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# Simulation Modelling for Scenario Planning to Evaluate IVHM Benefit in Naval Ship Building

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**Abstract**

Naval ships are long life assets that could be called upon to perform missions not considered in their original design. The through life support arrangement is influenced by the military requirement as well as contracting practice. In navies that contract out the building and support of ships in different competitive packages, condition monitoring technology for through life health management may be stripped out to reduce ship building cost. This paper investigates the potential benefits of incorporating health management for the test and commissioning stages in naval shipbuilding to reduce the overall cost of a ship programme. Scenario planning using simulation suggests that for ships of high complexity in a multiple ships programme, health management is likely to enhance the lessons learnt process. The benefits to the follow on ships could justify the investment.


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*Keywords:* Naval Ship Testing, Integrated Vehicle Health Management, IVHM, Scenario Planning, Simulation, AnyLogic.

## 1. Introduction

Integrated Vehicle Health Management (IVHM) is an approach to deliver the capability to recognise, evaluate, isolate and mitigate faults to enhance the reliability and safety in complex engineering systems. Up-to-date information of system health supports operations and maintenance decisions in Through-Life Engineering Services. Many of the component technology in sensing and monitoring have been developed over the last few decades and begin to be used effectively to provide engineering asset and system health information.

The UK has a strategic military naval shipbuilding industry. New build naval ships are designed with condition monitoring on key systems and generates volumes of data that could be used to support ship operation and maintenance. However, there is a possibility to reap benefits of the information gathered during the build, test and commissioning stages of the ships. Effective use of health information in the test and commissioning phases can inform the design and build of follow on ships. This paper reports on the scenario planning simulation to model the potential benefits of using IVHM in the test and commissioning of naval ships.

### *1.1. Background*

The Cranfield IVHM Centre has developed a systematic engineering approach to design IVHM systems according to the failure and maintenance characteristics of the engineering assets, in the context of the concept of operation. The approach combines operations and maintenance analysis to evaluate the full business case for IVHM. This approach provides the design of the IVHM technical system and the changes in operation and maintenance practice to exploit the information advantage for business advantage.


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In some navies, the acquisition and support of naval ships is managed as contacts issued to different commercial and naval dockyards and service providers. When budget cuts are imposed, condition monitoring equipment that benefits operations and maintenance, but increase ship building costs, are likely targets to be removed.

The justification for IVHM in these situations will only be based on the benefits that could be gained in the build and commissioning stages of the ships. If IVHM can speed up the learning of test failure lessons, and the associated engineering changes to design or build out the fault, then the next repeating component/sub-system could avoid the testing and repair work for repeating the same fault. In a programme of multiple ships, the follow on ships could be completed faster as faults in earlier ships are avoided.

### *1.2. Aims and objectives*

#### *1.2.1. Aim*

The aim of this project is to define the scenario planning problem to justify IVHM in naval shipbuilding and commissioning, and advise shipbuilders the potentials of IVHM in different scenarios.

#### *1.2.2. Objectives*

- Model naval ship engineering and system structure, ship building, test and commissioning procedures; and the lessons learnt and engineering change paths.
- Develop and test simulation tool in AnyLogic.
- Conduct scenario planning analysis to investigate IVHM benefits potential.

## 2. Literature review

### *2.1. IVHM*

IVHM technology enables the collection of accurate data by embedding smart sensors to engineering assets. It provides information on performance, failure and health conditions for the system [1]. IVHM enhances engineering assets' availability and reliability with diagnostic and prognostic techniques using the data collected. The implementation of system monitoring technology in modern civil aircraft has proven its cost saving benefits for maintenance [1].

It is also reported that IVHM system enables fault isolation quicker and more accurate, which reduces labour cost and time [2]. In a study that investigated accidents and incidents, correlation between equipment malfunction with the non-usage of IVHM is suggested [3]. The result shows that 80% of aircraft mechanical defects could be detected, thus avoiding accident and failure. In practice, engine manufacturers have also adopted IVHM principles to reduce cost and improve safety by detecting and predicting engine faults before they reach safety-critical levels [4].

Many cases have shown the benefits of IVHM technology in aircraft manufacturing and flight operations.

### *2.2. Naval ship quality assurance*

#### *2.2.1. Naval ship classification and testing*

The safety and reliability of commercial ships are regulated in the naval classification process to provide confidence that the ships and their systems are in compliance with the relevant regulations. It is usually done by independently auditing the design, equipment and material supply, construction and though life maintenance of the ships [5]. Classification of ships through the standards provides assurance for materials and equipment verification. Class assignment means that the ship and all of its features has been benchmarked against international legislation. As military/naval ships sail in the high seas alongside commercial ships, naval ships are expected to meet at least similar standards. Each navy has its own regulations and processes, some of them are published in the public domain. A good resource is the US Department of Navy Standard Ship Test and Inspection Plan, Procedures and Database [6], which covers the typical testing procedures of an oil tanker sized ship, and can be further customised to other types and tonnages.

#### *2.2.2. Ship systems testing*

A ship is made up of many sub-systems and components, provided by an eco-system of suppliers, and integrated at the dockyard. There are different shipbuilding philosophies. Traditionally a ship is built from keel up to a floating structure, then took to water and fitted out. Another approach is to build sections of ships partially fitted out, and then connecting the sections together. Components are typically tested at the manufacturers and then at the dockyard before being installed in the ship structure. There are further tests at the multiple stages of build until the whole ship is complete. Tests are normally run in parallel with fitting out. Any issues identified at tests are rectified. In principle, rectifying issues earlier in the build process is cheaper than later. The final set of tests are sea trials when the ship is taken to sea and proved before handing over to the customer. The fitting out, test and commissioning of a complex naval ship takes several years.

#### *2.2.3. Ship systems breakdown*

Health condition monitoring are specific to the failure behaviour characteristics of the components and sub-systems. The naval ship industry has multiple, but not an universal, models to divide a ship into systems and sub-systems [7]. The ship breakdown shown in Figure 1 combines two existing classifications that is used in naval ship industry.

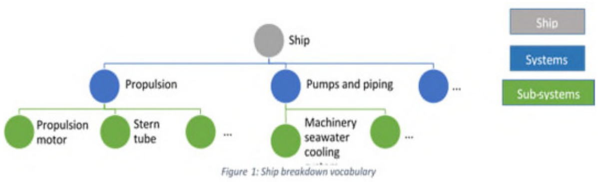


Figure 1 Ship systems breakdown

The Ship Work Breakdown Structure used by the U.S. Navy identifies each of the naval ship's sub-systems with a unique sequence number [8]. This classification is mainly used for naval ship maintenance programme and facilitates the identification of each of the components. Another classification used is the Test and Evaluation Master Plan [9] that focuses on the test operations before commissioning. Although this classification was created for cargo ships, most testing procedures are suitable for naval ships.

This non-exhaustive classification covers a typical naval ship and is designed to be generic, in order to be easily adapted to different ship types (Table 1).

Table 1 Ship systems and sub-systems

| Main System | Number of Sub systems |
|---|---|
| Pumps and piping systems | 9 |
| Accommodation | 6 |
| Propulsion systems | 6 |
| Air compressor system | 3 |
| Interior communication equipment | 3 |
| Naval communication equipment | 4 |
| Auxiliary systems | 10 |
| Control system | 4 |
| Electrical plant | 5 |
| Structure and hull Equipment | 5 |
| Armament | 5 |
| Deck machinery | 8 |

## 2.3. Scenario planning

Scenario planning is rooted in military strategy studies, where Herman Khan used it to demonstrate the consequences of a thermonuclear war [10]. This technique became a business tool in 1965, when Pierre Wack developed a scenario planning system used by Shell. Scenario planning is a tool specifically designed to deal with major and uncertain parameters that affect a process. It is not about predicting the future, but attempting to describe which outcomes are susceptible to happen. Therefore, the aim is to learn about the future by understanding the nature and the impact of key driving forces that affect a business process.

The concept involves the consideration of alternative scenarios other than the ones identified by forecasts. Managers will formulate and implement strategies based on the scenario analysis. The scenario planning process follows a sequence of actions as described in Figure 2. Every scenario planning project is unique and the process design will depend on the specific objectives and organisation context [11].


Figure 2 Scenario Planning Sequence

# 3. Research methodology

## 3.1. Methodology

The research methodology used is shown in Figure 3. Three main topics (naval ships, ship testing, IVHM) were reviewed in literature. Naval ship research helps to define the main and sub-systems in a naval ship; ship testing research helps define the standard test procedures; IVHM technology research helps in broadening the understanding of health management systems. From the literature analysis, the ship testing logic was defined and the simulation model was created in the AnyLogic platform. Scenario simulations were run, and the analysis generated insights for situations when IVHM is beneficial.

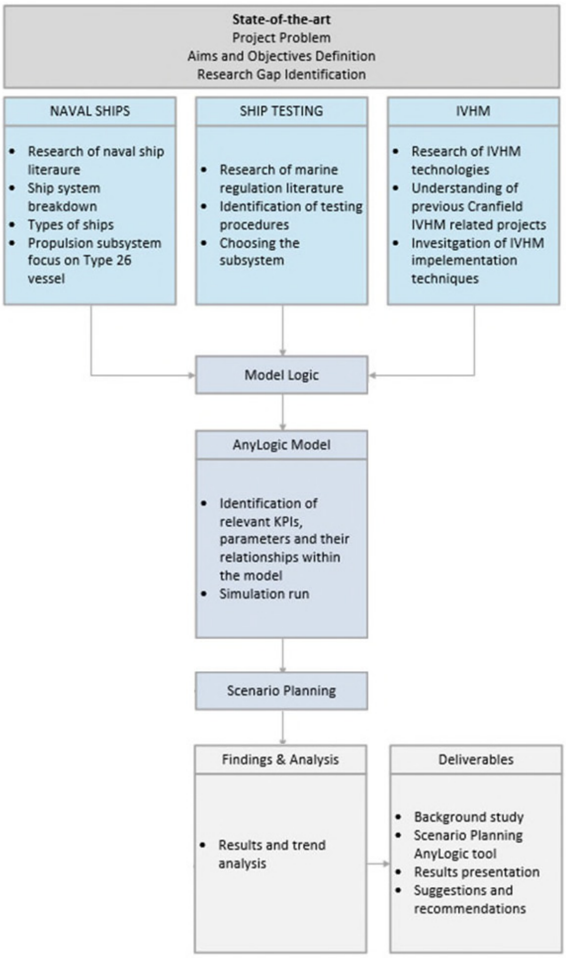


Figure 3 Research Methodology Chart

## 3.2. Modelling platform

AnyLogic is a simulation platform that combines three modelling methods: System Dynamics, Discrete Event Modelling, and Agent Based Modelling. This software has been used in different applications in supply chain and logistics, manufacturing and transportation. Its appeal for this project is the intuitive graphical modelling interface and flexible modelling language. The agent concept is used to allow the tool to be rapidly scaled up in ship complexity, as well as adapting to different ship building and test process.

*3.3. Input and parameter research*

Figure 4 shows the three types of data defined in the scenario simulation. The ship programme describes the characteristics of the shipbuilding contract, and the resources the shipbuilder intends to deploy. The ship parameters are the quality and time data relating to tests, failures and costs. KPIs are the business measures to analyse IVHM effectiveness.

The project used public domain resources to define the naval shipbuilding scenarios. The Royal Navy Type 26 destroyer programme was chosen as the baseline scenario programme. The engineering failures, tests and cost parameters required to build the simulation were derived from engineering handbooks and scaled mathematically. The work reported in this paper focuses on the health information of the propulsion system. Fault Tree Analysis (FTA) analysis was used to identify the failure probability of its 6 sub-systems. Weibull, Normal and Lognormal distributions were used for probabilistic simulation. The cost parameters were derived from historical data of SPAR Associations.

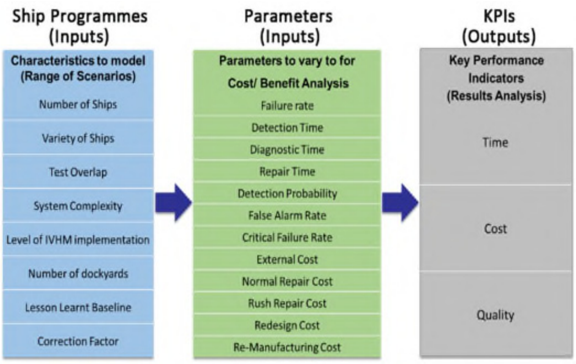


Figure 4 Scenario Model Inputs and Outputs

## 4. Simulation model

*4.1. Model Structure*

The relationships among parameters were analysed using system dynamics approach as shown by the Causal Loop Diagram (CLD) in Figure 5. This diagram clarifies the intricate processes and root causes in a systemic perspective as well as the interactions between variables in the system [12].

The level of IVHM implementation is the central element of the system dynamics model. It is defined as the completeness and complexity of the IVHM solution that is implemented in a ship test system. It can also be understood as the target improvement level from the existing test process, and it is restrained by the amount of IVHM investment.

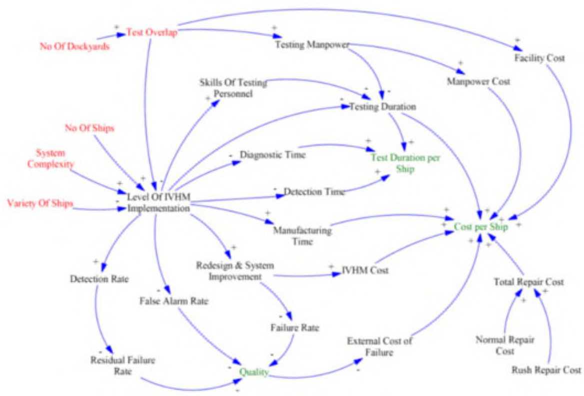


Figure 5 Ship Testing Causal Loop Diagram.

Three groups of KPIs are used to measure the benefits of adding IVHM.

**Cost per ship** – This is the cost of the Test and Commissioning stage of shipbuilding, not the total cost of the ship. The test cost of each ship is built up from the facility cost, manpower cost, etc. When faults are identified at tests, the redesign and remanufacturing cost will be added.

**Test duration per ship** –This is the time the ship is in test. It is built up from the actual time to perform the test, and the diagnostic time when fault is detected. IVHM could reduce the test duration with the use of smart sensors and analysis, and enhance lessons learnt from retained test data.

**Quality per ship** – The quality KPIs has two groups. The external quality is the undetected faults that are passed to the customer. The internal quality measures the inherent faults in the ship before the test process starts, the faults that are detected as failures in the test, and the quality of the tests. It is reflected in the model as the average number of undetected failures, failure rates and false alarms of the ship during test.

IVHM has the potential to improve the quality of test and the lessons learnt process. Lessons learnt is the consolidation of insights gained in a ship test programme that can be applied to the follow-on ship or even to future projects. It allows the test organisation to learn from both its mistakes and successes. Ideally, IVHM application not only increase the speed and quality of the test procedures, but also speed up the lessons learnt. IVHM information could help to trigger the redesign and remanufacturing process, leading to lower system failure rate.

*4.2. Model Logic*

The discrete event simulation feature in AnyLogic University Edition 7.3 was used to build this model. The process logic diagram for the generic test is shown in Figure 6.

- For a particular test where no fault is detected, test passes successfully and proceeds to the next test.
- For the cases where a fault occurs and is not detected, this is known as an undetected fault which may occur after the delivery of the ship to the customer. This is undesirable, as it will result in external cost of failure which may have costly warranty.

- For the cases where the fault is detected, test personnel will have to assess if it is a false alarm. If it is a false alarm, test is considered to have passed with lessons learnt logged.
- For the cases of a true fault, test personnel will go into a complete fault isolation process to determine the root cause of the fault and whether it is a critical fault.
- For a non-critical fault, the defect repair may be postponed or deferred and repair can be carried out at a convenient time that does not delay the overall ship test programme. This is applicable to simple faults and the test is also considered to have passed with lessons learnt logged.
- For a critical fault, rush repair is carried out and the test is repeated, with lessons learnt logged.
- IVHM could speed up the lessons learnt process and improve the failure rates, detection rate, false alarm rate, and fault isolation time.

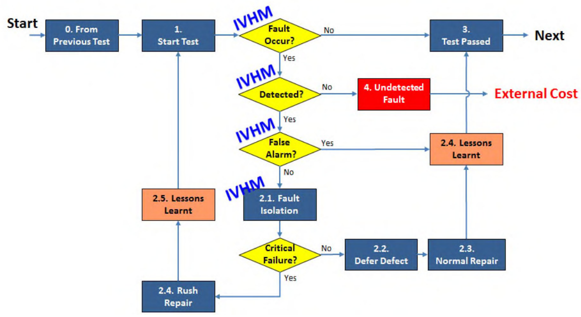


Figure 6 Test Logic of Ship Testing

### 4.3. Model Function Block

The model functional blocks below shown in Figure 7 is derived from the system dynamics diagram.

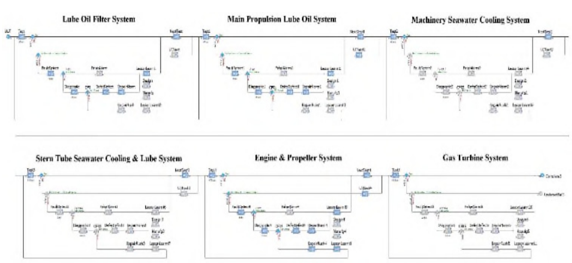

Figure 7 Functional Block Diagram of Model

The IVHM factor uses ship programme characteristics as inputs with a weighted average approach: the number of ships, test overlap, variety and complexity of ship. The equation to compute the average weight is as shown below.

$$Weight_{Average} = {}^{1}/_{4}[(Weight_{Ship} \times Rate_{Ship}) + (Weight_{Overlap} \times Rate_{Overlap}) + (Weight_{Variety} \times Rate_{Variety}) + (Weight_{Complex} \times Rate_{Complex})]$$

The weights of the inputs are assumed to be equal. These factors are on a scale of 1 to 10, with 10 being the maximum and 1 being the minimum. For example, if the ships in production have high variety with many variants, it is rated as 10 and if the ship system is considered to be relatively complex, it should be rated as 10 as well. This has a very similar concept to the nine-point scale defined by [13] that is used for decision making in Analytical Hierarchy Process (AHP).

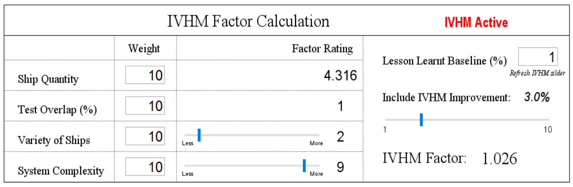


Figure 8 IVHM factor

The lesson learnt baseline defines the improvement limit in the shipbuilding programme without IVHM, and the slider bar below it sets the maximum improvement limit with the addition of IVHM. The output from this calculation is the IVHM factor which determines the amount of improvement to the system parameters such as the failure rates, detection rate, false alarm rate and fault isolation time from each instances of lessons learnt process.

### 4.4. Process Logic Model

The process logic model integrates the process block diagrams of the sub-systems. Each of these sub-systems is defined with its specific parameters such as test duration, failure rate, detection rate, diagnostic time, repair time, detection probability, false alarm rate and critical failure rate. The number of iteration runs is dependent on the number of ships and the output of the model are the performance measures such as the overall test duration, the number of detected and undetected failures, false alarms, critical failures and lessons learnt.

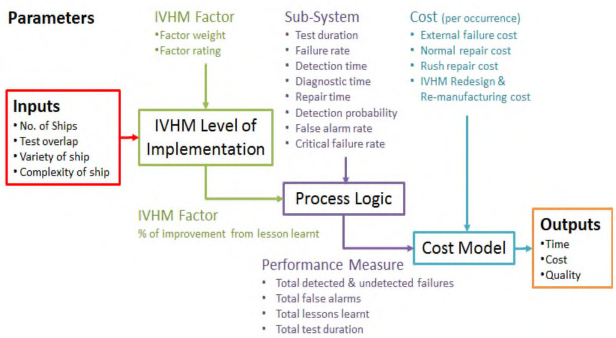


Figure 9 Process Logic Model

### 4.5. Cost Model

The performance measures obtained from the process logic model are used to calculate the costs related to testing. This includes IVHM investment cost; external cost caused by undetected failures; repair costs from detected failures.

Moreover, the total time spent in the test will also have influences on the cost, which are reflected upon the manpower cost and facility occupation cost.

## 5. Result analysis

Based on the combination of ship programmes inputs and levels of IVHM implementation, 152 scenario simulations were performed. It is important to emphasise that the results are indicative only. It shows the simulation tool's ability to evaluate IVHM potentials, rather than the definitive results for ship testing. Furthermore, this result only models the main propulsion system.

It was observed that the average test cost per ship is higher with IVHM at 3% and 5% than without IVHM, when the ship quantity is low. The breakeven ship quantity is 9 for IVHM at 3%, 6 for IVHM at 5% and 3 for IVHM at 10%. Also as the number of ship increases, there are smaller differences in cost benefit between IVHM at 5% and 10% (Figure 10).

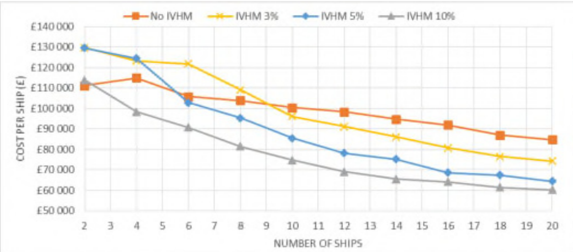


Figure 10 Cost vs Number of Ships

Testing time per ship reduces as the level of IVHM implementation and the number of ship increases. Similarly, as the number of ship increases, there are smaller differences in time benefit between IVHM at 3% and 10% (See figure 11).

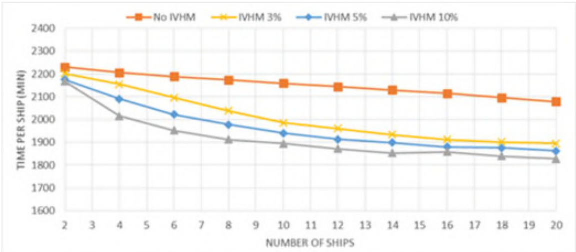


Figure 11 Time per Ship vs Number of Ships

The undetected failure rate decreases as the level of IVHM implementation and number of ships increases. Similarly, as the number of ship increases, there is smaller difference in undetected failure rate between IVHM at 3% and 10%. In fact, the undetected failure rate is almost the same for IVHM at 5% and 10% for ships quantity of more than 16 (Figure 12).

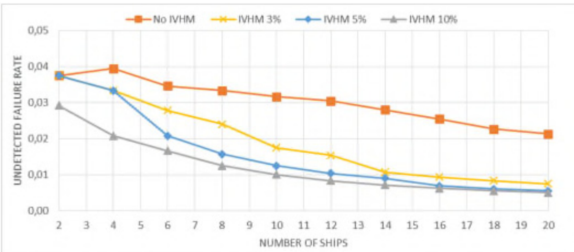


Figure 12 Undetected Failures vs Number of Ships

The simulation results suggest that the naval ship testing can benefit from IVHM. The benefits analysis shows that the returns are influenced by the ship programme contract as well as the engineering quality.

## 6. Conclusion

The work developed a scenario planning tool for evaluating IVHM benefits in naval ship building. The tool created has shown the capability to calculate KPIs relate to time, cost, and quality in different scenarios with or without IVHM. The result shows positive potential that for the right ship programme, it is profitable for the shipbuilders to invest in IVHM for ship manufacturing, instead of considering to cover the full maintenance lifespan. The model itself also were developed to be customisable, which can represent various ship types and programmes.

## Acknowledgements

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