 parameters and each of these can be adjusted to tune the model.

The 400 Warriors each have over 100 parameters. The Warriors are modelled with different starting condition to represent the different time they were manufactured or upgraded. This is more representative to real asset situation and the maintenance and spares requirements are correctly spaced out rather than all required at the same time.

5. Inventory Scenarios

The Warrior simulation is to illustrate the fleet sustainment model built in Aerogility as a potential tool to support the military logistics planner in using different rules and policies for decision making. The simulation is run based on the same Warrior life.

- Total scenario period is 25 years
- Number of assets is 400 Warriors, divided into 4 fleets
- The same fleet mission for each scenario

Five inventory policies were used to highlight the differences these could make.

5.1. Planned Manufacturing – excessive

This is the baseline scenario where 10 items of each part is manufactured every 6 months and sent to the main UK warehouse. This quantity is well above what is needed. It is a good illustration of the ordering policy to provide a stable order for industry.

5.2. Planned Manufacturing – low

This scenario orders 8 items of each spare part every year to be sent to the UK warehouse. Variation of the re-order quantity and frequency allow the tradeoff between the various availability and cost KPIs.

5.3. Environmental wear and tear

This scenario adds in the accelerated wear and tear for certain missions. This scenario allows the comparison of different deployment mission assumptions on the effect of spares inventory.

The environmental factors were applied to the Mean Time Between Failure(MTBF) on the parts to account for the additional use and the effect of sand on the Warriors. The training mission in UK and Germany is used as the base line and factor as 1. The wear and tear in Afghanistan and Somalia is 3 times, and the Middle East is 4 times.

5.4. Automatic scenario optimisation

This scenario is an Aerogility feature that automatically changes a user defined set of simulation parameters to seek the optimal settings. With the large number of parameters, this is a very useful feature to assist planners.

5.5. Immediate spares

This scenario does not use a periodic re-order policy. This scenario assumes a part is available whenever one is needed. This scenario allows the planner to work out the demand of the parts based on the fleet deployment characteristics. It can be used to reverse calculate the order pattern for new parts.

6. Findings

The simulations provide results in KPIs as well as the plots of the dynamic variations of availability, inventory and costs. Within the page limit of this paper, only the KPI findings are presented for comparison.

Scenario one provides the baseline to compare the effects of changing the policies in the other scenarios.

6.1. Planned Manufacturing – low

Table 1 compares the KPIs between the baseline and low scenarios.

Table 1. Planned Manufacturing.

KPI	Baseline	Low Manufacturing
Asset availability (%)	88.0	88.0
Parts availability rate	100.0	100.0
Stocking cost	62,624	34,956
Spare turn rate	8.26	12.55
Part unavailability count	0	0
Emergency shipments	0	0
Part manufacture cost	918,000,000	389.400.000
Total cost	1,138,129,684	608,691,946
Unavailability Cost	0	0

Both re-order policies provide the same support to asset operation, as asset and part availability are the same. There is, however, a big difference in the total cost as both the part manufacture and stocking costs are significantly lower in the low manufacture scenario. Thus determining the right spares re-order policy has a major impact on the logistics cost over the asset life.

6.2. Environmental wear and tear

Table 2 compares the effect of the additional wear and tear effects.

Table 2. Environmental factor.

KPI	Baseline	Environmental Factors
Asset availability (%)	88.0	72.4
Parts availability rate	100.0	55.7
Stocking cost	62,624	66,643
Spare turn rate	8.26	9.03
Part unavailability count	0	3,382
Emergency shipments	0	0
Part manufacture cost	918,000,000	918,000,000
Total cost	1,138,129,684	1,395,066,603
Unavailability Cost	0	176,566,500

This scenario is run with the excessive manufacturing re-order policy so the part manufacture cost is the same. However, the effect on asset and part availability is marked, leading to a high unavailability cost. The total cost increases with the cost of unavailability as well as the need to ship parts between to the overseas warehouses.

This scenario highlights the need to be smart with the movements of spares so that the right quantity is in the right place at the right time.

6.3. Automatic scenario optimisation

In the automatic scenario, Aerogility varies the re-order quantity of turret and track. The results show a lower re-order quantity of 4 turrets and 6 tracks would satisfy the availability target and reduce the total cost.

This scenario highlights the benefits of intelligent simulation to vary the large number of possible re-order policies to fine the ‘optimised’ logistics solution.

6.4. Immediate spares

The immediate spares rule was run over a number of simulations using Monte Carlo variations on the probability of failures and repair times. A schedule for part manufacture re-order was generated. The re-order quantity reflects the consumption of spares according to the deployment. The first point worth noting is that not many spares are needed in the earlier years of the scenario as the asset is still new and the parts have much life. The second is that the spares demand matches the mission scenario. If there are major changes in the scenario, the spares demand would be very different. The third point is realistic order lead time. In real world, parts may need six months or more to be manufactured and so planning is essential.

7. Discussion

A sustainment simulation model has been built for the fleet of Warrior IFV using the Aerogility modelling platform. The Warriors model has an engineering breakdown into its major sub-systems, and has the concept of multiple variants and configuration. The modelling concept represents the engineering changes and upgrades over the long life of a military asset.

The model has the concept of fleets to organise vehicles into units for deployment mission in the way military planners plans. The model captures a realistic 25 years deployment profile of the Warrior distinguishing between peacetime training and active deployment. The deployment regions represent potential areas of operations of the UK military. These regions wear out the life of the vehicle and parts at different rates, and the shipping of the asset and parts takes time and cost.

Scheduled maintenance of the vehicles and parts are triggered by use life in scheduled maintenance. Unscheduled maintenance is triggered by probabilistic events, which is related to the deployment mission.

Four lines of maintenance are modelled as practiced by the UK Army. The maintenance activities consume parts which are located in a global network of warehouses. The inventory manager realistically represents the decision options and policies for managing the ordering and movement of stock between the warehouses and manufacturer. The complexity of the model represents the real world operation and support of military assets.

Five different simulation scenarios have been run for this paper. The scenarios highlight the different inventory policies needed to cope with optimizing the sustainment cost to cope with the uncertainty in the tempo of operation and the different wear and tear in mission deployment. The complexity of the life of military assets requires sophisticated inventory planning.

The five scenarios is only a small number of the many possible combinations of scenario parameters. For example, environmental wear and tear could be run with a lower manufacture re-order quantity. The fleet size for deployment could be varied to represent small units than a full brigade. The full range of scenarios help planners to develop policies that should be used in different deployment life assumptions.

The model could be made more detailed by increasing the levels of engineering breakdown and configuration. This increases the computation needed for the simulation and the level of details should match the decision making needs of the military planners.

This simulation model demonstrates a tool that can help to develop and evaluate different polices and the situation they should be used.

8. Conclusion

Military logistics is a difficult problem, as the availability of assets in the right place and at the right time is critical to national security, yet the events leading to the deployment of the military are very uncertain over the life time of the asset. Making the best decisions for the long term sustainment of military assets is best supported by evaluating possible future scenarios. Computer based simulation accelerates the playing out of future events and is a very useful tool. This paper reported on a Warrior fleet sustainment model using a flexible simulation platform. The various scenarios run on the model demonstrate its potential as a decision support tool for logistics planners.

Acknowledgements

The authors would like to thank the partners and members of the Cranfield IVHM Centre for their support of this work, including Alstom, BAE Systems, Boeing, Meggitt, Rolls-Royce, Thales, UK MOD and the East of England Development Agency (EEDA); also Aerogility as technology collaborator.

References

[1] Ostrowski, S. L(1999), Comparative analysis of military and commercial logistics: Present and future possibilities for the transfer of principles and practices. Thesis. Cranfield University.

[2] Banks, J. (2005), Discrete-event system simulation, 4th ed, Pearson Prentice Hall, Upper Saddle River, NJ.

[3] Nance, R. E. (1993), "A History of Discrete Event Simulation Programming Languages", TR 93-21, Virginia Polytechnic Institute and State University.

[4] Panait, L. and Luke, S. (2005), " Cooperative Multi-Agent Learning: The State of the Art". Autonomous Agents and Multi-Agent Systems Vol 11(3).

[5] Gaud, N., et al. (2008), " A Verification by Abstraction Framework for organizational Multi-Agent Systems", in AT2AAI-6@AAMAS'08, Estoril, Portugal.

[6] The British Army, Warrior Infantry Fighting Vehicle, available at: http://www.army.mod.uk/equipment/fighting-vehicles/1476.aspx (accessed 14/June/2012).

[7] BBC, £1bn upgrade for British army's Warrior vehicles, available at: http://www.bbc.co.uk/news/uk-15446928 (accessed 14/June/2012).

[8] Defence Industry Daily, WSCP Program, Technologies, and Bid Teams, available at: http://www.defenseindustrydaily.com/WCSP-Britains-Warriors-to-Undergo-Mid-Life-Upgrade-05967/#uk-mod-wscp (accessed 14/June/2012).

2013-09-27

Warrior vehicle fleet sustainment using intelligent agent simulation

Fan, Ip-Shing

Elsevier