

**Applying Queueing Theory and
Architecturally-Oriented Early Stage Ship
Design to the Concept of a Vessel Deploying a
Fleet of Uninhabited Vehicles**

by

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"Ἐὰν ταῖς γλώσσαις τῶν ἀνθρώπων λαλῶ καὶ τῶν ἀγγέλων, ἀγάπην δὲ μὴ ἔχω,
γέγονα χαλκὸς ἠχῶν ἢ κύμβαλον ἀλαλάζον"

Προς Κορινθίους Α' 13 ἐπιστολή Παύλου

"If I speak in the tongues of men or of angels, but do not have love, I am only a
resounding gong or a clanging cymbal"

1 Corinthians 13:1 Paul's Epistle

Declaration

I, Nikolaos Kouriampalis, declare that except where explicit reference is made to other sources, this thesis is the result of my own work. I confirm that this thesis has not been submitted for any other degree at University College London or any other institution.

Print Name: _____

Signature: _____

Abstract

Uninhabited vehicles technology is becoming important in naval warfare, providing an entirely new capability. By projecting power through the deployment of such vehicles, the exposure of humans to military threats is reduced. Although the Royal Navy is pursuing the employment of uninhabited vehicles for a variety of applications, the concept of a substantial fleet of such vehicles, operated from a mothership, able to host and support their operations during a mission scenario, is still a novel design challenge. In the initial design stages, when little of design effort has been committed, ship design details will be far from fully defined and are still amenable to change without significant implications on the programme budget, or schedule. Consequently, there is a need to consider how more informed, early, but yet significant design decisions can be made regarding the design of a mothership deploying a fleet of uninhabited vehicles. Delivering a mothership's operational capability through a complement of uninhabited vehicles would determine the ship's configuration. The proposed approach, developed as part of this research, consists of decision-making and ship concept design tools, and provides a holistic means of integrating aspects of a fleet of uninhabited vehicles into early stage mothership design. The first tool uses queueing theory and has been employed to capture the impact of the required facilities to host and support a fleet of uninhabited vehicles carried in the ship's mission bay and subsequently impact on the overall ship design, as well as providing a measure of the ship's mission effectiveness. The second tool utilises the advantages of architecturally-oriented initial ship design approach to obtain balanced mothership designs and perform some early stage naval architecture analyses. The overall aim of proposing a quantitative approach to mothership performance has been demonstrated, showing the impact of operating a fleet of uninhabited vehicles, resulting in large costly vessels. Several limitations identified during the development and the implementation of the new approach have suggested areas for future work. It was concluded that the proposed approach would be appropriate to inform early investigation of the implications of operating a fleet of uninhabited vehicles from a new mothership configuration, since it allows a relatively fast exploration and comparison of different mothership design options against cost-capability criteria. However, it is suggested that while favourable design options could emerge through such comparative studies, these would merit from further investigations using simulation techniques that could refine the inputs to such novel ship concepts.

Impact Statement

The design of a mothership able to accommodate and support a fleet of uninhabited vehicles is a new concept of operations for navies and other maritime operators. Such a new technology is a multifaceted problem and hence a considerable number of issues need to be properly investigated for its implementation. Despite that, it is considered that this research has contributed to enhancing the extent of what can be assessed in the very early (i.e. early concept), but formative stages of the design process of complex engineering systems like warships.

This research project was partly sponsored by BAE Systems, the largest defence and shipbuilding company in the U.K. and one of the world's largest producers of complex warships. During the four years of research work at UCL, regular project meetings with BAE Systems representatives contributed to gaining practical insights regarding the broad demands and likely emergent issues for such a very early-stage mothership design scenario. The potential mothership pre-concept design options developed as part of this research were based on such broad specifications.

It is hoped that the outcome of this research will support BAE Systems to identify and better address potential issues regarding the integration of a fleet of uninhabited vehicles in a mothership, as well as the likely implications of such technology on the warship design. Therefore, this research will encourage BAE Systems to adopt an approach, such as the one demonstrated in this thesis, at the earliest design stage of a potential actual mothership design programme in the future. The insights emerged throughout this research could also justify further research into a certain area to refine the proposed mothership design approach, namely simulation techniques as a more realistic and less limited means to conduct operations research.

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Nomenclature

AAW - Anti-Air Warfare	24
ASuW - Anti-Surface Warfare	24
ASW - Anti-Submarine Warfare	24
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C3 - Command, Control and Communications	39
C4I - Command, Control, Communications, Computers and Intelligence	85
CAD - Computer Aided Design	79
CAMM - Common Anti-Air Modular Missile	167
CASD - Computer Aided Ship Design	222
CIWS - Close-in Weapon System (Short range defence system)	167
CN3 - Communication and Navigation Network Nodes	24
COEA - Cost and Operational Effectiveness Analysis	86
CONOP - Concept of Operation	34
DBB - Design Building Block (UCL Architectural Design Approach)	75
DRC - Design Research Centre	130
ECM - Electronic Counter Measures	167
ESM – Electronic Support Measures	167
ESSD - Early Stage Ship Design	33
EW - Electronic Warfare	24
FCFS - First Come First Served	106
FOC - First of Class	82
GUI - Graphical User Interface	131
IS - Infinite Number of Servers	106
ITT - Invitations to Tender	60
LAR - Launch and Recovery	34

LARS - Launch and Recovery System	26
LAURA - Launch and Recovery of Any small craft from surface ship. Anglo-Dutch Joint Government Industry Research Project (JIP)	49
LCS - Littoral Combat Ship (U.S.A. Navy Class Designation).....	24
MCM - Mine Countermeasure	37
MIW - Mine Warfare	24
MS - Maritime Security	24
MVA - Mean Value Analysis	106
OA - Operational Analysis	29
OPV - Offshore Patrol Vessel.....	132
OR - Operations Research.....	26
PVF – Payload Volume Fraction	169
QT - Queueing Theory	95
RHIB - Rigid-Hull Inflatable Boat.....	47
SHF - Super High Frequency	167
SRD - Systems Requirements Document (U.K. MoD Acquisition Procedure).....	59
SSI - Shipbuilder’s Supplied Items	83
T26 GCS - Type 26 Global Combat Ship for Royal Navy	25
TLC - Through-Life Cost.....	82
UAV - Uninhabited Aerial Vehicle.....	24
UGV - Uninhabited Ground Vehicle	35
UPC - Unit Procurement Cost (See definition).....	82
URD - User Requirement Document (U.K. MoD Acquisition Procedure)	59
USV - Uninhabited Surface Vehicle	26
UUV - Uninhabited Underwater Vehicle.....	26
UXVs - Uninhabited Vehicles (Aerial, Surface, Underwater).....	24
VTUAV - Vertical Take-off and Landing Uninhabited Aerial Vehicle	167

WBS - Weight Breakdown Structure 77

WLC - Whole Life Cost (UPC + TLC)..... 82

List of Symbols

Δ_D – Ship deep displacement

B_{UD} – Ship amidships upper deck beam

B_{wl} – Ship waterline beam

C_B – Ship block coefficient

C_M – Ship midship section coefficient

C_P – Ship prismatic coefficient

C_{WP} – Ship waterplane area coefficient

D – Ship amidships hull depth

GM_F – Ship transverse metacentric height with free surface effects

GM_S – Ship solid transverse metacentric height

GZ – Ship transverse righting lever arm

kts – Knots (unit of speed)

L_{oa} – Ship overall length

L_{wl} – Ship waterline length

Nm – Nautical miles

T – Ship amidships deep draught

V_G – Ship total enclosed volume

v_s – Ship superstructure proportion

ρ – Ship overall density

M – Number of uninhabited vehicles

C_k – Number of service facilities

T_k – Service time of a service facility

N_k – Number of customers seeking service at a service facility

N_{qk} – Number of queueing spaces at a service facility

Chapter 1: Introduction

1.1 Uninhabited Vehicles in Naval Operations

Uninhabited Vehicles (UXVs) are seen as essential components of future naval forces [Yan et al., 2010]. They are considered to be able to operate as effectively and reliably as the equivalent inhabited vehicles in high-threat environments, keeping personnel as far out of harm's way as possible [Clapper et al., 2007]. The employment of UXVs during war dates back to World War II, where uninhabited aircraft were used as air to surface weapons. Thereafter, camera-equipped Ryan Firebee Uninhabited Aerial Vehicles (UAVs) were launched from aircraft carriers, in the Vietnam War for reconnaissance purposes. More recently in the operations in Afghanistan and Iraq UAVs have been deployed for enhanced acquisition and rapid dissemination of Intelligence, Surveillance and Reconnaissance (ISR) information. Additionally, the successful deployment of the Predator UAV armed with Hellfire missiles in Afghanistan demonstrated that the deployment of UXVs systems, carrying weapons, could significantly increase the operational capabilities of defence forces, including navies [Committee on Autonomous Vehicles in Support of Naval Operations, 2005].

In recent years, Western navies have been attracted to the concept of deployment of UXVs in naval operations for a broad range of roles, including targeting, Communication and Navigation Network Nodes (CN3), detection and identification of threats, battlespace awareness, Maritime Security (MS), Electronic Warfare (EW), Mine Warfare (MIW), Anti-Submarine (ASW), Anti-Air (AAW) and Anti-Surface (ASuW) Warfare [Clapper et al., 2007] [Gates, 2016]. The ongoing advances in computer software, speed and processing power, improved sensor technologies and enhanced communications resulting in greater ranges of operation, better image-processing capabilities together with efficient and miniaturized propulsion systems providing longer endurance, have significantly replaced outdated technologies. This has contributed to an even greater deployment of UXVs in naval operations [Committee on Autonomous Vehicles in Support of Naval Operations, 2005].

Western navies are actively implementing the deployment of UXVs from surface ships. Littoral Combat Ship (LCS) is a large class of surface combatant in the U.S.

Navy that can accommodate and support a few UXVs, which are deployed for littoral zone operations [O'Rourke, 2016]. Type 26 Global Combat Ship (T26 GCS) class of imminent multi-mission warships for Royal Navy will have an adaptable mission space for a limited number of UXV modules, providing the capability to deploy uninhabited air, surface and underwater modules [Ministry of Defence, DE&S, 2012]. In contrast to the limited discrete-type UXVs capability of both LCS and T26 GCS, the concept of supporting and deploying a large fleet of UXVs from a mother vessel can be seen as a new operational concept. Consequently, there is a need to investigate the ship design implications of this more extensive implementation of this new technology at the concept level, if this operational concept is to be a realistic option.

The way in which the naval ship concept design process has been historically carried out, normally prioritises the numerical ship design aspects of S⁴ (i.e. Speed, Seakeeping, Strength, Stability), the combat systems and the budget criteria imposed by the rising warship ownership costs [Andrews and Dicks, 1997]. As a result, UXV operational features, as well as any emergent issues regarding the architectural integration of such uninhabited assets into a functional fighting unit, namely the mothership, are likely to be given insufficient attention. Hence, the lack of such an early design investigation could impede the implementation of extensive UXV-related considerations. If this is left to be addressed later in a given ship design, or not considered at all, the design will be too constrained for such proposals to be adequately addressed.

1.2 Research Aim and Scope

The deployment of a fleet of UXVs in worldwide theatres of operations is likely to require the presence of a mother vessel capable of hosting such assets and supporting their overall operations. This means using a design approach to explore the physical implications of a UXVs fleet on the design of a mothership, as well as to investigate how the fleet of UXVs and any related equipment and support systems could be integrated into the design of a mothership at a concept level. Current studies are focused on the deployment of UXVs in naval operations. In particular, this thesis addresses issues of the deployment and support of a large number of Uninhabited Surface Vehicles (USVs) and Uninhabited Underwater Vehicles (UUVs) from surface ships for naval operations. The deployment of USVs and UUVs from surface ships could be accomplished through common Launch and Recovery Systems (LARSSs), as such assets operate in the same environment. Although UAVs are also deployed in naval operations, the use of such assets has not been the main focus in the current research, given that their related on-board ship support systems, as well as the means of deploying and retrieving the UAVs from a surface ship are seen similar to the current naval combatant or aircraft carrier technology.

The objective of the research presented is to consider the integration of a fleet of UXVs, into a mothership design during the explorative early stages of the naval ship design process. The fleet of UXVs may comprise more than one type of UXV and the number of the UXV fleet assets may vary. Such fleets are expected to have significantly impact on the mothership size, configuration and ship performance parameters, due to the required equipment and systems, including additional crew, fuel and ship services, necessary to accommodate and support a UXVs fleet throughout its operations.

The mothership design approach described in this thesis uses a combination of two distinct sets of tools, firstly a widely established decision-making and evaluation technique, commonly used in Operations Research (OR), and secondly an architecturally-orientated concept ship design tool. These assist the ship designer in applying a holistic design approach to integrating many UXVs into a mothership design. The former set of tools is based on queueing networks [Bose, 2002] and

models the impact of the required facilities to host and support a fleet of UXVs on the design of a mothership. It can also provide a basis for determining a mothership's UXVs capability. The latter is a toolset utilising the advantages of the architecturally-oriented ship design method [Andrews, 2003 b], in order to obtain early stage balanced mothership design solutions and also perform naval architecture analyses of the resultant mothership design options. The required operational capability of a UXV mothership through its complement of a fleet of UXVs would largely determine the ship's size, configuration and performance. Hence, the proposed queueing network tool and the ship design toolset have been used in a tandem, cyclical manner to support the ship designer's efforts to carry out a holistic investigation in the early design stages of a UXV mothership.

The validity and reliability of the proposed approach is illustrated through a number of ship design case studies. These studies involve the application of the above tools to enable the assessment of a given fleet of UXVs in terms of the mothership facilities required to host and support such assets and their operations. Moreover, the mothership design case studies have included variations of a mothership's UXVs capability, which are considered through incremental, or step design changes to a baseline mothership design. The resultant potential mothership options, which can accommodate a given UXVs fleet, are assessed against broad early stage cost and operational effectiveness assessments. The ship designs were carried out using the UCL architecturally-orientated concept ship design approach and are sufficiently detailed to demonstrate the application of the proposed decision-making and evaluation approach. For this purpose, the unclassified UCL naval ship design procedure [UCL, 2014 a] and database [UCL, 2014 b], seen to be broadly representative of the U.K. MoD design practice, were used to develop the mothership designs.

In summary, the overall aim of this thesis is to propose a new mothership design approach that could capture the impact of a fleet of UXVs operated from a surface ship on the design of the ship. It will also enable the ship designer to quantify potential operational effectiveness measures with basic costing criteria, for comparing a range of ship design alternatives. The approach is demonstrated through a series of design studies, where the ship architecture, as introduced by the architecturally-orientated

approach, is emphasised in order to allow a more effective and prominent consideration of UXV implications on the mothership during the concept phase of naval ship design.

1.3 Thesis Structure

The thesis is composed of eight main chapters accompanied by specific appendices that provide additional material relevant to the main text.

This first chapter consists of three sections. The first section is a brief introduction to the employment of UXVs in naval operations and the issues relevant to the scenario of a fleet of UXVs supported by a mothership. This is followed by the research aim and scope, and finally the structure of the thesis.

The second chapter, consisting of three main sections, presents a state of the art review and an explanation of the proposed mothership design approach. The first section, on UXVs technology, gives a summary of the current employment of UXVs in support of naval operations. Considerations of the support of the operations of UXVs from surface ships are then discussed, followed by highlighting the likely implications of such vehicles on a ship from which they are operated. Deployment and retrieval methods of UXVs from surface ships are outlined, given the likely LARSs are seen to significantly impact the design of such ships and thus act as potential design drivers. The second section covers the background to the process of modern naval ship procurement and design, focusing on early stage naval ship design. Then the UCL originated architecturally-based ship synthesis approach is described, facilitated by the advances in computer graphics. Finally the cost of owning a warship and the potential measures for defining the operational effectiveness achieved through a proposed design solution are discussed. The third and last section reveals the gap in the knowledge and concludes that a holistic ship design approach is necessary to address the likely implications of a fleet of UXVs on the design of a mothership.

Chapter 3 has seven main sections and focuses on the development of the mothership design approach adopted for this research. The first section outlines the proposed approach to assess the impact of a UXVs fleet on the design of a mothership, as well as briefly covering the methods available for the development of the suggested approach. The second section describes the method adopted to develop a mathematical tool that implements the proposed Operational Analysis (OA) approach (i.e. queueing network modelling) to a UXV mothership design. The following section highlights how the proposed OA approach communicates with an architecturally-

oriented concept ship design tool and how information can be exchanged between the results of using these two tools. The fourth section considers verification and validation assessment regarding the proposed OA approach, with the next section discussing the use of simulation techniques as an alternative means to implement the proposed approach. The sixth section demonstrates the features of the UCL tools employed for the ship design options and the associated cost estimations undertaken in the research. Finally, the last section gives an outline of the research proposal.

The fourth chapter, comprising of four sections, presents an application of the proposed OA method, demonstrating the capabilities of the adopted method and the information that can be extracted from the developed tool. The first section describes the principal constituents and features of the OA tool's application under study, followed by a brief explanation of how the developed tool can inform the design of a potential UXV mothership. In the third section, a sensitivity of the OA tool is assessed, in order to analytically demonstrate the queueing network tool's capabilities, as well as the outputs related to naval ship design. The last section of the chapter lists a number of the OA tool's characteristics.

Chapter 5 has two sections describing the development of the ship design case studies that were used to demonstrate the application of the proposed mothership design evaluation approach outlined in Chapters 3 and 4. The first section describes in detail the development of the baseline mothership design chosen as the basis of this research. The second section considers the choice of design variations and outlines the ship designs developed.

The sixth chapter, consisting of two sections, describes the application of the proposed mothership design approach to the ship design case studies described in Chapter 5, as well as presenting the assessment results. The first section provides a detailed explanation of the application of the proposed mothership design evaluation approach to the assessment of the baseline mothership design. The second section presents the assessment results for the mothership design variants.

Chapter 7 consists of two main sections and provides a comprehensive discussion of the proposed mothership evaluation approach in the early design stages. In the first section, the results presented in Chapters 5 and 6 are discussed in detail, as well as the

wider ship design implications. The second section addresses the need for the proposed mothership design approach, by relating this to the gaps identified in the research background outlined in Chapter 2. This is then followed by discussing the implementation of that proposal and its appropriateness in UXV mothership design. Thereafter, the research limitations and the assumptions employed in the demonstration of the proposed approach are reviewed. The chapter is concluded by discussing the areas that merit further investigation.

The eighth chapter addresses whether and to what extent the overall research aim has been achieved.

Chapter 2: Review of the State of the Art of Uninhabited Vehicles in Naval Operations Supported from Surface Ships

2.1 Introduction

This chapter, consisting of three main sections, provides an overview of the investigations carried out to identify and reveal the knowledge gap. This leads on to the problem addressed and tackled through the research project, which considers the deployment of a UXVs fleet from a naval surface ship. It explores the areas of UXVs and naval ship design with the aim of identifying issues that are both relevant and feasible in investigating naval UXVs supported by surface vessels.

The first section of this chapter is split into five sub-sections. Initially, a summary to the background of UXVs technology is provided. The increasing deployment of UXVs for certain naval missions from surface ships is then highlighted. The third sub-section addresses a number of technical considerations regarding UXVs operated by surface ships, as well as their likely implications for the supporting vessels (i.e. motherships). Carrying on the operational considerations of UXVs, the sub-section that follows considers LARSs for UXVs operated from surface ships, since the deployment and retrieval of a fleet of UXVs as part of a potential mission is crucial in UXVs operations towards the successful completion of the particular mission scenario. Particularly, this sub-section examines the issues related to the deployment and retrieval of UXVs from surface naval ships. The integration of LARSs into the mission-oriented spaces of a host ship and subsequently their potential impact on such a mothership are explored in the last sub-section, given such systems' impact on ship size and layout.

The second section is split into five sub-sections. First, the background to the process of naval ship design and procurement is outlined, which briefly explains how a ship design programme is initiated and progresses through life, followed by a further explanation of the process of naval ship design. The next two sub-sections cover the traditional approach to early stage naval ship design and investigate the advantages of architectural modelling in initial ship design, as well as describing an established architecturally-based design approach in preference to the more traditional approach

to Early Stage Ship Design (ESSD). This is seen as particularly relevant to research at the concept stage for a naval ship acting as a host vessel to support the operations of a fleet of UXVs. The final sub-sections consider the cost of owning a warship and also measures to describe the operational effectiveness of a potential ship option, as relevant to assisting any design based proposals.

The last section addresses the necessity for a method to evaluate the impact of a fleet of UXVs on the design of a supporting vessel.

2.2 Deployment of Uninhabited Vehicles from Surface Ships in Naval Warfare

2.2.1 Background to Uninhabited Vehicles

A UXV is defined as a powered vehicle that does not carry on-board any human operator, can be operated autonomously or remotely, can be expendable or recoverable and can carry a lethal or nonlethal payload [Clapper et al., 2007]. The design of a UXV is driven not only by the equipment it needs to carry, such as payload, sensors, communication equipment and weapon systems, but also by the performance criteria it is required to achieve, including speed profile, operational range and endurance. Concept of Operations (CONOPs) studies, normally conducted by mission scenario specialists, are usually employed to identify the likely capabilities of UXVs and their performance features required for a set of mission scenarios. UXVs can be employed to perform dangerous and time-demanding tasks in a hazardous environment that may be impossible, or undesirable for humans to perform. UXVs can be generally categorized into distinct groups, according to their level of autonomy and the medium within which they operate.

The level of autonomy appropriate for a type of UXV indicates the level of intervention intended to be exercised by remote human operators. Highly autonomous systems are capable of operating independently for extended periods of time, whereas less autonomous/sophisticated systems require higher levels of human input. However, even for highly autonomous systems, human intervention is considered necessary for mission direction and coordination, applying operational constraints during mission and to support their Launch and Recovery (LAR) operations [Benjamin et al., 2010]. There are three distinct classes of autonomous vehicles according to the level of autonomy:-

- Scripted autonomous vehicles: This category of vehicles uses a pre-planned script in order to achieve the intended mission aim. Such systems can be described as "fire and forget" systems, without human interaction once the vehicles are deployed [Roberts and Sutton, 2006];
- Supervised autonomous vehicles: Such vehicles embody automation for the functions of planning, sensing, monitoring and networking. Information is

transferred via communications links and the remote operator is engaged in a feedback decision loop with the UXVs, in order to process sensor data, C2 and monitor their progress towards achieving the allocated goals [Ashdown et al., 2010] [Committee on Autonomous Vehicles in Support of Naval Operations, 2005]. The on-board sensors of UXVs are the "eyes and ears" of their remote human operators. The UXVs commonly deployed by a navy are likely to fall into this category [Kiick, 2012] and could be remotely controlled/operated by a number of dedicated personnel on-board a mothership, or even more remotely;

- Intelligent autonomous vehicles: Attributes of human intelligence are implemented within the software and control systems of such autonomous vehicles. Such intelligent autonomy involves decision-making, information interpretation and collaboration with other systems via communications networks without a human in the loop [Kiick, 2012] [Roberts and Sutton, 2006].

The set of capabilities any UXV carries drives its own design, but consequentially affects the design of a ship that is dedicated to accommodate, LAR and generally support a predefined number and type(s) of UXV(s). The environment that the UXVs are designated to operate in, i.e. air, ground, water surface or underwater, classifies the vehicles into four particular groups [Clapper et al., 2007]:-

- Uninhabited Ground Vehicles (UGVs), which are not likely to be employed in naval applications (with an exception of possible applications in amphibious operations);
- UAVs, including fixed-wing and rotary vehicles;
- USVs, including semi-submersibles vehicles;
- UUVs.

The employment of marine based UXVs is currently growing and also new naval ships are being designed to launch and recover such vehicles. LARSs are not standardised as the variety of UXVs is considerable. Furthermore, UXVs are developed at a faster rate than the life span of potential host ships [Eaton et al., 2014]. Integrating UXVs and their related support systems into naval ships is demanding, due to the complexities incurred by having to be incorporated alongside with many advanced systems on-board potential host ships. LAR options depend on the type of UXVs they

need to be designed to handle and should be considered at an early point of the design of a mothership, since they are likely to heavily impact the design if not drive it.

2.2.2 Use of Uninhabited Vehicles in Support of Naval Missions

UXVs offer a number of potential benefits to naval operations, as they can act as a force multiplier, while reducing simultaneously the operational risks to which any assets carrying personnel would be exposed [Savitz et al., 2013]. The future vision of naval operations envisages autonomous vehicles that could enable reductions in force personnel and costs, as they do not have to provide for the needs of humans for space, life support and special threat protection [Canning, 2005], as well as keeping the human out of the dirty (i.e. dealing with hazardous material), dull (i.e. long duration) and dangerous (i.e. exposure to hostile environment) tasks [Alkire et al., 2010] [Pawling and Andrews, 2009]. Additionally, removing humans from on-board the vehicle can significantly reduce of the vehicle's size, and thus lowered its signature (enhanced susceptibility performance, i.e. reduced probability of detection and weapon hit by hostile forces) [Clapper et al., 2007]. Thus, a fleet of UXVs could provide an increased capability to undertake predefined tasks in naval missions, since UXVs would be able to carry out operations remotely supported by the presence of a mothership [Committee on Autonomous Vehicles in Support of Naval Operations, 2005].

A major role of a navy is to be able to provide credible and sustained combat power from the sea, when and where it is necessary. This vision now involves naval forces that employ autonomous vehicles in Sea Strike and Shield missions. Sea Strike operations refer to a broad range of missions, where precise and persistent offensive power is projected from the sea. According to such a concept, networked autonomous naval sensors provide persistent ISR that are also able to strike enemy targets. Sea Shield operations involve a range of operations regarding the protection of national interests from distributed sea based defence forces, where the navy maintains vital sea lines of communication, in order to protect either infrastructures or its own forces, as well as projecting a defence umbrella that contributes to detecting and intercepting hostile vessels [Committee on Autonomous Vehicles in Support of Naval Operations, 2005].

A significant potential threat that a navy might encounter in littoral regions is the presence of mines. Mines act as a serious impediment to the operation of naval forces in the littorals, as they can be widely deployed at sea and their detection and neutralisation can be difficult and tedious. Recent technological developments enable the employment of UXVs for the detection and neutralisation of mines, before the main naval forces access a littoral area. UAV imaging and intelligent systems could indicate the presence of mines in the littorals [Committee on Autonomous Vehicles in Support of Naval Operations, 2005]. The surveillance data received through UAV systems could provide reconnaissance information (i.e. military observation of a region in order to locate hostile or ascertain strategic features) to the naval forces operating in such areas. A sonar that is either carried by UUVs or towed by USVs could be deployed for detailed sea bottom mapping with sufficient resolution to detect and identify mines, thus enabling mine neutralisation and hence a safe passage way for the naval forces operating in the littorals [NRAC Committee, 2012]. However, the entire area of interest would need to be kept under constant surveillance in order to deter any further minelaying activities [Committee on Autonomous Vehicles in Support of Naval Operations, 2005]. An example of a naval combatant employing UXVs in Mine Countermeasure (MCM) warfare is the U.S. Navy LCS, which is able to deploy and support a number of UXVs in order to secure littoral regions from mine laying activity [Hewish, 2004].

The range of roles of UXVs used in by the U.S. military are summarised in Figure 1, where the potential applications of UXVs by navy, air force and army are distinguished [Clapper et al., 2007]. In addition to this, Table 1 provides a comprehensive list of applications of UXVs in naval missions operated by a navy.

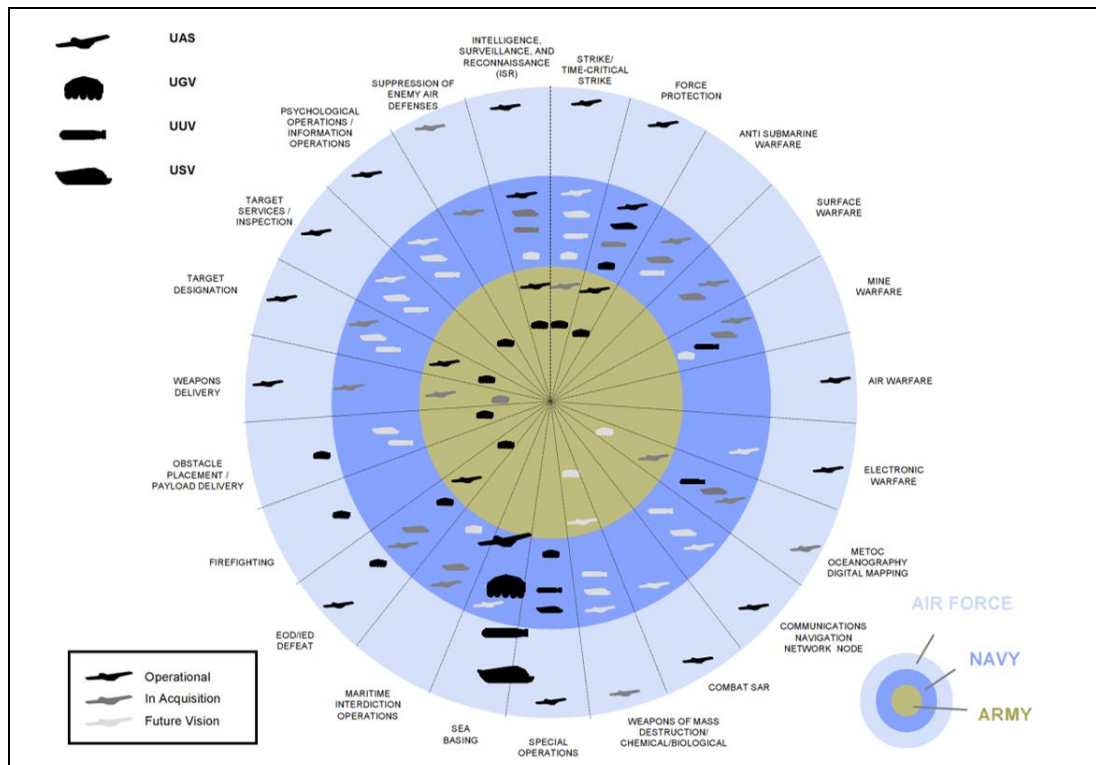


Figure 1: Potential roles of UXVs [Clapper et al., 2007]

UXVs in Naval Operations		
UAVs ¹	USVs ²	UUVs ³
ASW	ASW	ASW
ASuW	ASuW	Barrier Patrol (Anti-Terrorism, Force Protection)
CN3	CN3	CN3
EW	EW	EW
ISR	ISR	ISR
MCM	MCM	MCM
MS	MS	Oceanography
Strike	Strike	Strike

1 - [Alkire et al., 2010]; 2 - [Savitz et al., 2013]; 3 - [Button et al., 2009]

Table 1: Application of UXVs in Naval Operations

2.2.3 Operational Considerations of Uninhabited Vehicles and Design Implications for Mother Vessels

A mission profile for each type of UXV in a fleet is derived from the appropriate CONOPs. This then defines the UXVs fleet composition in terms of both number and type of UXVs required. Distinct UXV types bring particular capabilities and performance, including specific payloads, endurance (i.e. in distance and time), operational range and maximum/deployable speed, in order to meet the appropriate

CONOPs scenario requirements. However, the capabilities required of a UXV for a specific mission should be given by the relevant mission scenario. Consequently, the mission criteria and operational expectations translate into technological requirements for both the UXVs (i.e. mission-centric design of UXVs) and their equivalent support vessels [Canning, 2005]. OA can reveal the set of operational capabilities to meet a particular CONOPs criteria and thus provide the mission profile requirements. Koenig et al. (2008 a, 2008 b) proposed an approach to the synthesis and analysis of naval fleets composed of crewed vessels, based on a given mission scenario.

The overall operation of a fleet of UXVs to achieve a particular naval mission scenario covers all stages, from the deployment of the vehicles towards the mission theatre to their recovery on-board the host ship, including the required support throughout the mission. Such operations can be distinguished between those taking place off-board the mothership, i.e. at sea, and those on-board. The off-board tasks involve the support of the UXVs while on-station, i.e. monitoring, identification of potential problems, C2, sensor information interpretation, communications and interoperation, authorisation of weapon systems use or other mission related activities, refuelling/recharging and replenishing ordnance on-station. Operations on-board the mothership include troubleshooting and repair, maintenance, refuelling, rearming, stowage, pre-mission checks and LAR. The support of UXVs during a naval mission, which can include aspects of LAR, storage, maintenance, C2 and communications (i.e. C3), replenishing ordnance and refuel on-station, is an operational and design issue regarding both the uninhabited assets and their potential support ships [Broadbent and Binns, 2006] [Clapper et al., 2007].

Although the human element is not co-located in the immediate theatre of operations, the role of humans is not entirely eliminated [Clapper et al., 2007]. Remote operators would normally be located on the support ship(s), in order to coordinate the overall operations and perform high level decision-making tasks. Consequently, for a mothership to support the UXVs while on-station, appropriate systems are required to enhance the interface between remote operators and UXVs. Such systems would support planning and decision-making, sensing and perception, communications, as well as monitoring and diagnosis infrastructure [Ashdown et al., 2010]. Such systems would not only contribute to the management of the UXVs fleet, but also provide

decision support for C2 within a fleet of inhabited and uninhabited elements. The U.S. Navy in order to support UXVs in theatres of operations, has developed an Information Technology platform, i.e. "FORCEnet", which integrates sensors, C2, communications and weapon systems in order allow information tracking, data processing and thus decision-making [Committee on Autonomous Vehicles in Support of Naval Operations, 2005]. The need to take into account such mission support systems in mission-centric design of UXVs and their support vessels, i.e. motherships, is part of reliability in successfully operating UXVs from a mothership [Ashdown et al., 2010].

UXVs are considered to be important navy assets in enhancing naval operations. However, despite the advances in utilising UXVs, their limitations also need to be appreciated. Characteristically, larger vehicles tend to have greater operational ranges and durations. However, greater endurance and operational range increase the mass and size of a vehicle and associated C2 systems [Committee on Autonomous Vehicles in Support of Naval Operations, 2005]. An alternative to refuelling on-board a support ship, which could be a time consuming process involving retrieval of UXVs [Petersen et al., 2015], refuelling on-station could ensure that the endurance of UXVs is increased. The latter would require UXVs to dock with refuelling infrastructures, such as refuelling docks at sea, replenishment vehicles (i.e. auxiliary ships), or docking with a mothership (without being retrieved) by employing bespoke refuelling systems.

Operational risk can be limited by reducing the time a host ship must stay in the mission areas and also by increasing its distance from such areas [Petersen et al., 2015]. Hence, a mothership is expected to operate remotely and not in the immediate mission environment, as it is seen as a valuable navy asset and refuelling of UXVs in the vicinity of the host ship or any other auxiliary ship during a mission is likely to expose them to threat. In addition to this, recovering of UXVs on-board a mothership might be more difficult in certain sea conditions and also likely to restrict the mothership's course and speed. Hence, refuelling on-station (i.e. in the vicinity of UXVs' mission area) is seen as an attractive alternative in order not only to keep costly navy assets out of harm's way, but also to achieve better utilisation of UXVs during a mission through avoiding them travelling back to the ship while on mission [Petersen et al., 2015]. Refuelling of UXVs on-station poses design challenges for both the

vehicle and the refuelling means [Galway and Harris, 2010] and requires a firm connection between the UXV and the refuelling source through which the vehicle can refuel and recharge [Galway, 2008 a]. Petersen et al. (2015) proposed a remote autonomous replenishment buoy for USVs, shown in Figure 2. This floating configuration would provide a means of at sea (i.e. on-station) docking for refuelling and rearming of USVs [Petersen et al., 2012, 2015].

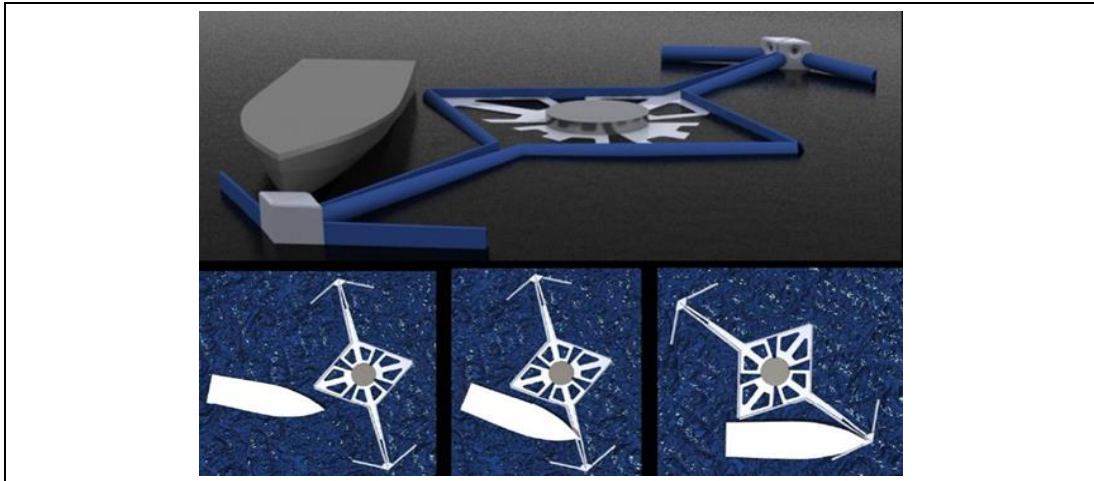


Figure 2: Replenishment docking station for USVs [Petersen et al., 2012, 2015]

Alternatively, relatively slower speeds of deployment have been considered as an option towards increasing the endurance of UXVs and therefore contributing to a decrease of fuel consumption and refuelling needs [Committee on Autonomous Vehicles in Support of Naval Operations, 2005]. Rather than replenishment on-station, the exhausted vehicles could be replaced with extra UXVs stowed on the host ship, dependent on time and mission efficiency, spatial requirements and overall cost outcomes. The same concept of replacement could be also applied to damaged vehicles during a mission as an alternative to repair/maintenance, i.e. repair by replacement. However, the availability of spare vehicles is likely to demand more storage and hence space on-board the mothership, compared to providing workshops on it for maintenance and repair activities [Pawling and Andrews, 2013]. In addition to this, repair (or depot or maintenance) ships, as shown in Figure 3, could provide appropriate workshop and repair facilities to support damaged UXVs during a mission [Kimber, 2006]. Whether this is considered in a naval force mix, or damaged/failed UXVs are just sent back for factory repairs is questionable. If such local repairs were to be undertaken then transfers back to the operational mothership could be done by similar means to normal pre-deployment loading (see page 57).

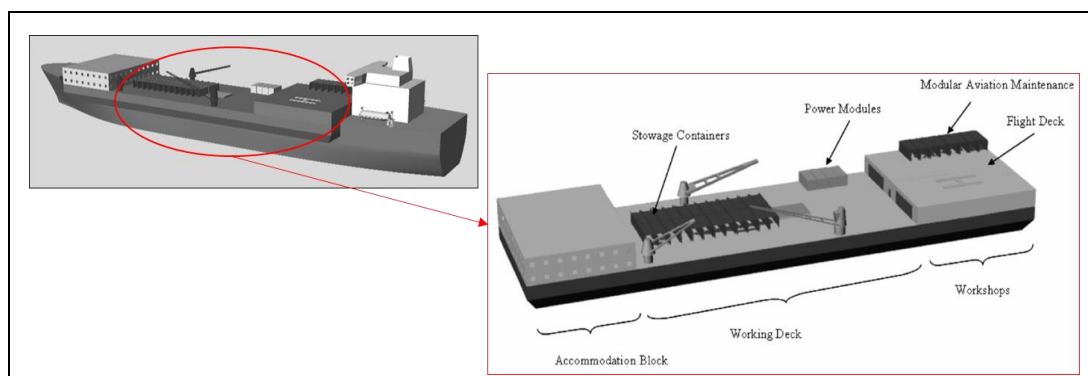


Figure 3: Depot ship concept [Kimber, 2006]

Likewise, rearming of uninhabited assets on-board a host ship could prove a tedious and inefficient option, as it would also require to bring UXVs aboard the host ship first. Therefore, refuelling/recharging and rearming on-station may be time-saving enhancing the mission efficiency. The benefits include improved mission time, less host ship exposure, reduced risks to the personnel involved in LAR operations and the possibility of refuelling and rearming multiple UXVs at the same time [Galway, 2008 a]. However, refuelling and ordnance on-station is an immature technology. Research on such technologies as automated refuelling and rearming of UXVs is being conducted by U.S. Naval Surface Warfare Centre (NSWC) [Galway, 2008 a], U.S. Space and Naval Warfare Systems (SPAWAR) [Lebans et al., 2012] and by Rolls Royce [Mullens et al., 2004]. On-station replenishment of UXVs (i.e. power resources and of ordnance) would contribute to more efficient operation of UXVs in the mission theatre, as their operations could be hindered by the limited on-board power reservoirs. UXVs' application to naval missions might also be impeded due to their restricted payload capacity and limitations in sensor, C2 and communication systems. Other UXV operational limitations also include immature LAR capabilities from surface ships. Such systems are discussed in the next subsection, not least because LARSs are likely to have a great impact on the design and performance of the support ship.

2.2.4 Launch and Recovery Issues of Uninhabited Vehicles Operated from Surface Ships

The trend of deploying UXVs from naval ships has significant implications on such ships, as they become host ships, i.e. carrying and supporting uninhabited vehicles [Thomsen, 2007]. A UXV mothership would provide the vehicles' stowage, maintenance and LAR facilities, and also be the hub of the C2 and communications,

in order to manage the UXV operations [Braithwaite, 2013]. Successful overall UXV operations will depend on the mothership’s capability to deliver and recover the vehicles from the operational area [Thomsen, 2007], thus the ability to launch and retrieve a UXV is a critical aspect of naval missions [Rauch et al., 2008].

LARs and the equivalent LAR procedures are related to the size of UXVs operated by them, as well as the host ship characteristics, with LAR of large (~ over 10 tonnes) surface and subsurface crafts being a noteworthy engineering challenge [Walsh and Smith, 2004]. Larger vehicles will require larger surface vessels for LAR operations [Rauch et al., 2008]. Table 2 lists several potential ways of deploying and retrieving UXVs from naval ships. However, certain types of UXVs require be-spoke systems for their LAR. A more comprehensive overview of LAR methods, already implemented in surface vessels, is given at Appendix 1. Furthermore, Appendix 2 demonstrates a range of LAR methods, yet to be implemented at sea, for USVs and UUVs operated from surface vessels. Table 3 also lists three main types of LARs, i.e. crane, stern ramp and well dock, as a means for LAR of USVs and UUVs from surface ships. It also provides a list of the advantages and disadvantages of such deployment systems. It is also noteworthy that existing deployment and recovery technologies for aircraft, which facilitated LAR operations from surface ships, i.e. helideck, runway, aircraft catapult and ski-jump ramp, have been recently been adopted for the LAR of UAV systems from surface ships in some instances [Austin, 2010] [Cheng, 2008].

	UXVS		
	UAVs	USVs	UUVs
LAR Methods	Flightdeck	Side LARS	
	Aircraft Catapult	Crane Arrangement	Crane Arrangement
	Ski-Jump Ramp	Net Arrangement	Net Arrangement
	Railgun Catapult Launcher	Stern LARS	
	Arresting Gear	Crane Arrangement	Crane Arrangement
	Skyhook	Ramp	Ramp
	Net	Well Dock	Well Dock

Table 2: LAR methods for UXVs operated from surface ships

LARS	Advantages	Disadvantages
Crane	Cranes have low impact on the mothership design.	Single lift point cranes are susceptible to pendulum motions. Need to be placed amidships for ship motion minimisation.
	They give a flexible arrangement that can lift any object within the crane's load capacity and the necessary dimensional clearances on the mothership.	Unbalanced weight on the one side of the host ship might need to be counterbalanced. Cranes require connection to the vehicles, which especially during recovery could be extremely tedious.
Stern Ramp	Greater UXV weight than crane for LAR.	Stern wake might reduce the motion stability and controllability of the deploying and recovering vehicles.
	Rapid LAR times (i.e. momentum: gravity launched, self-propulsion recovered) and reduced deck crew required for such operations compared to crane systems.	Normally, stern ramps cannot accommodate a wide range of vehicles, as they are tailored for a particular craft. Thus, they may need to be modified to accept different types of vehicles.
		LAR availability is susceptible to sea states and ship motions. Must be built into the host ship, thus likely more costly in overall ship costs than crane based LARSs.
Well Dock	High flexibility for recovering numerous types of craft.	Adds major complexity to the mothership.
	Offers the capability of deploying and retrieving more than one craft at the same time.	Restricts the options of the employed propulsion systems for the host ship, such as waterjets. May not be compatible with high speed mothership hullforms.

Table 3: Advantages and disadvantages of LARSs for USVs and UUVs [Broadbent and Binns, 2006] [Kimber, 2012].

Normally, stern ramp systems can accommodate larger vehicles than can typical ship side crane-based LARSs. They can also offer a higher LAR capability in higher sea states with less manpower required, than conventional davit-based LARS [Randles, 2012]. There are likely to be many considerations in the selection of the most appropriate LARS for the deployment and retrieval of a UXV system in a ship. Issues include deck positioning, space requirements and clearances, deck loading (i.e.

structural integrity), the need for well-trained personnel, limiting sea state conditions, freeboard, LARS operational availability due to the wave-induced motions to the ship, available power and cost implications [Lester, 2007].

LARSs and their operational requirements vary depending on the size and shape of the UXVs employed. Certainly, the achievement of LAR of UXVs at sea poses distinctive technological challenges [Galway, 2008 b] [Knight, 2013]. Such operational considerations and the necessity for specific technological solutions to cope with, are described in the following two sub-subsections.

2.2.4.1 Sea State Impact on the Operation of Launch and Recovery Systems at Surface Ships

The incorporation of safety features throughout LAR operations and the operational availability of a LARS, due to the effects of higher sea states, should be considered when operating such systems from surface ships. Excessive ship motions and motion related phenomena in higher sea states might increase the length of time to undertake a particular task, or indeed prevent the task from being undertaken at all. The presence of such dynamic conditions under which deployment and retrieval of vehicles takes place not only can significantly impact the undertaken LAR procedures, by restricting the operational availability of the employed LARSs, but also has potential to damage the mothership and (or) the UXV.

To address a stern ramp's operational availability limitations caused by wave-induced motions, incorporating sufficient sill depth may be essential and thus drives the stern ramp operability, i.e. safe and efficient recovery operations of USVs (or UUVs) on to a mothership. This is likely to have implications to the whole stern arrangement of a mothership. Sill depth is the depth at the aft end of the stern ramp (i.e. ramp immersion), as shown in Figure 4, and is a function of the time the ramp is available for safely recovering a USV. In general, greater sill depths entail greater operability of the stern ramp in higher sea states [Kimber, 2012] (typically above Sea State 6). However, there could be an optimum sill depth for a given stern deployment arrangement, but this depends on the ship design and the limiting seas in which the vehicle must be recovered. Sheinberg et al. (2003) suggest the stern ramp sill depth should be equal to the vehicle's draught when conducting LAR operations. Extendable

stern ramps have been introduced as a means of controlling and providing sufficient sill water depth for successful LAR operations, as shown in Figure 5 [Kimber, 2012]. It is noteworthy that the stern edges of a stern ramp might come into contact with the vehicle being recovered and usually are sealed with rubber to protect the vehicle.

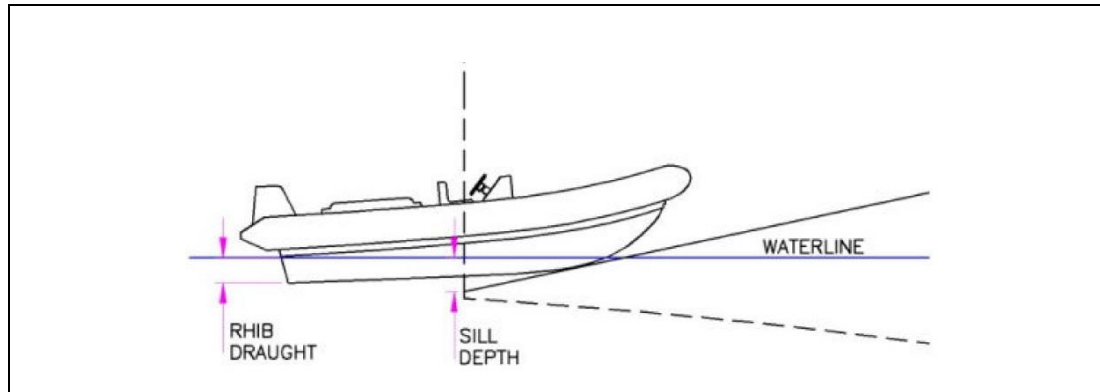


Figure 4: Stern ramp sill water depth [Kimber, 2012]

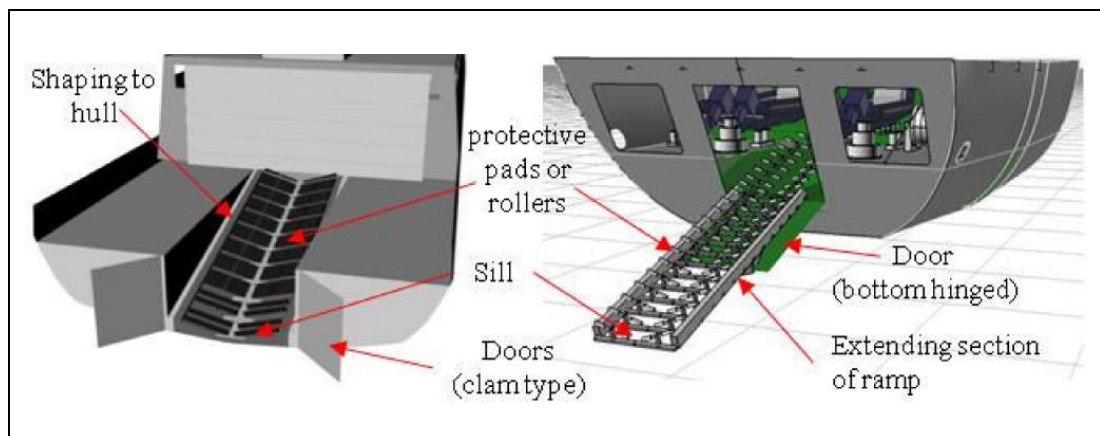


Figure 5: Stern ramp geometry [Kimber, 2012]

Another common dynamic is the pendulum effect, which is schematically shown in Figure 6. Such a condition can pose risk to the mothership and (or) the employed USVs (or UUVs), due to potential collisions when deployed or recovered via cranes installed on-board the ship [McTaggart et al. 2012]. Solutions have been proposed to mitigate such crane LAR issues, providing dual lifting points to the crane, as well as sophisticated crane control systems (i.e. motion compensating systems). Motion compensated cranes may allow safe LAR operations up to Sea State 6 [Messineo and Serrani, 2009] [Kimber, 2012]. Moreover, unconventional mothership types, i.e. multihull vessels (e.g. SWATH, catamaran or trimaran), can also provide more stable platforms for LAR operations of UXVs in general compared to the equivalent

monohull solution, due to their inherently better seakeeping performance in higher sea states.

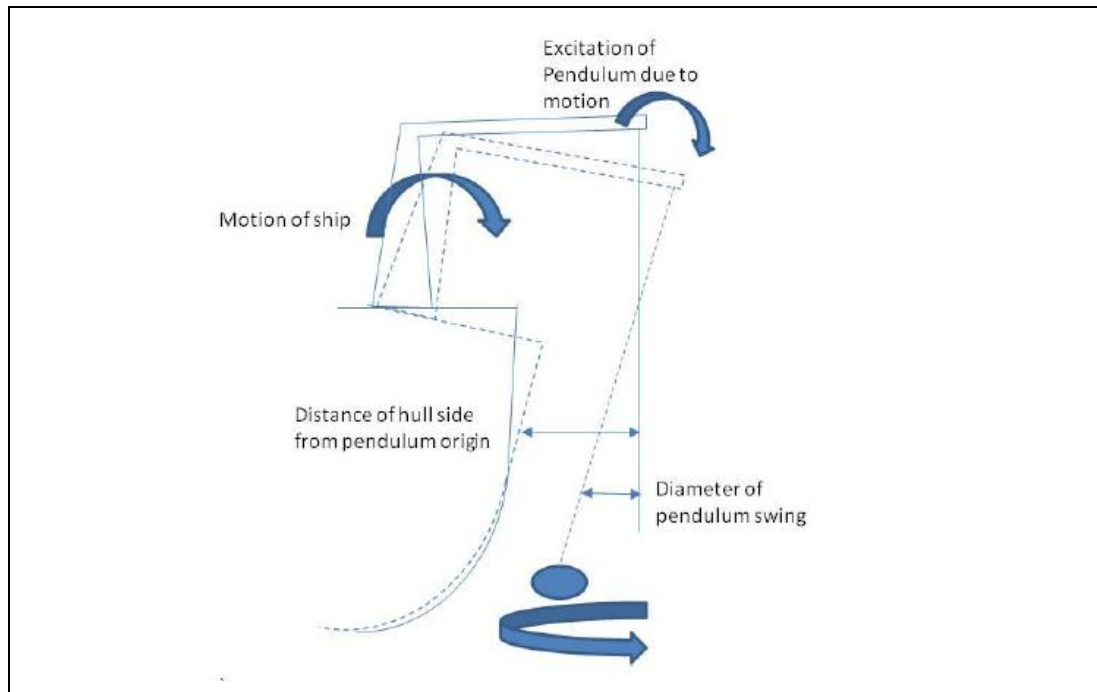


Figure 6: Mothership-side crane LARS pendulum swing [Kimber 2012]

Normally, it is a practice for new (or bespoke) LARSs to test their robustness prior to real time operations. This can be accomplished by either computer modelling environment (i.e. simulations), or lab-based modelling (i.e. wave/towing tanks) by building scaled prototypes (i.e. model testing) [Chun et al., 2012] [Henry et al., 2009]. In both cases, a sea state environment and the resultant sea water flow and wave-induced motions to a LARS and the deployed/recovered vehicle can be simulated or modelled. This allows the designer to assess a particular LAR process, regarding the seakeeping performance of both the mothership and the resultant motions of the proposed LARSs, as well as the vehicle under LAR operation. Such testing enables the designer to apply any necessary changes to the design of the ship, the employed LARS, or the vehicle, and also to make suggestions regarding the way a LAR process is conducted. Kimber (2012) presents an example of computer simulating a side craning LARS operating a typical Rigid-Hull Inflatable Boat (RHIB) of 2.2 tonnes at approximately midships on a 90 m vessel for various ship headings at Sea States 5 and 6. The results indicate the potential occurrence of the swinging vehicle to collide with the side of the ship, by showing how the diameter of the pendulum swing varies with

its height above the water surface, as the pendulum diameter exceeds the horizontal distance to the hull.

Another example is given by Chun et al. (2012), where stern ramp LAR of a RHIB operated by a Korean coast guard ship was tested at model scale in a towing tank. This experimental investigation attempts to assess how ramp sill water depth variation impacts the successful recovery operation, i.e. defined by Percentage of Time Operability, of the ramp at the transom of the mothership. The operating conditions tested are defined by Sea States 3 and 4, two mothership speeds (i.e. 5 and 8 kts) and two wave directions (following seas (i.e. 0°) and ahead seas (i.e. 180°)). Variation in depth of the sill defined the ramp availability time to recover a RHIB, thus the recovery was strongly dependent on the sill depth sufficiency. The sill depth threshold for successful ramp recovery is commonly set to be equal to the draught of the RHIB in still water. According to Chun et al. (2012), although a stern ramp can launch a RHIB at higher sea states (i.e. Sea State 6 and above), the recovery might be restricted by the sea state and also the ship cruising speed. Taking into account the ship motions (i.e. heave, pitch and roll) and the vertical motions at the stern ramp, as well as the relative motion between the ramp and vehicle, results show the LAR time duration, as well as the percentage of LAR success based on a number of successive LAR operations [Chun et al., 2012].

At higher sea states, relative motions between the mothership and the operated UXVs are likely to occur, resulting in difficult LAR operations [Pawling and Andrews, 2013]. Since such mutual motions, induced by wave excitation, are not linear, their prediction is difficult. Besides technological advancements, such those mentioned above employed by LARS to limit motions effects, UXVs can use motion prediction and accurate relative position systems, without a human in the loop of command line/judgement, in order to embark on-board the mothership [Kimber, 2012]. Such systems are embodied on the uninhabited vehicles, contributing to safe LAR operations [Ferrier et al., 2017]. Moreover, altering the ship's heading in significant seaways can reduce, to some degree, the intensity of wave-induced motions if this is operationally appropriate [Smith, 2008].

Another type of dynamic condition may be incurred by the proximity of a LARSs, such as a stern ramp, to the main ship's propulsion systems. This can affect the

functioning of the USVs and UUVs, in terms of the vehicles' seakeeping performance and helm response [Galway, 2008 b], due to the resulting wake field of the ship during LAR operations [Thomsen, 2007]. Greater host ship speeds are likely to impede the LAR of UXVs. The LAURA Anglo-Dutch Joint Government Industry Research Project (JIP) is considering LAR operations of USVs at moderate ship speeds (~ 5-15 kts) up to sea state 6, able to be conducted relatively quickly (i.e. targeting at 5 min per launch) [Marin, 2016]. For instance, according to Sheinberg et al. (2003), the ship speed for most current stern ramp launchings is between 3 and 6 kts, as this gives the mothership enough forward motion to maintain course, but still slow enough to limit the effects of stern wake turbulence on the vehicle. Sheinberg et al. (2003), also recommend the USV can better maintain seakeeping and manoeuvring (i.e. directional control) ability through the hydrodynamic effects of the stern wake, if it accesses the stern ramp through the middle zone of propulsion systems, if for instance the ship employs a twin screw propulsion system. This would facilitate operating safely within the propulsion system's envelope, with sufficient margins to allow for overload conditions due to surges in sea/wind conditions and ship motions.

2.2.4.2 Other Operational Considerations for Launch and Recovery Systems at Surface Ships

Adaptation (or interoperability) of LARSs in order to accommodate a broad range of vehicle variants. It is noteworthy that ships normally have a service life span of 25-50 years, whereas a UXVs may be obsolete within a period of 5-10 years, possibly rendering a given LARS obsolete. This implies that a vessel will operate at least three generations of UXVs and thus it cannot be designed for just a single generation of uninhabited assets [Broadbent and Binns, 2006]. Thus, a ship is likely to be upgraded several times through life in order to accommodate newer and more efficient generations of UXVs. This would also facilitate upgrading the LARSs as much as possible, hence accommodating newer technologies [Pawling and Andrews, 2013]. In particular, an extensive ship LAR capability to operate a fleet of UXVs is likely to have a significant impact on host ship design and thus should be addressed in ESSD.

Structural interfaces on the host ship to accommodate ship-mounted LARSs need to be robust enough, in order to handle the loads imposed on them during extreme LAR

evolutions [Galway, 2008 b]. The possible extreme loading conditions that the host ship and its LARs might be subjected to during operations, especially those loads due to ship's motions in limiting sea state and headings, would need to be taken into account to achieve safe and successful LAR operations [Lester, 2007]. Moreover, the integration of the large mission bays into the overall ship design would be a significant structural design issue, with for example the structural integration of large enclosed mission bay spaces into the main strength decks of the ship would need to be carefully considered. Figure 7, illustrates a potential discontinuity issue in integrating the two-deck height mission bay as it would breach the ship's strength deck [Kimber, 2012]. The step change along the strength deck would cause a discontinuity in the ship's structure and would need careful compensatory structural detailing to mitigate any possible fatigue issues.

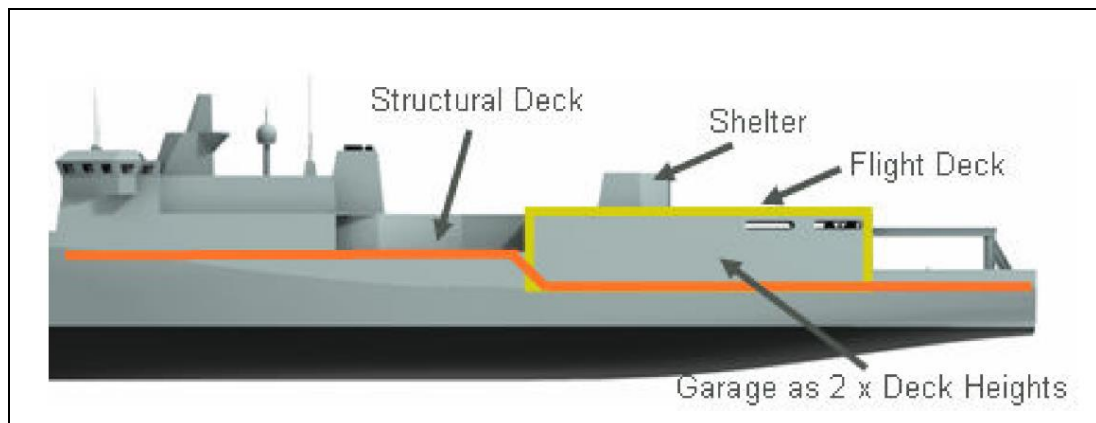


Figure 7: Mission bay (garage) structural integration consideration [Kimber, 2012]

Normally, to smoothen out the step change transition in the ship's structure (i.e. remove stress concentrations from the region), additional material, using steel of high strength and toughness, can be provided at the sides of the strength deck to transfer the load into the ship's side, which then should be stiffened to cope with such loading conditions and avoid hull girder buckling. The load can be diffused into the rest of the hull through the side plating. In addition, it is advisable to fit a transverse bulkhead that extends at least one deck below (or a deep transverse girder) at the transition point, in order to transmit the vertical forces [Chalmers, 1993].

2.2.5 Integration of Launch and Recovery Systems into the Mission Bay of a Host Ship

The ship designer is responsible for integrating the requested operational capabilities indicated by any relevant OA studies, into a balanced ship design solution. Thus the ship's performance requirements (i.e. stability, powering, structural integrity and seakeeping) and the criteria given in the CONOPs both need to be met. Recent naval ship designs have incorporated several UXVs (e.g. Type 26 and LCS). However, a dedicated UXV mothership could be designed to have the ability to deploy a much larger number of UXVs, giving multiplication effect to a naval force. A mothership could transit to the theatre of operations, and once there it would launch its uninhabited assets, creating a network of interconnected UXVs, remotely operated from the mothership and adjusted to the changing operational needs [Braithwaite, 2013]. This could be achieved by providing flexible and functional mission compartments on the host ship and capable of supporting the vehicles while on operations: accommodating LARs; stowage spaces; systems for internal on-board handling of the UXVs; support equipment (such as refuel, ordnance and maintenance); as well as C3 systems. Such compartments and systems could enhance the capability of the host ship to provide logistical support (i.e. stowage, LAR, refuel, maintenance, ordnance) to a fleet of UXVs, as well as provide operational support capabilities (i.e. C3). LARs are of importance, as without such systems the uninhabited assets could not be deployed or retrieved on-board. The selection of an appropriate LAR strongly depends on:-

- Any actual CONOPs would identify the number and types of UXVs, setting the basis for LAR time restrictions regarding deploying a specific UXV capability (i.e LAR frequency) and safe LAR operations [Kimber, 2012];
- The space requirements and arrangement to be adopted on the mothership, in order to integrate such systems in the overall ship design [Kimber, 2012];
- The ship's general performance criteria. Thus, the speed profile of a host ship is a significant performance criterion of the ship relevant to delivering a predefined UXV capability to the theatre of operations.

A mothership's mission bay is a compartment (or group of compartments) on-board the ship that could provide the basis for accommodating a fleet of UXVs and their

related support systems, including: LARs; maintenance and repair; refuelling; ordnance and UXVs stowage facilities. Normally, C3 systems and the personnel required for vehicles' remote operations (i.e. apart from the personnel that is involved in mission bay activities) are not collocated in the mission bay area. C3 could be positioned at the superstructure of the ship (e.g. mast(s)), while their associated consoles, as well as any required personnel are located in dedicated ship spaces, such as UXVs control room and ship's operations room (in the hull, or superstructure). Consequently, the integration of mission related equipment into mission bay arrangement and subsequently the integration of the mission-oriented spaces into a mothership design is a naval architecture challenge [Eaton et al., 2014].

An example of existing motherships that the U.S. Navy is procuring are the two LCS variants (First of Class are USS Freedom - monohull and USS Independence - trimaran), which both are able to accommodate an integrated UXVs suite extending from amidships to stern [Committee on Autonomous Vehicles in Support of Naval Operations, 2005] [Irani and Spencer, 2014]. Figure 8, shows the overall general configuration of both LCS versions, giving the overall disposition of the mission bay arrangements, machinery and ship mission systems [Pawling and Andrews, 2013], while Figure 9 provides a more detailed 3D illustration of the LCS (trimaran version) mission bay arrangement. Both figures show the mission bay impact for a relative small combatant is very significant. A much larger complement of UXVs is expected to have a similar impact on a larger mothership.

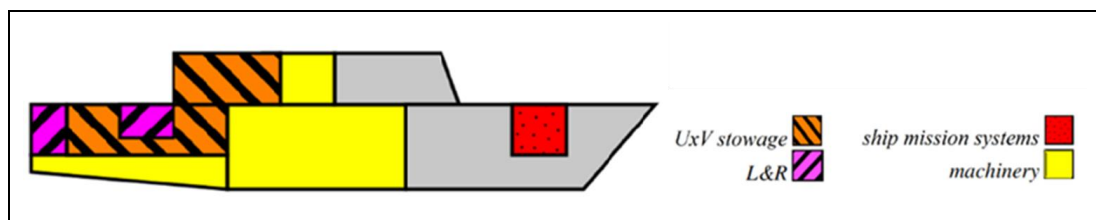


Figure 8: General configuration of both LCS design variants [Pawling and Andrews, 2013]

Both LCS variants have a large mission bay compartment under the flight deck that provides [Eaton et al., 2014] [Pawling and Andrews, 2013]:-

- Space for stowage of the mission modules;
- Handling system for internal movement and stowage of the mission modules;

- Side and stern LARS, where USVs and UUVs can be deployed and retrieved. Regarding the stern deployment method, the monohull version has a stern ramp, whilst the trimaran version employs a set of extending davits to carry the vehicles clear of the stern;
- Potential stowage of aviation systems in the mission bay was enabled by the mission bay's proximity to the hangar and flight deck. Randles (2012) highlights that an advantage of a midships mission bay, in comparison to a stern located one, is the additional flexibility provided for aviation assets. Besides mission bay stowage, rotary-wing UAVs are accommodated along with an inhabited helicopter inside the hangar, which is adjacent to the flightdeck. Hence, UAVs and inhabited helicopters can be launched and recovered from the flightdeck.

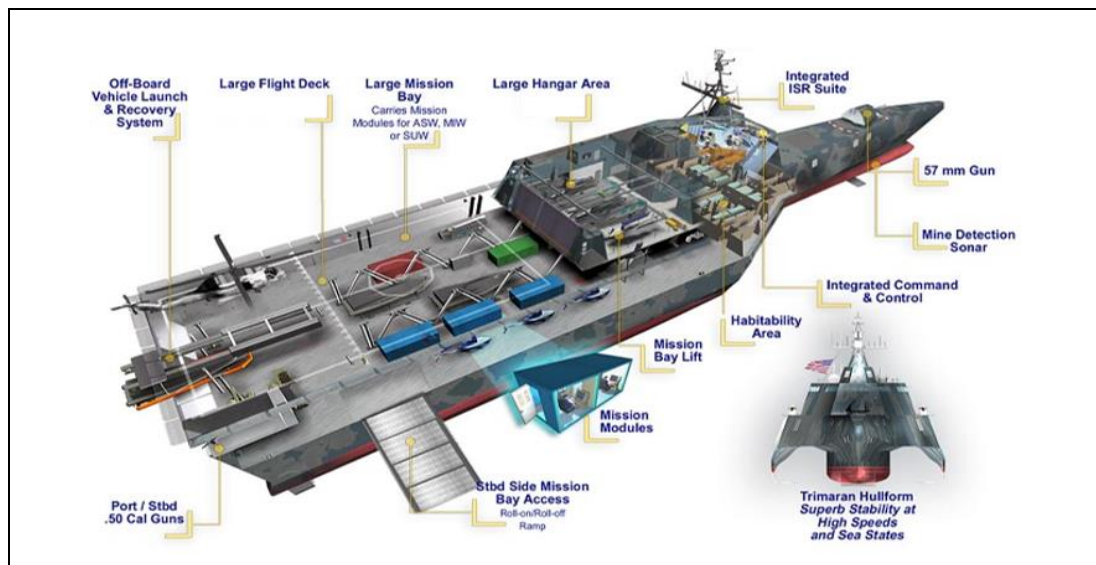


Figure 9: USS Independence mission bay arrangement [Defence Industry Daily, 2016]

To enhance safety, multi-mission capability, mission effectiveness and affordability, the mission-oriented spaces need to be integrated into the mothership architecture, taking into account any potential integration issues at the ESSD. Such UXV related design integration issues for the mothership design include [Pawling and Andrews, 2013] [Eaton et al., 2014]:-

- LARSs;
- Stowage spaces;

- Handling systems with a lifting allowance required to allow for the vehicles to be moved inside the mission bay;
- Maintenance and repair equipment;
- Refuelling and rearming equipment;
- Relevant crew and crew support;
- C3 systems;
- Capability of a mothership to host and deliver a UXVs fleet, i.e. ship performance, including speed profile, operational range, endurance, seakeeping and stability.

The implications of a fleet of UXVs on a host ship design and the resultant interfaces between the ship and the UXVs are of vital importance, and hence ought to be considered early in the design of the host ship. Consequently, the design of a mission bay and its successful incorporation in the overall ship design would be a design challenge. Moreover, mission bay interoperability (i.e. operational flexibility) would allow a mothership to perform a broad range of roles by embarking a wide array of uninhabited assets, and could also pose a demanding design task.

Flexibility within a mission bay would allow the ship to re-role in order to suit emerging tasks and also have the space provision for future upgrades [Randles, 2011]. Although future upgrades and evolution of UXV systems are not readily predictable, employing LARs with operational flexibility would allow the operation of alternative UXV compositions, as resulted by CONOPs studies, as well as newer generations of UXVs. Thus, flightdeck, well dock and crane LARs all provide high levels of interoperability, as opposed to a stern ramp that is normally a bespoke ship system and likely to limit the LAR operations to specific types of vehicle. Moreover, Board Margins should always be allocated in ESSD, as to give some provision for future ship upgrades [UCL, 2014 a], while maintaining ship performance levels. However, trade-off studies are normally necessary, in order to come up with a viable set of solutions, as adaptability and enhanced functionality attributes might drive up the complexity of a design and thus cost, resulting in non-affordable solutions. Towards that purpose, a number of considerations, as illustrated in Figure 10, should be taken into account by the designer in the early stages of ship design. This would enable the designer to define

affordable options regarding the mission-oriented spaces and their integration in a UXV mothership [Eaton et al., 2014].

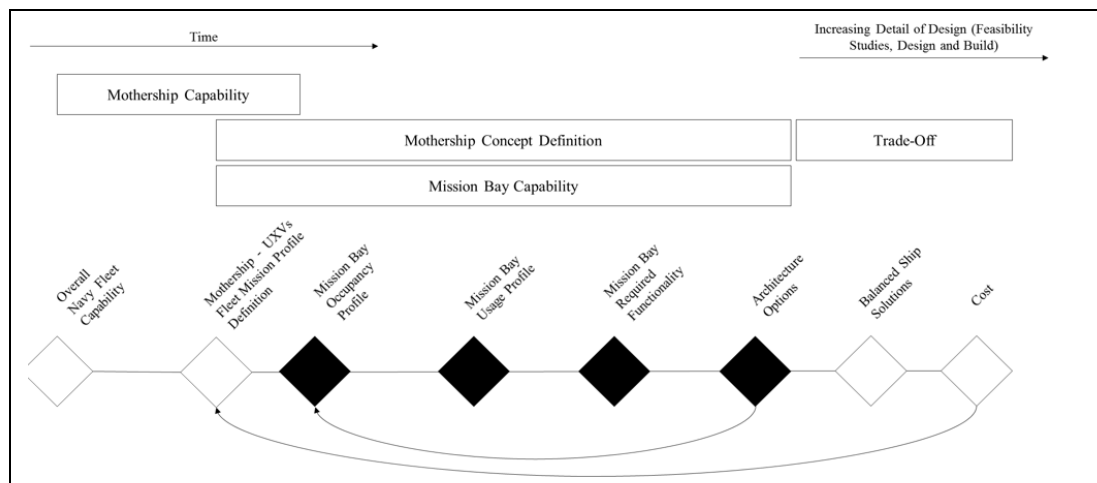


Figure 10: Considerations regarding the definition of a mission bay [Adapted from Eaton et al., 2014]

Initially, the capabilities of a mothership along with its UXVs should be defined according to a set of mission profile scenarios, spelt out in CONOP studies. Early in the process of a mothership design, the ship designer along with the mission scenario specialists have to determine the necessary mission bay capability, resulting from the UXVs fleet composition required for a particular set of missions and the mission criteria requirements. That would not only impact the configuration of the mission bay itself, but also integrating the mission-oriented spaces into the ship would affect the overall mothership design, in order for the ship to provide sufficient support to the UXV operations. A mission bay occupancy profile would help to indicate the spatial requirements consumed by: LARSs; required UXV stowage; UXV handling systems and spaces (i.e. for moving UXVs inside mission-oriented spaces); UXV maintenance, refuelling and rearming features; UXV and personnel accessing routes for any associated personnel involved into the UXV mission bay-based tasks. Such features would determine the required mission bay size. Moreover, a mission bay usage profile would be insightful regarding the frequency and duration of the operations conducted at the mission bay, i.e. LAR, stowage, maintenance, refuelling and rearming. Normally, at the beginning and the end of a mission, LAR operations dominate, due to disembarkations and embarkations of UXVs, respectively. Such considerations would enable the designer to understand each system in the mission-oriented spaces [Eaton et al., 2014]. An example configuration of mission-oriented spaces on a surface

ship, emphasising on the UXV operations that take place in these spaces, and also demonstrating a proposed flow of UXVs through the mission bay, hangar and flightdeck [Broadbent and Binns, 2006], is shown in Figure 11.

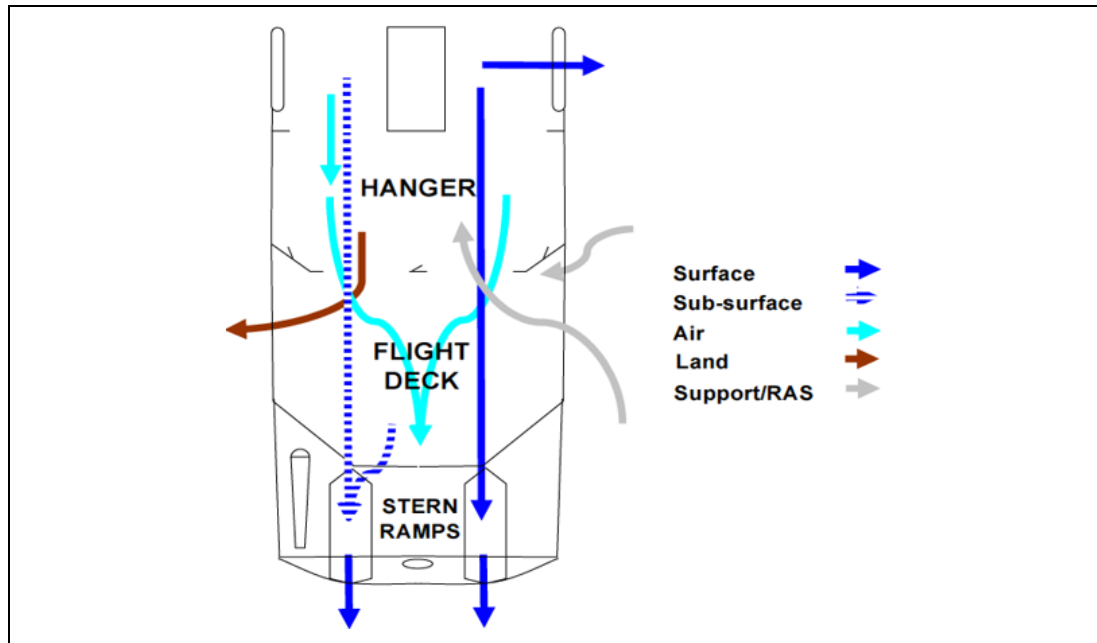


Figure 11: Suggestion of UXVs mission-oriented spaces on a surface ship [Broadbent and Binns, 2006]

The ship designer ought to examine numerous mission bay configurations considering the mission bay occupancy [Eaton et al., 2014]. The mission-oriented spaces would be developed in parallel with a UXV mothership as a single integrated entity, able to deliver the required capabilities as set by CONOPs criteria. Moreover, more than one mission bays might be integrated into a single mothership, depending on the number and type of UXVs carried on-board, as well as on the extent of LARs of multiple UXVs to be deployed and recovered simultaneously. Different mission bay configurations and locations on a host ship would provide distinct capability benefits. Therefore, it is essential to systematically develop and investigate a number of design alternatives, perform cost estimations and carry out trade-off studies on requirements and affordability. These assist the dialogue between the customer and ship designer regarding the feasibility and affordability of design options (i.e. Requirements Elucidation [Andrews, 2011]), allow early design decision-making activities and mitigate the risk of errors and prolonged expensive design reworks (Andrews, 1985).

Since the capability of deploying and recovering UXVs from surface ships has to date been limited to a small number of UXVs (e.g. LCS, Type 26 Frigate), an interesting

parallel with regards to the potential development of a host ship for a large number of UXVs requiring more extensive LAR support of UXVs fleet operations could be drawn from the early development of seaplane to the modern aircraft carrier, as illustrated in Appendix 3 [Brown, 2004]. Seaplane tenders were regarded as the first carriers of aircraft that not only carried seaplanes on-board, but also supported their operations by providing all the necessary facilities, including LARSs and maintenance kits. Ark Royal (1914) was the first British seaplane carrier, which was converted from a merchant ship and was able to carry seven seaplanes. Seaplanes took off from the sea surface and land on the water to be winched back on-board the ship by using cranes. On-board launch of seaplanes was seen difficult to accomplish, as reaching take-off speeds would require a long runway on the upper deck of warships, which at that time were crammed with guns and equipment. Integration of catapults into the upper deck of warships was considered as a means to launch seaplanes and later aircrafts without the need for a long runway. Moreover, recovery of seaplanes at sea and then pulling them up on-board the ship with cranes was limited to low sea states. Thus, redesign of the superstructure in the form of an island positioned on the starboard side of the ship led eventually to the 1937 Ark Royal, which could be seen as the model for the subsequent aircraft carriers, with her layout providing a generic aircraft carrier template. Consequently, the technological developments led to the transition from seaplane carriers, which were capable of supporting a small number of seaplanes, to the current highly developed aircraft carriers, like the USS Nimitz-class aircraft carriers that are able to host and rapidly deploy/recover a fleet of 90 fixed wing jet aircraft and helicopters. The enhancement of aircraft LAR operations on aircraft carriers has occurred through the adoption of features (i.e. LARSs), such as extended and angled runways, ski-jump ramps, catapults and arresting gears [Brown, 2004]. Consequently, the gradual transition from seaplane tenders towards the current super aircraft carriers might suggest how the employment of a fleet of UXVs would radically change the design of future UXV motherships, which would act as both a host and support ship for a wider range of autonomous vehicles. It is proposed that the support of more than one or two UXVs from a ship is the next step in maritime deployment of UXVs, and the progression to a proper mothership is likely to be considerably different to two or three generations from now.

Such a large number of UXVs being carried by a prospective UXV mothership will impose an added issue, that of pre-operational installation of the fleet and a further issue as to whether it is necessary to "top up" the complement of UXVs in a more operational situation. For the former (i.e. loading alongside the mission bay which is in the superstructure), this could be readily accommodated by a hatch in No. 02 Deck. This might also be utilisable for replacing a limited number of UXVs at sea from replenishment vessels. This would need some RAS facilities on No. 02 Deck in way of the hatch arrangements down to the mission bay.

2.3 Design of an Uninhabited vehicle Mothership

2.3.1 Naval Ship Acquisition Process and Requirements Elucidation

Many engineering design processes, unlike the design and construction of a combat ship design, commence with a precise set of requirements [Andrews, 2012]. Brown (1993), argues that the design and subsequently construction of a new warship, such as a mothership, is normally initiated by the need to launch new capability at sea, or replace existing capabilities. Andrews, emphasises that a major feature of the management of the design of complex systems, such as naval ships, is the application of formal procedures in order to conduct their design and procurement process [Andrews, 1998]. The U.K. MoD has adopted the Smart Acquisition process, which is summarised in Figure 12, as a means of defining an equipment project's life cycle to meet an enhancement of defence capability. Such a cycle was seen as the means to acquiring and supporting equipment more effectively regarding its cost, performance and the efficient introduction into service, although this cycle has been questioned by Andrews (2003 a), particularly for complex naval vessels.

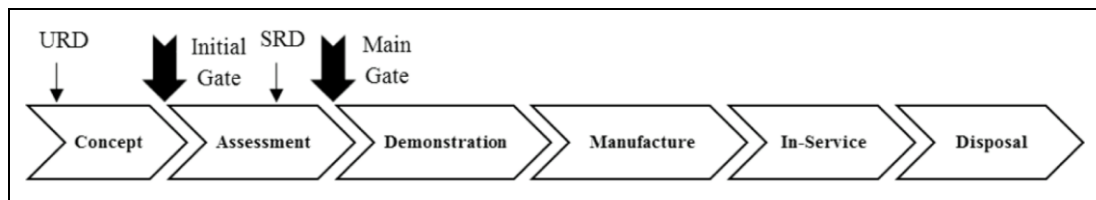


Figure 12: Smart Acquisition process [Redrawn from U.K. MoD, 2002]

According to the Smart Acquisition process, in the Concept Phase, the customer issues a User Requirements Document (URD) that describes the capabilities the customer requires from the new equipment project, which could be a warship, or class of warships. It is essential at this stage to identify potential technology and procurement options that merit further exploration, obtain funding and finally identify performance, cost and time schedule parameters regarding the programme. At the Initial Gate, which takes place at the end of the Concept Phase, a review is undertaken in order to examine whether the programme is feasible. Should the programme be approved, funds are released for the Assessment Phase that follows.

The next phase of Smart Acquisition is the Assessment Phase, where a Systems Requirements Document (SRD) is produced to define what the system must do, in

order to accomplish the customer's requirements indicated in the URD. Invitations to Tender (ITT) are offered to industry, and Assessment Phase contracts are subsequently awarded to a short-list number of companies, or consortia (i.e. for major combatants). At this phase, feasibility studies and trade-off studies between cost, time, performance and risks take place, in order to identify a cost-effective technological and procurement solution, which is consistent with the Initial Gate criteria, as well as mitigate the risks to an acceptable level consistent with delivering a system within restricted time and cost boundaries. At the end of this stage, the Main Gate review occurs, where a preferred procurement option is generally made. However, it is too late for a naval ship design project to conduct trade-off studies at the Assessment Phase, since such studies should be performed during "Requirements Elucidation" in ESSD, as discussed later in this sub-section.

In the Demonstration Phase of Smart Acquisition, which follows, progressively eliminates the development risks in order to fix certain performance targets for manufacture, as well as ensures that the selected solution meets the requirements agreed at Main Gate [U.K. MoD, 2002]. Although it is a normal practice for other defence equipment and systems to produce full scale prototypes at this phase, this is not the case for naval ships, which do not enjoy the luxury of prototypes due to the complexities incurred by the prototype size demands, the cost and schedule implications. This is where ships are different to other major equipment, with prototypes, i.e. "test before buy", and manufacturing are set up for production runs in new production lines [Brown and Tupper, 1988]. It is noteworthy that actual shipbuilding costs cannot be contracted until the shipbuilder finishes a year to obtain a contactable price, where negotiations between the shipbuilder and the various equipment and subsystems suppliers take place.

The following Smart Acquisition phase is Manufacture Phase, where production is mainly carried out in order to deliver the military capability within the time and cost boundaries, according to the contract, which is governed by the agreed Build Specifications. The following stage in project's life is the In-Service Phase that starts with acceptance trials to ascertain that the manufactured system is available for operational use, which ought to be spelt out at Main Gate. Finally, the Smart Acquisition process ends with an efficient, effective and safe disposal of the system

[U.K. MoD, 2002]. Although the disposal plan should be a part of the Initial and Main Gate, according to Smart Acquisition process this is realised at the end of project's life, i.e. for a class of ships.

Although Smart Acquisition process is the official U.K. MoD policy for the design and procurement of defence capabilities [U.K. MoD, 2002], it has been characterised by Andrews (2003 b) as flawed for reasons highlighted above. Andrews (2003 b), emphasised that such process is unable to effectively capture the actual requirements of complex systems, such as the modern warships. Instead, the overall structure of the ship design process can be divided into distinct phases [Andrews et al., 2012], as shown in Figure 13 [Andrews, 1998], leading to a more comprehensive practice for investigating in considerable depth and in material-specific terms the requirements for a naval ship programme, achieved through the dialogue with the requirements owner (i.e. naval staff). As the design process in Figure 13 progresses, the level of detail of all disciplines (see Table 4) relevant to naval ship design increases and emergent rectifying changes have to be controlled, as they can be disastrous to schedule and cost [Heather, 1990].

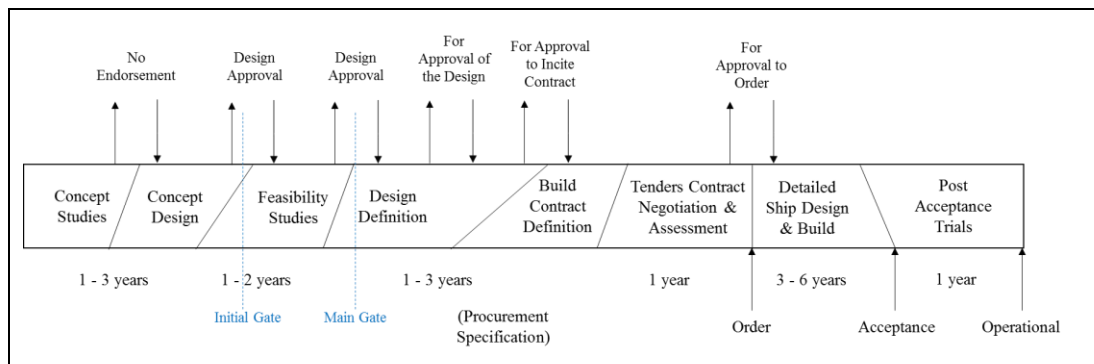


Figure 13: Phases of ship design process [Redrawn from Andrews, 1998]

Discipline	Description
Design	Design of complex systems, ships and floating structures
Aesthetics	Overall shape, colours, details, visual impact
Aerodynamics	Superstructure design, airflow over flight deck
Ergonomics	Overall layout, detailed arrangements of compartments and main machine interfaces
Hydrostatics	Basic stability, floatation considerations, vulnerability effects
Hydrodynamics	Resistance calculation, powering requirements, hullform design, propulsion consideration
Materials Technology	Fundamental strength and failure mechanisms of engineering alloys and composites, heat treatment, welding, manufacturing and forming techniques
Ship Response	Dynamic response to waves, seakeeping, manoeuvring
Marine Engineering	Engine design and limitations, engine-propulsion matching, ship services (electrical, water, air, waste)
Structural Mechanics	Main hull and appendage structural design, strength against failure, efficiency of structure, flexural and vibration characteristics
Other	Computing, production technology, project management

Table 4: Disciplines relevant to ship design taken from Andrews (1993) with the addition of relevant UXV technologies

Andrews (2013), asserted that the Concept Phase (i.e. pre-feasibility) ought to consist of three stages, which are to be undertaken prior to the Initial Gate decision point [Andrews et al., 2012]. Such stages would assist towards a baseline design that matches the evolving crude requirement and the agreed Initial Gate requirements would finally result from the trade-off analysis. Hence, a technically achievable and affordable mothership solution should emerge from the three stages summarised below, which are necessary to achieve the "Requirements Elucidation" process [Andrews, 2003 a, 2011, 2013]. It is noteworthy that this research study is not a full concept phase, which would be followed by U.K. MoD design process relevant to a new UXV mothership project. The three stages are:

- Concept Exploration stage. It starts with investigating for a new ship concept and it should be an extensive consideration of all possible options, including modernising existing ships and modifying existing designs [Andrews, 2013]. If the need is for a replacement of an existing ship or class, then designs broadly akin to the current ship are likely to be extracted from data bases and further assessed [Andrews, 1993]. At this stage the following solution space should be

explored [Andrews, 2013] without initially rejecting any option [Andrews, 2011]:-

- Packaging the primary functions of the ship concept, i.e. type of vessel, e.g. combatant, aircraft carrier. For a UXV mothership this would be the support functions of UXVs integrated in one hull;
 - Ship capabilities to deliver the required functions, i.e. speed, endurance, complement, standards and style features;
 - Technology options to achieve the perceived functions and capabilities of the concept, i.e. unconventional hullform and technologies (i.e. degree of novelty, style), utilities, new build, conversion, or merchant ship based design.
- Concept Studies stage. This stage takes on the insights provided from the first stage and focuses more on the perceived design drivers, so that their impact on overall characteristics, including ship size and performance are investigated widely before an integrated ship design has been produced [Andrews, 1993, 2003 a]. Thus, major design drivers should be investigated before the hullform is fixed. For instance, for a UXV mothership, the integration of mission bay arrangements is expected to be major design driver, hence various arrangements may need to be considered. Other potential design drivers could be the main propulsion and power generation, as well as the upper deck layout influenced by the disposition of intakes, uptakes and combat systems. Therefore, assuming only one or two solutions developed at concept exploration are taken forward, features including payload demands, as well as ship characteristics, including speed profile, seakeeping, endurance (i.e. fuel and stores), survivability and crew/accommodation, merit further investigation looking at likely options. This is best done before the final stage, in order to inform the following trade-off studies and further working up the requirement elucidation process. These investigations influence the downstream design, but most importantly need to be debated with the requirements owner, since their impact on ship's performance, overall design and affordability should be a part of the requirements elucidation dialogue with the requirements generator (i.e. owner of the naval capability), before the solution is too precisely fixed and potential changes result in extra costs and schedule delays [Andrews, 2013].

- Concept Design stage. Although the term of concept design is often used for any design work ahead of Feasibility, it should not be confused with Concept Design stage. At this stage from the complete range of material options considered, the ones that look most likely to be attractive in terms of achieving the requirement should emerge through dialogue with the requirements owner. The Concept Design stage focuses on producing-working up a baseline material description, informed by Concept Exploration and Concept Studies stages, also including costs, as well as trade-off studies [Andrews, 1993]. In Concept Design the naval architect only goes to a minimum level of definition required, appropriate for that new project. However, in certain areas of significant importance, such as the mission-oriented spaces of a UXV mothership, sufficient level of detail to encapsulate the potential emergent requirements is required [Andrews, 2003 a]. Prior to the Initial Gate, where approval is made to commit to a more substantial design effort, the Concept Design stage focuses on the technical representation of the ship that is balanced and sufficient enough to spell out refined cost estimations from emergent cost-capability trade off studies [Andrews, 2011, 2013].

Andrews (1992, 1998) emphasised that in acquisition process and particularly early in the ship design process, i.e. during concept phase, dialogue between the naval staff and concept design team is of major importance, in order to assess the viability of the user's requirements and define what is affordable and achievable before requirements are fixed, as each ship project is distinct regarding its objectives and constraints [Andrews, 2011]. Andrews (1985) also added that the identification and definition of the actual requirements for complex systems, like warships, and the final design solution depend on the interpretation of the user's often quite early/uninformed needs by the concept design team. Andrews has also drawn the attention to urban designers' use of the term "wicked problem" that can be applied to the process of working out a warship's requirements. This is because the latter is actually more challenging to pin down than the subsequent required ship design work to meet these requirements [Andrews, 2012]. It is essential that un-constrained dialogue is jointly undertaken and maintained between the requirement owner (i.e. naval staff) and the ESSD team, in order to cope with the "wicked nature" of the process [Andrews, 2013]. That dialogue elucidates the best mix of requirements and helps the decision-making process, by

using materially potential solutions that meet affordability and feasibility criteria. This process allows for gradual and interactive definition of actual material solutions with reference to specific equipment, which otherwise would be left to the choice of the finally selected contractor, who cannot be an unbiased partner in the elucidation of the problem. This also demonstrates why a contractor cannot realistically be held liable for any failure to meet user's requirements [Andrews, 2003 a]. Subsequently, Andrews (2003 a) strongly suggested that a process of formulating requirements of complex systems, such as modern naval ships, is a better description of ESSD, than the U.K. MoD's URD and SRD requirements engineering process, since the requirements elucidation process, as a trial and error dialogue can only sensibly take place between the requirement owner and the designer to successfully inform the eventual achievable requirement.

The concept phase aims to produce a baseline ship solution that matches the emergent user's requirements and results from a trade-off analysis through the requirement elucidation process [Andrews, 2011]. Dialogue is precisely what is meant by requirements elucidation, moderating any needs expression by what is achievable and affordable, and not just informing the requirements owner, but also ensuring both sides are equal partners in the dialogue [Andrews, 2013]. Initially, the concept process takes the form of a dialogue with the requirements owner, informed by a wide range of design options (i.e. many ideas are explored in an attempt to probe customer's needs and reveal other ways of meeting the emergent needs, trade-off studies exploring requirements, affordability and operational capabilities) [Andrews, 2011]. Beyond concept the process is progressive, leading to an increasingly more detailed design by a substantial and expanding multidisciplinary team that works up a design definition capable of being manufactured and assembled. The later design phases require comprehensive design management procedures that are constrained by the early design decisions regarding the overall configuration and important aspects of the ship and are undertaken in teams rather than by individual engineers and specialist designers [Andrews and Pawling, 2009].

Consequently, Smart Acquisition with non-solution specific Requirements Engineering has been argued by Andrews as inappropriate for a naval ship, because i) it fails to ensure top level characteristics are fixed in concept phase, before carrying to

the Assessment Phase and feasibility studies, ii) it does not take into account that trade-off studies should be a part of the concept phase, while feasibility studies are necessary to work up the design in order to show whether it is technically achievable, and iii) Demonstration is not possible for ships, as full scale prototypes are not available. For an actual mothership project that needs to meet the evolved user's requirements, by seeking a feasible and affordable option, a comprehensively conducted ship acquisition process, such as the one just discussed would be undertaken. However, for the purpose of this research, which can be seen as "Pre-Concept" stage without any formal navy need for a "UXV mothership", the above process cannot be followed. Thus, the ship design studies that are reported in this thesis are in the nature of an early concept exploration of a very early stage concept of a UXV mothership. The above outline has been produced in order to place the subsequent design research studies in the real world context.

2.3.2 Background to Naval Ship Design

Andrews (1985), stated that ship design is the process of integrating all the components of multidisciplinary subject areas into a functional entity (i.e. synthesis) with desired overall characteristics, in both a scientific and architectural way. He emphasised that an architectural approach to ESSD is crucial, since a design cannot be described purely numerically, but the arrangement of spaces and equipment in them is also necessary. Andrews (1998), also highlighted that warships are regarded as highly complex systems, due to the fact that:-

- They integrate diverse complex technologies into a fighting unit;
- They are designed for multiple roles, operate in a broad range of demanding and hostile environments and provide permanent habitation for personnel;
- They carry stores, fuel and spares in order to support personnel, prime movers and maintenance needs (i.e. have long endurance and self-sufficiency).

Gale (2003) similarly highlighted the architectural nature of ship design, by defining the ship design as the activity involved in producing drawings (or 3D computer models), specifications and other data needed to construct an object, in this case a ship. He also emphasized that ship design is a function of the ship type and the designers' personal preferences, as well as involving engineering and artistic aspects [Gale,

2003]. According to Gale (2003), the primary purposes of the design process are to ensure feasibility, satisfy user's requirements and facilitate the ship's construction. Moreover, Heather (1990) emphasised that the main high risk areas of naval ship design, are seen to be:-

- The development of complex weapon systems and their integration into the ship. All major combat systems have to be determined at early design stages, as they are likely to be crucial towards ship sizing (i.e. topside deck layout). However, the development of complex weapon systems and particularly the software that is related to their operation often do not perform as required, or do not meet the promised timescales, hence weight, space and power requirement estimates are often not reliable;
- Bottom-up (i.e. components to overall design) weight estimates are required for any novel designs;
- Power generation requirements;
- Configuration of key spaces, e.g. bridge, Operations Room.

The ability of a ship designer to identify quickly what features are the main driving issues for a ship design, not only expedites the process itself, but also leads to a more functional and affordable solution [Watson, 1998]. Ship designers normally have access to ship design databases, covering ship-level and system-level information from past designs, enabling them to obtain quick first estimates of a new ship design at early design stages [Gale, 2003], which assists in risk reduction in ESSD [Heather, 1990]. Such estimates are usually based on historical data and previous ship designs in order to produce a first rough estimate regarding the size and layout of a proposed ship, and therefore assess whether the design merits of further investigation in later design stages. Andrews (1993), emphasised that the early stages of a ship design are crucial, as major decisions and trade-offs are made regarding the final design solution, whereas little of the expenditure has been committed. Moreover, early design stages reveal to ship designers most of the issues to which they have to pay attention and deal with [Andrews, 1993]. In the concept phase, alternative mothership solutions ought to be investigated and promising options can then be developed in sufficient detail, to give realistic estimates regarding ship size, cost and its capabilities [Brown, 1986]. A concept ship design study can be generated within ESSD team, by taking into account

all major features of the ship, as illustrated in Figure 14 (i.e. this demonstrates aspects of the traditional approach to ESSD, prior to the holistic architectural-centred design approach) [Andrews, 1993], including ship overall dimensions, main machinery, structural continuity and preliminary block layout.

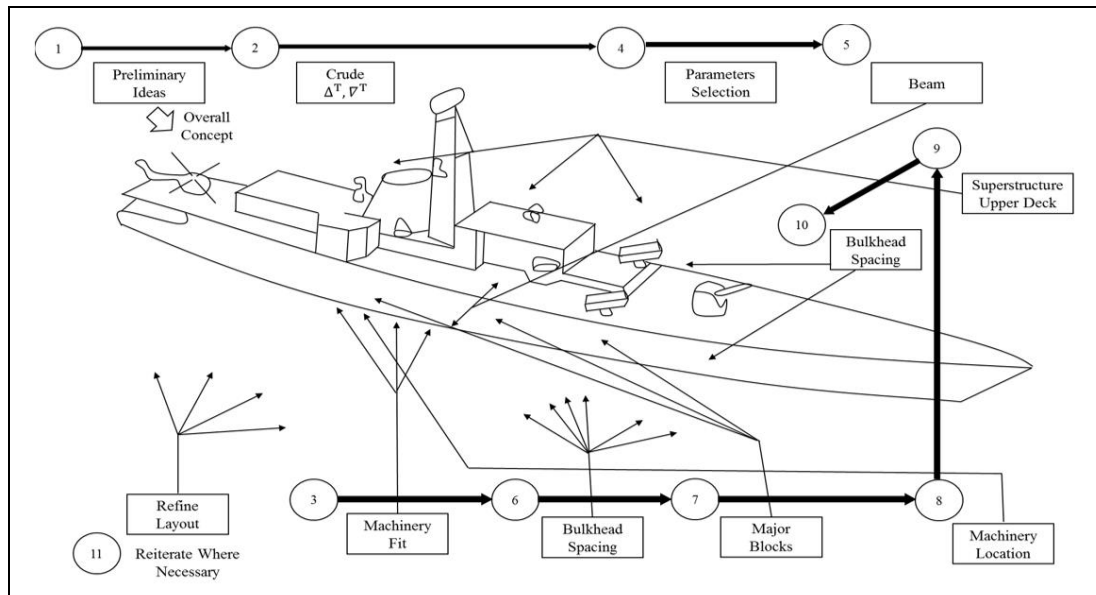


Figure 14: Steps in a typical ship concept design study/option [Redrawn from Andrews, 1993]

The complexity and risks in a ship design increase with the degree of novelty [Gale, 2003], which justifies the suggestion that a new design should have only 25% of novelty and the rest 75% should be based on a well-tried practice [Brown, 1986]. However, Brown (1986) suggested that concept phase is the only time the designer can introduce genuine design novelty. Andrews (1985), outlined a range of ship design processes based on the degree of novelty of the design solution, where radical options would require huge research and development and probably construction of a prototype. The various conflicting goals and budget limits adds to the complexity of the ship design [Brown and Tupper, 1988]. Although computer-based simulation tools might reduce the need for physical models, the absence of full scale prototypes, due to the size, cost and time restrictions, contribute to the ship design difficulties. Andrews (2003 b), emphasised that a comprehensive ship design method should assist ship designers to undertake requirements elucidation within the complex acquisition environment of physically large and complex systems [Andrews, 2013]. Hence, such a design method should produce ESSD options that have the following characteristics [Andrews, 2013]:-

- Coherent solutions, i.e. solutions resulted from constructive dialogue between the customer and ship designer, including numerical measures of ship's performance, a cost estimate and a visual representation;
- Believable solutions, i.e. solutions that are both technically balanced and sufficiently descriptive;
- Revelatory method, i.e. potential design drivers are identified early in ship design, in order to explore plausible solutions;
- Creative method that facilitates as wide an exploration of solutions as possible, in order to ensure that the eventual design choice emerges from a divergent investigation rather than just considering predisposed ship solutions;
- Open method that responds to customer concerns, i.e. not a black box decision system, so that realistic, affordable and low risk requirements are elucidated by the naval architect from dialogue with customer.

2.3.3 Early Stage Naval Ship Design and Architectural Modelling Applied to Early Stage Mothership Design

ESSD is important, as it sets the "skeleton" upon which the subsequent detailed ship design will be built [Andrews et al., 2012]. It is the only time the ship designer can be divergent and truly radical in their thinking, by exploring new whole ship concepts. If new options are not considered at this phase, then they will never be [Andrews, 2011]. At this design stage, the overall design must be sufficiently detailed for the requirements are to be elucidated. However, it is only necessary to explore those aspects that can provide the necessary early assurance of the requirements and the resultant solution space, in order to proceed to the next stage of the design process [Andrews, 1993]. In the case of a mothership design, those aspects need to address the issues associated with integrating a fleet of UXVs, and their equivalent support systems, into the design of a host vessel, that is able to support those vehicles' operations throughout a set of predefined mission scenarios.

To demonstrate how the ship designer deals with the various aspects of ship design sequentially and iteratively, the first design spiral was developed by Evans (1959) and many other versions have been produced since then [see examples brought together by Andrews et al., 2009]. However, Brown (1986) argued that the naval architecture

aspects of the ship design are so difficult to structure and are not properly represented by flow diagrams such as the design spiral. Consequently, such depictions of the ship design process have been criticised as:-

- i. It is not a closed, sequential process without external interactions and constraints [Andrews 1981, 2018], but consists of interacting closed loops and intuitive leaps (i.e. discontinuous) by the ship designer from one spot to another in the spiral as knowledge is gained throughout the design [Brown 1986] [Gale, 2003] [Andrews, 2012, 2013];
- ii. It describes the individual technical processes, rather than the fundamental decision-making nature of ship design [Andrews, 2012];
- iii. It is insensitive to ship type [Watson, 1998].

Andrews (1998), considered that the ship design process for a naval ship consisted of three essential and sequential sub-processes:-

- Initial sizing, where gross ship size is obtained (i.e. length, beam, depth, draught, form coefficients, gross mass, volume and superstructure volume/ratio) [Andrews, 1981];
- Parametric exploration, where principal dimensions and hullform parameters are assessed against ship's performance criteria, usually powering requirements, stability and seakeeping;
- Architectural synthesis, which has progressively performed within the size and hullform previously selected.

In the sequential ship design process, described in the paper entitled "An Integrated Approach to Ship Synthesis" by Andrews (1984), the initial sizing of a ship is traditionally based on a purely numerical approach of balancing weight and space. Andrews (1981, 1985), presented the sequential ship design process to achieve a design that is balanced in space and weight through a simplified sequential and iterative initial sizing process, in order to show the necessary associated assumptions and data sources [Andrews, 1985]. Thus the initial sizing is strongly reliant on existing ship data and scaling ratios to develop first estimates of weight and space requirements [Brown and Andrews, 1980]. The initial sizing process has then been followed by a parametric survey to refine underwater hull coefficients and main hull dimensions,

normally assessed against ship powering and stability performance. However, the architectural arrangement of the ship was left at the end of the initial design process, where the overall ship size and shape were already determined and largely fixed through the initial numerically balanced sizing and the hullform parametric survey [Andrews, 1985]. Brown (1986), also highlighted that architecture of the ship is not given the attention it deserves and left to later design stages, since more easily addressable associated with hydrodynamics, structural and stability considerations of the hull were prioritised.

Andrews (1981), emphasised that the traditional numerical ship design process assumes a disposition of mass and space in the ship, which effectively assumes the location of the different spaces within the overall design envelope (i.e. following previous practice), hence the process is bound to limit design variety. Consequently, the ship design solutions were restricted within the strict confines of the numerically derived form. This traditional and numerical ESSD approach has been also criticised as not being fully integrated and comprehensive, as it restricts the ship designer in considering the likely interactions within the ship in the early design stages, hinders innovation, creativity (i.e. since new designs are based on existing vessels) and full exploration of alternative solutions [Andrews, 1981]. A ship design is not just the incorporation of a number of equipment weight and gross volume demands, but it also needs to achieve a set of physical characteristics, including configuration, S^4 and style issues, like survivability, that can support its operational performance requirements [Andrews, 1998, 2003 b]. Although S^4 were traditional subjects of naval architecture, Brown and Andrews (1980) added a fifth element, called "Style", hence the new term " S^5 ". Style is cross-cutting, where one decision impacts the subsequent solution areas and design features. For instance, levels of survivability is a style decision option. Thus the survivability level selected can influence a range of design aspects, such as the choice of signatures and defensive systems (i.e. to prevent a hit, an example of susceptibility consideration), the number and spacing of transverse bulkheads (i.e. to resist weapon effects and flooding, an example of vulnerability consideration), compartment arrangements (i.e. to protect vital spaces and aid in recovering, an example of recoverability measures) and structural issues (i.e. to resist shock, an example of vulnerability measures) [Pawling et al., 2013]. Besides survivability, other style-related issues include unconventional hullforms and ship zoning [Andrews, 2003

b, 2018]. However the traditional ship design approach can only address many style related issues once the configuration (especially general arrangement) is properly addressed after the initial ship synthesis. If this is delayed until later in the design, design changes will lead to cost and schedule overruns.

Consequently, Andrews (1981), postulated that a warship's design initial synthesis should be driven by its internal and upper deck configuration, i.e. configuring the spaces required to achieve primary functions of the vessel (i.e. functional arrangement), yielding a 3D block layout around which a hullform could be wrapped (i.e. enveloped) of desired S^5 features (i.e. designing the ship "inside out"). This approach (proposed in Andrews' thesis (1984)) of emphasising the architectural nature of warship design was also spelt out by Brown (1986). He defined a warship as an assembly of multipurpose spaces that interact in a complex manner and located within the hullform (i.e. envelope), the overall shape of which is largely governed by hydrodynamic performance requirements and constructed by internal partitioning, due to structural continuity and damage containment requirements. Hence, Brown (1993), concurred that warships are neither weight nor space driven, but primarily architecturally driven, since the interactions of ship elements and their integration into a single unit are related to its architecture and are likely to impact the cost. For instance, the upper deck layout of a warship is strongly affected by the disposition of weapon systems, the machinery equipment through the uptakes and downtakes paths, as well as vehicles' operations, including helicopter, boats or UXVs [Andrews and Dicks, 1997]. However, due to the complex nature of warship's architecture and the often conflicting requirements it has to meet, ensuring the arrangement's viability is challenging.

When it comes to sizing unconventional hullform configurations, e.g. SWATH, or trimaran, since their hullforms are based on the configuration of their major spaces, which are likely to be a main design driver for determining the vessel's dimensions and principal form parameters, an architectural approach is essential [Andrews et al., 2006]. Furthermore, layout related issues, such as personnel access routes (i.e. for different ship operations), as well as location of transverse bulkheads that is strongly determined by damage stability and structural continuity requirements, might end up being design drivers. Without a more comprehensive architecturally oriented ship

design approach, the internal arrangement could only be considered after overall sizing, risking operational inefficiencies [Andrews, 2006], with corrective actions being lengthy and costly and also likely to be compromised [Andrews et al., 2009].

Therefore, Andrews (1981), proposed a ship design process that integrates ship's architecture on an equal basis with the numerical description, in order to produce what he called creative approach to ship design. This was subsequently demonstrated to be a more holistic approach to a fully integrated ship synthesis, enabling concurrent engineering [Andrews, 2003 b]. Furthermore, Andrews (1985, 2012) revised the numerical version of the initial sizing process taking spatial aspects into account, thus describing the decision-making process that incorporates the architectural element in the initial ship design synthesis. Andrews has described the overall design process for complex vessels in terms of the main decisions conducted throughout the overall process and are spelt out in Figure 15. This holistic ship design approach integrates initial ship synthesis, naval architectural ship analysis, engineering analysis of its systems and design of combat systems. Consequently, since future warships, such as a UXV mothership, will be architecturally driven, integrating architectural modelling with the initial ship sizing (i.e. weight, space and hullform parameters) at ESSD would allow:-

- The designer to better identify risk areas and design drivers and deal with complexities;
- Consideration of innovative options and a broader range of design alternatives;
- Produce a better contribution to trade-off studies, cost estimates and comparison between design options;
- Better ensure the overall ship dimensions and hullform characteristics to be readily adjustable as the ship design progresses to achieve a more efficient layout with the desired performance, including hydrodynamic, stability, seakeeping and structural aspects, as opposed to the traditional numerical approach that tends to restrict the designer to the predefined hullform, making any ship increase (i.e. displacement) unattractive;
- Facilitate the exploration of ship aspects that are difficult to be addressed in a pure numerical approach, such as design style aspects (e.g. zoning, vulnerability) and integration of combat systems;

- Foster a better requirements elucidation attitude, since it can only be properly undertaken concurrently during developing the solution(s) [Andrews, 2003 b, 2011];
- The risk of omissions leading to costly reworks can be mitigated by employing an architectural approach to ESSD [Andrews and Pawling, 2007].

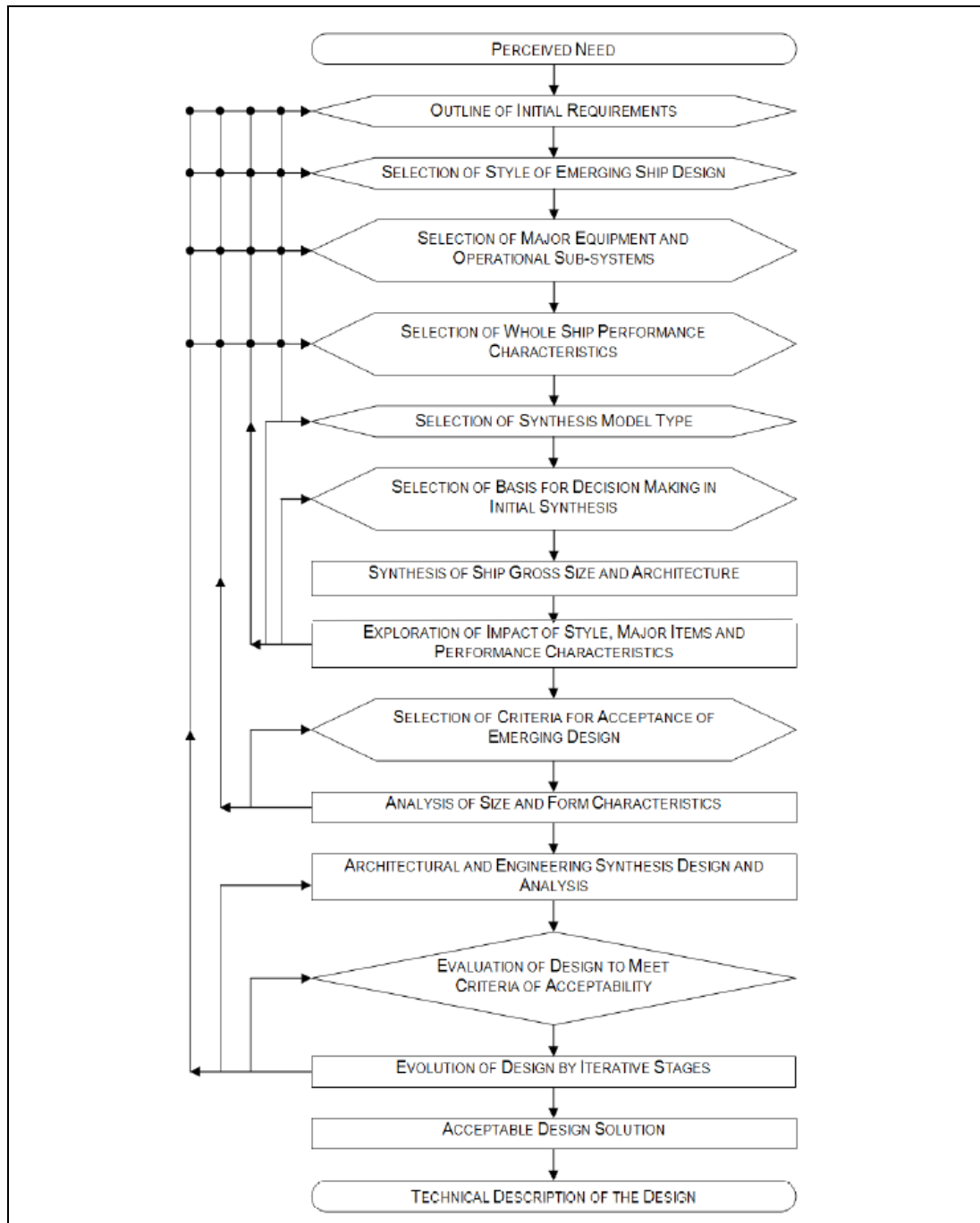


Figure 15: Holistic ship synthesis decision-making process [Andrews, 2018]

The combination of an architectural and numerical balanced ship description (i.e. fully integrated ship synthesis) provides the designer with the ability to take into consideration many of the ship's design potential drivers in the early stages of ship design, contributing to alternative solutions, trade-off studies and options cost analysis [Andrews, 1985, Andrews, 2003 b]. An architectural integrated approach would also allow the designer to investigate operational inefficiencies, such as crew and vehicle movement (i.e. handling) on-board [Andrews and Pawling, 2009], in the infancy of a ship design, before the ship size and hullform parameters have been imposed on the overall design [Andrews, 2006]. In addition to this, a more architecturally-oriented ESSD approach would enable the ship designer to take into account aspects of the ship, such as decks, access, structural continuity, aesthetics, bulkheads position, zoning, habitability, vulnerability, design margin allocation and superstructure size (rather than having to use default values, often based on inappropriate historic data) [Andrews, 1985]. Integrating the ship architecture with the numerical sizing (i.e. weight, space and hullform parameters) would also mean the ship overall dimensions remain adjustable and flexible throughout the concept phase, so there is a better basis for the layout and balanced solution envisaged (Andrews, 1985).

Developments in computer graphics over recent decades have facilitated this holistic (i.e. fully integrated) ship design synthesis, producing a numerical and configurational description of ships, as well as an initial analysis of the ship's naval architecture attributes [Andrews and Pawling, 2003]. A new approach integrating ship architecture in the initial ship sizing, called the "Design Building Block" (DBB) approach to ESSD was first developed for submarines (SUBCON) [Andrews et al., 1996] and a surface ship DBB approach was subsequently developed for Andrews by GRC (SURFCON module in GRC-QinetiQ Paramarine), and it is since seen as an accepted standard ESSD approach of complex vessels [Tupper, 2013]. It has then been employed to undertake numerous ship design studies, including design studies to explore the concept of fast mothership options transporting small fast assets to the littorals, shown in Appendix 4. This module enables an architecturally-centred synthesis, as well as integrating analytical tools able to assess stability, powering, seakeeping, manoeuvring and structural strength. Figure 16 shows an example of Paramarine SURFCON module application to ESSD based on the requirement for the U.S. Navy LCS-trimaran version [Andrews and Pawling, 2008].

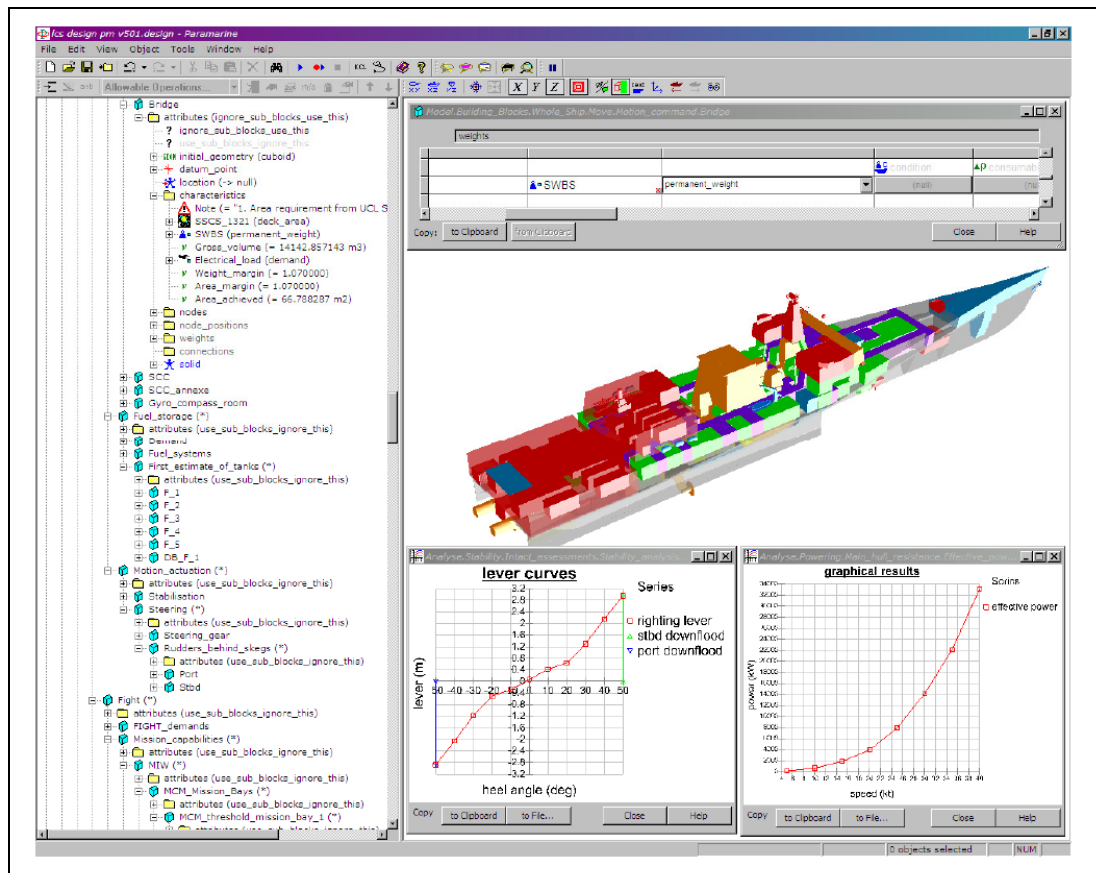


Figure 16: SURFCON representation showing the three panes for tree structure, graphics (DBBs) and tabular interfaces, with stability and powering results also visible [Andrews and Pawling, 2008]

To address and investigate the implications on the design of a prospective mothership of deploying various UXV fleets, as well as providing related support systems and equipment, it is seen as logical to adopt an architecturally-oriented ship design approach. Such an approach enables the ship designer to have a more holistic view of the design of a mothership in the early design stages, since the design of mission oriented spaces and their integration into the overall ship design cannot readily be produced just numerically. Hence, this allows the naval architect to investigate the impact on the design of a mothership of requirement for deploying such a UXVs fleet accommodating on-board and supporting the LAR operations of the fleet [Andrews and Pawling, 2009]. Additionally, 3D computer modelling could potentially reduce the need for physical modelling, i.e. mock-ups of ship or ship compartments, which is time consuming and costly to construct and modify [Gale, 2003].

2.3.4 The Design Building Block Approach Applied to the Early Stage Design of an Uninhabited Mothership

Complex ship design studies, such as a UXV mothership, cannot be adequately done in what has been described by the traditional numerical design approach, as such vessels are configurationally driven and hence the architecture of a UXV mothership needs to be taken into account into the early design stages [Andrews, 2003 a].

In the development of the DBB approach to avoid ESSD being driven to specific configurations and systems solutions, the approach broke away from the U.K. MoD Weight Breakdown Structure (WBS) (i.e. hull, personnel, ship systems, machinery/propulsion, electrics, payload and variables) and the equivalent weight driven design approach. A more suitable descriptive breakdown structure was therefore seen as that of Float-Move-Fight, describing the functions that the elements of a concept design are intended to meet [Andrews et al, 1996] and the surface ship oriented DBB approach also adopted this functional breakdown. More specifically, the functional and sub-functional elements, required for a new ship, are linked to discrete design elements, called building blocks [Andrews and Dicks, 1997]. By adding the Infrastructure group to the functional breakdown of Float-Move-Fight, it was seen appropriate to use this functional breakdown as an alternative option to the WBS, in order to describe a ship [Andrews et al., 1996].

Table 5 provides the functional group breakdown along with their related typical components [Andrews and Dicks, 1997]. The building blocks are categorised into Float-Move-Fight-Infrastructure groups and have been allocated distinct colours, Blue-Yellow-Red-Green, respectively, in the 3D representations of design studies [Andrews and Pawling, 2003]. Each building block contains geometric and technical attributes regarding the functions of that particular block [Andrews and Pawling, 2003]:-

- i. Numerical data (e.g. weight, power, manning);
- ii. Constraint data (e.g. mast spacing, proximity of antennae);
- iii. Parametric data (e.g. structural mass of hull dependent upon, say hull length);
- iv. Geometric data (e.g. volume, area, shape, location);
- v. Descriptive data (e.g. name, explanatory notes on function and performance).

Functional Group	Typical Components
Float	Hull Structure, Access
Move	Prime Movers, Fuel Tanks
Fight	Operational Room, Mission Bay(s), Combat Systems
Infrastructure	Accommodation, Ship Services

Table 5: Functional breakdown of warship design [Modified from Andrews and Dicks, 1997]

According to Dicks (1999), the Fight and Move groups have characteristics of directly determined requirements and generally tightly controlled configuration options that tend to drive the design to certain restricted architectures. Whereas, the Float and Infrastructure groups were seen as dependent groups rather than main drivers of the ship design, as they are normally defined to a significant degree as a result of the Fight and Move functional groups. However, such considerations cannot be applied to rigidly, but seen as useful design guidance.

Besides addressing S^4 considerations, the core of the DBB approach is that it puts together the numerical sizing and balancing approach with an architectural description of the ship to produce more comprehensively naval architecturally balanced solutions. The resultant design description consists of a 3D image and the numerical description of the whole ship, contained in the "Master Building Block", that results from the ship designer's putting together a putative configuration of building blocks. Typical information in the Master Building Block are the overall ship requirements (e.g. speed, seakeeping, stability, powering, longitudinal strength, manoeuvring), ship characteristics (e.g. weight, space, dimensions, centroids) and overall margins [Andrews and Pawling, 2003]. The hierarchical relationship between the overall ship description and the individual components is reproduced in Figure 17. The configuration progresses by either introducing new building blocks or moving existing ones, in order to achieve a better solution that is assessed whether it is functionally and naval architecturally acceptable. It is the ship designer's judgement to decide how to modify a resulted design, in order to achieve the necessary level of balance [Andrews, 2003 b].

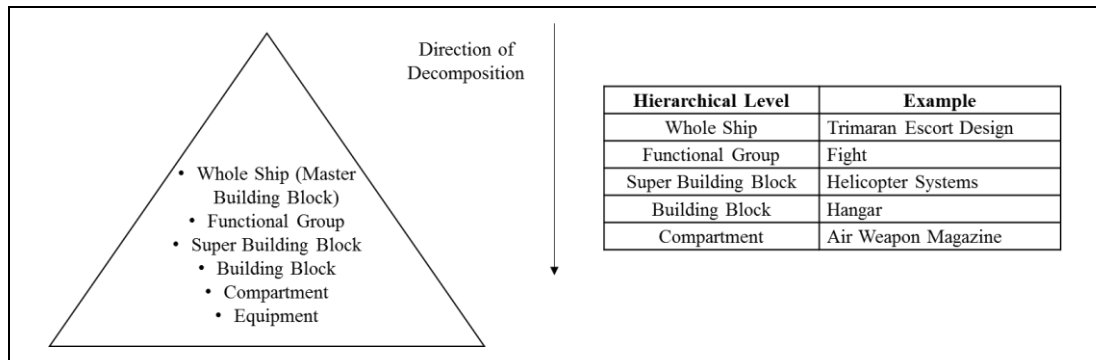


Figure 17: Functional hierarchy [Modified from Andrews and Dicks, 1997]

In essence, the DBB approach focuses on the ship architecture and how it is produced alongside the traditional numerical sizing and naval architectural balance [Andrews and Pawling, 2007]. The DBB approach for surface ships is schematically shown in Figure 18, which summarises a comprehensive set of analysis processes, most of which are unlikely to be used in the initial setting-up of the design, or even at the early iterations of building blocks geometric definition and ship size balance. In fact, several of the inputs shown in Figure 18, are either specific to naval combatants, such as the topside features, or these inputs omit aspects that could be dominant in special vessels, such as the personnel and vehicle flow that are likely to dominate the internal ship configuration of aircraft carriers or amphibious warfare vessels.

The DBB approach can be summarised by the following sequence [Andrews and Dicks, 1997]:-

- i. A very broad outline requirement is identified and the likely design style is proposed to meet that requirement (e.g. UXV mothership requirement);
- ii. Drawing on novel ideas and/or historical data, a series of design building blocks are defined (i.e. Computer Aided Design (CAD)), or selected from a library, containing geometric and technical attributes regarding their functions;
- iii. The design building blocks are located as required, according to the ship designer's perspective, within a prospective or speculative configuration space and a tentative hullform;
- iv. Overall weight and space balance and necessary ship performance (e.g. powering, stability) are assessed;
- v. The configuration is then manipulated until the designer is satisfied with both configurational and naval architecture balance;

- vi. Decomposition of building blocks to ever greater levels of detail is undertaken as required, and balance and performance assessments are maintained at the appropriate level [Andrews et al. 2012 a].

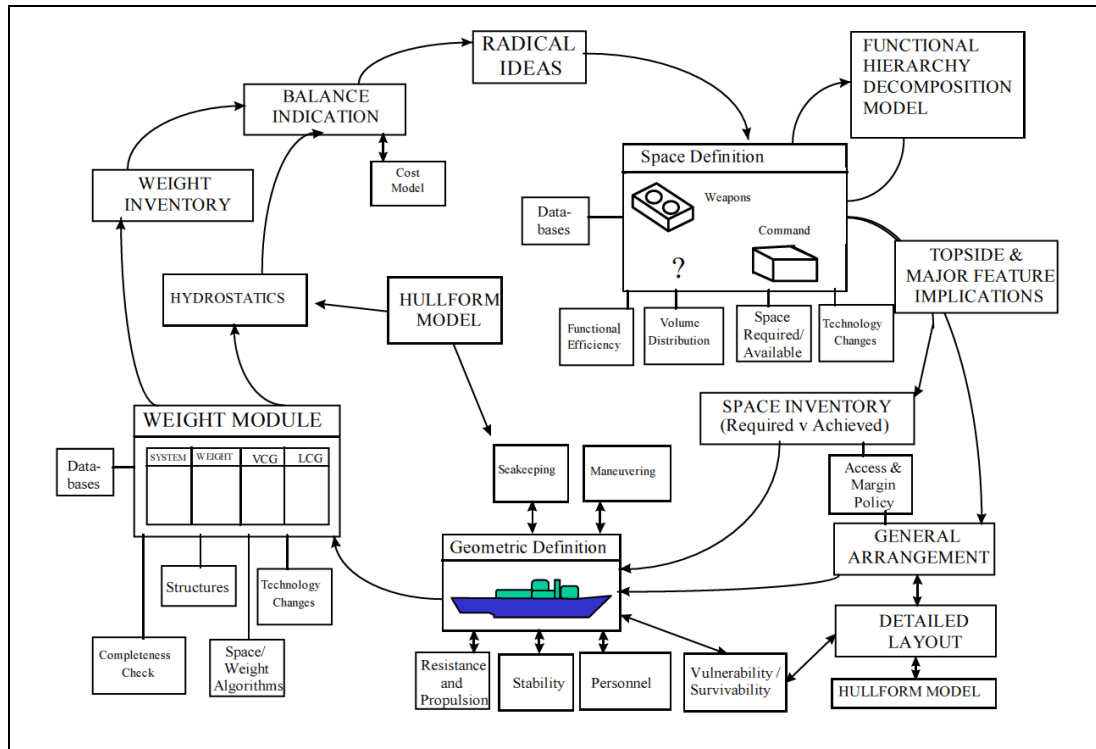


Figure 18: An overall summary of the UCL DBB approach applied on surface ship [Andrews and Dicks, 1997]

Table 6 shows the specific design steps in the DBB approach, where starting from a very broad and incomplete set of major (style) choices and moving to a reasonably detailed compartments allocation. These main steps were exemplified by Andrews and Pawling (2006) for a trimaran solution to the U.S. Navy LCS fixed requirements. As the ship design progresses, the ship designer has to assess whether they are satisfied with the resultant configuration and has achieved sufficient naval architectural balance (i.e. essentially hydrostatics and powering) [Andrews and Dicks, 1997]. It is up to the designer to decide what changes might be necessary, in order to achieve balance and meet the evolving requirements set that emerges through the requirement elucidation process [Andrews, 2003 b, 2011].

Design Preparation
Selection of Design Style
Topside and Major Feature Design Phase
Design Space Creation
Weapons and Sensors Placement
Engine and Machinery Compartment Placement
Aircraft Systems Sizing and Placement
Superstructure Sizing and Placement
Super Building Block Based Design Phase
Composition of Functional Super Building Blocks
Selection of Design Algorithms
Assessment of Margin Requirements
Placement of Super Building Blocks
Design Balance and Audit
Initial Performance Analysis for Master Building Block
Building Block Based Design Phase
Decomposition of Super Building Blocks by Function
Selection of Design Algorithms
Assessment of Margins and Access Policy
Placement of Building Blocks
Design Balance and Audit
Further Performance Analysis for Master Building Block
General Arrangement Phase
Drawing Preparation

Table 6: Typical component tasks undertaken in the main DBB approach steps for a new ship design synthesis [Andrews and Dicks, 1997]

Consequently, since a mothership can be sensibly seen as a warship mainly driven by the integration of its mission-oriented spaces, it was considered that the DBB approach was necessary in any investigation of UXVs fleet implications on the design of a UXV mothership, capable of accommodating on-board and supporting the vehicles' overall operations.

2.3.5 Cost Analysis Issues for Early Stage Uninhabited Mothership Design

As part of requirements elucidation, concept design investigations are necessary to explore trade-off studies on requirements and on cost to assess affordability [Andrews, 2018]. Although cost estimation and affordability are very questionable for such a future concept of a UXV mothership, as it is dependent on the UXV technology

advances (i.e. vehicles and support systems), it is still the only yardstick in order to control requirements aspirations. The concept phase is seen to be the most crucial of the ship design phases, since that the major decisions are made, which then incur the main cost commitments, as shown in Figure 19 [Brown and Andrews, 1980]. Thus, in general the primary design choices are made, so that 70% or more of the cost implications are committed despite less than 5% of the overall expenditure being spent [Andrews et al., 2012]. Brown and Andrews (1980), described a typical concept phase for a naval ship as requiring six people for six months compared to hundreds of people for the much longer later phases of the project. However, it is difficult to make realistic cost estimates of an entirely new warship in the concept phase, due to the uncertainties and difficulties in quantifying aspects of a warship's performance and capabilities. This means there can only be a broad evaluation of the overall design success [Brown and Tupper, 1988], and thus one has to make trade-off decision on a comparative cost basis comparison between various design options with a margin of risk on the final cost outline, since incremental cost-capability insights from incremental variant can be very informative.

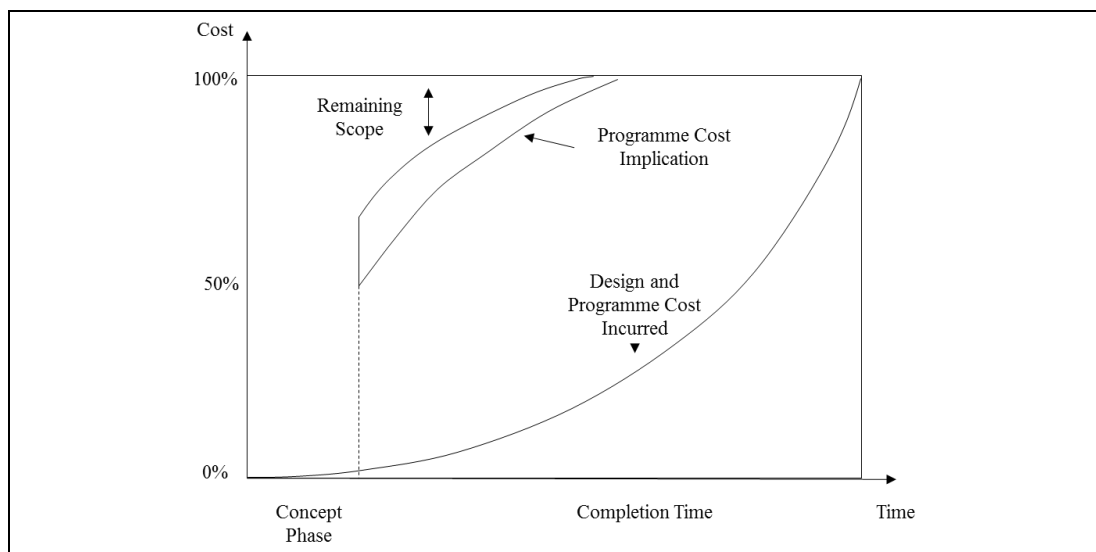


Figure 19: The importance of ESSD regarding ship cost impacts [Redrawn from Andrews et al., 1996]

The Whole Life Cost (WLC) of a warship, such as the postulated UXV mothership, can be divided into the Unit Procurement Cost (UPC), First of Class (FOC) Cost plus the Through-Life Cost (TLC), i.e. costs to operate, support and eventually dispose a ship or class of ships. The warship cost breakdown is illustrated in Figure 20 [Brown and Andrews, 1980], with expenditure across the life cycle phases.

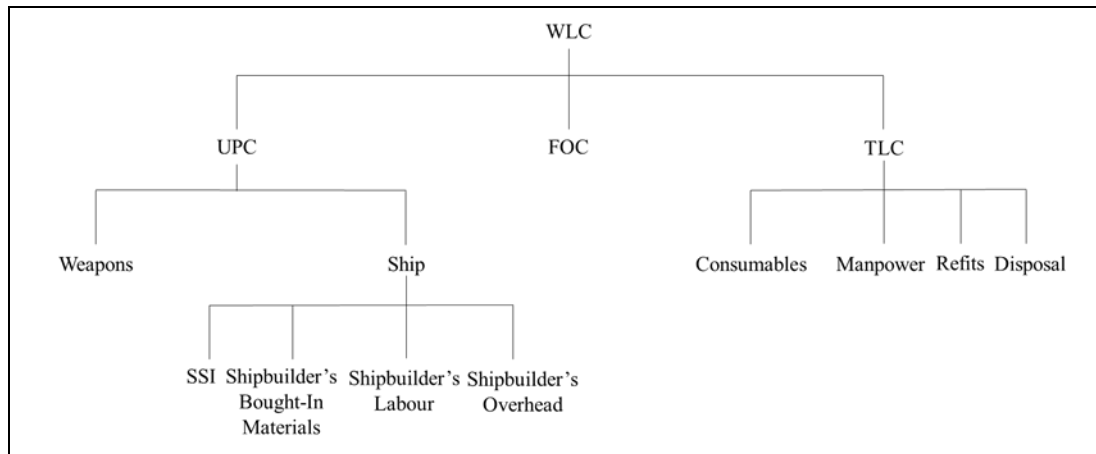


Figure 20: Breakdown of naval ship WLC [Redrawn from Brown and Andrews, 1980]

Warship UPC normally refers to the fabrication, assembly and bought in equipment and systems expenses of a warship, as briefly analysed:-

- Weapon systems and associated equipment (but not actual missiles and ordnance);
- Shipbuilder's Supplied Items (SSI) that may involve shipbuilder's subcontractors' costs, e.g. main machinery, aircraft lifts;
- Shipbuilder's bought-in materials, including paint, steel, wood and pipes;
- Shipbuilder's labour employed;
- Shipbuilder's overheads that involve costs regarding the physical security of the shipyard and the ship itself, as well as fire protection [Brown and Andrews, 1980].

Moreover, the other two constituents of WLC, i.e. FOC and TLC, include:-

- FOC refers to costs, including ship drawings and tools, producing ship and compartment models, unique tests and trials on the first ship of a class (usually spread over the overall class of ships);
- TLC is the costs incurred during the in-service period of a warship, including the costs of consumables (i.e. fuel, ordnance, stores, spares), direct crew borne for that ship personnel (i.e. including relevant portions of training, payments, pension costs), maintenance (i.e. including major refits with upgrades as well as upkeep, dockings, and essential defects that routine off ship's maintenance cost) and eventually ship's disposal [Brown and Andrews, 1980].

The cost of a new ship, such as a UXV mothership, would be a function of various distinct variables, i.e. technical, physical, managerial, financial, political and temporal [Carreyette, 1977]. In addition, economic trends and current international regulations could impact the design of a ship significantly, as for instance, fuel cost trends would affect the decision on the employed propulsion system types and subsequently the overall ship design, whereas environmental legislation might demand double hull infrastructure, for ships like in oil tankers [Gale, 2003]. Rawson (1973), argued that naval ship cost estimation is regarded as an important aspect (if not the most) in the naval ship acquisition process [Rawson, 1973], as part of a government ensuring appropriate allocation of its resources.

Ship costing is a critical part of the concept design process for naval ships, since it strongly determines the feasibility and cost-effectiveness of the programme, as well as being essential to avoid budget overruns and incurred consequences, such as performance cutbacks, prolonged time schedules and funding escalations [Gerdemann et al., 2012] [Rudius, 2012]. Warship costs have increased since the end of World War II [Brown and Andrews, 1980], resulting in an overall reduction in fleet size for most major western navies. The rising cost of warships has been caused by both economies and user-driven factors:-

- Inflation rate growth (i.e. economy-driven factor) that causes labour and equipment cost increase [Andrews and Brown, 1982] [Arena et al., 2006];
- Increased capability (i.e. user-driven factor). The need for more capable on-board features, as well as enhanced whole ship performance has inevitably led to bigger and consequently more expensive ships;
- Increased complexity of ship's capabilities (i.e. user-driven factor). Modern equipment has increasingly costly demands regarding their support from the ship. For instance, the operations of a UXVs fleet supported by a host ship would require the integration of LARSs and other equipment in the host ship design. Moreover, the need for improved performance of a warship, such as low-signature (i.e. stealth) and increased seakeeping capability, adds to the complexity of the ship and consequently its cost;
- Higher standards (i.e. owner-driven factor, e.g. government) of modern warships. Despite the trend of reductions in crew sizes leading to increased

automation in modern warships, current habitability standards are particularly demanding with regards to the on-board spaces dedicated for the personnel to live and work comfortably and safely [Andrews and Brown, 1982] [Brown and Andrews, 1980] [Brown and Tupper, 1988].

The decline in defence budgets has also led navies to adopt apparent cost reduction approaches in new warships, such as the increased employment of commercial standards in naval ships with the risk of compromising a ship's capabilities, but considered easier and cheaper to build [Arena et al., 2006]. Traditionally cost reduction approaches have been aimed at limiting the UPC rather than the TLC of a warship [Brown and Andrews, 1980]. For instance, UPC has been targeted, particularly the quantifiable aspects of S^4 and the weapon systems of a new warship have been seen as major ship cost drivers [Brown and Andrews, 1980]. However, the majority of WLC of a ship is incurred during the in-service period, i.e. TLC [Brown and Andrews, 1980], as also illustrated in Figure 21 [Page, 2011]. Rawson (1973), also argued that minimising the UPC of a warship by neglecting through-life support aspects (i.e. TLC) of a ship, is likely to entail severe difficulties in the maintenance and modernisation of the ship. It is also noteworthy that research and development costs (usually small for the ship element, but very high for weapon, sensor and C4I systems) are likely to be higher for novel ship designs, and this might apply to a UXV mothership. The increased novelty in such ship design may require large scale partial prototypes, in order to assess for instance, the integration of LARSs into the mothership design, as well as test the design under realistic service conditions [Brown and Tupper, 1988] [Andrews, 2000].

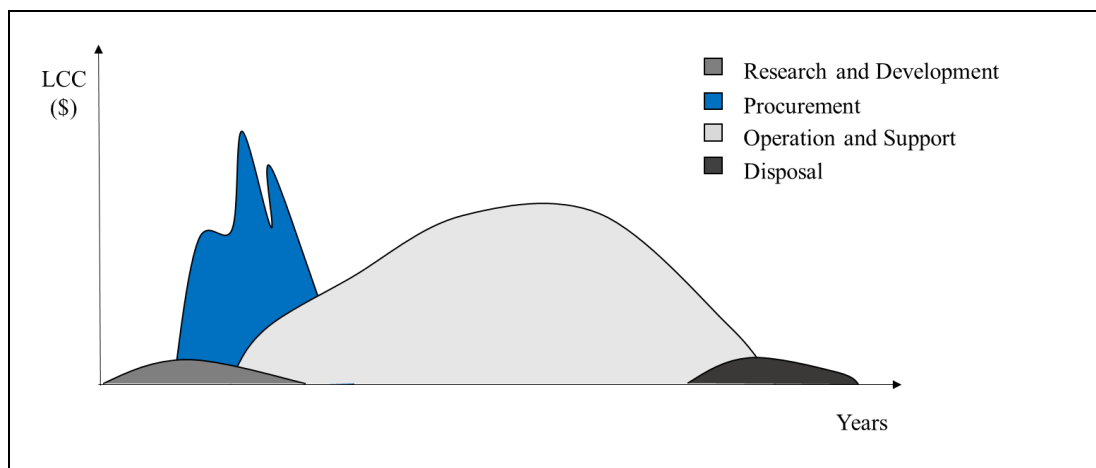


Figure 21: Ship's WLC [Redrawn from Page, 2011]

Estimating the WLC at concept enables the ESSD team to investigate the cost effects of varying the design's capability both in weapon fit and ship characteristics (e.g. style). Hence, alternative solutions and trade-off studies can be undertaken to explore cost reduction opportunities [Carreyette, 1977]. According to Depetro and Hoey (2011), there are two possible approaches to minimising a ship's WLC, to be considered during the early stages of ship design:-

- Improve the techniques and tools employed in the early stages of design, in order to facilitate a better decision-making. For instance, architectural modelling in ESSD, such as the DBB approach, facilitates proper requirements elucidation, i.e. more informed ship cost-capability studies;
- Design in a way that keeps the design fluid, i.e. flexibility is maintained throughout the design process so that any changes that may be necessary later in the process could be implemented without significant implications on the overall programme schedule and budget [Page, 2011]. For instance, as opposed to the traditional point-based design [Evans, 1959], Set-Based Design, is a design approach that enables the ship designer to keep the design fluid until the later stages of the design process, however it has yet to be applied to the design of new large complex naval vessels.

2.3.6 Measures of Operational Effectiveness for Early Stage Uninhabited Mothership Design

Cost and Operational Effectiveness Analysis (COEA) is an analytical decision-making method that brings cost into the ship design process, and aims to attain a desired level of operational effectiveness of a proposed ship design solution at a minimum possible cost [Hockberger, 1999]. A ship concept design exercise is normally driven by a set of capabilities, in order to meet operational requirements over a range of potential life cycle CONOP scenarios. Every system of a naval ship, which is part of the configuration of a larger system (i.e. warship), contributes to the overall ship capability. What ship attributes constitute being effective in meeting that capability and subsequently any measures of effectiveness could enable the ship designer to quantify whether mission effectiveness is achieved [Hockberger, 1996, 1999]. For instance, a fleet of UXVs supported by a mothership would require a set of capabilities

on the host ship, including LARSs and communications equipment, in order to achieve a desired level of operational effectiveness (i.e. mothership's support capability to make UXVs operations effective). Hence, a mothership's capability to host and support a fleet of UXVs throughout a set of mission scenarios can be seen as an indication of operational effectiveness. Consequently, it could be concluded that a mothership with greater supporting capability would lead to enhanced operational effectiveness in a mission over a less capable option.

Operational effectiveness is usually seen as a matter of whether a ship can do what has been designed for inside the theatre of operations. It is a function of what capabilities and characteristics are required in a new naval ship that contribute to the operational effectiveness of the system. According to the judgement of the concept team and naval staff, for a range of alternative concept ship designs, an overall balance between mission effectiveness and cost of a new ship can be investigated. What COEA seeks to accomplish is not just low cost or high effectiveness, but a balanced cost-effectiveness ship solution, i.e. a balance between what a new naval ship is capable of doing in a range of CONOPs scenarios and the cost that must be invested to obtain that level of performance. Such information can be demonstrated graphically, as shown in Figure 22, with each alternative represented as a point with its distinct cost and effectiveness coordinates, assisting thus the decision-making process at the infancy of ship design process [Hockberger, 1996, 1999]. Desired options could be seen as those lying on the Pareto front and particularly at any significant "knee" in the Pareto Front curve. According to this, the so called "optimum" solutions are those where, the state of resources allocation from which it is not possible to reallocate in order to make any individual criterion better without making at least one preference criterion worse, i.e. those options which with the same amount of expenditure could result in higher measures of operational effectiveness [Deb, 2001]. It is also essential that the decision makers need to know how reliable those estimates are (i.e. the area of risk), in order to develop a holistic view of the alternative design options [Hockberger, 1996].

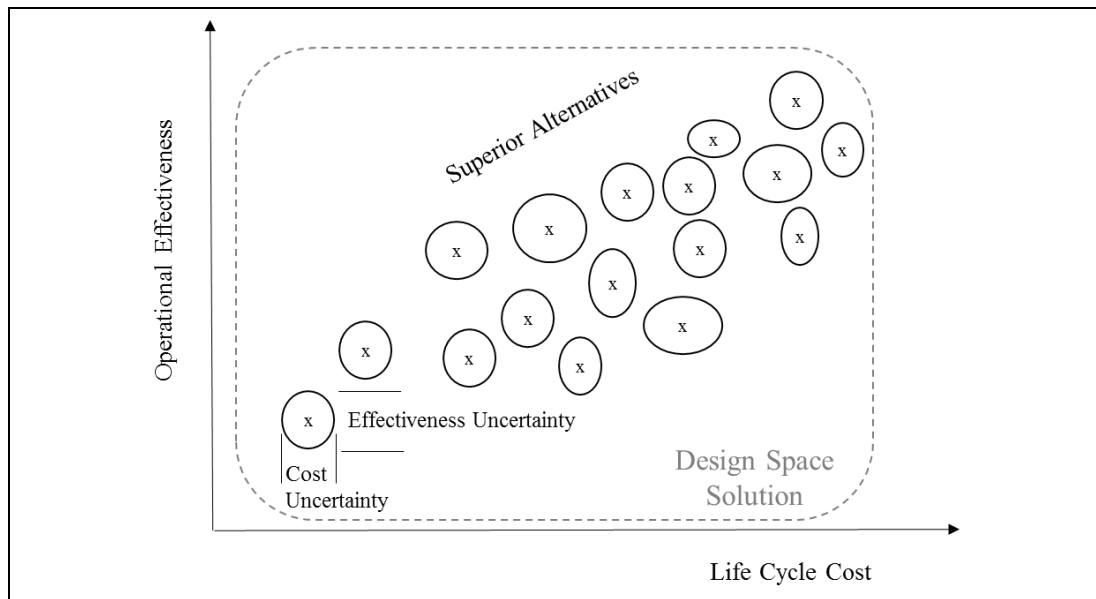


Figure 22: COEA score of alternative ship concepts [Modified from Hockberger, 1996]

Every aspect of performance that is provided in a ship (i.e. measures of performance) is likely to have some potential for contributing to the successful accomplishment of a mission (i.e. measure of effectiveness). Measure of performance quantify attributes of a physical system's behaviour as a consequence of the particular physical configuration. By contrast, measures of effectiveness (i.e. operational) are inherent in a mission and external to a ship design. They are expressions of what a specific engagement requires, irrespective of the capabilities (i.e. measures of performance) a particular ship concept may bring into that engagement, i.e. metrics of defining the degree of effectiveness reached in attaining a predetermined requirement. Normally, measures of effectiveness are defined based on a given mission's objectives. The ship's effectiveness (i.e. measures of performance) has to do with the change in a military situation (i.e. measure of effectiveness) that results from its involvement in the engagement. Therefore, the measures of performance are inputs to an engagement (i.e. mission), whereas the measures of effectiveness are the outputs [Hockberger, 1996]. However, Brown and Tupper (1989) emphasised that it is challenging to quantify many measures of a ship's performance (e.g. survivability and adaptability), as well as it is difficult to define in number the operational effectiveness of any conceivable mission. To this extent, Keeney (1981), proposed the use of "Proxy" measures (i.e. indirect) that do not directly measure an objective (i.e. mission accomplishment), but can relate to the degree to which an objective is attained.

Therefore, given the fact that it is not possible to predict all potential missions a future UXV mothership is likely to be involved throughout its lifecycle, as well as the difficulties in obtaining measures of operational effectiveness for any possible mission scenario, then more generic/indirect quantifiable measures that are non-mission reliant can be used instead. For a UXV mothership, measures of performance quantifying the LAR capability of the ship could be seen as meaningful proxy measures. Since a potential naval mission commences with the deployment of a UXVs fleet and terminates with the retrieval of the fleet, then from the ship's perspective, the better the LAR capability of a UXV mothership is, the more effectively a mission can be accomplished.

COEA is not suitable for providing absolute values of cost and effectiveness of potential ship solutions, but enables the ship designer to compare numerous ship design options on a cost-effectiveness basis and gain insights. The ship designer could either compare ship variations by applying incremental design changes to a baseline ship design, or produce completely different design options (i.e. step design changes). The process adopted for developing a COEA has been summarised for the Type 26 Frigate as follows [Randles, 2012]:-

- The potential mission bay configuration options have been developed to a sufficient detail level;
- These options have been integrated and further worked up in the context of the whole ship, in order to provide balanced design solutions. Variations of mission bay configurations result in either an increase or decrease of the overall ship size;
- The cost of each ship design solution was evaluated by employing appropriate cost models (i.e. "ballpark" UPC);
- The cost estimates were then plotted against selected operational effectiveness criteria achieved from each aforementioned ship design option.

The above adopted process to assess and compare Type 26 Frigate proposed configurations can be seen as similar to the decision analysis process (i.e. structuring decision problems) suggested by Keeney (1982). It is noteworthy that attention should be given in identifying and structuring the likely objectives for a new design project (i.e. as suggested through requirements elucidation process), as this would contribute

towards identifying the required equipment and systems (i.e. measures of performance) and their capability to successfully accomplish a set of missions and achieve a favourable missions outcome (i.e. measure of effectiveness).

Such a cost-effectiveness approach could be also adopted for the comparison of potential mothership design options that are seen as a means of supporting the operations of a UXVs fleet. For the purpose of this novel research topic, which can be seen as "Pre-Concept", COEA cannot be precisely followed, but partially given the immaturity of the fast developing technologies associated with UXVs and potential usage, plus specific issues, such as UXV LARSs.

2.4 Conclusion from the State of the Art Review

Western navies are now starting to incorporate UXVs as a means of a more effective way to accomplish a number of missions. The deployment of UXVs also aims to protect naval forces from the immediate risks in the theatre of operations, thus distancing personnel involved from harm's way. A surface vessel is envisioned to operate as a mothership that would be able to host a significant number of UXVs (unlike the U.S. LCS and U.K. Frigate Type 26), launch and recover them, as well as support their operations throughout their deployment. Current vessels can accommodate and support only a restricted number of UXVs, deployed in naval missions, including ISR and MCM. Consequently, a flexible fleet-type UXVs capability that can be deployed in naval warfare and remotely supported by a mother vessel is seen as a new concept for Western navies.

Consideration to date of the design of a ship that would be able to carry and support the overall operations of a number of UXVs has been limited to CONOPs studies. CONOPs studies, commonly performed by people with mission and operations related expertise, can contribute to the estimation of the UXVs fleet composition, i.e. number and type of UXVs, that is required to bring distinct capabilities into the theatre of operations for a particular set of predefined naval scenarios. However, an OA assessment that is restricted only to the study of CONOPs scenarios is seen to be insufficient to achieve a complete and thorough mothership solution. This is because such studies do not take into account any potential issues regarding the physical impact of a fleet of UXVs on the design of an equivalent mothership (i.e. appropriate equipment and systems). Besides the aforementioned direct impacts that a UXVs fleet has on a mothership, other indirect implications involve any complement and on-board services (e.g. electrical power) demands in order for the mothership to be capable of hosting and supporting a fleet of UXVs throughout its operations. Another issue of significant importance is packaging the required features into a hull, in order to enable the mothership to deliver its primary UXV support function.

Any scenario of operating uninhabited assets supported by the presence of a mothership would be multifaceted. Many of these operational aspects have been given attention to date (see Sub-Sections 2.2.3 and 2.2.4). Specifically:-

- i. LAURA project investigation regarding LAR and LARSs of USVs and UUVs from surface ships, as well as related sea state considerations (i.e. seakeeping assessments) [Knight, 2013];
- ii. Exploration of automated refuel and ordnance on-station exploration and suggestions [Galway, 2008 a][Lebans et al., 2012] [Mullens et al., 2004] [Petersen et al., 2012, 2015];
- iii. UXVs' C3 platform, i.e. "FORCEnet" [Committee on Autonomous Vehicles in Support of Naval Operations, 2005].

However, the development of a rational scheme at concept phase able to provide insights regarding the impact of the overall operations of a UXVs fleet on the design of a mothership (i.e. physical impacts and integration issues) does not currently exist. Given the necessary ability of a mothership to host and support a UXVs fleet would have implications on its size, configuration and performance, the lack of a numerical and structured evaluation approach appropriate to capture such impacts at ESSD means future planning and decision-making analysis is currently significantly limited. Given the nature of UXVs technology is immature, the evolution of upcoming UXVs and their related on-board a mothership support systems, such as LAR equipment, particularly for such a number of vehicles (i.e. fleet scenario), cannot be fully addressed. Furthermore, such systems have normally been bespoke, i.e. customisable, due to the fact that their functions depend on the operated UXV types. Consequently, given these uncertainties, any potential physical demands the UXVs might have on a mothership are likely to be speculative.

There was therefore seen to be a need for a novel OA approach that could couple the information resulted from CONOPs studies with the investigation and identification of any potential physical impacts of a fleet of uninhabited assets on the design of a mothership. CONOPs studies are not a part of this thesis and are only speculative in terms of potential UXVs fleet compositions. Consequently, it was seen worthwhile to consider the resulted design issues regarding integrating the various ship components into a vessel able to meet the UXVs fleet capability requirements. Since warships are architecturally driven, the investigation of the implications of a fleet of UXVs on the design of a mothership in the early design stages, would be facilitated by an

architectural-oriented ship design approach, such as DBB. Such a ship design approach would allow:-

- i. The demonstration of potential mothership solutions;
- ii. The investigation of possible issues regarding the integration of the required facilities into the mothership design/unit, since such issues are architecturally driven/identifiable and not wholly numerical defined;
- iii. The results of sufficient naval architecture analyses would indicate the type of balanced mothership solutions (at a concept level of definition) likely for a significant fleet of UXVs.

Consequently, a more holistic approach, which puts together OA studies with architecturally-centred ship design tools, would be necessary to consider a more comprehensive set of mothership options. Given significant decisions are made at concept phase on which the subsequent detailed ship design is based, the ship designer can apply the best approach possible to address any emerging problems with regards to the implications of a fleet of UXVs into the design of a mothership and subsequently be in position to make more informed decisions. This can be achieved with the use of an approach able to appropriately model the interaction between the overall operations of a UXVs fleet and the design of the equivalent mothership. Such an approach would firstly assist in assessing the implications of appropriate ship functional requirements (i.e. LARSs, C3 and stowage), including any potential integration issues into a ship entity. Secondly, besides costing of possible ship options, it is desirable that quantifiable measures of effectiveness (direct or indirect, i.e. proxy) could result from such an approach, which would then equip the naval architect with a framework to compare various mothership solutions in terms of their capability to support the operations of a given UXVs fleet, leading to a fuller COEA. Taking the above into consideration, a more holistic mothership design approach that engages OA and ship design tools could contribute to early mothership investigations to identify potential ship design drivers, which might otherwise be treated as secondary issues at later design stages, and thus lead to more believable, coherent and revelatory mothership design solutions.

Chapter 3: Development of an Evaluation Approach to Assess the Impact of a Fleet of Uninhabited Vehicles on the Design of a Mothership

3.1 Introduction

This chapter, consisting of seven sections, focuses on the development of a new quantitative evaluation approach proposed as part of this research to enable the investigation of the demands of a fleet of UXVs on the mothership. This approach was published in the International Conference on Computer Applications in Shipbuilding (ICCAS) 2017 in Singapore. The published paper is attached in Appendix 5. When presented at 2017 ICCAS Conference, this approach was generally treated positively with potential to investigating the impact of supporting a fleet of UXVs on the design of a mothership.

The main difficulty of an early consideration of the implications of a fleet of UXVs on the design of a naval ship, that would act as a host and support ship, have been outlined in Section 2.4. This concluded that to bring consideration of such implications into the early design stages, an evaluation approach should:-

- Include comprehensive OA studies that besides defining and assessing a UXVs fleet composition, should also address the physical implications of the vehicles and their associated support systems on the ship;
- Take advantage of architecturally-centred ESSD approach, such as that using DBBs to identify and take into account the configurationally driven issues, such as the potential integration aspects of incorporating a UXVs fleet into a mothership;
- Quantify direct or indirect (i.e. proxy) operational evaluation measures that could provide the basis for COEA comparative studies.

The first section provides a general description of the evaluation approach adopted for the investigation of the impact of a UXVs fleet on the design of a mothership. This is followed by investigating potential methods for such an approach. The second section outlines the mathematical method used in the proposed approach, also explaining why

the method was selected. The adopted method is a mathematical tool that allows the naval architect to have a more holistic view of the interactions between a mothership and the overall operations of a fleet of UXVs that it would support. The tool is based on Queueing Theory (QT), can emulate the operations of a fleet of UXVs through considering the facilities required by the mothership to support the uninhabited assets. The third section discusses how the proposed evaluation approach can be embedded within an architecturally-oriented concept ship design tool, such as one utilising the DBB approach. The following section addresses verification and validation assessment of the proposed approach, followed by highlighting the advantages and disadvantages of using simulation techniques as an alternative to model queueing networks. The sixth section briefly describes the basis behind the UCL DRC's ongoing development of a new ship concept design software and the current status of the work at UCL on this, employed along with UCL costing tool for the subsequent ship design and cost analysis studies. The chapter concludes with an outline of the research proposal. This section provides a detailed explanation of how the three principal tools of a QT mathematical tool, the UCL concept ship design tool and the UCL ship costing method are proposed to investigate and gain insights on the UXVs' implications for a naval ship at ESSD. Since most of the major design decisions are made in the concept phase, key design drivers for a UXV mothership need to be identified. Therefore this justifies the proposed approach in obtaining a more appropriate/holistic mothership design approach.

3.2 A Proposed Approach to Investigate the Impact of the Operations of a Fleet of Uninhabited Vehicles on the Design of a Mothership

For an indicative design of a mothership of UXVs, the likely operations of that fleet of UXVs have to be examined. These speculative operations can be used to identify any potential interactions between the UXVs and the mothership for a given mission scenario, in order to inform the initial sizing of a mothership's support systems and spaces in the mission bay(s), and subsequently the overall mothership. A comprehensive list of operations of UXVs during a mission are presented in Table 7. To avoid confusion between the overall operations of UXVs and the term of operations normally used to describe potential mission scenarios, the UXV operations are differentiated by the term "tasks".

UXV Tasks	
On-Board Mothership Tasks	Off-Board Mothership Tasks
Quick Pre-Mission Checks	Theatre of Operations
Mission Bay Handling (i.e. internal)	Mission-related activities
Launch	
Recovery	UXVs Network Support in Mission
Troubleshooting, Repair and Maintenance	Refuelling and Recharging On-Station
Refuelling and Recharging	Ordnance On-Station
Rearming	C3
Stowage	

Table 7: Comprehensive list of overall UXV tasks supported by a mothership

The likely tasks of a fleet of UXVs supported by a mothership, as listed in Table 7, could be represented by a number of sequential interconnected nodes forming a network system, as shown in Figure 23. Each node at the network system represents a task from the list of UXV tasks in Table 7, connected to others via links (i.e. arcs or connectors) to form a path. Consequently, the network system can represent a defined number of physical and discrete items, i.e. UXVs, which flow through each node of the system in a given sequence of activities, in order to perform appropriate tasks, in the context of the overall UXVs operations.

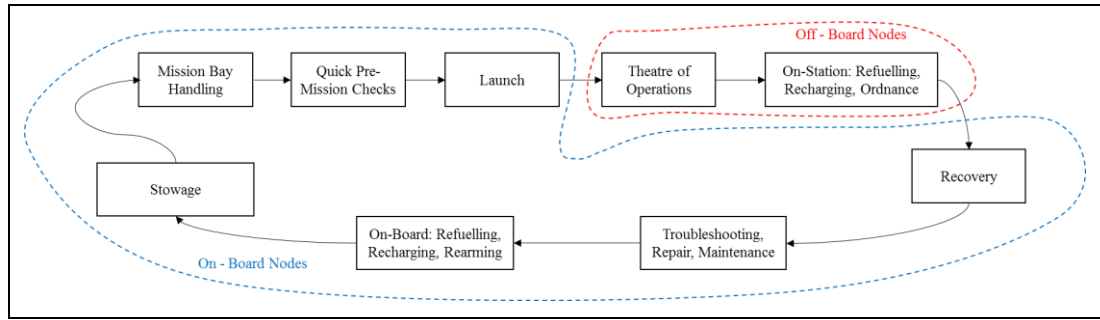


Figure 23: Physical network of UXV tasks

During naval operations once the vehicles are launched towards the theatre of operations, the deployed fleet of UXVs is expected to be controlled and coordinated through a C3 infrastructure likely to be on the mothership. C3 systems are the key to manage the battlespace, exploit information and thus support a fleet of UXVs employed in accomplishing appropriate activities within certain naval missions. Effective C3 infrastructure on both the mothership and the deployed UXVs fleet, including any relevant payload, such as radars, sensors and weapon systems, can assure situational awareness, as well as providing the ability to control the fleet of UXVs at all necessary levels of command. Consequently, C3 systems act as decision support resources, where all the relevant information is exchanged and tracked between a mothership and the deployed fleet of UXVs. Besides the actual physical impacts these systems are likely to have on the mothership and the uninhabited vehicles due to the demands of the relevant equipment, these are also likely to have further on-board service implications (i.e. power and chill water requirements) and complement demands for the mothership [Committee on Autonomous Vehicles in Support of Naval Operations, 2005].

C3 systems could be also seen as a network of interconnected nodes, formed by the distributed naval forces, i.e. UXVs fleet and the mothership, where each node represents a single asset of the overall system. Non-physical and non-discrete items (i.e. data) flow in the network system from the distributed naval forces (i.e. UXVs and the support mothership) in the theatre of operations. Therefore, data and information are exchanged and processed through each node in a set of possible sequences, given that the information exchange path is strongly dependent not only on the mission itself, but also on the situation awareness at any time during a mission. An example of such a network can be seen in Figure 24. FORCEnet, mentioned in Sub-Section 2.2.3, which is a communications platform developed by the U.S. Navy, contributes to

communication, information tracking and monitoring, as part of the C2 for a network of distributed UXVs [Committee on Autonomous Vehicles in Support of Naval Operations, 2005]. Although such networks are likely to be important in managing the exchanged information and subsequently coordinating the overall mission, they are not directly relevant in modelling physical interfaces between a fleet of UXVs and the mothership. However, the ship designer has to take into account any C3 equipment, including sensors, radar, antennae, satellite systems and other support systems and services, in the early stages of a mothership design, since these have demands on the ship (e.g. spaces, ship services, personnel) and should be integrated into a UXV mothership.

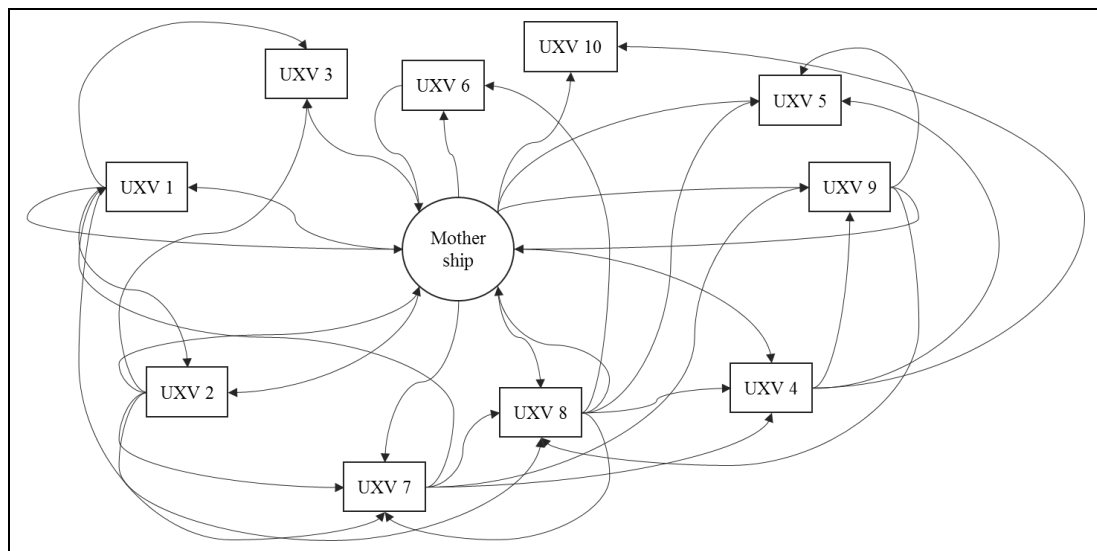


Figure 24: Example of a C3 network system of a fleet of UXVs and a mothership

It can be concluded that the overall tasks of a fleet of UXVs during a mission scenario are likely to reveal the relevant functional requirements for a mothership to support the uninhabited assets. This then gives the equipment and systems demands (i.e. facilities/resources) for the ship to host a given UXVs fleet on-board and support them during operations. Furthermore, the performance of a mothership should meet criteria, such as those shown in Table 8, which could indirectly indicate operational effectiveness. Since operational effectiveness criteria are difficult to quantify, proxy indicators can be used. These would be expected to be identified and set by the ESSD team working with mission specialists during the requirements elucidation process in the early design stages.

Proxy Operational Effectiveness Criteria	Considerations	Potential Solutions
Safe LAR Operations	Sea State	LAR Method Performance
		Operational Availability of LAR Method (e.g. crantage, stern ramp)
		LARS Technology (i.e. LAR specs, e.g. motion compensating crantage)
		Mothership Performance
		Mothership Stability
		Mothership Seakeeping
		Mothership Speed
	Structural Loads	LAR Method
		LARS Technology (i.e. LAR specs, i.e. crantage deadweight)
		Mothership
		Mothership Structural Analysis (e.g. FEA of structural interfaces LARS-ship)
LAR Length	Duration	LAR Method (e.g. stern ramp is normally a faster means of LAR compared to side crantage)
		LARS Technology (i.e. LAR specs, e.g. motion compensating crantage LARSs allow a faster means of LAR in higher sea state compared to conventional cranes)
		Number of LARSs

Table 8: List of potential proxy operational effectiveness criteria, considerations and possible options to meet these in the design of a UXV mothership

OR practitioners have readily applied network models for various problems, including optimising considerations and resource management and planning. Typical components of networks listed in Figure 25 [Hillier and Lieberman, 2001].

Nodes	Arcs	Flow
Intersections	Roads	Vehicles
Airports	Air lanes	Aircraft
Switching points	Wires, channels	Messages
Pumping stations	Pipes	Fluids
Work centers	Materials-handling routes	Jobs

Figure 25: Typical components of networks [Hillier and Lieberman, 2001]

The fundamental concepts of network-flow models are considered to be threefold, where the first two categories seek the best way to achieve a goal, while the third is used to consider resources allocation, to improve a service being provided:-

- Distance networks: Used for applications where the solution is achieved by picking a sequence of activities to "optimise" a desirable objective function [Garcia-Diaz et al., 2011]. The objective of such a network model is to find the shortest path, i.e. minimum total distance path, from the origin to destination. Other applications of this problem do not only involve minimising the distance travelled, but instead the arcs could represent other activities, so selecting the path would correspond to the best sequence of activities. Thus, the objective might be to define the sequence of activities that minimise the total cost or time, such in a design transportation network minimising the total cost of providing the road or rail lines [Hillier and Lieberman, 2001];
- Capacitated networks: Used for applications where the solution is to achieve a maximum flow per unit time along an arc path from the origin (i.e. source) to the destination (i.e. sink) [Garcia-Diaz et al., 2011]. For instance, maximising the flow through a company's distribution network system from its factories (i.e. sources) to retail points (i.e. sinks) [Hillier and Lieberman, 2001];
- Queueing networks: Used for applications with a network of interconnected activities, where the completion of a task is followed by another predefined task, structured in the form of a pathway. In such networks the overall process is achieved through a number of sub-processes (i.e. nodes), where an appropriate (and different) service is provided at each of the nodes. Such networks can be analysed to assess performance measures. Thus, the service provided at each node is assessed in terms of the time required to provide the appropriate service and the length of the queue formed [Hillier and Lieberman, 2001]. For instance, a network system, where several different service facilities might be required, could represent the overall service provided at a bank branch, where customers might need to get served by different cashiers in a predefined sequence, hence customers need to queue up at one cashier to get served before they can proceed and queue up for the next cashier and so on. QT is a prominent analytical technique used in OR, with queueing networks being in widespread use, as well as there is active ongoing research. A network

based on queueing network approach can be either numerically modelled or simulated by developing computer programs in order to obtain performance measures.

The first two categories of network models, i.e. distance and capacitated networks, were not seen to be applicable in analysing a representative fleet of UXVs operated by a mothership, since these models cannot address the physical impacts of a UXVs fleet on the design of a mothership. However, a queueing network model was seen to be able to capture the likely implications of uninhabited assets on a host ship, since the on-board ship systems and equipment can be represented as service facilities providing an appropriate service to the UXVs. This is considered further in the following section.

3.3 Application of Queueing Theory in Modelling a Network System that Represents a Fleet of Uninhabited Vehicles Supported by a Mothership

3.3.1 Introduction to Queueing Theory

The means, adopted in this research, to model a network of UXVs operations supported by the presence of a mothership is QT. It is a mathematical representation of waiting lines, i.e. queues. Appropriate performance measures from the application of QT can be used in meaningful decision-making activities. Designing a queueing system normally involves making one or a combination of decisions about what type and number of resources should be allocated, in order to provide the relevant service within certain time limitations [Hillier and Lieberman, 2001]. Since such problems in decision-making can be formulated in terms of a queueing model, this becomes a powerful tool capable of providing valuable information for scheduling and designing queueing systems based on evaluating the system's performance [Bhat, 2008].

QT models are mathematical models of real life systems. They have been beneficially employed in both the manufacturing and service domains, including production lines, transport systems (e.g. airports, road networks), telecommunications and the internals of computers [Bhat, 2008] [Suri et al., 2007]. Such models can be constructed to predict/evaluate the performance of a queueing network system and also contribute to understanding the behaviour of such systems. The performance measures describe the queue length (i.e. number of customers waiting in the queue) and the total time for the completion of the particular service (i.e. actual service time plus the waiting time) [Bhat, 2008]. A recently published application of QT describes modelling (i.e. simulation rather than numerical modelling) of the road network system between Maidstone and Dover (i.e. M20/A20 motorway), in order to assess the congestion impact on the M20/A20 caused by a potential check time increase at Port of Dover and Eurotunnel (the Folkestone entrance). The congestion impact has been assessed by quantifying the queue formation and travel time. The results showed that even 1 or 2 minutes of extra check times at the two early points would result in a significant increase of congestion, with queues extending up to 30 miles from Dover/Eurotunnel

towards Maidstone and travel time approaching 5 hours in peak hours, which currently takes approximately 1 hour [Han et al., 2018].

Queueing systems can represent systems that provide a particular service and may model any system where the arriving customers look for a service of some kind and depart once the appropriate service has been provided [Bose, 2002]. A simple queueing model can be described by two distinct areas: the waiting and the service area, as shown in Figure 26, where a fleet of UXVs is the example. Such a model may be used to represent a number of customers (i.e. UXVs) that arrive at a waiting area, where they queue up if all servers are busy and eventually get served from an available server (i.e. facility) and thereafter leave when the required service (such as the service activities listed as UXVs tasks in Table 7) has been obtained. It is relevant that both the service and waiting areas entail requirements for physical space. These space demands depend on the type and number of available service facilities at the node service area, whereas for the node queueing area the space needs are defined by the estimation of the queue length. This is a function of:-

- i. The number of customers to be served at the particular service facility;
- ii. The number of service facilities available;
- iii. The actual service time (i.e. type) of the specific service facility.



Figure 26: Simple queueing model [Adapted from Bose, 2002]

It is regarded as quite common for customers to require service from more than one facility. Usually in real-world systems, customers can be served by more than one node, where the nodes (i.e. service facilities) are arranged in a network structure. This network structure is considered as a collection of service nodes, which are interconnected with a path/route [Robertazzi, 1994]. Once a customer is served at one node, it can then either leave the network or join another service node, where they queue up to obtain the next appropriate service. Therefore, each node of the network

system representing UXV tasks, shown in Figure 23, can be described by a simple queueing model that, along with the other nodes, forms a queueing network of interconnected nodes.

The ideal situation can be thought of as the one where both the arrivals and service processes proceed strictly according to a prearranged procedure, thus no queue is formed in front of the service node and no queueing delays are incurred. However, in practice this is very unlikely to happen due to external factors (i.e. uncertainties), and also due to the limitations with regards to the system's capacity (i.e. availability of space and number of servers) [Bhat, 2008]. In the case of a UXV mothership, the arrival of UXVs at the service points is not likely to follow a planned schedule, due to unpredictable operational requirements, while the mothership's capacity is not infinite, since the ship is designed to accommodate a specific number UXVs and a finite amount of support systems and equipment. In addition to this, the need for a mothership to perform UXV-related tasks as quickly as possible for a potential mission scenario, within the limited ship's capacity, leads to the likelihood of formation of queues ahead of the service points.

Thus, in the occurrence of a mission, the fleet of UXVs should be able to be deployed in the theatre of operations as quickly as possible. The vehicles should be first launched from the mothership by employing LARSs. A well dock, for example, would allow the almost concurrent launching of multiple USVs when compared to side cranes or a stern ramp systems. Although different types of LAR methods might allow more vehicles to be launched at the same time than others, the limited number of LARSs on-board a mothership to serve such a big number of vehicles (i.e. fleet) is likely to cause queueing delays and queue formation. This would happen as a consequence of the vehicles piling up while waiting for an available server (i.e. LARS) to get served (i.e. launched) during the overall launching process. Besides the nature of the restricted number of launching service facilities, the urgency caused due to an imminent mission (i.e. activities do not follow a strictly scheduled plan), would also contribute to queueing ahead of the LARSs. However, any effort to schedule (i.e. control) the UXVs launching process, in order to avoid any on-board queue formations, would mean the total time to perform such controlled launching activities would be much longer. This would then be counter to the urgency of the mission, due

to the pauses imposed in the sequence of activities ahead of launching the vehicles from the ship (i.e. non-continuous launching process).

However, in the case of a node where the number of servers is always greater or equal to the maximum number of customers that seek service at this particular node, this is described as the node having an infinite server queueing discipline [Bruell and Balbo, 1821]. In such a case, none of the customers will ever experience a queueing delay at this specific node. Hence, this node's total time to serve a customer would equal the actual service time, as the waiting (i.e. queueing) time is zero. However, such an ideal scenario is unlikely to apply to in the case of a UXV mothership, given that the number of on-board facilities is restricted (i.e. ship size limitations), and also given the fleet scenario concept of this research, the number of service facilities on-board a mothership would be smaller than the number of vehicles in the fleet.

3.3.2 Application of Queueing Theory on Launch and Recovery Systems

One of the major areas of interest in investigating the tasks of a fleet of UXVs, relevant to the mothership's design, is that of LAR method chosen for a surface ship. LAR methods are the only means that would enable the launching of a number of UXVs from a mothership, to be deployed in the area of interest, and then subsequently recover them on-board. Compared to the rest of the on-board mothership support systems (i.e. C3, stowage, maintenance/workshops), the LARSs are expected to significantly affect the design of a host ship, in terms of their actual physical impacts on the ship, as well as their integration into the whole ship. Moreover, the ship's performance, including issues such as dynamic stability (i.e. seakeeping), constitutes specific ship design aspects that affect safe and successful LAR operations. However, this does not mean that other UXV tasks and their related on-board support system are not important, or that they have no impact on the ship design, but that LAR methods and the resultant on-board systems can be seen to be more important, due to the major role they play in the overall operations and also to their noticeable implications for the ship design. For instance, less conventional LARSs, such as a well dock, could be employed as a fast means of LAR, but it is likely to have significant implications on the design and performance (i.e. powering, seakeeping) of the ship, and subsequently

the ship's speed and endurance, as opposed to more conventional LARs like cranes, or stern ramps.

Different LAR methods and systems, as mentioned, can achieve significantly different LAR rates. Hence, depending on the number of vehicles to be launched (or retrieved) and the requirement for a total time to launch a given number of UXVs from a surface ship, as defined by the appropriate CONOP studies, means various LARSs need to be considered. LAR of a number of UXVs could be modelled by a queueing network, such as that in Figure 23, where the key elements are the UXVs (i.e. customers) and the appropriate LARSs (i.e. facilities). Hence, LARSs can be regarded as resources that need to be allocated on a mothership, in response to the total launching time requirements of a UXVs and the implications of such systems on the design of a host ship. A comprehensive explanation of how queueing network modelling can communicate with and feed information to ship design models, in order to obtain a more holistic mothership design approach, is provided in the following section.

3.3.3 Applying Queueing Theory in Network Modelling

A queueing system is normally described by [Bose, 2002]:-

- Interarrival time, i.e. it describes the time between arrivals at the queue;
- Service time, i.e. this describes the size (i.e. duration) of jobs undertaken at a service node;
- Number of servers at the particular service node;
- System's capacity, i.e. gives the maximum number of customers in the system, including both the ones currently being served and those waiting for service;
- Service discipline, i.e. this describes the service rule according to which the customers are selected to be served, such as FCFS (First Come First Served), or IS (Infinite Number of Servers).

There are two numerical methods described in the bibliography for modelling and analysing queueing networks, namely the Convolution algorithm and Mean Value Analysis (MVA) algorithm [Bose, 2002]. The Convolution algorithm is the more complex algorithm and consequently computationally more difficult, compared to the MVA algorithm. Its computational complexity increases rapidly with larger networks

and larger population of circulating customers (i.e. UXVs), thus such an algorithm is likely to be more susceptible to numerical accumulated errors for larger systems (i.e. numerical errors that are carried on through the sequence of calculations as indicated by the algorithm and hence accumulated by the end of the process). However, although the Convolution algorithm is more susceptible to numerical errors, the results obtained from these two algorithms do not significantly differ. This can be seen by analysing a network, such as that shown in Figure 27, where four customers circulate through the depicted network system consisting of three single server nodes. The results, also presented in Figure 27, show the throughput " λ ", which is an indication as to how fast (or slow) is the system's performance under study (i.e. measure of number of queueing and service activities per unit time) [Bose, 2002]. It can be seen from the results presented that these two algorithms give comparable results for such a simple network system.

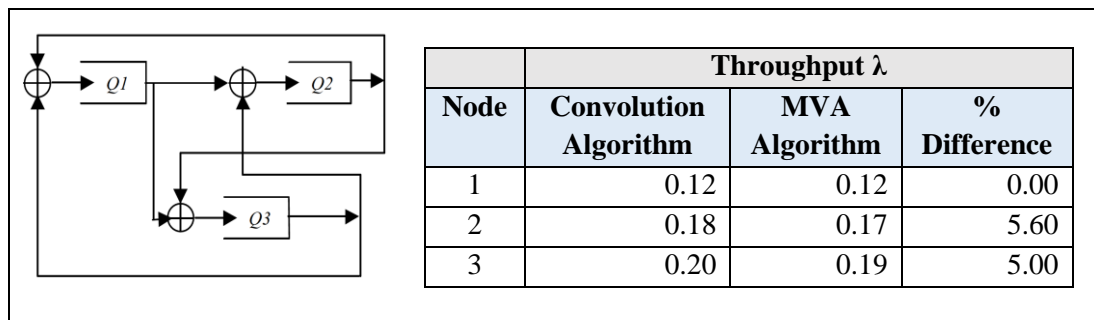


Figure 27: Comparison of Convolution algorithm and MVA [Adapted from Bose, 2002]

Modelling the behaviour of complex network systems using numerical techniques allows the comparison of alternative networks (i.e. options/solutions) efficiently, subject to the validity of the input parameters provided by the user (i.e. ship designer in this instance). Although the activities of a USVs fleet during a mission scenario can be quite complex, a queueing network system, such as that suggested in Figure 23, could capture the fundamental process of the overall UXVs fleet-mothership operations, by modelling the behaviour of the system and thus giving valuable information about the nodes' functionality from the model outputs. Therefore, such a model can indicate potential areas of difficulties, i.e. underperformance of nodes according to the designer's judgement based on potential mission related requirements (i.e. direct or proxy operational effectiveness indicators), and subsequently point out potential solutions and improvements. Consequently, given the QT capabilities on

network applications and the relevant information that can be extracted from such models for the design of a potential mothership, it was decided to model the behaviour of the proposed UXVs network of activities using the MVA algorithm. This decision was based on the relative simplicity of MVA algorithm, compared to the Convolution algorithm, and also on its proven robustness regarding the calculating measures of performance, as seen in the example of Figure 27. The MVA algorithm for modelling a queueing network system was implemented in FORTRAN, given the strong performance of the programming language in numerical problems, and also the author's relative familiarity with this language. A more comprehensive description of the MVA algorithm is provided in Appendix 6, which describes:-

- i. Equations and sequence of calculations;
- ii. Variables (i.e. information the algorithm is imported with);
- iii. Metrics that can be extracted from it (i.e. quantified measures of performance for each node in the network system).

MVA is a numerical algorithm that uses the recursive technique to obtain the transient, i.e. $m = 1, 2, \dots, M-1$ and final state, i.e. $m = M$, performance measures for each node of a network system, where M represents the number of UXVs in the fleet. For a given number of UXVs (i.e. M), these measures describe:-

- i. Node throughput, which is rate of UXVs queueing and service activities processed at a particular node per unit time;
- ii. Node processing time, which is the total time taken (i.e. actual service time plus queueing time) to serve the customers seeking a particular service;
- iii. Queue formation/length, i.e. number of customers in the queue.

For a network system consisting of k , $k = 1, 2, \dots, K$, nodes (i.e. UXV tasks), with m , $m = 1, 2, \dots, M$, customers (i.e. UXVs) present, the MVA algorithm works recursively. This means that the algorithm initiates performing the relevant calculations, by starting with zero customers in the network and incrementally calculating the performance measures of the nodes in the network system. This is done so that, as the customer population increases, by increments of one at a time, the predefined desired maximum number of customers (i.e. M) in the network is reached [Bose, 2002] [Cooper, 1981].

Figure 28, shows schematically the structure of the QT tool developed in FORTRAN, where the input parameters and the metrics the tool provides, are also described. Figure 29 gives the logic of the queueing network tool developed (the full coding produced is given in Appendix 6). The code consists of three distinct parts:-

- i. Input file, in the form of "txt" file, that describes the necessary information fed to the algorithm, i.e model inputs in Figure 28;
- ii. Actual Fortran code implementing the queueing network algorithm;
- iii. Output file, in the form of "txt" file, which provides the information resulting from analysing a queueing network, i.e. model outputs in Figure 28.

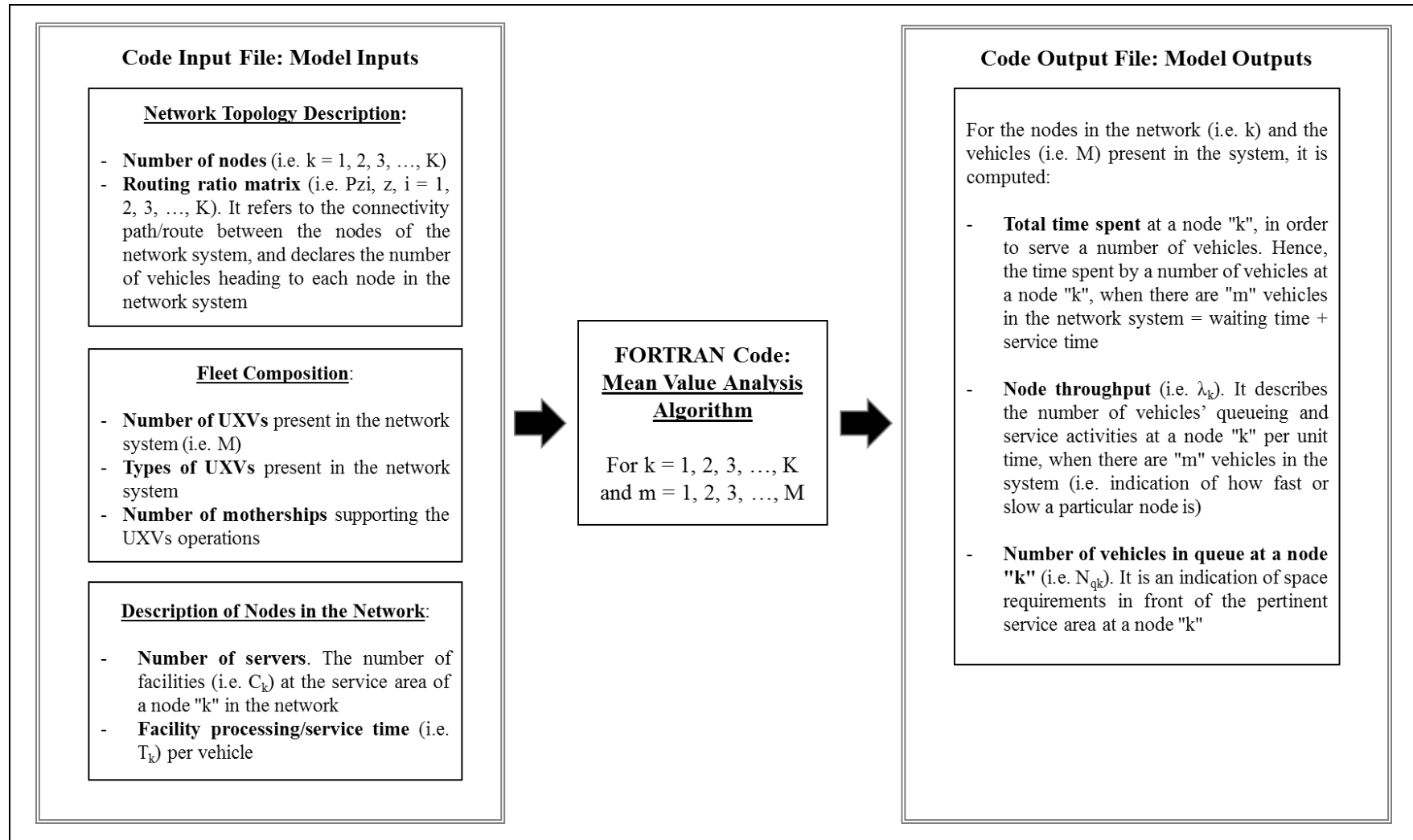


Figure 28: Structure of FORTRAN code modelling queueing networks that represent UXVs operations supported by a mothership, using the MVA algorithm

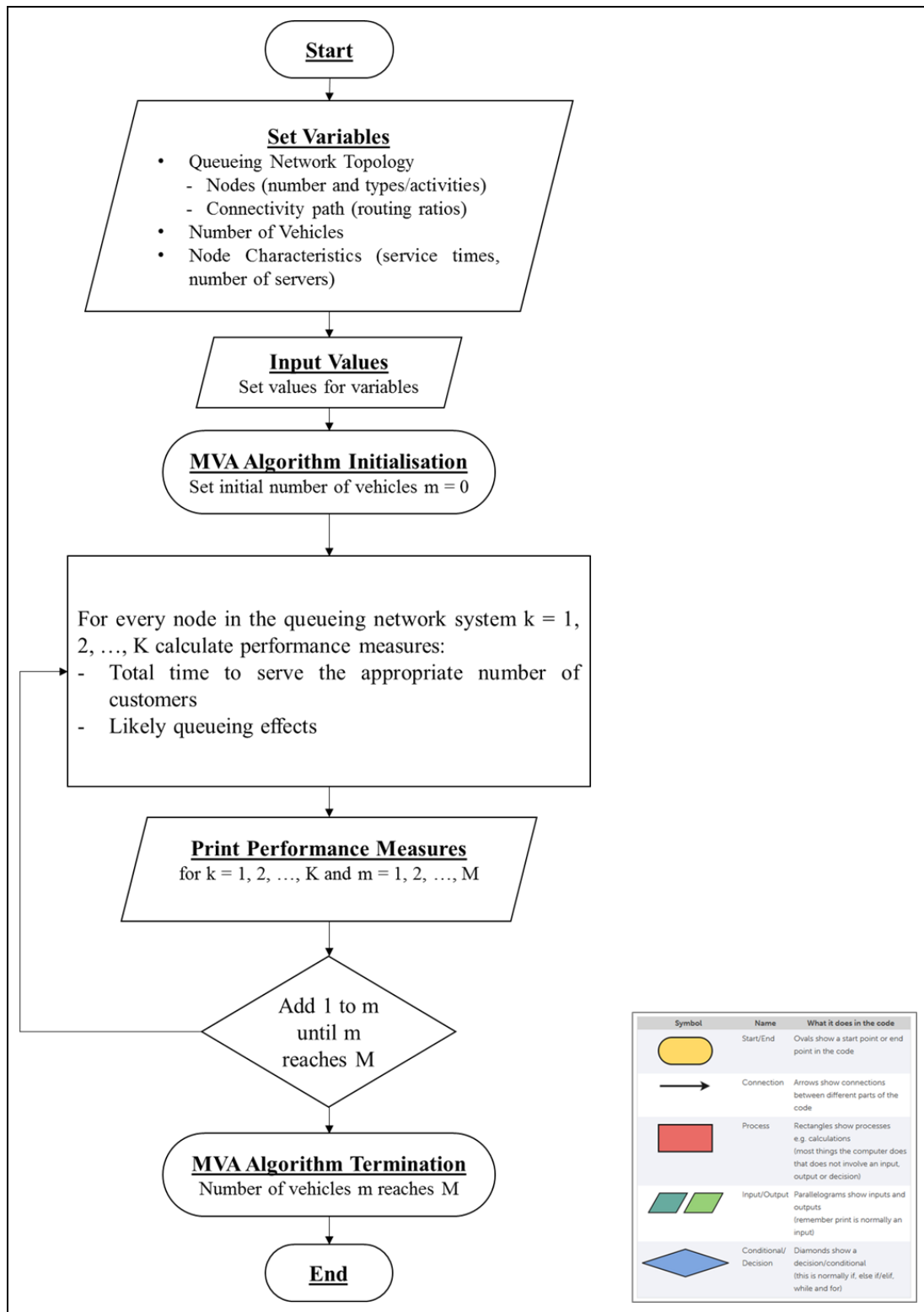


Figure 29: Flowchart of the queueing network tool developed (see Appendix 6 for actual coding)

3.4 Application of Queueing Network Tool in a Mothership Concept Design Process

3.4.1 Defining Ship Impact and Measures of Operational Effectiveness through Queueing Network Modelling

Modelling the tasks of UXVs as a queueing network is seen as a means to investigate and gain insights into the implications of potential UXVs fleet composition on the design of a mothership that is able not only to host the vehicles, but also to support their needs during a set of possible mission scenarios. Such queueing network modelling can provide support allowing the ship designer to take into account UXV-related implications on the mothership design, and enable comparison of various mothership design options, based on the resultant network measures of performance. Therefore, an architecturally-centred concept ship design tool acting with the proposed QT approach would contribute to a more holistic decision-making process.

Given that the proposed QT tool can "emulate" the on-board tasks of a given fleet of UXVs that is supported by a mother vessel, then the information extracted from the tool's application allows the naval architect to assess the performance of the relevant nodes in the network system. Such information along with the architecturally-oriented ship design modelling could contribute to the design of a more complete mothership. Thus modelling would take into account:-

- The UXV operations (i.e. mission-centred design);
- The UXV operational requirements on-board a mothership;
- Potential material solutions to meet the UXV operational requirements that have been identified;
- The physical impact on the ship and the integration of the UXVs fleet and its support systems into a ship.

The performance measures of a node in a queueing network system are provided by the QT tool as quantified metrics. These measures provide two distinct types of nodal information, namely ship-related information and behaviour-related information. Regarding the ship-related information, each node, which models a UXV activity, consists of a waiting and a service area with physical space demands. These

requirements describe the spatial needs for the queueing activities while customers pile up ahead of the server(s), and the server(s) (i.e. facility/ies) that provide the appropriate service, respectively. Hence, for the UXV activities that take place on-board a mothership, the equivalent nodes' modelled waiting and service areas represent those tasks require space requirements on-board. Such space demands, i.e. queueing spaces, equipment and support systems (i.e. servers) need to be taken into account at the early design stages, as they are likely to play a significant role (if not driving) in the mission bay sizing and layout. Consequently, an operational approach, such as that of queueing network modelling the overall UXV operations supported by a mother vessel, would inform the sizing and configuration of the mission bay(s) and subsequently the ship design characteristics.

Eaton et al. (2014) and Broadbent and Binns (2006), have also emphasised that a mission bay and subsequently a significant element of a mothership design would be the result of an operational design approach. Since the configuration of a mission bay is strongly driven by the operations/functions that take place inside it, its size cannot be defined just by a purely numerical method, but also addressed through early architectural modelling. Thus, an architecturally-centred concept ship design approach would not only enable the ship designer to size a proposed mission bay, based on the operational requirements (i.e. QT application), but also would significantly assist in identifying potential mission bay issues when integrating such mission-oriented spaces into the mothership design.

Metrics quantifying the behaviour-related information of a node can define:-

- i. The overall time required to perform an activity (e.g. LAR) requested by a number of customers (i.e. UXVs), which is a function of the actual service time (e.g. LAR time per vehicle as specified by the manufacturer for a given LARS) plus the queueing delay (i.e. time spent while queueing to obtain the appropriate requested service);
- ii. The throughput, which is an indication of how fast (or slow) a specific node's queueing and service activities are performed.

It is noteworthy that these types of metrics providing insights about nodes' behaviour could be employed as indirect measures of operational effectiveness (i.e. proxy

measures). Since the operational effectiveness achieved in a mission by the deployment of a UXVs fleet-mothership system is hard to directly define and quantify, the nodal behaviour measures that result from a queueing network analysis, could act as proxy indicators demonstrating whether a UXVs fleet-mothership system contributes (more or less) to the successful completion of an undertaken mission. Such proxy measures would not act as absolute values of mission success and subsequently would not allow the designer to directly make engineering decisions, given that there are not any published data that can define mission success thresholds and hence for the designer to assess a proposed design against.

However, these indirect measures would constitute a solid basis to provide insights about the UXVs fleet-mothership system's behaviour, analysis of ship design trends and drivers. They could also be employed to comparatively assess the potential mission success (as proxy indicators) likely from different mothership design options, which are all able, but not identically, to accommodate and support the same UXVs fleet. For instance, the capability of a ship to deploy a UXVs fleet in the area of operations as quickly as possible, and thereafter retrieve it on-board once the mission is completed, could be regarded as a measure of a successful mission. Given there are not any available specific time limitations in deploying a UXVs fleet in a theatre of operations, such criteria are seen to be fluid. This is because they would depend on the nature of the mission and the urgency to perform certain naval tasks. So the capability of a ship to deploy a UXVs fleet sooner than another mothership option could be considered as an indirect means of achieving a mission more effectively.

3.4.2 Modifications to a Mothership Design Based on Queueing Network Performance

Figure 30, shows the operational interactions between a mothership and a UXVs fleet, which can be modelled as nodes in a queueing network system representing the UXV operations supported a host ship. The equivalent on-board a ship interfaces, required to allow the performance of such functions successfully, would impact the capability of a mothership to support a UXVs fleet, as well as the ship's configuration.

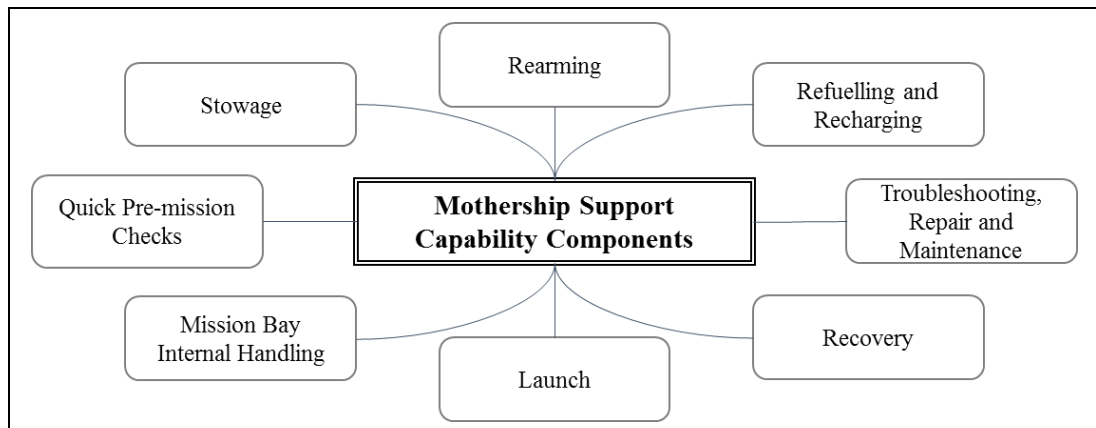


Figure 30: Mothership capability components to support on-board UXV activities

The queueing network tool allows the user to identify underperforming nodes in the network system. A node's poor performance can be captured by the tool's quantified metrics that demonstrate the formation of a long queue, restricted throughput and increased total time to serve a number of requests. Since the nodes in a queueing network model representing the on-board a mothership activities, refer to the ship's service facilities required to perform such tasks requested by the UXVs fleet, the QT tool can be then used in ESSD to apply and assess any necessary changes to proposed mothership design(s). Any radical options should be explored in the infancy of ship design process. The implementation of any type of modifications (i.e. incremental or step design changes) with regards to the on-board UXV-related service facilities are likely to have physical implications on the mothership (i.e. space demands and integration issues), and might have further implications on the personnel numbers and the ship's services with impact on ship size, configuration and performance.

The QT tool enables the ship designer to apply required modifications to its inputs in order to achieve enhanced performance parameters, should the proposed UXV-mothership queueing network not meet the criteria in terms of the relevant support capability. It is to the designer's judgement to determine the necessity and the extent of possible alterations to underperforming nodes, likely then to result in mothership design modifications. For example, the incorporation of a greater number of LAR facilities on-board a mothership, in order to enhance the behaviour of the equivalent LAR queueing network nodes, i.e. faster LAR of a given UXVs fleet, could be monitored via the metrics extracted from the model. An enhanced LAR ship capability results in a decreased length of queue formation ahead of the LARSs, increased throughputs and shorter total times spent by the vehicles at these facilities. However,

an improvement in a mothership's LAR capability might come at the expense of potential ship design implications and likely increase in ship's cost. However, as already discussed in Sub-Section 3.4.1, given the absence of threshold values to define successful LAR processes that could thereafter contribute to an increased mission effectiveness (i.e. proxy operational effectiveness measure), any modifications to a potential mothership design are purely for the purpose of demonstrating the tools' capabilities. Thus, this research, by a series of ship design applications and conducting comparative ship design studies on a COEA basis (i.e. cost-proxy operational effectiveness comparison), will demonstrate the QT tool, the concept ship design tool and the ship costing algorithm.

For a given number of customers to be served at a node of a queueing network, the behaviour of the node could be improved by enhancing the performance of its service area. To achieve this, the service rate of the particular node could be improved by either allocating more servers of an identical type, or by employing different types of servers that provide the same service in a lower processing time. It is noteworthy that the service time per vehicle for a certain type of service facility is determined by the specifications for which the particular equipment has been designed. Hence, both options would enhance a poorly performing node causing long queueing delays. The proposed queueing network model would allow the ship designer to alter the input parameters of the model, in order to assess their impact on the metrics extracted from it. Therefore, based on the extracted metrics, network variations would enable the ship designer to assess whether the performance of the resultant network is satisfactory. This then could contribute to a more holistic decision-making process with regards to the mothership design, as schematically shown in Figure 31. The decision-making illustrated in Figure 31 describes the proposed sequence of actions followed by a designer when assessing the performance of a UXV-mothership queueing network. Whether the performance of the network system is seen satisfactory, then the proposed mix of service facilities and resultant queueing space demands could be integrated in a proposed mission bay arrangement, which in turn should be incorporated into the design of a mothership. However, if the performance of a node in the network system is regarded non-satisfactory, then modifications can be applied to the underperforming node. These modifications would involve any of the following options that could

enhance a node's performance and are likely to result in distinct mission bay arrangements and consequently mothership design options:-

- i. Increase the number of service facilities installed on the mothership;
- ii. Install a different type of service facility that allows faster processing time per customer;
- iii. Decrease the number of vehicles to be served at the particular service facility.

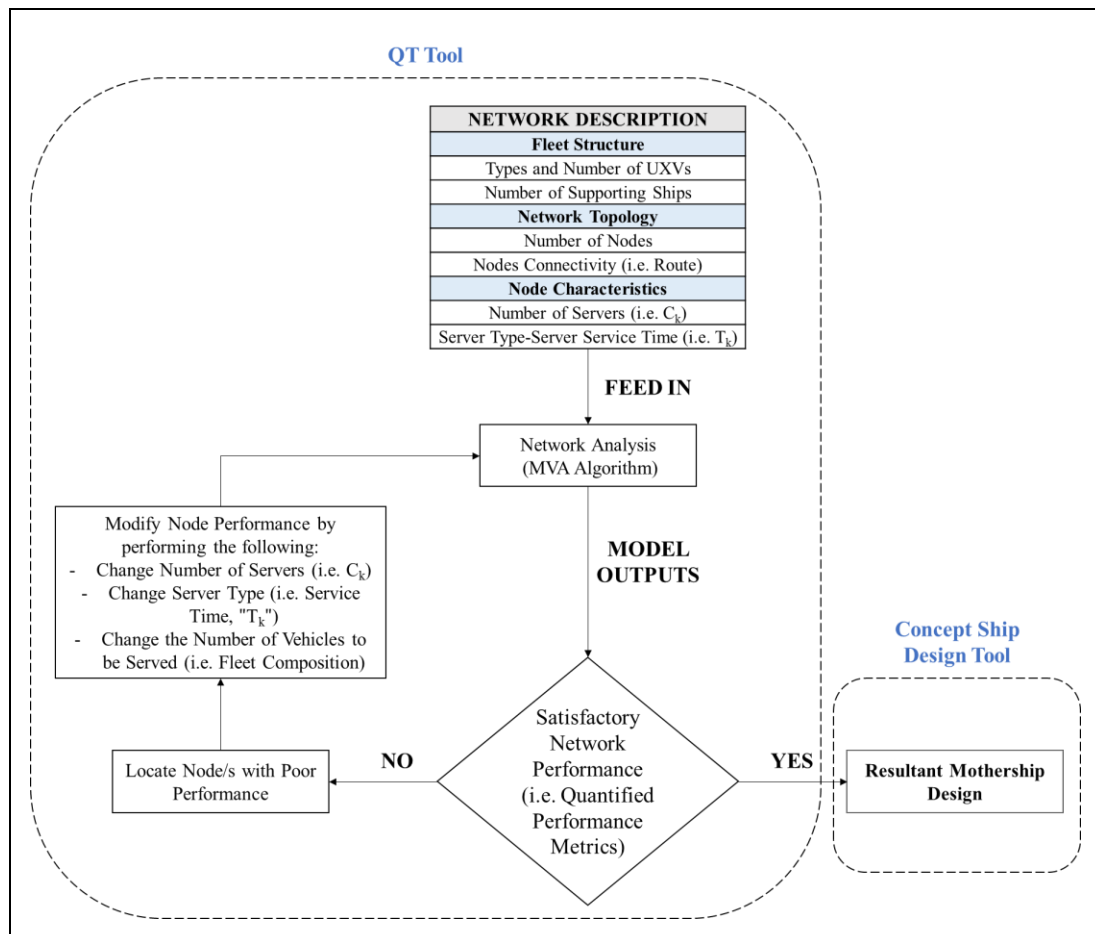


Figure 31: Decision-making process through queueing network modelling of a UXVs fleet-mothership system that informs the architectural modelling of a potential mothership design

The implemented QT tool enables the designer to investigate variations of service facilities, i.e. equipment and on-board systems, which are required for a mothership to be capable of hosting and supporting a UXVs fleet. Such variations are likely to have physical impacts on the ship, due to the different space demands and integration issues, with potential implications for the ship's complement and ship systems. Such implications on the ship size, configuration and performance might lead to proposing new and distinct mothership design options. The various ship solutions are likely to

have different capabilities in efficiently supporting the tasks of a particular fleet of UXVs, thus achieving distinct mission effectiveness.

Taking the above into consideration, variations of a queueing network structure would translate into different nodal overall performance measures that are likely to result in distinct mothership design options. This is due to variations of the network nodes might have impacts on the modelled UXVs fleet-mothership interfaces, which subsequently could necessitate distinct mothership size, configuration and performance solutions. The interfaces between the mothership and the UXVs fleet are likely to be major design drivers for the mothership given that:-

- They have significant implications on the spatial requirements of the mothership, due to the equipment footprints (e.g. LARs) and the necessary clearances for the personnel and vehicles accessibility and operation;
- They impact the ship layout and size, in order for the necessary equipment and proposed support systems to be successfully integrated into mission bay(s) (e.g. amidships or stern) that in turn can be effectively incorporated into a complete mothership configuration;
- They affect the performance requirements of a mothership in terms of the appropriate ship capabilities required to support the overall UXV operations, such as the required speed profile and seakeeping performance of a mothership in order to perform LAR operations successfully.

At this point, it is important to distinguish between the ship performance that refers to the ship characteristics, summarised under the S^4 terminology, and the service facilities, quantified through the QT metrics (i.e. nodal performance), that describes the mothership capability to support the overall UXV operations (i.e. tasks), which subsequently could act as an indirect measure (i.e. proxy) of operational (i.e. mission) effectiveness. The knowledge of nodal performance measures are practical for the design and assessment of complex systems [Yuzukirmizi, 2005], such that being considered, modelled as queueing network systems. Shorter times spent at on-board a mothership nodes, along with faster throughput and reduced queue formation values indicate a mothership design of enhanced UXV support capability.

3.4.3 Proposed Queueing Network Tool's Capabilities

The proposed research employs a QT approach to model the operations of a fleet of UXVs supported from a mothership, by developing an appropriate queueing network tool. The developed tool is flexible in that it provides the following capabilities:-

- It comprises a coded program, together with its associated input and output data files, as described in Figure 28. The code has been developed with a built-in flexibility to allow any queueing network system to be modelled without significant modification to the tool. It reads data from an input file containing the appropriate information and outputs the results in a user specified file. The input file has a simple structure that can be easily modified to model different networks or variations of the same network;
- Appropriate CONOP studies would be produced by mission specialists and the outputs of such studies are used to define the required UXVs fleet composition, i.e. number and type of vehicles. So the developed QT code should be able to model a wide range of UXVs fleet compositions. However, the more complex the composition of a UXVs fleet, the more difficult to construct and analyse the resulting queueing network system. The flexibility of the tool is necessary as the concept of UXVs fleets and their likely composition are both speculative, given the unpredictability of future UXV technology and mission scenarios;
- Many types of service facility can be modelled and assessed by the proposed QT tool (see the wide range of innovative LARS options, shown in Appendix 2). Such innovative systems might be represented using simplified concept level CAD models, in order to assess their LAR performance and the physical demands on a mothership. This could be done as part of input to the concept phase design studies, as it is the most appropriate ship design phase to introduce and investigate innovative solutions;
- CONOPs scenarios cannot be modelled through a queueing network, since such modelling cannot capture the actual mission activities and how a fleet of UXVs is likely to be dispersed into and operate within a potential theatre of operations. However, generic mission activities can be abstracted by representing them as distinct queueing nodes (within the network system) with

indefinite number of servers and a service time that equals the relevant mission duration. This would allow a more holistic network representation of UXV operations, including both on-board and off-board tasks. It also demonstrates the interaction between CONOPs studies and queueing network modelling, since the former informs the latter on the number and types of UXVs operated from a mothership. It can also address the nature of UXV functions supported from the ship and hence the relevant service facilities required to achieve those. Such nodes are not essential queueing nodes, in the sense of queue formations and vehicles piling up to get served by a service facility. This is because mission operations take place at sea and the deployed vehicles perform their determined mission-related tasks once off-board without having to wait for an available service facility;

- Any possibly disabled UXVs can be captured by a network with fewer vehicles modelled. Hence, any option referring to a smaller number of vehicles than actually present in the network can be obtained by referring to the desired number of vehicles. This is because the tool can perform the appropriate calculations incrementally with a step of one "customer" at a time in order to reach the final desired number of customers (i.e. vehicles). Should the performance of a network system be satisfactory for M vehicles, it would also be acceptable for less than M vehicles. However, the purpose of such a model would be to capture and investigate the implications of a fleet of UXVs on the design of a mothership, and not to simulate potential mission scenarios, or other UXV operational considerations;
- A multi-mothership option could be an alternative to a single large mother vessel. The flexibility in a mission provided by a single large mothership might be enhanced, if a given fleet of UXVs is operated and supported from more than one independent smaller mother vessel. Such a solution might result in a better overall mothership support capability and allow enhanced flexibility during a mission. A multi-vessel option could be modelled by separate queueing network systems, each one of them corresponding to an identical (sub) mothership solution. This option would be less vulnerable. However, a multi-motherships option is likely to be more expensive in direct acquisition, although more adaptable in force terms;

- The potential of multihull vessels to provide UXV mothership support capability is worth consideration and could be assessed through the proposed queueing network modelling. A multihull mothership design option might provide a greater flexibility of the upper deck layout of the ship, since multihull vessels are likely to readily provide larger upper deck area than an equivalent monohull configuration. Thus, say a greater number of cranes for LAR operations might be possible when compared to a monohull equivalent, while possibly also having other benefits, such as improved seakeeping performance.

3.5 Verification and Validation Assessment of the Proposed Queueing Network Tool

Verification and validation are procedures, independent of each other, that are normally employed to check whether a product (i.e. QT tool in this case) meets a set of requirements and specifications, as well as whether it achieves its intended purpose (i.e. user's operational needs). "Validation" can be expressed by the query "Are you building the right thing?", whereas the term "Verification" can be described by the question "Are you building it right?". Thus, validation refers to the user's needs, while verification tests if the predefined specifications are correctly implemented by the product [Schietekat et al., 2016].

The most basic verification of the constructed QT tool is that it should be mathematically sound, as well as the FORTRAN code been correctly implemented. This can be satisfied by the fact that the algorithm employed correctly maps (i.e. translates) the queueing equations, since it is a published algorithm, well-accepted and applied in various domains [Bose, 2002]. The second part of the verification process involves testing whether the algorithm has been correctly implemented in the programming environment. This has been achieved by running the implemented FORTRAN code against a series of published data in a study by Suri et al. (2007). In Suri et al.'s study another version of MVA algorithm, named "Approximate MVA", modelled queueing networks with multi-server stations (i.e. nodes). The exact MVA algorithm they used was computationally complex for networks with multi-server nodes and hence approximations to the algorithm were introduced. However, such approximations introduce high numerical errors, and the authors of this particular study developed a simple and computationally efficient approximate algorithm of high accuracy. The study tested the proposed approximate algorithm against the exact MVA solution provided for a simple network system of three multiserver nodes and with a number of eight customers present, as shown in Figure 32.

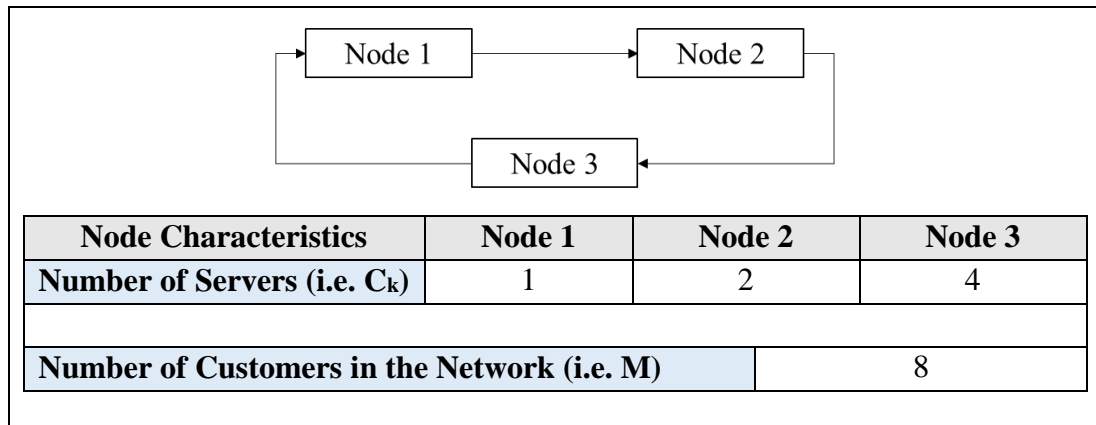


Figure 32: Simple queueing network system modelled by Suri et al. (2007)

This queueing network system was modelled using the implemented FORTRAN code, and subsequently the results were tested by the candidate against the results for nine different cases obtained by (i) the exact solutions provided in the study, and (ii) the numerical solutions given by Suri's et al. (2007) approach. The results are presented in Table 9, showing that the results produced by the FORTRAN code were the same as the exact solution, entailing zero numerical error. Consequently, it was concluded that the FORTRAN code has been correctly implemented and thus the tool has been verified.

Run Cases	Inputs			Outputs			Error	
	Service Time (T_i)			System Throughput (λ)			($\%$)	
	Nodes			Solution				
	T_1	T_2	T_3	Exact MVA	Approximate Algorithm (A. A.)	FORTRAN (F.)	A. A.	F.
1	1	2	2	0.84	0.83	0.84	1.19	0.00
2	1	2	4	0.75	0.76	0.75	2.41	0.00
3	1	2	8	0.48	0.46	0.48	5.51	0.00
4	1	1	2	0.97	0.93	0.97	4.12	0.00
5	1	4	2	0.50	0.47	0.50	5.14	0.00
6	1	1	4	0.83	0.82	0.83	1.20	0.00
7	1	4	4	0.49	0.46	0.49	4.94	0.00
8	1	1	8	0.49	0.46	0.49	6.54	0.00
9	1	4	8	0.41	0.42	0.41	1.18	0.00
				Average Error (%)			3.58	0.00

Table 9: Verification by the candidate of FORTRAN numerical queueing model against published data by Suri et al. (2007)

The validity of the implemented QT tool considers whether the tool addresses the user's requirement, which is to investigate the implications of a given fleet of UXVs on the design of a mothership that would subsequently be capable of sufficiently supporting the tasks of the vehicles. Such a question is usually difficult to answer, since many of the real physical systems, such as the one examined in this research, do not currently exist. So the purpose of modelling is to investigate the behaviour of the emulated system and compare several proposed system configurations to enable selecting the one that best suits the requirements. A useful validation test could be to examine how the model's results change as the configuration of the system alters, even if there is no basis for checking the reasonableness of the obtained measures of performance for the particular modelled system [Hillier and Lieberman, 2001]. Therefore, it is proposed that the validation of the QT tool can be achieved through a series of applications of the tool. This is explored further in Chapter 5 and Chapter 6, where a series of mothership design studies are presented, to demonstrate how the proposed constructed queueing network tool can inform a UXV mothership design process and, thus along with an architectural-centred concept ship design tool, provide a more holistic range of mothership design solutions.

3.6 The Use of Simulations to Model Queueing Network Systems

Physical real-world phenomena can often be described by a set of equations that describe the underlying processes. A mathematical model is essentially an approximation of a real process [Bhat, 2008]. Since the analytical solution of a mathematical model is not always feasible, numerical techniques are often employed to provide realistic, but approximate solutions. Models implementing such techniques are tractable usually only if simplifying assumptions are made [Bose, 2002]. Besides the fact that numerical modelling might become intractable for complex systems, solutions provided are likely to be less accurate, due to the fact that complex systems lead to complex numerical models, which are more susceptible to computational errors [Bhat, 2008]. Instead, computer programs may be used that can mimic (i.e. simulate) the behaviour of a system more realistically (compared to numerical models), thus providing more accurate solutions regarding the behaviour of the simulated system. The basic ideas behind developing a simulation model for a real system are illustrated in Figure 33 [Bose 2002], which shows the relation between a real physical system and the equivalent simulation model.

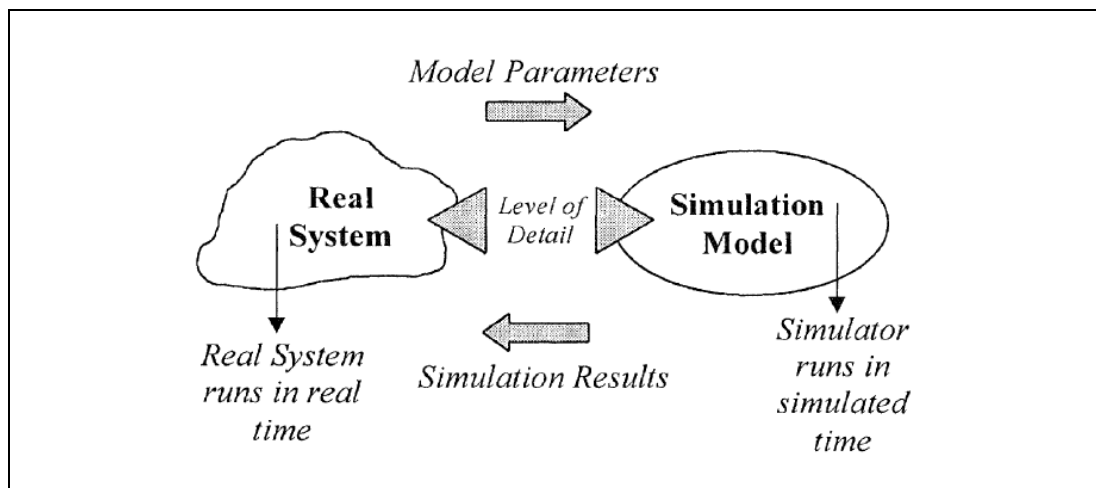


Figure 33: Simulating a real physical system [Bose, 2002]

In order to make a simulation model as realistic as possible, as many features and details of the real system as feasible ought to be captured. However, this is not always possible, or even practical to capture all the details of a real system in constructing the simulation model. When building a simulation model, it is advisable to make compromises regarding the incorporation of only those aspects of the real system (i.e. model parameters) that are thought to be pertinent to the goals of the study. Hence, the

model parameters need to be carefully selected in order to satisfy the simulation requirements (i.e. meaningful simulation) [Bose, 2002].

The accuracy (disregarding computational errors) of a simulation model depends on how clearly the modelled system is understood, the interactions within it and hence the quality of the developed software [Bhat, 2008]. A real system has its own entities with their respective attributes that might interact with each other (i.e. interdependencies). An entity is defined as an object of interest in a real system, such as in the simulation of a queueing network, where the individual queues and the paths followed are important functional entities. The attribute of an entity is defined as the relevant property that it is desired to study through the simulation, such as the length of queues, or the time required to serve a customer (i.e. including time spent at queue) [Bose, 2002]. In order to track a system's state, before the initiation of a simulation model, variables are set to define the system's parameters, including the service rates. Finally, changes in the system can be tracked by the employed state variables that model the parameters the user is interested to study, such as the number of customers waiting at each server, or the total time taken to serve a customer [Bhat, 2008] [Bose, 2002].

The time increments in a continuous time simulator could be set arbitrarily small, if the simulator allows, thus entailing a simulation that effectively looks like a continuous time simulation. Generally, whether the state of a system can be considered continuous or discrete, and hence whether the system is a continuous or discrete time, respectively, strongly depends on the nature of the physical system modelled. Queueing systems are examples of discrete time systems, where changes (i.e. events) in such systems happen only at specific (i.e. discrete) time instants, which are normally referred as simulation or event times. Hence, queueing system simulators are discrete time simulators that trigger their internal simulating actions only when events affecting the system's state take place [Bose, 2002]. An event is seen as a point (i.e. discrete) in the time (i.e. continuous) when the state of the modelled system changes. For a queueing system an event can be the start or the end of a service [Bhat, 2008]. Discrete time simulators keep a "master event list" of the events (sequentially) that are scheduled to happen at the instants when they are going to happen. All arrival events to the service facilities of the simulated system are set at the beginning of the

simulation [Bhat, 2008]. Once an event at the top of the event list is being successfully processed, the simulation time increments to the time of the next event in the list happening that is then processed [Bose, 2002]. Generally, queueing simulations based on next-event incrementing procedure require fewer iterations to cover the same amount of simulated time than the fixed-time one [Hillier and Lieberman, 2001].

The best way to assess how a system behaves would be to construct a prototype model and study its behaviour (i.e. exact performance) [Hillier and Lieberman, 2001]. However, this is not usually feasible, due to time and cost limitations, especially for large complex systems. Consequently, the choice is whether numerical or simulation models best describe the physical system. The following points listed ought to be considered in making a balanced decision [Bose, 2002]:-

- Simulations are generally more realistic (i.e. closer to the real system) than numerical models, since they typically require fewer and less extreme simplifying assumptions than the latter. Also, simulations could provide crosschecks on the results provided by numerical models (i.e. verification through simulations), and can be used to assess the validity of any implied assumptions adopted in any numerical analyses;
- Simulations may allow the study of the behaviour of any attribute of any entity in the system, by simply monitoring those during the simulation runs, which would not be available from numerical models;
- A good simulation model is able to mimic a real system realistically, but would typically take long time to construct and run. The fact that simulators are computationally expensive constitutes the significant drawback that inhibits the use of simulators over simpler numerical models;
- A simulator would typically provide as outputs the moments of the parameters under interested and hence monitored during the simulation (1st moment refers to mean value, whereas 2nd moment refers to variance). However, unlike numerical modelling, simulations can also generate time series of selected parameters of interest, in order to demonstrate the way these change during the simulation process, in case this is of particular interest for the design of a queueing system;

- One of the major strengths of a numerical model is that it can abstract the essence of a problem and reveals its underlying structure, thus providing insights regarding the cause and effect relationships inside the system. Consequently, if one is able to construct a numerical model that is both an acceptable and reasonable idealisation of the physical real problem, as well as amenable to a solution, this approach is usually preferred to a simulation. However, many problems are too complex to be modelled numerically and simulation often constitutes the only practical approach [Hillier and Lieberman, 2001];
- Animation capabilities for displaying simulations in action can be also developed by simulators, thus enabling the user to better understand the behaviour of a modelled system. Visualisation of the operation of a system could validate a simulation model [Hillier and Lieberman, 2001];
- Neither a numerical model, nor a simulation of a physical system are likely to produce exact values for the measures of performance of the particular system, since such approaches are approximations of the real system. However, simulations are generally much better approximations of a real system, hence seen to produce better solutions [Hillier and Lieberman, 2001].

By investigating the performance of a system for a number of alternative options, one can evaluate and compare these options before narrowing down [Hillier and Lieberman, 2001]. A queueing network system can be either modelled or studied through algorithms (i.e. mathematical-numerical modelling) or through simulations. The best course of action is usually to employ a combination of both of these approaches if applicable [Bose, 2002]. Given the limited access to commercial simulation software, the option of analytical modelling a queueing network system, as described in Sections 3.3 and 3.4, was employed to analyse the proposed network of UXVs fleet-mothership. This is a sensible, given the "Pre-Concept" nature of the research, without any current formal requirement for a UXV mothership. However, for a more formal concept phase for a UXV mothership a combination of both numerical modelling and simulation techniques would be preferable, as simulations could be conducted to refine subsystems options. In the concept phase mothership design options and alternative solutions would be considered at a sufficient, but not a totally comprehensive level of detail. One (or occasionally two) options should be

selected at the end of the concept phase to be subsequently worked up in later design stages, with more resources employed. The selected option would then be developed to a deeper level of detail in assessing its technical feasibility and beyond in working up the production definition. Simulation environment has been employed, for instance, in (i) modelling ship air interface framework, predicting ship-helicopter operating limits for recovering the aircraft onto the ship for new ship designs, (ii) replenishment at sea, [predicting the behaviour of ships alongside when mechanically coupled by a solid transfer system and (iii) NATO submarine rescue system, predicting the recovery system's behaviour in high sea states [McTaggart et al, 2018] [Henry et al., 2009].

3.7 UCL Concept Ship Design Tools

3.7.1 Design Research Centre Concept Ship Design Layout Tool

The DBB approach has been successfully incorporated into a fully developed ESSD CAD system, PARAMARINE, through the SURFCON module for surface ships [Andrews and Pawling, 2003], developed by GRC Ltd, now owned by QINETIQ [QINETIQ, 2018]. The Paramarine toolset allows the ship designer to architecturally synthesise a proposed ship design and also to assess the resultant design for a range of engineering performance areas. However, sophisticated ship design 3D CAD packages, like Paramarine, have a number of drawbacks regarding their use in this ESSD investigation of the UXVs fleet implications on naval ship design. These include [Pawling et al., 2015]:-

- i. The restricted availability and access due to license requirements;
- ii. The high level of detail in such high-capability and high-fidelity CAD modelling tool provides;
- iii. The precision that can be inappropriate at the early design stages, when elucidating the requirement (concept phase);
- iv. The high learning and familiarisation overhead.

Consequently, although Paramarine allows great flexibility and precision in naval architectural analyses for ship design studies, it can be demanding to learn for new users [Pawling et al., 2017]. However, any simplified ESSD tool will need to be supplemented and (later in the design process) replaced by dedicated naval architecture tools, such as Paramarine, as the latter offers superior analytical capabilities for aspects, such as damaged stability, hydrostatics, powering, seakeeping and strength analysis. Additionally, detailed arrangement ship drawings can be worked up using specialised CAD tools, such as AutoCAD to provide the necessary level of detail required at later design stages, where ship details are increased [Pawling et al., 2015].

An alternative implementation of the DBB approach has been developed by the UCL Design Research Centre (DRC) for early ship design research applications. The key features that such a simple tool provides include: easy accessibility; low learning and

familiarisation learning demands; fast operation; flexible in level of detail; not ship-type based; not automated; task-focused; reliable; an appropriate level of precision in ESSD; and ready integration of ESSD models, datasets and evaluation approaches [Pawling et al., 2015]. The tool has been developed by using commercial online non-CAD software, i.e. JavaScript, but can currently only be applied to monohull ship designs. JavaScript was chosen, as it offers the ability to develop an online tool with an interactive Graphical User Interface (GUI), high responsiveness and is accessible where an internet connection is available, since it runs on a web browser from any PC (i.e. easy compatibility). In addition, given the open source nature of JavaScript, the code can be modified and enhanced. The general arrangement model in JavaScript uses a grid-patterned representation of the arrangeable space of a ship design, albeit in two dimensions rather than 3D space representation in Paramarine. The JavaScript-based ship design tool consists of two principal input files, namely "Ship Data" and "DBB Data", which are formatted as Comma Separated Value (CSV) files:-

- The "Ship Data" file includes information on major dimensions, watertight bulkhead positions, number and position of hull and superstructure decks, hullform geometrical coefficients, maximum speed and powering margins;
- The "DBB Data" component provides a cellular description of all building blocks incorporated in the design space, including their location in the design area, their dimensions, as well as the equivalent weight, space and volume requirements. The building block data are structured according to the UCL-defined functional groups of Float, Move, Fight and Infrastructure.

To create a new layout, the above data files are fed into the online ship design tool, which then presents the general arrangement of the ship, through the disposition of the building blocks in the design space, specified by the ship designer. The layout also displays the designer allocated locations of the transverse main watertight bulkheads. The interactive tool's GUI allows the user to visually apply any necessary modifications to the ship configuration (i.e. internal arrangement and hullform) on the screen, without the need for the user to go back to the input files for every single change. This is achieved by the tool's tabular interface that provides the designer with the capability to change the overall ship and individual DBB dimensions, as well as the position of the transverse bulkheads and the disposition of the DBBs, if desired. A

much more comprehensive description of this JavaScript ship concept design tool by the DRC is intended to be published after this thesis' completion.

Figure 34 provides an illustration of the graphical output of the tool for an Offshore Patrol Vessel (OPV) design study, along with the tool's tabular interface on the right hand. The DBBs in the general arrangement are assigned with labels and a visible outline for identification, as well as a colour according to the DBB functional breakdown (Float-Blue, Move-Yellow, Fight-Red, and Infrastructure-Green). The JavaScript-based ship design toolset is capable of auditing area and volume requirements of the proposed ship layouts. It also provides data, including centroids and hydrostatics, as well as information of the resultant design can be inputted to other tools for further analyses. Such analyses could include aspects of ship performance assessment. This currently only includes basic static stability and resistance/powering estimation, alongside extracting spatial properties from the layout for further analysis of a proposed configuration. The latter includes compartment adjacencies via network analysis and 2-D modelling. An example of complete adjacency network is shown in Figure 35 for a USV mothership OPV, the design of which is described by Pawling and Andrews (2013). However, the tool currently lacks the ability to assess ESSD studies against damage stability criteria, seakeeping performance and stress analysis, and further separate calculations would need to be performed.

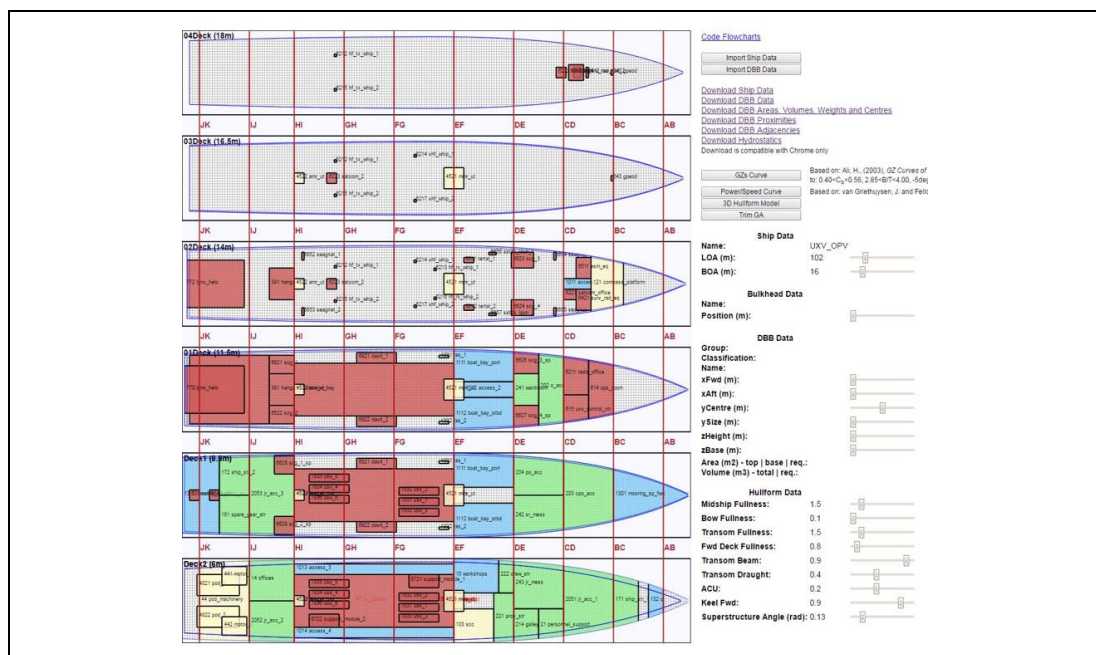


Figure 34: UCL JavaScript-based ESSD tool output for an OPV design study [Piperakis et al., 2018]

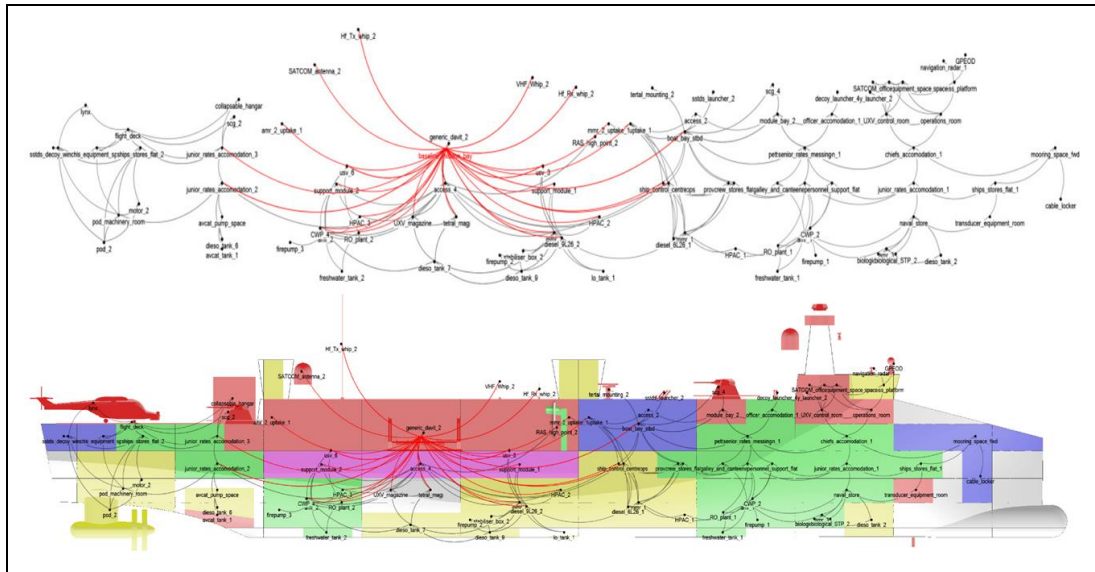


Figure 35: Adjacency network for an OPV design study [Pawling et al., 2015]

In comparison to Paramarine, the UCL JavaScript-based ship cases design tool allows the ship designer to generate ship configurations at an appropriate level of detail suitable for the early stages of design process, quickly and without a significant modelling effort. Thus, various early stage UXV mothership design options can be visualised, assessed and compared to each other. The tool provides the ship designer with the flexibility to generate mothership design options at high level, while providing more details in those areas of the ship that may need to be focused upon, such as the mission-oriented spaces. Given that UXV on-board operations and the related support systems would impact (i.e. physical demands, integration implications) a mothership, several mission bay arrangements could be readily explored. The main scope of concept ship design studies undertaken the current research is not to provide fully worked up solutions, but to explore a number of potential options regarding the likely implications of a fleet of UXVs on the design of a mothership.

3.7.2 UCL Unit Procurement Costing Algorithm

Although ship costing consists of several different components, as discussed in Sub-Section 2.3.5, only UPC (material and labour costs) has been employed in this research to cost ship options. The associated cost analysis has not included TLC, because ship operating conditions, including personnel training, fuel and stores are even more speculative for the design investigation of a UXV mothership design. Furthermore, the simplifications in TLC estimates used in UCL ship design studies generally cannot

readily reflect a concept level ship's architectural aspects and how these might impact maintenance costing [Esbati, 2018]. Only UPC has been used as a cost measure in the current research. Therefore, the UCL UPC calculation approach has been adopted along with the proposed indirect operational effectiveness metrics (discussed in Section 3.4), in order to provide a means for COEA likely comparison of the mothership design options.

Costing a ship at concept phase depends upon the ship type (e.g. naval or commercial structural standards), as well as on assumptions, including a shipyard's place, along with the purchase and shipyard overheads, the frequency of dockings and refits, the incurred inflation rate and the learning curves given that ships of the same class are different resulting to different costs. However, it is essential in a ship design project to perform costing estimations with a reasonable accuracy at the early stage in the design process. This enables the ESSD team to conduct trade-off studies between the fighting capability and the cost of a warship. In order to produce cost estimates as accurate as possible, it is desirable to account the equipment and installation costs as long as these are available.

For a warship the only systems and equipment likely to be known in the concept phase are major weapon systems, propulsion systems and power supply equipment, including generators and chilled water plants. However, for other systems and equipment little is known, including installation costs. So for the majority of the design, cost estimates are based on historical regression data plotted against various ship characteristics derived by the ship designer. Typical parameters used are group weight (i.e. hull, personnel, ship systems, propulsion, power generation, payload and variables), volumes, areas and power levels. Such an approach to cost estimation is known as "Parametric Costing" and is being widely used, as it aligns with the broad definition in concept phase. There is normally a number of levels in parametric costing, since cost data might be applied at group, sub-group, or even sub-sub group level. It is also relevant that cost databases need to be updated to reflect the current financial year inflated from the last database update [UCL, 2014 a].

The advantages of parametric costing include using what-if assessments (i.e. alternative options) despite broad costing estimates in the concept phase. The parametric UCL UPC approach gives a UPC cost for each significant study summing

all costs resulting from each individual group [UCL, 2014 a]. The data from UCL ship database are only for concept design exercise purposes, used on a comparative basis. Thus, the incremental cost differences obtained this way are primarily useful to see the differential cost implications between ESSD variants and options, and so they are less meaningful in absolute terms. This is consistent with the research programme on UXV mothership present here.

3.8 Outline of the Research Proposal

The research task addresses the following question:

"What are the implications of a fleet of UXVs on the design of a potential UXV mothership able to host such assets on-board and support their overall operations during naval mission scenarios".

An insight to the research question is given by Petersen et al. (2015), where it is stated that "If the host vessel can only launch/recover one USV at a time (as is typically the case), this creates a queueing problem for groups of USVs".

Andrews (1993, 2011) proposed that a comprehensive concept phase should commence with a full exploration of the possible solution space consisting of three axes, allowing for technical feasible assessment. For a UXV mothership, these axes are seen to be:-

- i. Packaging the primary functions of the mothership, which are defined by the need to host and support the operations a fleet of UXVs. Packaging addresses the required facilities dedicated to deliver the main functions of the ship. Such facilities for a UXV mothership involve the mothership's payload, including LARs, stowage and C3 systems for UXVs, as well as related potential personnel and ship services requirements;
- ii. Mothership capabilities-requirements necessary to deliver the primary ship functions. These capabilities refer to a mothership's performance and includes: speed; endurance; stability; seakeeping; communications and control of the ship;
- iii. Technology options to achieve the required functions and capabilities of the ship. Such options comprise the ship equipment and systems standards, such as mission bay solutions, enhanced materials and systems, as well as design style, such as ship configurational options (i.e. monohull, SWATH, trimaran).

A proposed material description of a mothership, produced at concept phase, has to be seen as one of three interlinked components, as shown in Figure 36, which are necessary in order to produce an achievable solution [Andrews, 1993], as further analysed:-

- The technological issues (i.e. technical feasibility) that are identified by the material description of a proposed mothership design;
- The UPC that can be obtained from the resultant material description;
- The OA that can provide measures of effectiveness (proxy or direct) of an adopted material solution, quantifying the extent of performing certain evolutions in specified scenarios.

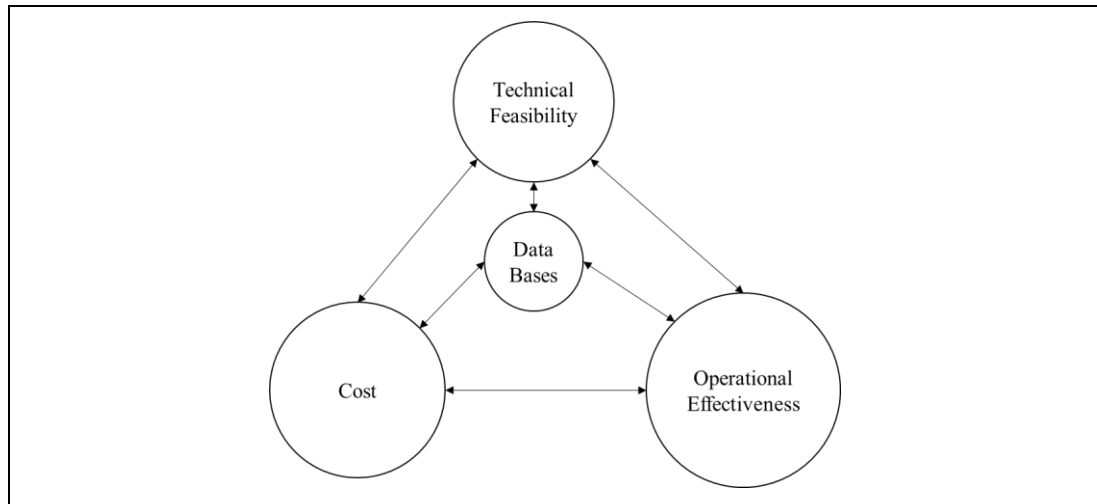


Figure 36: The components of prefeasibility (i.e. concept phase) design [Redrawn from Andrews, 1993]

The technical feasibility of a mothership design can be assessed in terms of integrating the required set of features (i.e. ship functions and capabilities) in one or more hulls (i.e. material solutions), in order to accommodate and support a fleet of UXVs effectively. Andrews (2003) argues that the design of all warships is driven in large measure by their internal and upper deck configuration, and that a configurationally-centred approach to design (the Design Building Block Approach) should thus be used. As the design of a UXV mothership must be synthesised emphasising the layout, this can be carried out in the JavaScript-based UCL concept design tool, subsequently producing numerically balanced mothership solutions. Consequently, DBB approach allows the investigation and visualisation of the implications of various UXVs fleet compositions on the design of a mothership. In addition to the UXV mothership configuration, there are many other aspects that should be considered in a holistic analysis, with a particularly notable example being seakeeping (that is crucial for delivering mothership's primary functions, i.e. LAR of UXVs fleet). Although integrated ship design tools, such as Paramarine, contain seakeeping analysis tools suitable for use in concept design, the simplified web-based implementation of the

DBBA used in this research did not. This could be justified, since the focus of this research was on the implications (on a UXV mothership) of a large diverse fleet of UXVs rather than a full concept exploration considering items (ii) and (iii) above.

The UCL design tool only allows the assessment of resistance/powering and intact stability performance, thus any seakeeping, although particularly important for successful LAR operations, has not been addressed in the current research. Furthermore, besides conventional (i.e. monohull) mothership configurations, the DBB approach readily facilitates consideration of unconventional ship solutions, such as the SWATH or trimaran configuration, where the former could provide enhanced seakeeping performance pertinent to LAR operations, or the latter might provide a dynamically stable and hydrodynamically efficient ship solution. However, given that the UCL JavaScript concept ship design tool is not currently able to handle unconventional hullforms, so the UXV mothership design studies undertaken in this research are limited to monohull solutions.

A mothership's UPC can be estimated through UCL cost analysis algorithm that uses parametric cost data and empirical relationships. The operational effectiveness of a mothership design describes its capability to deliver its primary functions, leading thus to evolutions during the operations of a fleet of UXVs in the mission theatre. However, since quantifying such measures is not easily undertaken, proxy measures have been employed to define the operational effectiveness achieved through a proposed mothership design. The QT tool is able to model the operations of any fleet of UXVs operated and supported by a mother vessel and subsequently provide decision-making guidance in terms of the required facilities (i.e. material solutions) for a mothership to deliver its primary functions. Such decision-making focuses on the modelled number of service facilities employed on-board a mothership and the incurred space demands, including both the service and queueing area requirements (i.e. model outputs). In addition to this, among the QT tool's outputs are measures of performance of an under-study network, which reflects a particular UXVs fleet-mothership system, that can quantify the mothership capability to host and support a fleet of UXVs. A meaningful measure could be the total time to serve a number of UXVs, including the actual service time and queueing delay (i.e. waiting time) at a particular node, such as the total time to LAR a fleet of UXVs. Therefore, such capability of a mother vessel is

regarded as an indirect operational effectiveness criterion (i.e. indicator), since the more capable in the efficient queueing processing of a UXVs fleet a given mothership is, the more effectively the mission would be accomplished.

Based on the proposed mothership design approach, illustrated in Figure 37, various fleets of UXVs may be assessed in terms of the required UXV-related support capabilities, size, configuration, performance, complement and on-board services on a mother vessel. Since distinct queueing network structures reflect variations of UXVs fleet compositions and/or number and type of service facilities, which subsequently are likely to result in different mothership solutions, the various potential ship design options could be compared on a COEA basis. Figure 37 illustrates the proposed mothership design approach which comprises of two distinct toolsets, namely OA and ship design tools. The former toolset, consisting of CONOPs (which is in the form of broad operational assumptions for this research) and QT tool, produces the basis for decision-making that is employed to model a UXVs fleet composition (based on the appropriate mission scenario requirements) and assess the impact of the required on-board mothership facilities on the capability of the mothership to host and support a fleet of UXVs. Particularly, the QT tool models the physical interactions/interfaces between the UXV operations and the mothership and it provides information on the required queueing and service spaces for a mothership. The combination of QT tool and concept ship design toolset utilises the advantages of the architecturally-oriented ship design approach to demonstrate how the required mothership capabilities, pertinent to UXV operations, would impact the size, configuration, performance and cost of a proposed mothership design. In particular, queueing networks inform the mothership design process with regards to the space demands for the facilities required for a mothership to be able to accommodate on-board and support a fleet of uninhabited assets. Given the extensive knowledge and experience on concept design of naval vessels in the DRC team at UCL, as well as the difficulty of obtaining the appropriate data from mission experts for a speculative operational concept of a fleet of UXVs, CONOPs studies have had to be speculative. This means that regardless of the potential mission scenarios, rough estimates of the number and type of uninhabited assets in a fleet of UXVs have been postulated (i.e. fleet structure), to feed such information into the research.

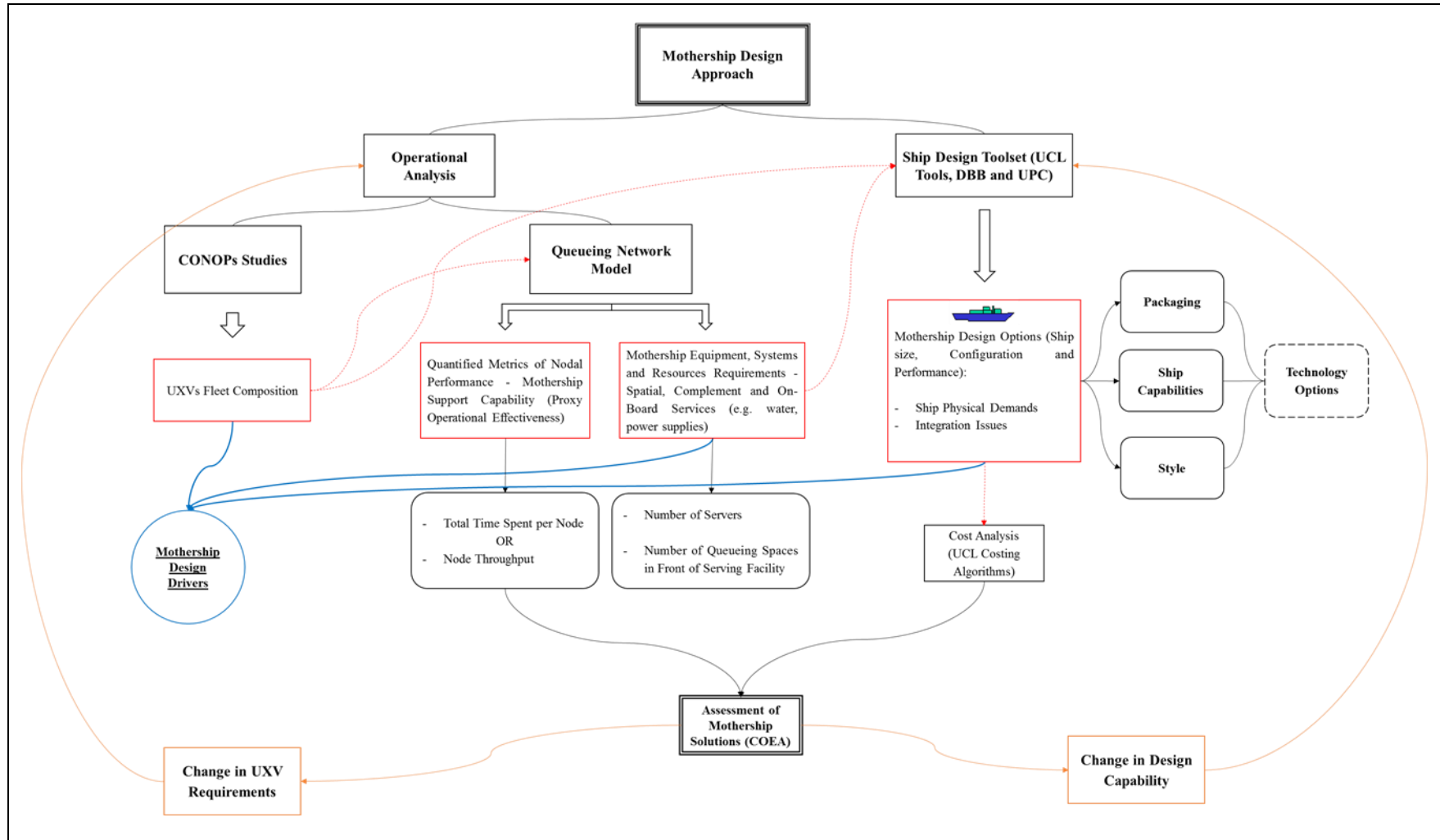


Figure 37: Proposed mothership design approach

Designing a UXV mothership is a multi-layered problem. Given the importance and complexity of the emergent LAR technology, the speculative nature of UXV support systems information, the immature stage of UXV technology and the equivalent support systems and equipment, as well as in discussion with the industrial sponsor (BAE Systems), it was concluded that LAR methods and their ship implications would be the focus of the current research. The number and type of LAR facilities integrated into a mothership are emphasised, as such systems: i) are the means to initiate a mission since they are essential for deploying a fleet of UXVs effectively, and finally retrieving it once the mission is completed; ii) affect the equivalent LAR procedures in terms of the ship performance requirements for successful LAR activities (e.g. speed and seakeeping); iii) are seen as likely major mothership design drivers. However, besides LARs, other aspects of UXV-related tasks and their equivalent on-board a host ship support systems are also considered, including stowage and C3 systems, in order to have a more holistic picture of the UXV impacts on the design of a mothership. Given the uncertainty of UXVs technology, any likely physical impacts of the UXVs on a mothership are speculative, for the reason of demonstrating the proposed mothership design approach.

The proposed mothership design approach, illustrated in Figure 37, for developing a COEA comparative studies for potential UXV mothership options is summarised below:-

- A potential fleet of UXVs is postulated (i.e. CONOPs studies in the form of broad operational assumptions);
- The QT is used to analyse the mix of the number and type of service facilities proposed for a potential mission bay. Such analysis provides: i) the incurred service and queueing space demands; ii) the resultant mothership LAR capability;
- Potential mission bay configurations are developed to a sufficient level of detail (using the UCL JavaScript ship concept design tool);
- A resultant mission bay is then integrated and further worked up in the context of the whole mothership to provide balanced design solutions;
- The cost of each resultant mothership design solution is estimated using the UCL UPC method;

- The cost estimates are then presented against proxy operational effectiveness criteria (i.e. LAR mothership capability) achieved from each aforementioned ship design option.

The behaviour of a system, such as a UXV mothership, can be described by three types of architecture, namely physical, logical and operational architecture. These types of architecture ought to be taken into consideration in a UXV mothership design process. The architecture of a system is defined as the manner in which its components are organised and integrated. The physical architecture describes the spatial and physical characteristics of the system and of its environment, i.e. locations and dimensions of compartments and equipment. The logical architecture represents the functional characteristics of the system and the linkages between each component of the system i.e. how different system components are connected to each other. The operational architecture refers to the temporal behaviour a system, including human-system interactions to some extent i.e. how a system and its components are used over time for an operational scenario [Brefort et al., 2018].

Taking the above into consideration, the proposed mothership design approach allows for the identification of potential ship requirements, which translate into specific equipment, systems, spaces and ship service demands, as well as it enables the investigation of design aspects that are likely to drive the design of a potential mothership. The design approach that has been adopted for this UXV mothership investigation is seen similar to the process adopted for developing COEA assessments for the Type 26 Frigate described by Randles (2012) and the decision analysis process suggested by Keeney (1982), which have both been considered in Sub-Section 2.3.5. The innovation in the current work is considered to be in the research concept and the proposed approach to tackle it, namely taking the fleet scenario concept of UXV to be operated from a mothership and the application of queueing networks to assess the implications of such a fleet of UXVs on the design of such a mothership. The COEA has therefore been restricted to the QT centred exploration of UXV LAR and the whole ship impact, rather than further related performance exploration.

Chapter 4: An Application of Queueing Network Modelling to Capture the Interfaces between a Fleet of Uninhabited Vehicles Operated from a Mothership

4.1 Introduction

This chapter provides an example of a network model, representing the operations of a fleet of USVs from a mothership during a mission. The network has been analysed using QT to demonstrate the capabilities of the tool and also to perform a sensitivity of the tool. The tool provides useful information at the early design stages regarding USVs' support systems, including LAR, stowage and internal handling systems, which subsequently have an impact on the design of a prospective mothership. Each node in the network system represents, from the perspective of QT analysis, two distinct areas, namely the waiting and the service area. The USVs, arriving at each node of the network, queue up at the waiting area, if necessary, where adequate space needs to be allocated to accommodate the number of vehicles waiting to be served from an available server (i.e. facility) in the node service area. The service area is represented by one or more identical servers that provide the required service to each USV.

The types and total number of servers at a node, within the QT representation of the USV support network, correspond to a combination of physical equipment and any associated crew needed to perform the appropriate tasks and procedures to support the USVs throughout a mission. The allocation of servers depends on the number and type of vehicles to be served and should also meet particular performance criteria, if available, such as the maximum time to carry out an appropriate task. For instance, the time to launch a number of USVs from a surface ship towards a theatre of operations might have to meet certain criteria/limitations that could be derived from the pertinent CONOP scenarios. Thus, the network can be used to analyse the performance of a proposed USV support system. Alternatively, if the number and type of servers can be set to be sufficient to meet the relevant performance requirements of the USV system, if available, then the QT model can be used to derive the

requirements in terms of the equipment, space, potential crew and on-board services demands for the system. This information can then be used as an input to the mothership design process.

The first section of this chapter provides a description of the queueing network system under study used as an example to demonstrate the tool's capabilities. The following section explains how queueing network can inform the arrangement of potential mission bay(s), with an emphasis on LARs, and which has to be subsequently integrated into the whole ship. The third section demonstrates the tool's capabilities by performing a sensitivity of the tool for the USV launching operations, already presented in the 2017 paper [Kouriampalis et al. 2017]. The chapter ends with a consideration of the capabilities of the queueing network tool pertinent to the design of a mothership.

4.2 Description of an Application of Queueing Network Modelling

The model presented in this chapter represents a physical network system of a number of nodes through which objects (i.e. USVs) flow, as shown in Figure 38. This model representation is seen to be a generic structure demonstrating the USV-mothership interfaces. More or less detailed models could be generated from such a generic network structure, depending on the nature of the problem and the level of detail necessary to capture the design aspects under interest, such as those related to LAR operations. According to this model, the tasks of a fleet of USVs supported by a mothership are represented using the following nodes:-

- The deployment of each USV starts with preparations that include appropriate quick pre-mission checks (pre-mission checks node);
- The vehicles stowed in the mission bay(s) are moved (movement node) towards the launching facilities, by using internal mission bay handling systems (e.g. overhead crane paths, trolleys);
- The vehicles are launched (launch node) into the water from the mothership;
- Once launched, they head towards the mission theatre (mission theatre node) to perform certain tasks according to the appropriate CONOPs scenario. While on-station the vehicles are remotely controlled and operated through C3 systems and sensors;
- In case of a detected malfunction (malfunction at sea node) the implicated vehicle may abort the mission and head back to the mothership (or other support vessel) to be recovered on-board for repairs and re-launching thereafter. A more efficient option would be "repair by replacement", which means spare stowed vehicles are launched to replace the malfunctioning ones;
- Given the power and munition capacity of a USV is rather limited, it may be necessary for every vehicle to be able to refuel and rearm close to or even at the mission theatre i.e. on-station (refuel and ordnance node);
- When the operations at a mission theatre are completed, all vehicles return to the mothership to be recovered on-board (recovery node);
- Once the vehicles are recovered on-board, they are maintained (maintenance node), if necessary, and get prepared for the next potential mission (refuelling and rearming nodes);

- Finally, the vehicles are stowed (stowage node) in the mission bay(s) with the assistance of internal handling systems and the cycle can then be repeated.

It is noteworthy that the models investigated in this research:-

- Represent the flow of UXVs through a queueing network system consisting of a number of nodes/activities, as discussed above, and not a sequence of discrete processes (consideration of issues is given at page 285 in Appendix 6);
- Are deterministic, since the routing ratios are defined by the user;
- When disabled vehicles return to the mothership, they are assumed to not interfere with the flow process.

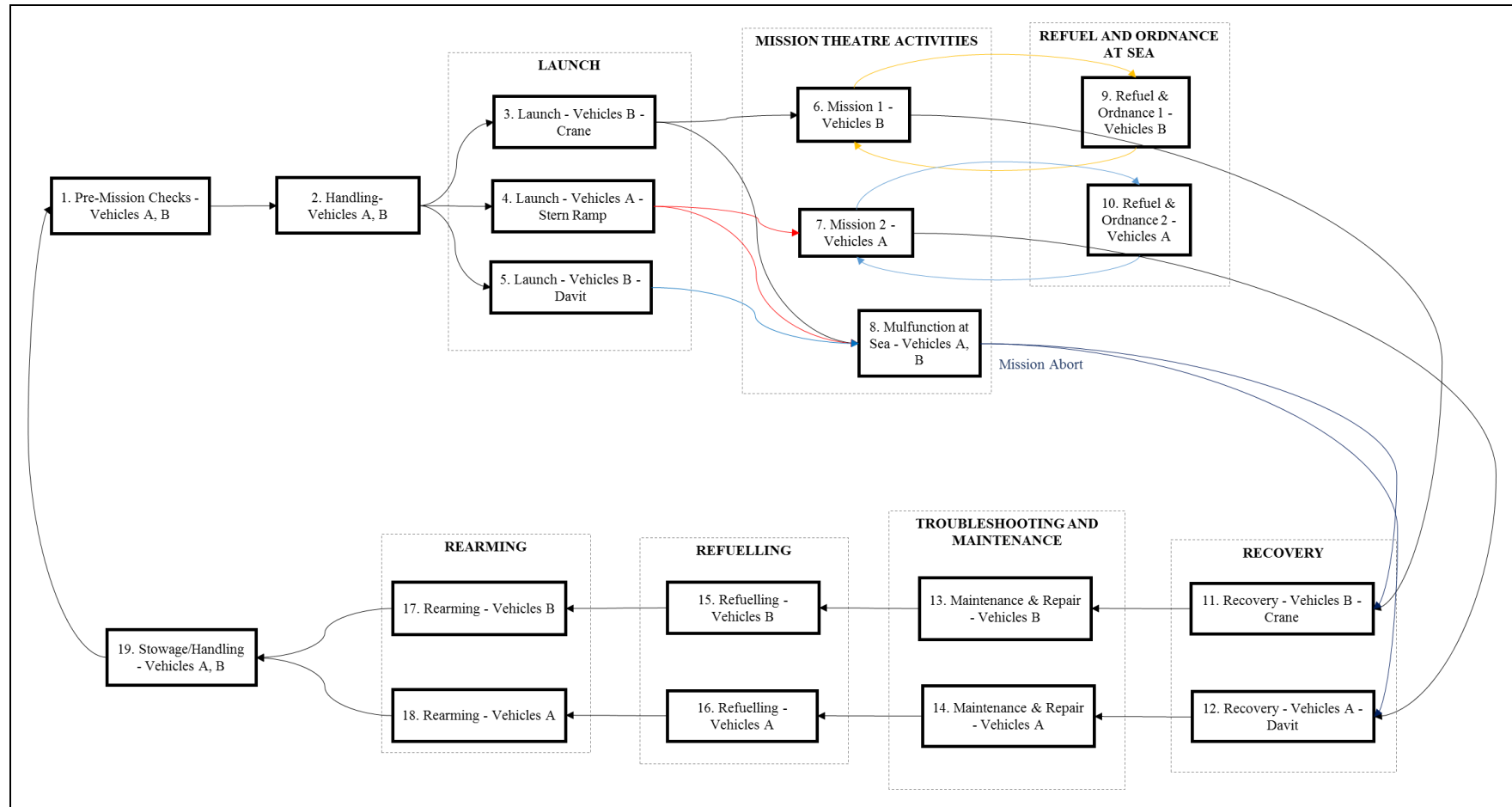


Figure 38: Queuing network model

This model involves two different types of USVs, termed vehicles of Type "A" and Type "B". Such vehicle types are hypothetical, with Type "A" having similar size to a RHIB (i.e. 11 m) and Type "B" being smaller non-disposable USV (i.e. ~ 3 m), respectively. It is likely that multiple types of USVs would be operated from a mothership to meet fleet adaptability criteria according to the various mission requirements. Using different USV types also demonstrates that the QT tool is capable of modelling complex UXV systems consisting of different types of uninhabited assets. It is sensible to model different UXV types, as they are likely to require distinct service facilities. The model describes the deployment of Types "A" and "B" vehicles in the theatre of operations, in order to perform allocated tasks according to CONOPs scenarios (i.e. abstracted scenarios, since CONOP studies were not undertaken in this research), denoted as "Mission 1" and "2". In this study, 60 USVs are deployed from a single mothership, 20 of them are USVs Type "A" and 40 are USVs Type "B". The vehicles flow through the nodes in the network system, shown in Figure 38, where they perform certain tasks (i.e. activities) following a path (i.e. route) indicated by the connectivity lines that form the particular network structure. The number of vehicles departing from each node in the network system and heading to the next node, according to the indicated path/route, is defined by the routing ratios, which form a $K \times K$ matrix (i.e. network of K nodes). The routing ratios show the number of vehicles heading to node j over the total number of vehicles present at node i . Hence, for the vehicles departing from node i towards node j , the routing ratio is defined as:

$$P_{ij} = \frac{\text{Number of Vehicles of Type "A" (and/or "B") at Node } j}{\text{Total Number of Vehicles (Type "A" and/or Type "B") at Node } i}$$

Any node represents a task in the network system, where the inputted data for this model are given in Table 10. Such data for each node in the network system include, the node name, the node number used in the analysis of the system, the type of the servers per node, the number of servers per node and the processing duration (i.e. service). Table 10, also shows which nodes of the network system refer to either on-board or off-board tasks and highlights whether a node is likely to have an impact on the mothership configuration or/and the operated USVs. The on-board nodes represent facilities and any necessary relevant resources that must be integrated into the mothership configuration, thus directly affecting the overall mothership design. However, the off-board activities do not directly impact the design of a mothership. While the nodes modelling the recovery operations are on-board nodes, their implications on the design

of a mothership only involve the equivalent service area demands (i.e. LARS installation and integration). This is because any recovery queueing activities would take place at sea and not on-board the mothership (i.e. nil queueing area demands). Finally, the facility levels per node reflect the maximum number of vehicles that can be simultaneously served by the servers of each node.

Network Structure Nodes								
Node Name	Node Number	Node Service Area			Node Space Requirement		Ship/Vehicle Impact	On/Off Board Node
		Facility/Server Type	Facility/Server Levels *	Facility Service Time (min)*	Node Waiting Area	Node Service Area		
Quick Pre-Mission Checks	1	Ship Spaces - Complement	10	1	QT Model Output	✓	Ship	On
Handling	2	Overhead Crane	3	7	QT Model Output	✓	Ship	On
Launch	3	Crane	1	8	QT Model Output	✓	Ship	On
	4	Stern Ramp	1	5	QT Model Output	✓	Ship	On
	5	Davit	1	7	QT Model Output	✓	Ship	On
Mission Theatre	6	Sea Space	∞	180	NA	NA	Vehicle	Off
	7	Sea Space	∞	240	NA	NA	Vehicle	Off
Malfunction at Sea	8	Sea Space	∞	45	NA	NA	Vehicle	Off
Refuel and Ordnance Station	9	Refuel and Ordnance Hub Type 02	5	10	NA	On-station platform	Vehicle	Off
	10	Refuel and Ordnance Hub Type 01	5	14	NA	On-station platform	Vehicle	Off
Recovery	11	Crane	1	9	NA	✓	Ship	On
	12	Davit	1	8	NA	✓	Ship	On

Node Name	Node Number	Node Service Area			Node Space Requirement		Ship/Vehicle Impact	On/Off Board Node
		Facility/Server Type	Facility/Server Levels *	Facility Service Time (min)*	Node Waiting Area	Node Service Area		
Troubleshooting, Maintenance and Repair	13	Ship Spaces - Complement	10	20	QT Model Output	✓	Ship	On
	14	Ship Spaces - Complement	10	25	QT Model Output	✓	Ship	On
Refuelling	15	Pump Type 02	5	5	QT Model Output	✓	Ship	On
	16	Pump Type 01	5	7	QT Model Output	✓	Ship	On
Rearming	17	Ship Spaces - Complement	10	8	QT Model Output	✓	Ship	On
	18	Ship Spaces - Complement	10	11	QT Model Output	✓	Ship	On
Stowage/Handling	19	Overhead Crane	3	7	QT Model Output	✓	Ship	On

* The values of the facility levels and processing times provided in this table are indicative, in order to demonstrate the tool's capabilities and do not necessarily represent actual model derived data or realistic values

Table 10: Description of nodes in the queueing network of Figure 38

4.3 Translation of Queueing Network Modelling into Mission Bay Arrangements

Variations in the selection of the mothership support systems are likely to modify the mission-oriented spaces of the ship, where the vehicles are hosted on-board and are represented as nodes in the queueing network system. For the particular model in this chapter, a simplified schematic representation of a potential mission bay arrangement illustrating only the employed LARSs, modelled as LAR queueing nodes, is shown in Figure 39. In this figure, the flow of USVs through the mission bay towards the LAR facilities is demonstrated with light blue line arrows, while the LAR procedures at the corresponding LAR facilities are indicated with red arrows.

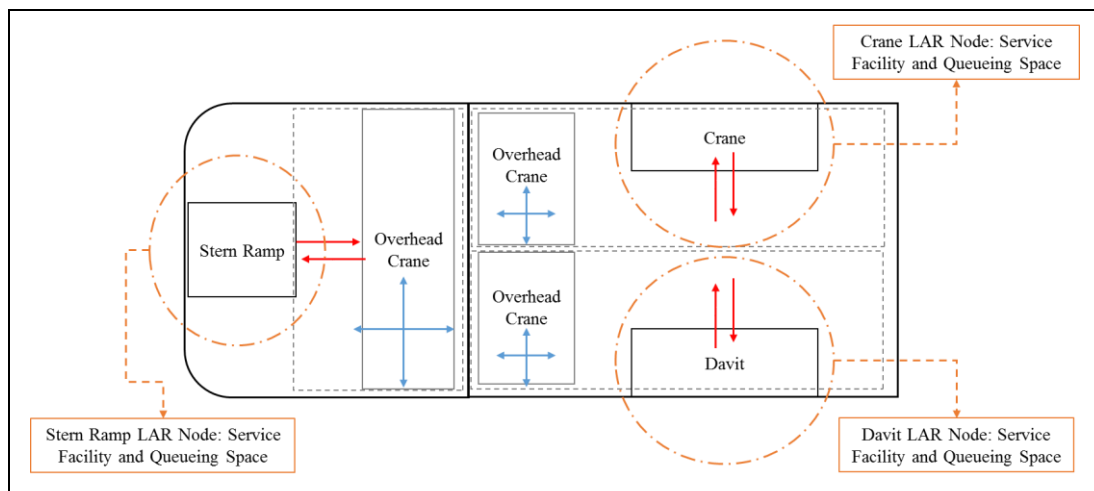


Figure 39: Example configuration of LARSs in the mothership mission bay

The number and size of the USVs accommodated would strongly affect their support facilities and the equivalent spaces on-board the ship, and thus the arrangement and size of the potential mission bay(s), which will have further implications on the design of the mothership. The mission bay(s) can be seen as tractable blocks that can be modified by the ship designer with the aid of the performance measures extracted from the queueing network model. This is further elaborated in the following section (Section 4.4), where the results extracted from modelling the queueing network under study are described and analysed, showing their implications on the configuration and size of a mission bay.

The designer team's judgement, along with dialogue with the requirements owner (naval staff), determine the extent of the mission bay(s) modifications, also depending

on any data available to assess whether the performance criteria for a particular mission bay are met, e.g. LAR time limitations. Subsequently, the mission-oriented blocks would be modified accordingly and thereafter integrated back into the mothership design. Naval architecture CAD software tools can be used to visualise and assess how variations of the mission-oriented spaces would impact the mothership size, configuration and performance requirements. For instance, Figure 40, shows details of a baseline mission bay arrangement and two variations for an OPV design study by Pawling and Andrews (2013), taking into account the LAR areas and the likely range of vehicles to be used during the ship's lifetime, which are subsequently integrated into a USV mothership OPV design, shown in Figure 41 [Pawling and Andrews, 2013].

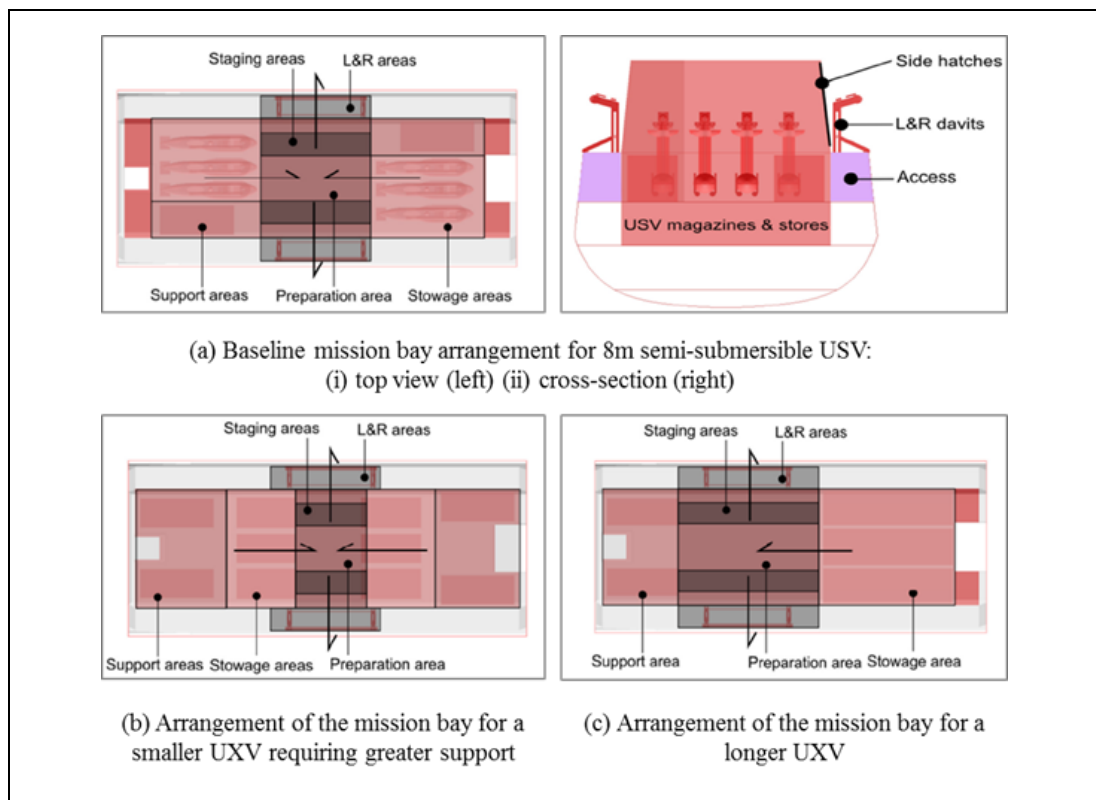


Figure 40: Mothership OPV mission bay arrangements [Pawling and Andrews, 2013]

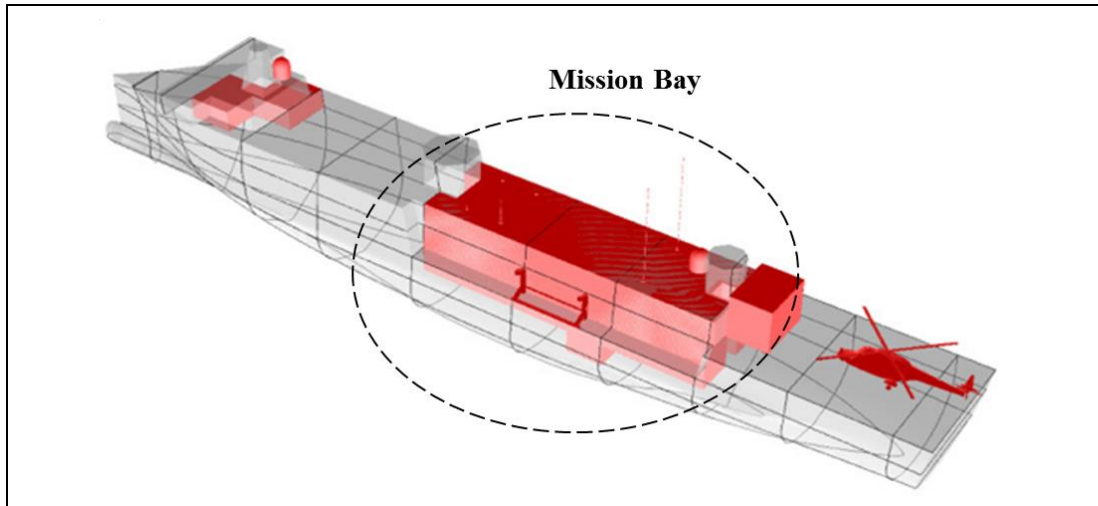


Figure 41: Mothership OPV Fight group elements with the mission bay of Figure 40 being integrated into the ship, as indicated [Modified from Pawling and Andrews, 2013]

4.4 Demonstration of the Capabilities of Queueing Network Tool through Sensitivity Studies

Using the QT tool, the queueing network presented in Figure 38, with the input data provided in Table 10, has been constructed and analysed. The results produced from running the QT tool for the analysis of the particular network for a mission scenario that requires a fleet of 60 USVs, give the measures of performance of the nodes in the network. The results presented in the current section focus on the performance of the nodes that model the launching process from a mothership, in order to demonstrate the QT tool output information and how this can be employed in the ship design decision-making process. The incorporation of the QT tool in the design procedure of a mothership is demonstrated through the following three cases, by assessing the performance of the relevant launching nodes and how this information can be translated into the implications for the design and the launching capability of a mothership, as shown in Table 11:-

- Case i** The implication of the number of USVs (M) on the design of a mothership, for a given set of LAR facilities on a mothership;
- Case ii** The implication of the number of LAR facilities (C_k) on the design of a mothership, for a given fleet of USVs;
- Case iii** The implication of the type of LAR facilities on the design of a mothership, for a given fleet of USVs. Distinct types of LAR equipment provide different LAR service time per vehicle (T_k), which has been defined using manufacturer system specifications. More enhanced and sophisticated LARSs are likely to provide faster means of LAR per vehicle (i.e. lower T_k).

The performance of the launching nodes is quantified using the metrics extracted from the QT. These metrics are:

- The total time spent to launch a number of USVs by employing a particular LARS. This can define the mothership's launching capability, since different means of launching would provide a distinct ship launching capability;

- The number of USVs waiting in the queue in front of a particular launching facility, which along with the service facilities would then demand additional space on the mothership.

The number of USVs in a queue at each of the launching nodes that represent a particular LARS, along with the number and type of the employed LARSs are indicators of the space and on-board service demands on the mothership.

	Node Performance		Ship Impact
	Total Launching Time	Number of USVs Queueing	
Number of USVs (M)	✓	✓	<ul style="list-style-type: none"> • Mothership size: <ul style="list-style-type: none"> - Spatial demands - On-board services - Complement demands • Mothership configuration • Mothership performance
Number of launching facilities (C_k)	✓	✓	
Service time of launching facility (T_k)	✓	✓	

Table 11: Impact of USVs and launching facilities on launching node performance and mothership design

The aforementioned three cases are presented in the following sub-sections (i.e. Sub-Sections 4.4.1, 4.4.2 and 4.4.3).

4.4.1 Case i: Implication of the Number of Uninhabited Assets on the Equivalent Node Performance

For a given set of launching facilities (e.g. one crane, one davit and one stern ramp), as described in Table 10, the QT code has been run for 15, 30, 45 and 60 uninhabited assets present in the network system (M), where each launching facility, i.e. crane, davit and stern ramp, has been set to serve/launch 5, 10, 15 and 20 of the 60 USVs of the fleet, respectively, by changing the routing ratios in the QT network.

The total time to launch the pre-set number of USVs from each launching facility (N_k) is shown in Figure 42, which demonstrates the total time spent at each LARS for an increasing number of vehicles. The time the vehicles spend in each launching node is

the summation of the service time provided by the particular launching facility/server (T_k) to serve a vehicle, plus the queueing delay/time that is the time the vehicles wait in front of the launching equipment in order to be served. While the vehicles flow through the network system they might have to wait in the queue until getting served, and would then pile up due to the restricted number of servers. For a given number of launching servers, the time spent at the relevant node increases, due to the queueing delay incurred as more and more vehicles spend time in the queue, since the service time (T_k) of a particular server type is assumed to be constant. For the same number of servers at each of the launching nodes (i.e. one crane, one davit and one stern ramp) and number of vehicles being served at each one of these nodes, the total time to launch the same number of USVs from the various LARSs differs, due to the distinct service time of each launching facility type (i.e. $T_{\text{Ramp}} < T_{\text{Davit}} < T_{\text{Crane}}$), stated in Table 10.

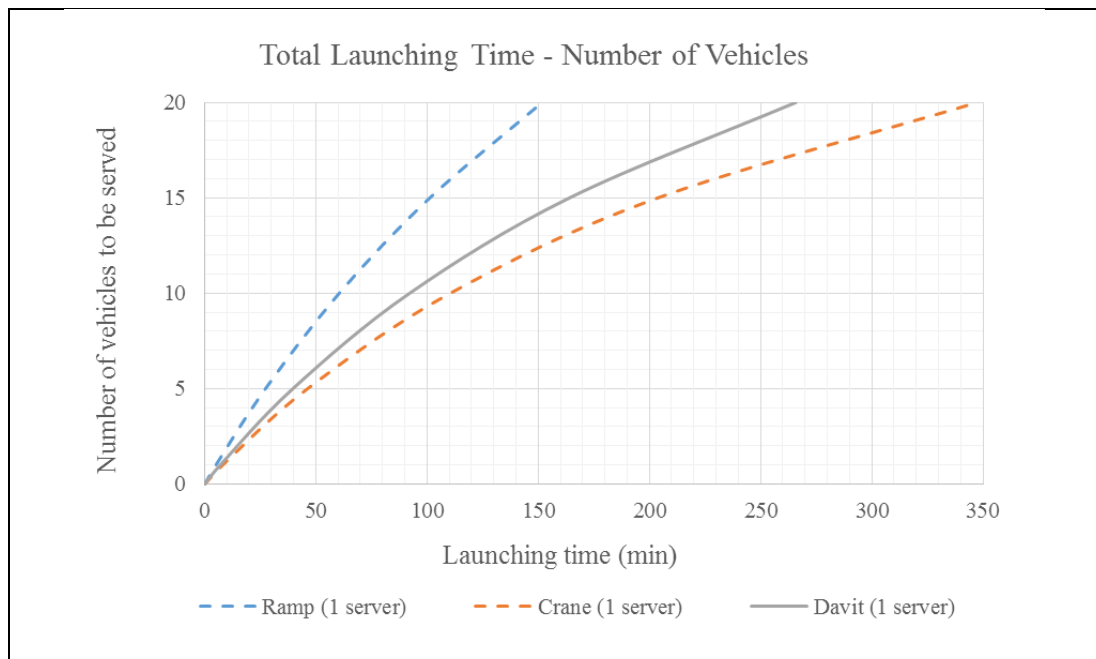


Figure 42: Cause and effect of the total time spent at launching facilities on the number of USVs to be launched from the particular facilities for the test mission scenario

Each node of the network system that represents an on-board mothership task entails space demands for the facilities providing the appropriate service (i.e. node service area), as well as further space allowance that might be required for any vehicles that have to wait in a queue ahead of a particular server to be served (i.e. node waiting area). Since the space requirement for a node's service area is defined from the employed launching facility, i.e. crane, davit and stern ramp, the node space demand for the equivalent waiting area, where the vehicles might need to queue and wait to be

served from the appropriate facility, then is defined by the number of vehicles in the queue. The queue length (N_{qk}) at each launching facility is shown in Figure 43, where for the given number of launching servers (i.e. one crane, one davit and one stern ramp) the number of vehicles in a queue increases as the number of the vehicles to be launched from these facilities increases. Thus, for the same number of servers at each node (i.e. one crane, one davit and one stern ramp) and requests (i.e. number of vehicles to be launched from each facility is equal), the queue length formed in front of each launching facility is higher for the nodes with the launching facilities that have the higher service time.

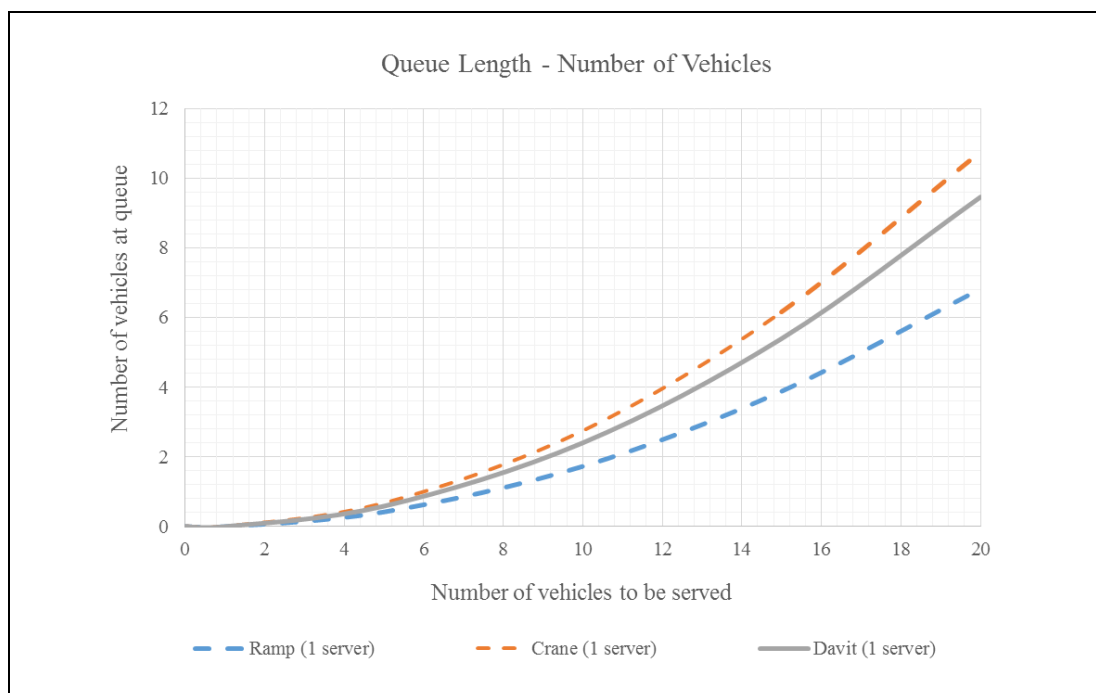


Figure 43: Cause and effect of the queue length at launching nodes on the number of USVs to be launched from the particular facilities for the test mission scenario

4.4.2 Case ii: Implication of the Number of Launching Facilities on the Equivalent Node Performance

For 60 vehicles present in the network system, where each launching facility, i.e. crane, davit and stern ramp, has been set to serve/launch 20 of the 60 USVs in total, the QT code was then run for twice the number of launching facilities available at each launching facility compared to case (i), i.e. two cranes, two davits and two stern ramps. When the number of launching facilities to provide the appropriate service increases, then the performance of the pertinent nodes with the mothership's launching capability enhances. This is verified by the metrics obtained from running the QT tool, as shown

in Table 12. Table 12 also provides a comparison to the "Design 1" that is a mothership design option with single LARSs (i.e. one crane, one davit and one stern ramp):-

- The total time required to launch 20 USVs from each launching node is decreased by 31%, 42% and 48% for the launching nodes of the network that represent the ramp, davit and crane system, respectively;
- The waiting space in front of the launching facilities, required for the USVs that pile up and wait to be served, is decreased. This is observed from the number of USVs in the equivalent queues of each launching node that is decreased by 86%, 80% and 82% for the launching nodes of the network that represent the ramp, davit and crane system, respectively.

Mothership	Node	LARS Type	Service Time (min)	No. of LARS	Total Launching Time (min)	No. of USVs in Queue
Design 1	Ramp	X	5	1	148	7
	Davit	X	7	1	255	10
	Crane	X	8	1	329	11
Design 2	Ramp	X	5	2	103	1
	Comparison to Design 1 (%)				- 31	- 86
	Davit	X	7	2	148	2
	Comparison to Design 1 (%)				- 42	- 80
	Crane	X	8	2	172	2
	Comparison to Design 1 (%)				- 48	- 82

Table 12: Performance of the launching nodes for twice the number of LARSs

In the case of deploying a fleet of USVs of 60 assets by employing two cranes, two davits and two stern ramps, the size, configuration and performance of the resultant mothership (i.e. Design 2) would be distinctly different to the one fitted with single crane, davit and stern ramp (i.e. Design 1), since the employment of a greater number of LARSs entails further space requirements on the mothership, albeit fewer queueing spaces. For instance, for a mothership to accommodate two adjacent stern ramps, this is likely to entail excessive stern width. The performance of the resultant mothership "Design 2" with respect to the launching capability is enhanced compared to mothership "Design 1", since less time is required to launch a fleet of 60 USVs as indicated by the faster processing launching nodes (i.e. Design 1:- Ramp = 148 min; Davit = 255 min; Crane = 329 min, whereas Design 2: Ramp = 103 min; Davit = 148 min; Crane = 172 min).

4.4.3 Case iii: Implication of the Type of Launching Facilities on the Equivalent Node Performance

For 60 vehicles present in the network system, where each launching facility, i.e. crane, davit and stern ramp, has been set to serve/launch 20 of the 60 USVs in total, the QT code has been run for different types of launching facilities. A single LARS is employed per launching node with a slower service processing type than in "Design 1", since different types of servers might be a slower (or faster) means of launching. In this case the service time for the crane, davit and stern ramp system is 11 min per US, 10 min per USV and 9 min per USV, respectively. By employing less sophisticated LARSs with higher service time per vehicle to provide the appropriate service (i.e. launch) required by the number of USVs at each of launching nodes in the network, it was observed that the performance of the pertinent nodes and thus the mothership's launching capability is diminished compared to mothership option "Design 1". This is demonstrated in Table 13, where the appropriate queueing metrics were obtained from running the QT tool for the different types of servers available at the launching nodes, and compared to "Design 1":-

- The total time required to launch 20 USVs from each launching node is increased by approximately 173%, 102% and 102% for the launching nodes of the network that represent the stern ramp, davit and crane LARS, respectively;
- The space required in front of the launching facilities, as waiting areas for the USVs that pile up and wait to be served is increased. This is observed from the number of USVs in the equivalent queues of each launching node that is increased by nearly 71%, 30% and 27% from the launching nodes of the network that represent the stern ramp, davit and crane LARS, respectively.

Mothership	Node	LARS Type	Service Time (min)	No. of LARS	Total Launching Time (min)	No. of USVs in Queue
Design 1	Ramp	X	5	1	148	7
	Davit	X	7	1	255	10
	Crane	X	8	1	329	11
Design 3	Ramp	Y	9	1	405	12
	Comparison to Design 1 (%)				173	71
	Davit	Y	10	1	516	13
	Comparison to Design 1 (%)				102	30
	Crane	Y	11	1	665	14
	Comparison to Design 1 (%)				102	27

Table 13: Performance of the launching nodes for different types of LARSs

It is expected that different types of crane, davit or stern ramp systems could provide a specific service time, as estimated by the manufacturer. More sophisticated and technologically advanced LARSs should produce faster means (i.e. lower service time) of deploying USVs. In the case of launching a fleet of USVs consisting of 60 vehicles by employing a slower type of crane, davit and stern ramp system (i.e. Design 3), may have implications on the size, configuration and the performance of the resultant mothership, compared to the ones that are more technologically advanced (i.e. Design 1). This is due to the likely different footprints of the LARSs, the potential incurred variations of the on-board service requirements, as well as the need for further queueing spaces, as more vehicles pile up in queue at the launching nodes of Design 3 than for Design 1. As presented in Table 13, the performance of the mothership with respect to its launching capability is reduced in the case of mothership "Design 3" when compared to mothership "Design 1", since more time is required to launch a fleet of 60 USVs, due to the slower means of processing USVs for deployment.

It is worthwhile mentioning that the three case studies, analysed above, demonstrated that the model produces suitable metrics and results. These can be meaningful for the design process of a UXV mothership in regard to defining the ship's LAR capability. Thus, they give the total time required to deploy and retrieve a given fleet of UXV. They also enable assessment of the UXVs impact on the ship configuration, in terms of the space demands for the various on-board UXV-related service facilities and the potential queueing effects ahead of those servers.

4.5 Resultant Tool's Characteristics from Demonstrating the Capabilities of Queueing Network Modelling

The model demonstrated in this chapter might not represent the analysis of a realistic mothership design option, due to the use of generic UXV combinations, as well as invented (but plausible) equipment and system specification. An arbitrary fleet of 60 USVs, consisting of 20 vehicles of Type "A" and 40 vehicles of Type "B", operated from a single mothership, has modelled the flow through the service facilities of a UXVs-mothership system. The purpose of this demonstration is:-

- To demonstrate and confirm the capabilities of the QT tool when applied to a mission scenario;
- To provide an indication of how the information resulting from such model can be integrated into the mothership design procedure, hence providing guidance to enable decision-making;
- To look at the veracity and sensitivity of the tool, by altering certain input parameters.

The information that can be extracted from the use of the QT tool, could be inputted into the ship design procedure for a potential UXV mothership, with regards to the necessary equipment and systems, as well as any service demands on the ship to be able to support a given fleet of uninhabited assets. The information seen as most appropriate to make decisions regarding a mothership design can be divided into two aspects. The first addresses the node performance that can be employed as a means to define the relevant mothership UXV support capability. Among the nodes of a UXVs-mothership network, the nodes modelling the appropriate LAR activities and the equivalent measures of performance can indicate a mothership's LAR capability. The LAR capability of a mothership is seen to be a meaningful metric, as it can be a proxy measure of operational effectiveness for a potential mothership design, since the faster a fleet of UXVs can be launched towards the theatre of operations and recovered on-board once the mission is completed, the more efficiently a mission should then be. This is due to the importance of the employed LAR methods, since LARSs are the means of initiating and completing a mission. The second aspect addresses the space demands for the number and types of on-board UXV service facilities, as well as any

queueing space demands that might be incurred ahead of the service facilities of each node while the vehicles wait to be served. Beyond the modelled space service and queueing space demands, a node might entail further ship requirements on ship services, including personnel and electrical power, which altogether influence the configuration of the ship. Consequently the metrics useful to the mothership design process are summarised in Table 14.

UXVs-Mothership Network Metrics			
Nodes	Impact	Metric	Measure
LAR	Mothership capability	Time	Measure of the total time required to provide the appropriate service meeting a number of requests (i.e. vehicles) at the relevant facility (i.e. LARS)
On-Board	Mothership design	Number of servers	Measure of the space required for the facilities (i.e. LARSs) that provide the appropriate service (e.g. LAR)
		Number of queueing spaces	Measure of potential waiting space required in front of the facility that provides the appropriate service

Table 14: UXV-mothership network metrics employed in the design process of a potential mothership

The QT tool could be employed to analyse different UXVs fleet operational scenarios, in order to gain an insight into how these are likely to drive the design of potential UXV motherships. Modifications to the employed on-board UXV support equipment and systems can be captured through the metrics provided by the queueing network modelling. Such alterations are expected to have an impact on the LAR capability of a UXV mothership, as well as resulting in distinctly different mothership solutions, due to their implications on the configuration of the ship's mission bay(s). Therefore, such metrics can be used in the investigation and assessment of distinct UXV mothership design options, such as those investigated in Chapter 5.

Chapter 5: Mothership Design Case Studies

5.1 Introduction

This chapter consists of two main sections, describing the development of the UXV mothership designs that were used to demonstrate the application of the evaluation approach outlined and exemplified in the previous two chapters.

The first section outlines the development of a baseline mothership design. The main ship performance requirements and major equipment chosen are justified, followed by the description of ship complement and the resultant major ship characteristics adopted. Moreover, certain ship design analyses were produced on resistance/powering and stability, together with a deck plan and UPC estimate. The second section describes the mothership design variants that were developed in order to investigate the effects of various architecturally driven changes (i.e. incremental (small) and step (big) design changes) in the mission bay spaces, also compared to those of the baseline mothership design. The impact of integrating the resultant mission-oriented spaces into the overall mothership configuration and the incurred UPC are presented. A comprehensive discussion of the results and wider ship design implications can be found in Chapter 7.

The queueing analyses performed to define the mission bay service facilities and queueing demands, which resulted in the distinct mission bay arrangements that were then integrated in the mothership design options presented in this chapter, are given in Chapter 6. Additionally, the impact of such mission bay variations on the measure of each mothership's LAR capability/performance, as an indirect measure of operational effectiveness, is also presented in Chapter 6.

5.2 Baseline Mothership Design

The basis behind producing the baseline mothership design was to develop a balanced (i.e. weight, space, speed, range, power and stability) ship design at (pre) concept level. Therefore, subsequent investigations of mission bay variations on the mothership design could be conducted using the proposed mothership design approach through variants of this baseline study. Without relying on any existing detailed design solutions and data, a broad specification for a UXV mothership was drawn up, in order to define the performance requirements and the appropriate payload equipment listing, using the UCL (2014 b) warship database. The baseline USV mothership design for this research was produced in accordance with the procedure, data and parametric relationships available for the ship design module in the UCL MSc Naval Architecture course [UCL, 2014 a and b] and where necessary other published data sources, including machinery [Vijlee et al., 2007] [Roll Royce, 2018 a and b] and LARSs data [VestDavit, 2018] [Eriksson and Ringman, 2010].

The following sub-sections describe: Main mothership performance requirements and major payload equipment selection; Complement and accommodation breakdown; Major mothership characteristics; Resistance estimation and powering; Stability assessments; Internal arrangement; and Mothership procurement costing. Since the UCL DRC has pursued an approach to reduce the reliance of ESSD research on fully sophisticated 3D CAD software, with high learning demands, like Paramarine, a number of ship design aspects were not considered in this research. This is because of the limited number of analytical tools provided by JavaScript concept ship design tool compared to (say) Paramarine. Consequently:-

- Damage stability was not extensively investigated. A simplified damage stability assessment was performed for a limited number of damage cases, by employing simplifying assumptions to perform relevant calculations (explained later in this chapter);
- A proper structural design consideration, including the extraction of wave-induced bending moments, amidships section structural analysis and grillage design were not carried out, since such assessments are normally not considered until post-concept (feasibility studies). However, structural considerations were considered to ensure that structural continuity was

addressed throughout the ship at a broad level. This was achieved through locating appropriate transverse bulkheads along the ship, including the forward and aft ends of the superstructure and the after cut-up. Moreover, the overall ship length to amidships hull depth ratio was ensured to be within limits (i.e. should be less than 12 [Chalmers, 1993]);

- Seakeeping performance of a potential mothership was not considered, although it might be a crucial factor for conducting relevant LAR operations. Such issues were restricted to the assumption that motion compensating LARs would be adopted, enabling LAR operations from surface ships up to Sea State 6 (as is the aim by LAURA project [Knight, 2013]). Furthermore, the likely size of the vessel (over 150 m length) would mean that seakeeping problems that occur with frigate size vessels would be far less prominent;
- Manoeuvring was not examined given the very early stage nature of the mothership design;
- Survivability issues were limited to zoning considerations, where major ship systems were duplicated and separated (e.g. power generation, chilled water, high-pressure air, sea and fresh water generation, air-conditioning and ventilation), as well as to locating certain significant ship spaces far from each other (e.g. Operations Room, Ship Control Centre and Bridge).

Although it is acknowledged that the proper development of a mothership design would require all the above design aspects to be thoroughly investigated, issues considered to be more relevant to an early evaluation of the implications of a USV fleet on the mothership were prioritised, consistent with the focus of this research.

5.2.1 Mothership Performance Requirements and Payload Selection

In discussions with BAE Systems (25/07/2017), the main ship performance requirements were based on broad specifications of a prospective USV mothership, while major weapon systems were selected for meeting the ship's self-defence. The payload equipment incorporated into the baseline USV mothership design and the main ship performance requirements, are shown in Table 15 and Table 16, respectively.

Payload Equipment	Quantity	Description	
Weapon and Missile Systems			
CIWS Phalanx	2	Point-defence system against missiles and aircraft	Guns
MSI Seahawk 30mm automated small calibre gun control	4	Automated small calibre naval artillery as general ship protection system	
GAU-17/A minigun	8	Machine gun as general ship protection system	
CAMM missile vertical launching system of 64 cells	64	Point-defence system against missiles and aircraft	
Sting Ray torpedoes	20	Anti-submarine lightweight torpedoes (launched from helicopter)	
Electronic Warfare Systems			
Raytheon AN/SLQ-32 (V.3) shipboard ESM and ECM	1	EW system with radar jamming capability	
SRBOC NATO standard decoy launching System	2	Aerial jammer for defence against incoming missiles	
Torpedo Decoy Launchers	2	Torpedo decoy system	
Radars			
Royal Navy type 1007	2	Navigation	
Type 997 3D Artisan radar	1	3D air surveillance	
Communications			
Astrium SCOT-5 SATCOM	2	SHF Naval satellite communications	
Aerial	1	Ship communications system (generic definition)	
Aerial	1	UXV communications system (generic definition)	
Habited Vehicles			
7 m standard navy RHIB	2	Ship boats-transport vehicle	
Westland Merlin helicopter	1	Helicopter for ASW	
UXVs			
Northrop Grumman MQ-8C Fire Scout (VTUAV)	4	ISR, light attack role, C3 hub	UAVs
USV Type "A" - 11 m RHIB	20	Role: Subject to CONOPs (Broad operational assumptions)	USVs
USV Type "B" - 6 m	40	Role: Subject to CONOPs (Broad operational assumptions)	

Table 15: Baseline mothership design payload based on broad specifications of a prospective USV mothership and typical UCL warship database items (2014 b)

Main Ship Performance	Requirement
Cruise speed (task group escort) (kts)	18
Maximum speed (kts)	25
Fuel range (Nm at kts)	7500Nm at 18kts
Stores endurance (days)	60

Table 16: Baseline USV mothership design main performance requirements

5.2.2 Overall Mothership Complement and Accommodation Spaces

An in-depth study of mothership's complement, i.e. Officers, Chief Petty Officers (CPOs), Petty Officers (POs) and Junior Rates (JRs), was not considered appropriate, due to the limited information available at this very early stage of mothership design. This is considered acceptable, as the end results are comparative and a reasonable complementing level was adopted (i.e. neither excessive nor assuming a highly automated outfit). From discussion with BAE systems (13/12/2017) and reflecting the likely trend to continue to reduce naval ship complements as much as possible, it was suggested:-

- i. A core ship complement of 100;
- ii. USV-related personnel of 60 (i.e. a person per vehicle);
- iii. Flight crew of 20 for aerial modules (i.e. helicopter and UAVs);
- iv. Training and advancements of CPOs, POs and JRs. This was estimated as a function of core complement [UCL, 2014 b], resulting in 10 additional personnel billets.

Taking the above into consideration, the total complement was estimated by the summation of the aforementioned complement groups, by also applying an appropriate margin (i.e. 5%) [UCL, 2014 a], resulting in a total accommodation of 200 people. The breakdown of the complement and hence total accommodation was estimated using empirical ratios and the information available in UCL guidelines on complementing [UCL, 2014 a]. The accommodation spaces were then sized based on the future surface combatant accommodation standards provided by UCL (2014 b). Table 17 shows the breakdown adopted in the baseline USV mothership design.

Rank		Total Accommodation Provision
CO		1
Officers		16
Senior Rates (S/Rs)	CPOs	23
	POs	28
JR's		132
Total		200

Table 17: Baseline USV mothership design accommodation breakdown structure for sizing accommodation spaces

5.2.3 Major Mothership Characteristics, Dimensional Ratios and Hullform Selection

The major ship characteristics and dimensional ratios (including design limits and justifications [Andrews et al., 2012] [UCL, 2014 a]) of the balanced baseline USV mothership design are shown in Table 18 and Table 19, respectively.

Major Mothership Characteristic	Value
Total Enclosed Volume (V_G)	64500 m ³
Deep Displacement (Δ_D)	12660 te
Light Displacement (Δ_L)	8955 te
Overall Density (ρ_s)	0.2 te/m ³
Superstructure Proportion (v_s)	0.24
Payload Volume Fraction (PVF)	0.433
Waterline Length (L_{wl})	162
Overall Length (L_{oa})	170
Waterline Beam (B_{wl})	22
Amidships Upper Deck Beam (B_{UD})	31
Amidships Deep Draught (T)	5.9
Amidships Hull Depth (D)	13.8
Amidships Freeboard (F)	7.9

Table 18: Baseline USV mothership design major ship characteristics

Dimensional Ratio	Value	Suggested Design Limit	Justification
Waterline length to waterline beam ratio (L/B)	7.4	NA	Hullform slenderness ratio, i.e higher ratios refer to higher speed hullforms
Overall length to amidships hull depth ratio (L/D)	12.3	< 12 (at concept phase)	To maintain structural strength of the hull girder without significant structural weight and hence cost impact
Waterline beam to amidships hull depth ratio (B/D)	1.6	> 1.5	For stability purpose
Waterline beam to amidships deep draught ratio (B/T)	3.7	4	To achieve reasonable transverse stability and natural roll periods
Circular M	7	> 5 and < 9	<ul style="list-style-type: none"> - A sensible range of values from a hydrodynamic point of view lies between 5 to 9. Values less than 5 will present resistance and propulsion penalties if wave making drag is significant, whereas values greater than 9 will present structural strength problems [UCL Ship Design Procedure, 2014] - Values greater than 8 would result in narrow and difficult to manufacture compartments at the extremes of length [Andrews et al. 2012]

Table 19: Baseline USV mothership design major ship dimensional ratios

Normally the initial selection of a hullform's coefficients is made based on the ship's speed-power and speed-time profile requirement, as well as on stability considerations. In ESSD, it is typical for the designer to draw on existing designs, which are similar to their design, in terms of displacement and speed requirements, in order to get a first estimate of suitable hullform coefficients for the given displacement and speed profile. However, this can act as a starting point and the designer should not restrict their decisions to past designs, but should be driven by emergent requirements informed by concept design studies (i.e. requirements elucidation)

In the parametric survey (part of ship sizing/synthesis) the designer ought to assess their hullform coefficient selection against desired ship performance criteria, including resistance/powering and fuel consumption, stability and seakeeping. In the Feasibility Assessment Phase, the selected hull is investigated with many more hull parameters, including rise of floor, transom area and beam, angle of entry and ship lines. Table 20 shows the ship design speed requirements, design characteristics, dimensional ratios and hullform coefficients for a Landing Platform Dock (LPD) ship design, undertaken in UCL MSc Ship Design Exercise by Rehman et al. (2014). Given this past ship design's speed profile and displacement is (relatively) similar to the UXV baseline mothership design, the hullform coefficients adopted for the latter and the relevant considerations for the chosen values are presented in Table 21 .

Speed requirement	
Cruise speed	18 kts
Maximum speed	22 kts
Design characteristics	
Deep displacement (Δ_D)	14685 te
Gross volume (V_G)	63575 m ³
Waterline Length (L_{wl})	160 m
Overall Length (L_{oa})	165 m
Waterline Beam (B_{wl})	26 m
Amidships Main Deck Beam (B_{UD})	28 m
Amidships Deep Draught (T)	5.7 m
Dimensional Ratios	
Waterline beam to amidships deep draught ratio (Kb)	4.5
Circular M	6.5
Hullform Coefficients	
C_P	0.64
C_M	0.96
C_B	0.62
C_{WP}	0.84

Table 20: LPD ship design requirements and characteristics from past UCL MSc Ship Design exercise [Rehman et al., 2014]

Hullform Coefficients	Value	Justification
Prismatic Coefficient (C_P)	0.65	C_P selection is normally based on the ship's speed requirements and fuel consumption [UCL, 2014 a]
Midship Section Coefficient (C_M)	0.9	C_M selection is based on practical considerations, including:- - Machinery layout considerations, i.e. machinery fit [UCL, 2014 a]; - Docking considerations
Waterplane Area Coefficient (C_{WP})	0.79	$C_{WP} = 2 C_P / (C_P + 1)$ [UCL, 2014 a]
Block Coefficient (C_B)	0.59	$C_B = C_M C_P$ [UCL, 2014 a]

Table 21: Baseline USV mothership design hullform coefficients selection

The top-level weight breakdown for the deep condition of the baseline USV mothership design, including all margins, as well as allowance for items, such as mountings appropriate for noise and vibration attenuation purposes, is shown in Figure 44.

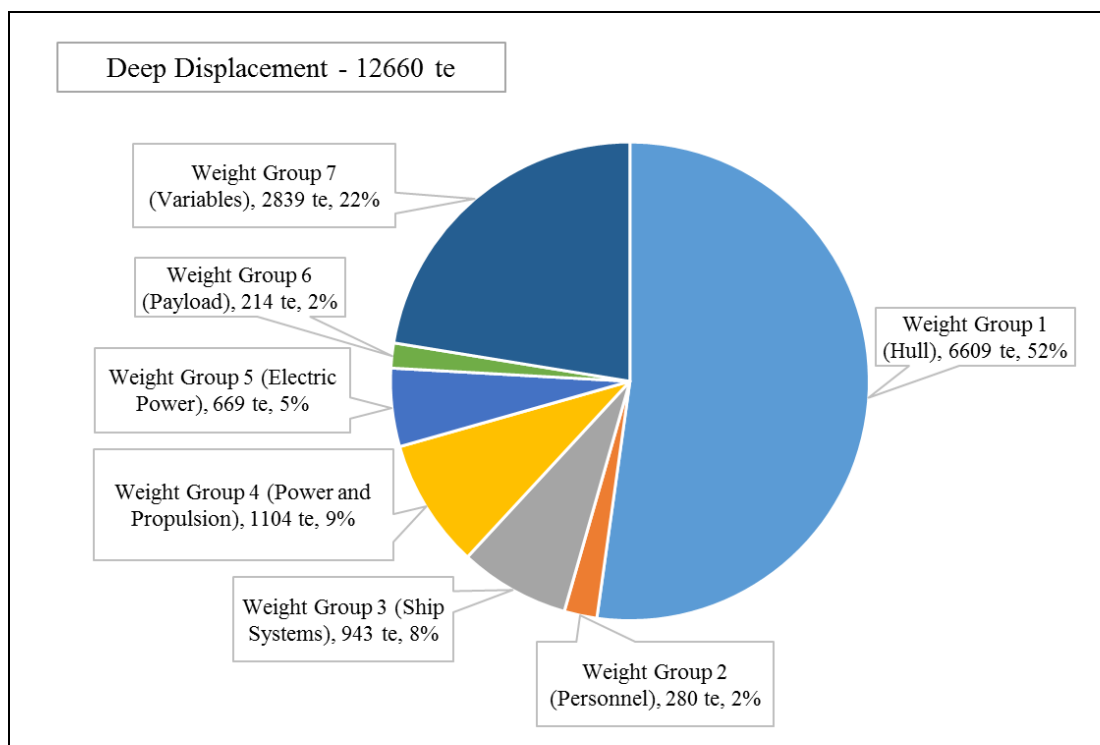


Figure 44: Weight breakdown of the baseline USV mothership design

5.2.4 Mothership Resistance Estimation and Powering

Powering considerations include propulsion and hotel power demands. The total ship resistance and the required propulsion power were estimated using the commonly applied Holtrop and Van Mennen power prediction method [Holtrop, 1984] [Holtrop and Mennen, 1982]. The hotel load was crudely estimated, due to the limited information available at this very early stage of mothership design, taking relevant information on power demands for each weight group items. Such information is provided in UCL Ship Design Procedure (2014 a) and Warship Data (2014 b), including major power demands for: propulsion; air-conditioning and ventilation; chilled water; and payload systems. The required hotel load was estimated to be 8.6 MW, including margins [UCL, 2014 a, b]. Figure 45 demonstrates the power-speed curve (i.e. effective power and shaft power including a sea margin of 20% [Molland et al. 2011]) for the baseline USV mothership design developed for a ship speed range of 0-25 kts. The shaft power at maximum speed, i.e. 25 kts, is 30 MW.

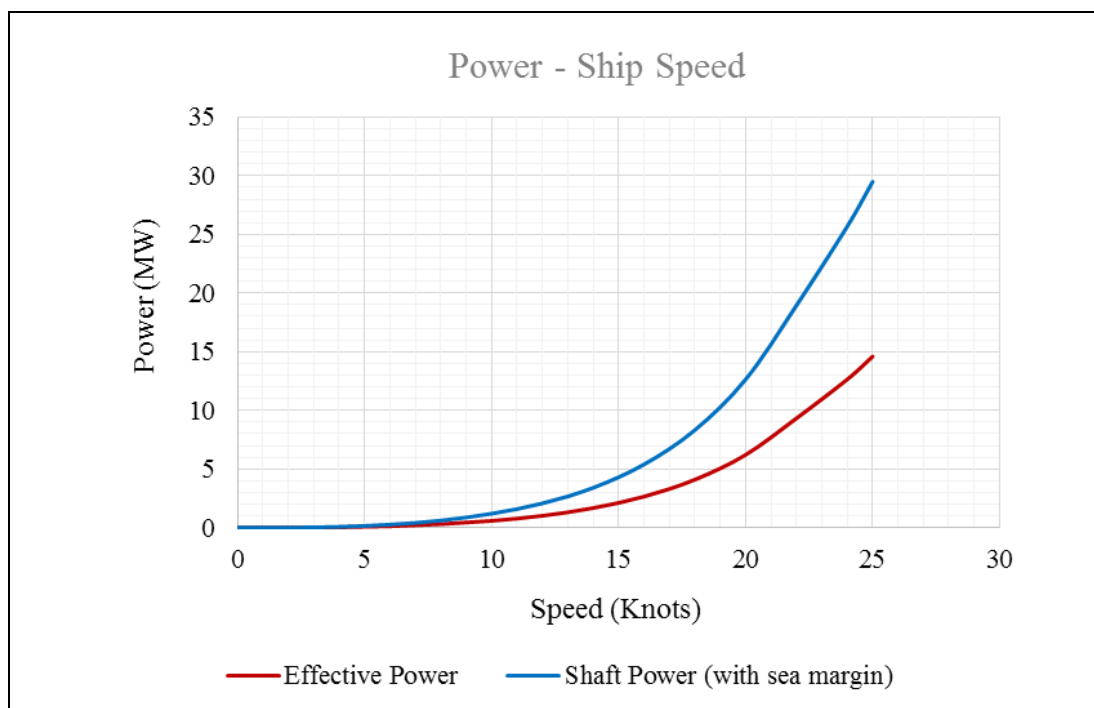


Figure 45: Baseline USV mothership design power speed curve developed using Holtrop and Mennen power prediction method

The selection of main machinery systems for the baseline USV mothership was carried following the Royal Navy's likely preference for adopting an integrated electric propulsion arrangement. Such an assumption was based on the maturity of that type

of arrangement, given it was adopted in the new Aircraft Carrier HMS Queen Elizabeth [U.K. Defence Journal, 2017]. Taking the above into consideration, an integrated electric propulsion arrangement was adopted for the baseline USV mothership design, albeit it could be a costly choice, because:-

- i. It gives more layout flexibility in machinery layout, as there is no need for alignment with shaft lines;
- ii. There is no necessity for gearboxes (i.e. reduction, split and reverse), which are noisy and likely to have great on-board space demands.

The total installed power to meet the estimated hotel load, as well as propulsion power requirements for both cruise and maximum speeds was provided by a mix of diesel generating sets and a gas turbine alternator. The single-mounted (i.e. seatings for equipment's structural support, vibrations dampening/absorbance and noise attenuation (stealth)) diesel generating sets provide low noise signatures and economical fuel consumption while transiting, whereas the gas turbine alternator enables fast sprinting [Bhatt and Arsenie, 2017]. The baseline USV mothership was proposed to consist of four Rolls Royce B32:40V12A2 generating sets of 5.3 MW each and a single Rolls Royce MT30 gas turbine alternator (i.e. 30 MW), thus providing a total installed power of approximately 52 MW.

5.2.5 Evaluation of Mothership Stability

5.2.5.1 Transverse Intact Stability Analysis

Transverse intact stability analysis was carried out for only the Deep Displacement, given that the JavaScript concept ship design tool is currently unable to provide hydrostatics data relevant to ship's waterline dimensions (i.e. length and beam) and draught depending on the loading condition (i.e. ship displacement). The transverse stability assessments were carried out using a stability analysis tool developed by Ali (2003), as part of an MSc dissertation project at UCL and it was based on the regression analysis of 98 hullforms (hullform criteria, as indicated by the tool, were met, for the tool's usage in assessing the mothership's stability). The results produced for the baseline USV mothership were evaluated against the Defence Standard 02-109 (NES 109) [U.K. MoD, 2000], summarised in Table 22.

Intact Stability Assessments	Defence Standard 02-109
Area under the GZ curve up to 30°	Not less than 0.08 m rad
Area under the GZ curve up to 40°	Not less than 0.133 m rad
Area under the GZ curve between 30° and 40°	Not less than 0.048 m rad
Maximum GZ value	Not less than 0.3 m
Angle of the maximum GZ value	Not less than 30°
GM fluid value	Not less than 0.3 m
Angle of vanishing stability	The minimum design aim is 70°

Table 22: Shape criteria for the GZ curve [U.K. MoD, 2000]

Given the approach by Ali (2003) is not capable of performing all necessary checks indicated by Defence Standard 02-109 [U.K. MoD, 2000], then basic naval architecture approaches were used in order to complete the assessments. These approaches include:-

- The value of metacentric height (i.e. GM) was estimated by finding the intersection between the tangent going through the GZ curve at small angles (i.e. approximately 0-10°) and the ordinate of 1 radian (i.e. 57°). Vertical centre of gravity (KG) was estimated by the weight allocation of equipment and systems along the ship (i.e. weight moments of DBBs), which resulted from the disposition of DBBs forming the mothership layout shown in Sub-Section 5.2.6;
- The appropriate areas under the GZ curve were approximated by employing the Trapezoid rule for numerical integration purposes, i.e. constructing (fitting) an appropriate number of trapezoidal shapes to estimate the areas underneath the GZ curve, as seen in Figure 47.

Moreover, the tool developed by Ali (2003) does not account for the free surface effects caused by the liquid tanks. Hence, the GZ curve had to be corrected. This was achieved following the proposed approach by Rawson and Tupper (2001). Given that in order to define the corrected GZ curve for multiple angles of heeling cannot be easily achieved without the use of computerised integrators, since ship tanks are usually not simple geometric shapes, it is therefore necessary to employ simplifying assumptions as proposed by Rawson and Tupper (2001). In addition to this, for the purpose of correcting the GZ curve, the ship tanks were simplified to appropriate geometric shapes (i.e. triangle, trapezium or rectangular). According to this approach, in order to correct a GZ curve for the free surface effects, it is common practice to

compute the GZ value for an angle of heeling of 45° allowing for the free surface. The corrected GZ curve up to 45° inclination is then constructed by drawing the curve through the corrected GZ value at 45° , following the general character of the uncorrected GZ curve. For angles greater than 45° , the reduction of GZ at 45° is applied as a constant correction, as shown in Figure 46.

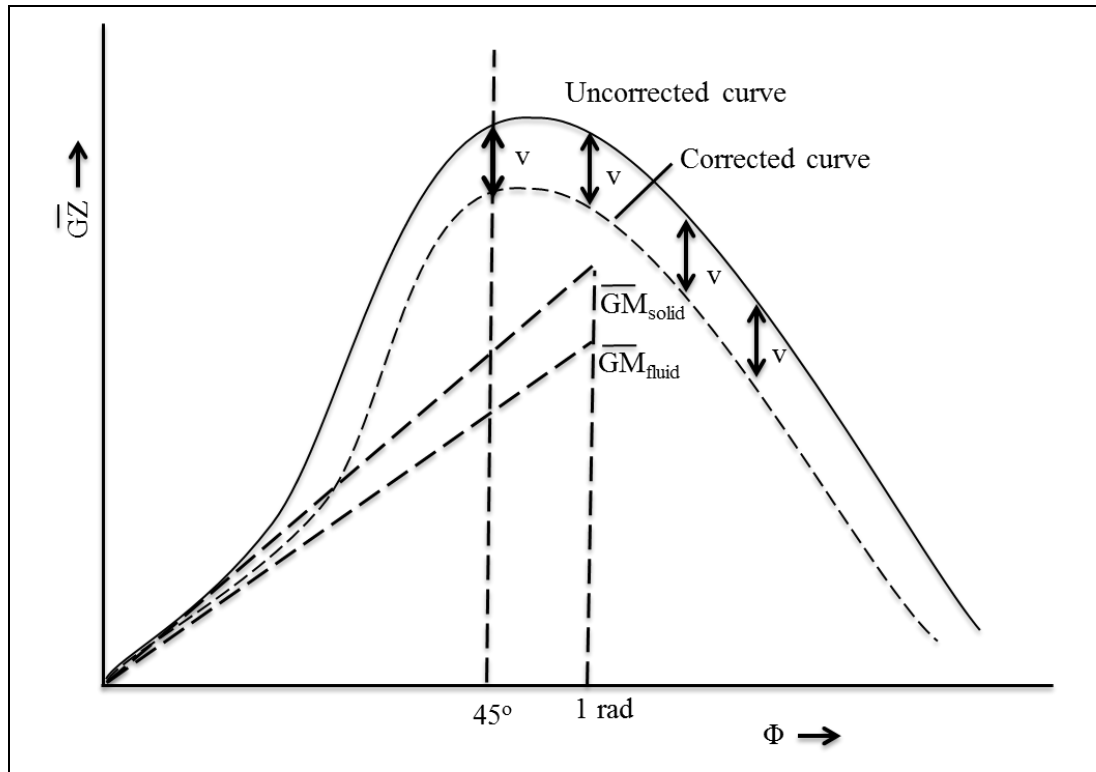


Figure 46: The method by Rawson and Tupper (2001) to correct the GZ curve for free surface effects

The uncorrected GZ curve for the deep condition for the baseline USV mothership design was produced employing the procedure developed by Ali (2003) and was then corrected following the approach proposed by Rawson and Tupper (2001). The metacentric height for both the uncorrected (i.e. GM_{Solid}) and corrected (i.e. GM_{Fluid}) GZ curve was then estimated by finding the intersection between the tangent going through the GZ curve at small angles (i.e. $0-10^\circ$) and the 1 radian ordinate. Moreover, the areas under the corrected GZ curve were estimated using the Trapezoid rule.

The evaluation of the transverse intact stability for the deep condition of the USV baseline mothership design is shown in Figure 47, which also provides a graphical demonstration of the aforementioned trapezoidal procedure. The results were tested against the Defence Standard 02-109 and are shown in Table 23, indicating a pass in

all categories. It is noteworthy that the GZ curve at initial angles (i.e. approximately 0-25 degrees) is likely to display a "trough", hence the gradient fitted at small angles (approximately 0-10 degrees), in order to estimate the metacentric height is shown in Figure 46. However, the approach by Ali (2003) does not take into account this point of inflection, thus the metacentric height (GM) is likely to be overestimated. The consequences of such an eventuality might need checking as it could lead to too stiff a roll motion.

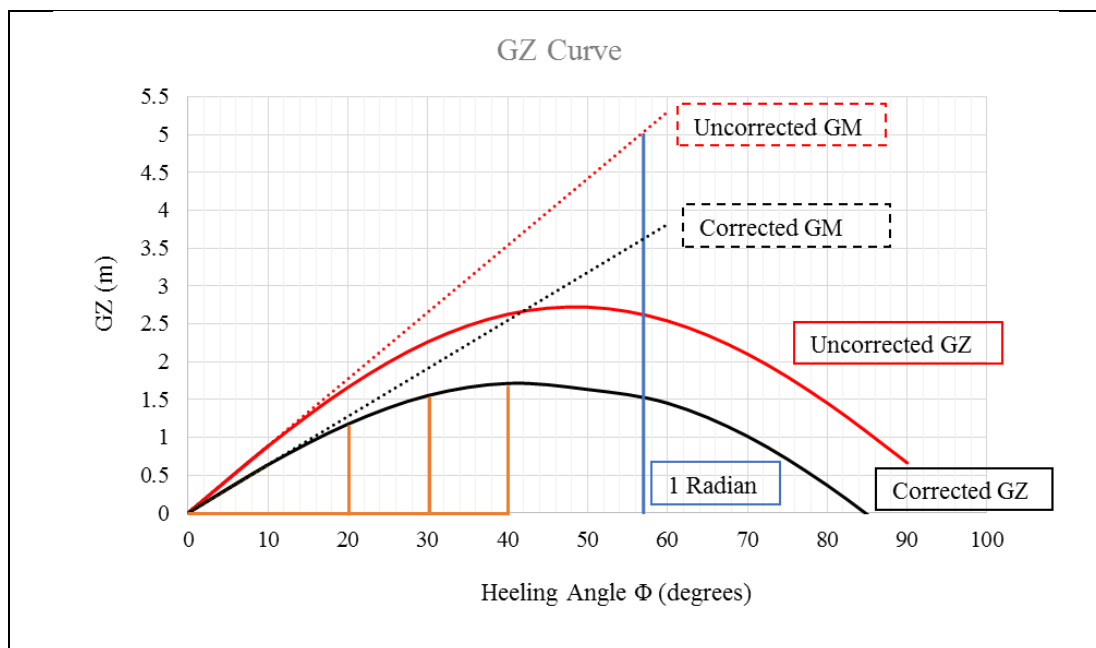


Figure 47: Baseline USV mothership design curve of statical stability for the deep condition with free surface effects correction

Intact Stability Assessments	Defence Standard 02-109	Intact Stability Results
Area under the GZ curve up to 30°	> 0.08 m rad	0.44 m rad
Area under the GZ curve up to 40°	> 0.133 m rad	0.73 m rad
Area under the GZ curve between 30° and 40°	> 0.048 m rad	0.29 m rad
Maximum GZ value	> 0.3 m	2.7 m
Angle of the maximum GZ value	> 30°	50°
GM fluid value	> 0.3 m	3.6 m
Angle of vanishing stability	> 70°	85°

Table 23: Assessment of the baseline USV mothership design for deep condition intact stability against Defence Standards 02-109

5.2.5.2 Damage Stability Assessment

Given the lack of a damage stability analysis tool, damage stability assessment was manually performed employing the "Lost Buoyancy" approach. According to this approach, parallel sinkage, fore and aft trimming of the ship can be calculated for the selected damage cases. A three compartment damage/flooding standard was considered. Compartment's permeability was roughly accounted for each damage case based on permeability factors given in U.K. MOD's Defence Standards 02-109 [U.K. MoD, 2000], shown in Table 24. Given the limited availability of naval architecture analytical tools incorporated into the JavaScript concept ship design tool, it was assumed (i.e. simplification) that symmetrical flooding occurs (given there are no longitudinal bulkheads), thus entailing no heeling effects, in order to perform the appropriate calculations to estimate ship's draught, as well as fore and aft trim levels per damage case. Furthermore, to perform such calculations, it was required the estimation of the centroids of floatation and buoyancy for each damage case examined. Given the lack of computerised integrator, simplifications on the hullform shape (i.e. simple geometrical shapes were fitted, e.g. trapezoids) were adopted to calculate the relevant (i.e. depending on the damage case) waterplane areas and second moment of areas, as well as the pertinent compartment volumes.

Space	Permeability Factor
Watertight Void Compartments and Tanks	97 (warships) 95 (auxiliary vessels)
Workshops, Offices, Operational and Accommodation spaces etc.	95
Vehicle Decks	90
Machinery Compartments	85
Store Rooms, Cargo Holds, etc.	60

Table 24: Permeability factors provided by U.K. MoD Defence Standard 02-109 [U.K. MoD, 2000]

Damage stability assessment studies determine whether the position of the defined damage control deck is appropriate, by estimating the deepest parallel sinkage for the damage cases tested. Therefore, for the worst damage case scenario, the deepest parallel sinkage draught mark ought to be below the defined damage control deck, as shown in Figure 48. If such criteria are not met, then design modifications should be

performed, such as internal arrangement, including number of decks, deck heights and hull depth, as well as position and number of transverse bulkheads.

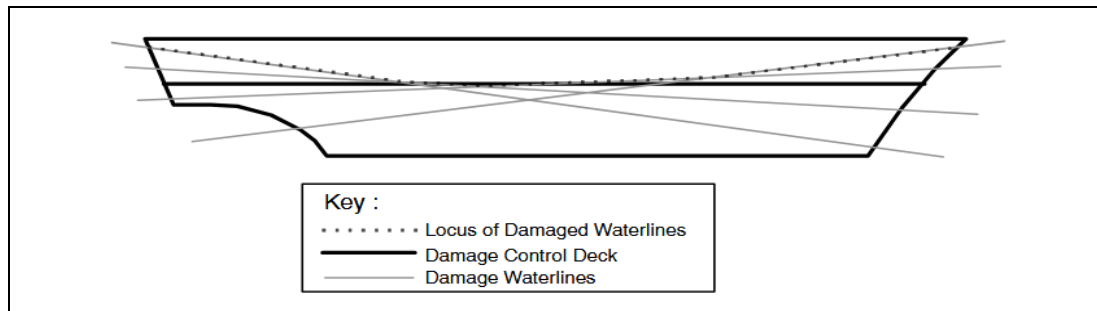


Figure 48: Envelope of damage waterlines [U.K. MoD, 2000]

The results for the damage cases assessed for the baseline USV mothership design are shown in Table 25, and describe the parallel sinkage (i.e. damaged draught) and fore and aft trim, entailed for each case. It can be confirmed that the defined damage control deck for the baseline design (i.e. No. 3 Deck at 7.8 m above keel, as shown in the following sub-section, where an internal arrangement is provided) is above the deepest immersion (i.e. 7.6 m).

Damage Case	Damaged Compartments (Bulkheads)	Initial Draught (m)	Parallel Sinkage - Damaged Draught (m)	Aft Trim (m)	Fore Trim (m)
1	IJ - FG	5.9	7.6	11.6	5.1
2	HI - EF	5.9	7.6	5.9	9.8
3	GH - DE	5.9	7.4	6.8	8.4
4	FG - CD	5.9	6.8	6.7	7.3
5	EF - BC	5.9	6.4	5.6	7.9

Table 25: Damage stability cases and resultant hydrostatics

The damage stability analysis undertaken cannot be considered entirely correct, due to the simplifications mentioned above. Furthermore, potential heeling effects, due to damage, ought to be taken into account for a more comprehensive analysis. Such effects can be assessed through the GZ curve for each damage case (i.e. angle of lol). However, GZ curve at damage cannot be produced given the lack of an appropriate analytical tool. At this very early stage of the USV mothership design it was considered that the damage stability results are reasonable for such a size and type of vessel as that produced. At Feasibility Phase (of the emergent/selected design), an in-depth damage stability analysis should be undertaken.

5.2.6 Internal Arrangement of Mothership

The baseline USV mothership design consists of five internal decks, including the double bottom (i.e. keel, Deck 5, Deck 4, Deck 3 and Deck 2), and two decks on the superstructure (i.e. Deck 1 (or Upper Deck) and Deck 01). No. 3 Deck is the Damage Control Deck, which along with No. 2 Deck, are the passing decks that serve as the main passageway decks each having a single central passageway. The two mission bays, namely stern and amidships, accommodate a different number and type of USVs, specifically 20 USVs Type "A" and 40 USVs Type "B", respectively. The distinct types of USVs were located in different mission bay locations along the ship, because they require different LARSs for the likely LAR operations. Consequently, given USVs Type "A" are launched and recovered via stern ramp LARS, they were located at the stern mission bay. However, USVs Type "B" are deployed via side crane and thus they were placed in the amidships mission bay.

The baseline USV mothership design and its internal arrangement were carried out according to the DBB approach and the relevant UCL functional groups of Float, Move, Fight and Infrastructure for naval vessels, as well as to the desired levels of relationships in general arrangements of naval ships, shown in Appendix 7. Figure 49 displays the baseline USV mothership design internal arrangement produced using the UCL JavaScript concept ship design tool. The DBBs displayed are assigned a nametag, a visible outline, as well as the appropriate colour to distinguish them in the general arrangement as part of a specific functional group through using the DBB functional breakdown colour code, i.e. Float-Blue, Move-Yellow, Fight-Red, and Infrastructure-Green. The internal arrangement also displays: the deck vertical positions measured from the keel; the deck outlines as blue lines; and the disposition of the main bulkheads as red lines.

The baseline USV mothership produced largely reflects U.K. practice for naval combatants (frigate, destroyers), where the design was worked up as a large version of those ships. Such a stylistic option might be questionable. However, the selection of a specific ship style, while important for synthesis [Andrews, 2013], once chosen was then only relevant to the consistent set of options considered. In particular, without an official requirement for a UXV mothership, the design was only necessary to enable

a very early investigation of the implications of operating a fleet of UXVs on the design of a mothership.

Furthermore, the type of USV technology assumed in the baseline USV mothership design and the two design variants is consistent with several sizes of existing USVs. However, the proposed mission bay arrangements and the resultant USV mothership design options could also be adopted to support UUVs. This is due to the generic nature of the proposed USV-related equipment and support systems, as well as to the fact that current UUVs use similar service facilities, including LARSSs, to those employed for USVs.

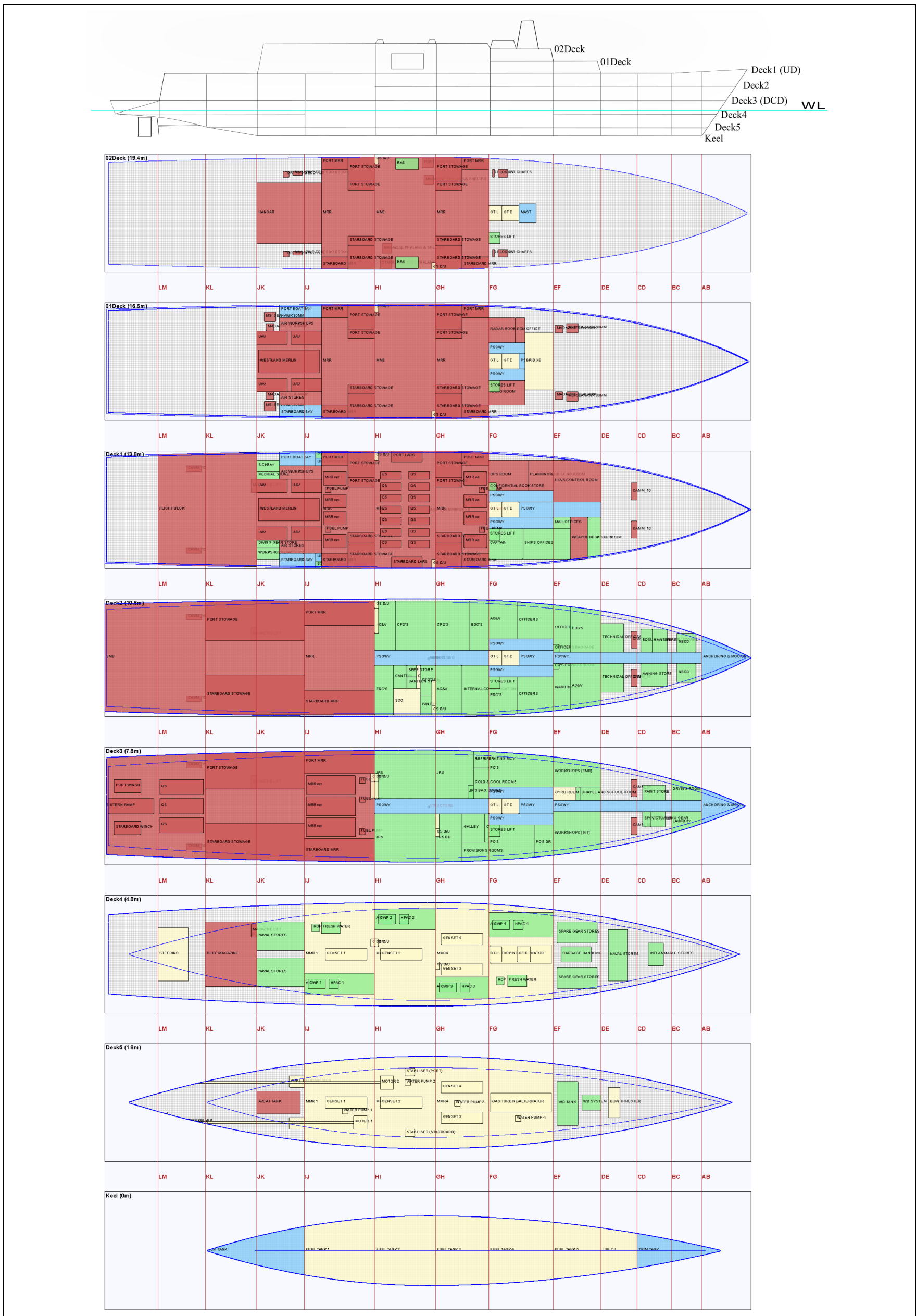


Figure 49: Baseline USV mothership design internal arrangement produced by UCL JavaScript concept ship design tool

5.2.7 Mothership Costing

The costing of baseline USV mothership design was limited to UPC. This is because the crude TLC and FOC estimations were unlikely to produce worthwhile information regarding the UXV implications on the design of a mothership, as discussed in Sub-Section 3.7.2. The UPC was estimated by applying the UCL parametric approach [UCL, 2014 a], where the UPC indicated using this approach is representative of the fourth vessel of a class of twelve ships and does not include FOC costs. UPC is based on the lightship displacement (i.e. does not include variable weights) without Board and Growth margins taken into account. The figures were also inflated to the equivalent of 2017 prices, since at the time of developing the UPC model the latest annual inflation data that could be obtained from the National Statistics Office was for the year of 2017 [Office for National Statistics, 2017]. Figure 50 demonstrates the baseline USV mothership design UPC of over £ 700 m (2017 price level), whereas the fleet of UXVs might well be only 1/10th of this, as well as the cost breakdown based on the warship weight groups.

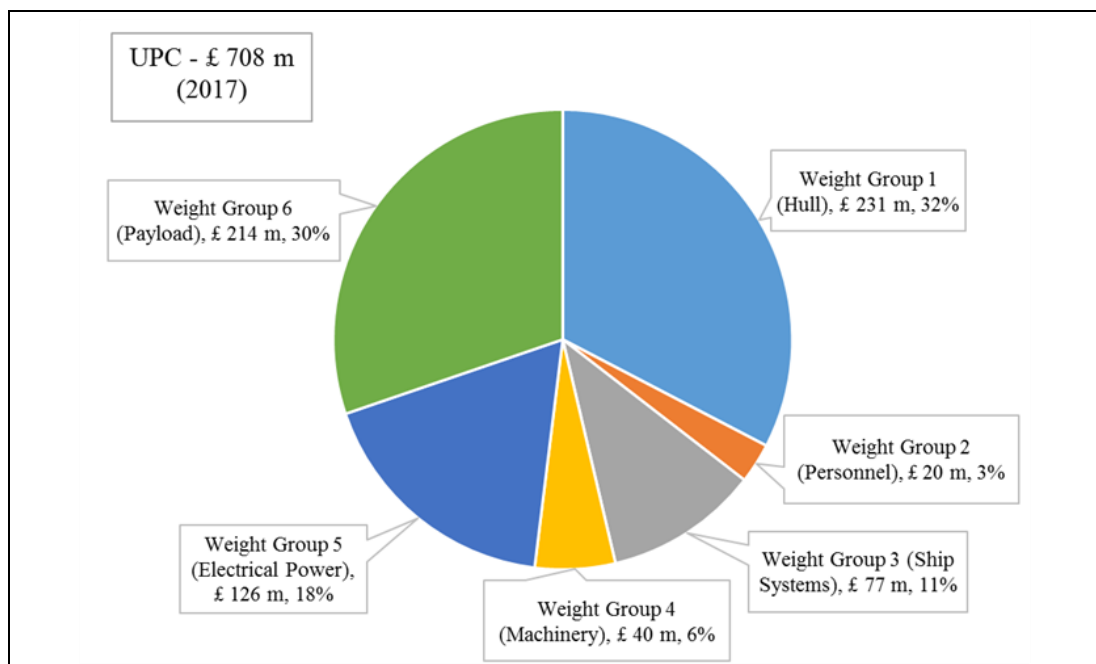


Figure 50: UPC breakdown based on the warship weight group for the baseline USV mothership design

5.3 Mothership Design Variants

USV mothership design variants were chosen to explore the effects of LARSs and USV fleet composition on the internal arrangement of the mission bay, and subsequently investigated the implications of integrating the resultant mission bay arrangements into the overall mothership design. Such variations can be captured and analysed from the queueing network tool, which provides information regarding:-

- The physical requirements indicated by (i) the employed LARSs and (ii) the incurred queueing spaces, and hence their incorporation in a mission bay arrangement;
- The resultant USV mothership LAR capability, which is seen as a proxy measure of operational effectiveness.

The design variants are shown in Table 26. Specifically, the USV mothership design variants provide insights on:-

- Incremental design change (i.e. enhancement of single ship LAR capability). The effects of increasing the number of LARSs fitted in a single mothership. In this mothership design variant, four cranes were fitted in the amidships mission bay (i.e. two port and two starboard cranes) and two ramps were installed in the stern mission bay. This is designated mothership Design Variant "1";
- Step design change. The effect of equally distributing the fleet of USVs in two identical mothership designs. This is designated mothership Design Variant "2").

	Baseline Design		Mothership Design Variants			
			Design Variant "1"		Design Variant "2"	
USVs Fleet	All		All		Equally distributed in two hulls	
	LARS	No.	LARS	No.	LARS	No. (per ship)
Amidships Mission Bay	Port crantage	1	Port crantage	2	Port crantage	1
	Starboard crantage	1	Starboard crantage	2	Starboard crantage	1
Stern Mission Bay	Ramp	1	Ramp	2	Ramp	1

Table 26: Baseline USV mothership design and variants

The main ship performance requirements adopted in all mothership variants were identical to those of the baseline USV mothership design. The ship payload equipment, complement and accommodation breakdown adopted in mothership Design Variant "1" were identical to those of the baseline USV mothership design. However, the ship payload equipment, complement and accommodation breakdown in mothership Design Variant "2" were not the same to those of the baseline option. This is due to the necessary (overall) duplication of ship payload systems (i.e. not UXVs), given the fleet was equally distributed in two identical ship designs, as well as to the reduction of complement per ship, given the reduction of each mothership design, as shown in Table 27. A comprehensive discussion on the results obtained from the development and analysis of the USV mothership design options is provided in Chapter 7.

	Items	Variant "1"	Variant "2"	
			Per Ship	Overall
Payload	Weapon and Missile Systems	Baseline* ¹	Baseline	Duplicated* ²
	Electronic Warfare Systems	Baseline	Baseline	Duplicated
	Radars	Baseline	Baseline	Duplicated
	Communications	Baseline	Baseline	Duplicated
	Inhabited Vehicles	Baseline	Baseline	Duplicated
	UXVs	Baseline	Halved: - VTUAV x 2 - USV Type "A" x 10 - USV Type "B" x 20	Baseline
	Mission Bay Systems (except LARs-handling)	Baseline	Halved	Baseline
Accommodation		Baseline	Captain x 1 Officers x 11 CPOs x 15 POs x 18 JRs x 81 Total = 126	Total = 126 x 2
*1 - Baseline = Identical to those of the baseline USV mothership design				
*2 - Duplicated = Twice as those of the baseline USV mothership design				

Table 27: Payload, complement and accommodation differences between USV baseline mothership design and variants

In Chapter 6, the resultant designs are compared to each other on a COEA basis, where the costs resulted from the USV mothership design options in the current chapter, while the operational effectiveness measures were quantified through the appropriate queuing network models presented in Chapter 6.

5.3.1 Incremental-Change Variant of the Baseline Mothership Design

The incremental variant of the baseline USV mothership (Design Variant "1") integrates two mission bays with twice the number of LARSs, compared to those fitted in the mission bays of the baseline design. Thus, the amidships mission bay has four cranes fitted; two cranes on the port side and another two cranes on the starboard side, while the stern mission bay has two ramps. The major ship characteristics and the estimated UPC of the resultant mothership design variant are compared to the baseline design in Table 28.

Major Ship Characteristics	Baseline Mothership	Design Variant "1"	
V_G	64500 m ³	63260 m ³	
Δ_D	12658 te	12540 te	
Δ_L	8955 te	8828 te	
ρ_s	0.2 te/m ³	0.2 te/m ³	
v_s	0.24	0.23	
L_{wl}	162 m	161 m	
L_{oa}	170 m	165 m	
B_{wl}	22 m	22 m	
B_{UD}	31 m	31 m	
T	5.9 m	5.9 m	
D	13.8 m	13.8 m	
F	7.9 m	7.9 m	
UPC	£ 708 m	£ 700 m	-1.13%

Table 28: Major ship characteristics of both baseline mothership and incremental-change variant (Design Variant "1"), as well as comparison of UPC

The top level weight breakdown for the deep condition of the mothership Design Variant "1" is shown in Figure 51. Moreover, Figure 52 demonstrates the resultant UPC of this first variant and the relevant cost breakdown for the UCL warship weight groups.

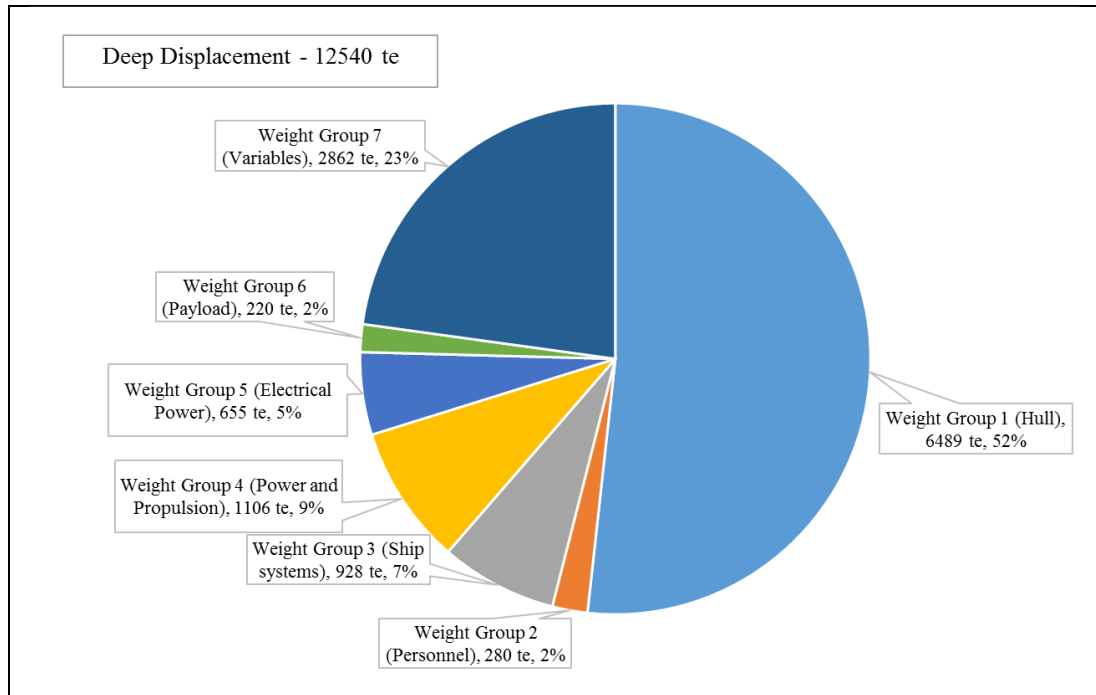


Figure 51: Mothership Design Variant "1" weight breakdown

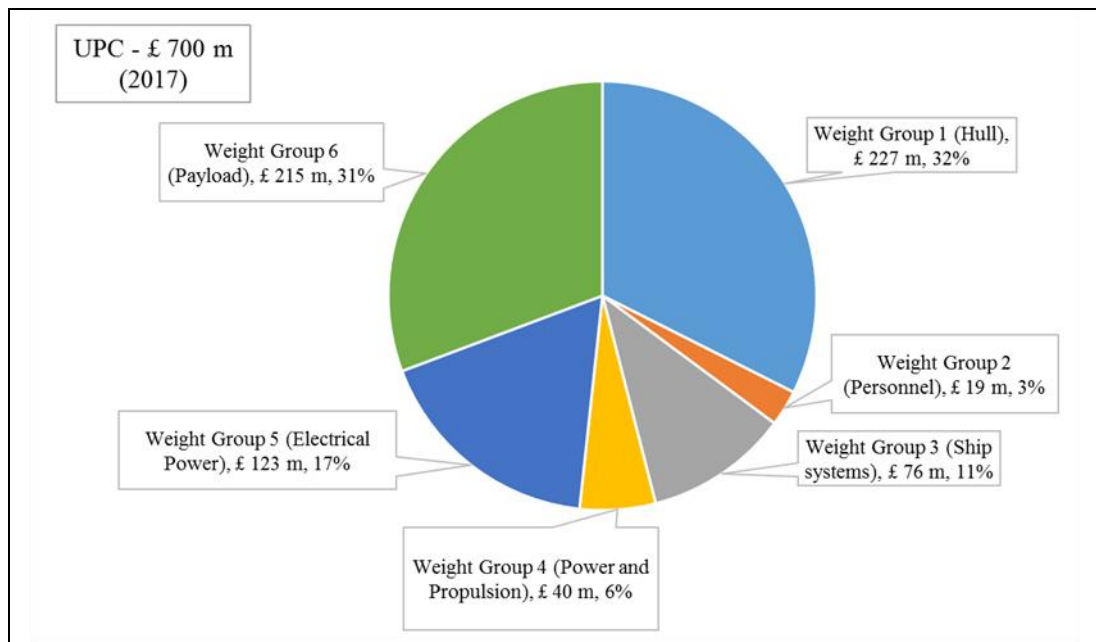


Figure 52: UPC breakdown for the mothership Design Variant "1"

The internal arrangement of the mothership Design Variant "1" is shown in Figure 53, where the two main passageway decks have a double sided passageway arrangement.



Figure 53: Internal arrangement of mothership Design Variant "1"

5.3.2 Step-Change Design Variant of the Baseline Mothership Design

In the step-change mothership design variant (Design Variant "2") the USVs fleet was equally split and distributed in two identical smaller motherships. Each of the resultant mothership integrates an amidships and a stern mission bay, with two side cranes (i.e. port and starboard) and a single ramp are fitted, respectively. The major ship characteristics and the estimated UPC of each resultant ship design variant and the baseline design are shown in Table 29.

Major Ship Characteristics	Baseline Mothership	Design Variant "2"	
V_G	64500 m ³	48245 m ³	
Δ_D	12658 te	9860 te	
Δ_L	8955 te	6820 te	
ρ_s	0.2 te/m ³	0.2 te/m ³	
v_s	0.24	0.21	
L_{wl}	162 m	144 m	
L_{oa}	170 m	146 m	
B_{wl}	22 m	20 m	
B_{UD}	31 m	26 m	
T	5.9 m	5.5 m	
D	13.8 m	13.8 m	
F	7.9 m	8.3 m	
UPC	£ 708 m	£ 572 m (per ship) £ 1144 m (overall)	-19.2% + 62%

Table 29: Major ship characteristics of both baseline mothership and step-change design variant, as well as UPC comparison

The top level weight breakdown for the deep condition of the Design Variant "2" is shown in Figure 54, while the UPC and the cost breakdown are illustrated in Figure 55.

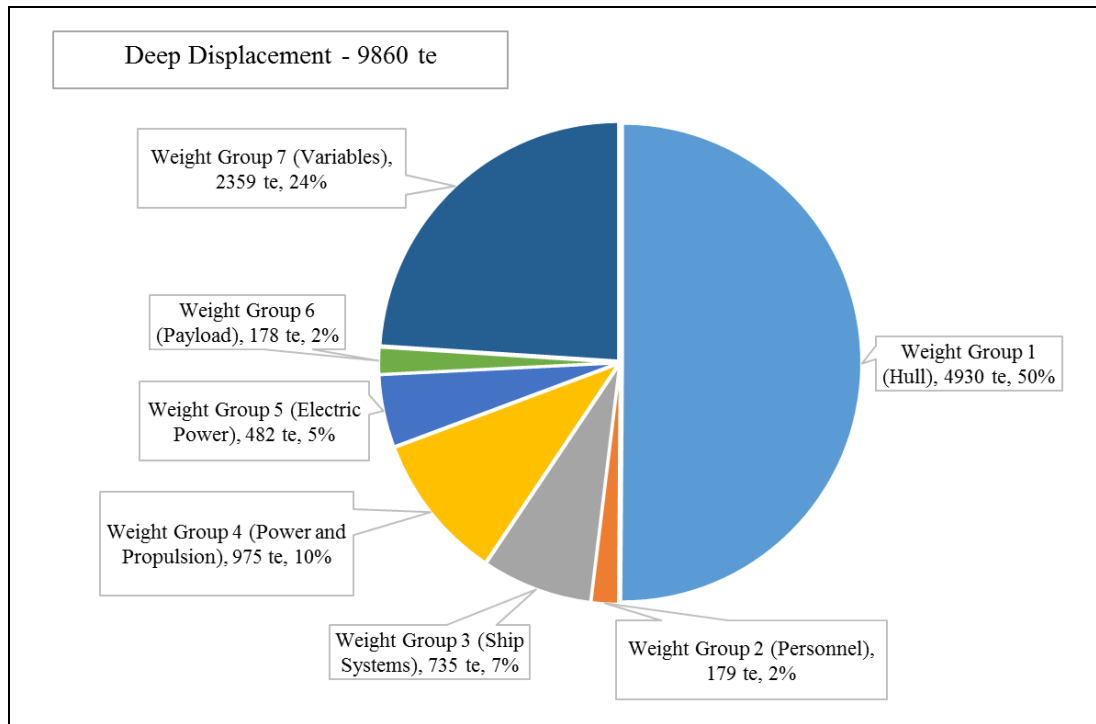


Figure 54: Weight breakdown for each mothership Design Variant "2"

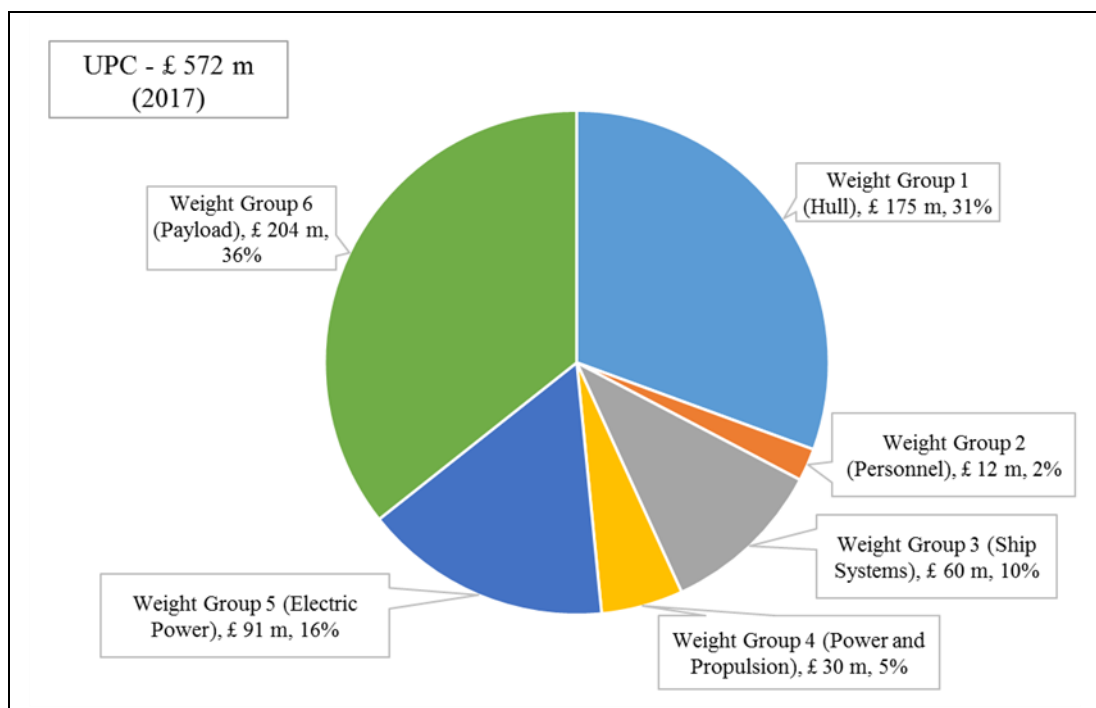


Figure 55: UPC breakdown for each mothership Design Variant "2"

The internal arrangement of each mothership Design Variant "2" is shown in Figure 56, which has two main passing decks with a single central passageway arrangement.

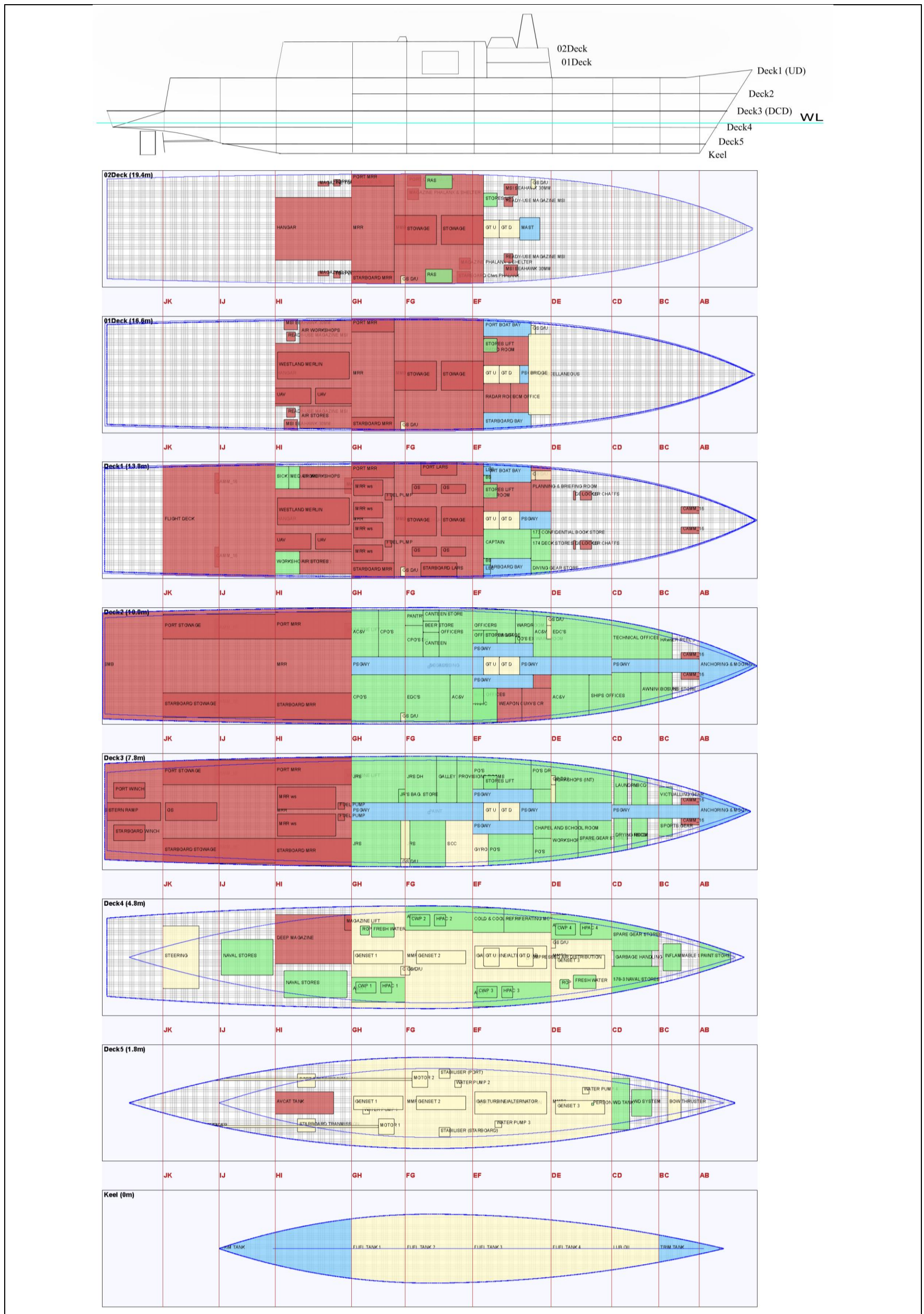


Figure 56: Internal arrangement of each mothership Design Variant "2"

Chapter 6: Application of the Proposed Mothership Design Approach and Presentation of the Results

6.1 Introduction

This chapter describes the application of the proposed mothership design approach to the ship design cases described in Chapter 5 and also presents the results of the cost effectiveness assessment. There are two distinct elements of information, namely physical impact and operational effectiveness measure, both of which result from queueing network modelling, thus providing insights to mission bay arrangements and mothership LAR capability. Consequently, the space demands resulting from the combination of the service facilities fitted in a potential mission bay and any queueing effects incurred ahead of those facilities, define the minimum space requirement for a mission bay. A mission bay arrangement was proposed based on those space requirements, also allowing clearances for accessibility and operations inside the mission bay, such as handling the USVs. Thereafter, the proposed mission bay arrangements were integrated into the overall design of mothership, as shown in the mothership design options presented in Chapter 5. Additionally, the LAR capability of a resultant mission bay arrangement was quantified using the QT application, providing the total time required to deploy and retrieve the given fleet of USVs for the baseline mothership design and the design variants (i.e. 60 USVs; 20 USVs of Type "A" and 40 USVs of Type "B"). The evaluation of LAR capability was then used as a proxy measure of operational effectiveness, which was then applied to the USV mothership design options. A comprehensive discussion of the results and wider ship design implications is given in Chapter 7.

6.2 Queueing Network Modelling to Baseline Mothership Design

Applying the queueing network model shown in Figure 57, the two mission bays integrated in the baseline USV mothership design were sized, based on the USV tasks throughout a speculative set of mission scenarios. For such a set of mission scenarios a total number of 60 USVs was assumed, in order to demonstrate the fleet nature of this research, with two different hypothetical types of USVs were employed, namely USV Type "A" and "B", to model likely mission bay adaptability for variations in CONOPs. This model of the support of a USV fleet represents a physical network system comprising a number of nodes for the various tasks through which the USVs undergo during a mission. The overall operation of the fleet of USVs is considered to be supported by a mothership that incorporates two mission bays, namely amidships and stern mission bays. The QT tool is used to model this particular mothership option and thus enables sizing the space demands for both mission bays. These space demands include the service facilities, as well as the likely queueing spaces that might form ahead of those facilities. The queueing spaces arise due to the vehicles accumulating before they get served at a facility on-board the mothership.

The nodes shown in Figure 57 were modelled as queueing nodes, where the inputted data for this model are given in Table 30, and represent the following USV tasks during potential operations:-

- The deployment of the USVs fleet for a given mission scenario starts with positioning the stowed vehicles on board the mothership adjacent to the LAR points, using internal handling systems (i.e. Stowage/handling node);
- The vehicles are directed towards the LAR points (i.e. launch nodes), where last quick pre-mission checks are performed, involving fuel-battery-ammunition levels checks and fault tracing, before launching them into the water;
- Once launched, the USVs transit towards the mission theatre (i.e. mission theatre nodes) to perform certain tasks according to the appropriate CONOPs scenario;
- In case of a detected malfunction (i.e. malfunction in sea node) the affected vehicle(s) abort the mission and head back to the mothership, if possible, where

they are recovered on-board for repairs, refuel/recharge and rearming (i.e. maintenance/refueling and rearming nodes) and are then re-launched, unless repair by exchange policy applies, where spare vehicles are launched to replace the defective ones. During peacetime (i.e. when no operations take place and all vehicles are recovered on-board and stowed), any necessary further vehicle repairs can be scheduled;

- Given that the installed energy and munition capacity of a USV is rather limited, it may be necessary for every vehicle to be able to refuel and rearm on-station (i.e. refuel and ordnance nodes);
- When the operations at the mission theatre are completed, the vehicles return to the mothership to be recovered on-board at the LAR points (i.e. recovery nodes). Thereafter the vehicles are stowed, while their ammunition compartments are replaced (unless directed energy weapons guns are used);
- Once the vehicles complete their allocated activities as part of a mission scenario, they are recovered on-board and stowed. While stowed the vehicles can undertake certain activities, including refuel/recharge, as well as exchange of any collected data/information with the mothership (i.e. through plug-ins, or without physical connections via wireless technology).

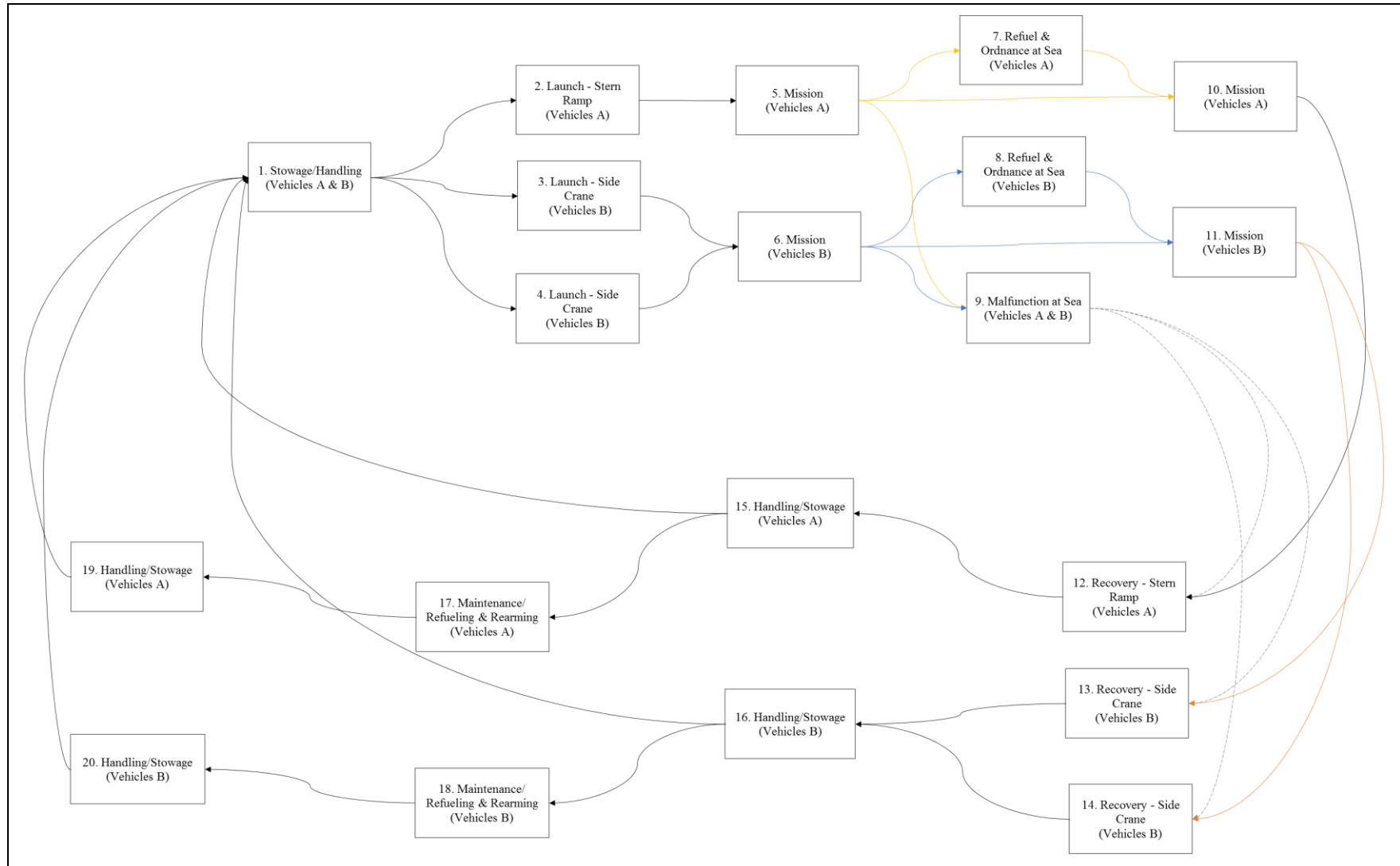


Figure 57: Queueing network modelling the mission bays integrated in the baseline USV mothership design

Network Nodes				
Node Name	Node Number	Node Service Area		
		Facility/Server Type	Facility/Server Levels *	Facility Service Time (min)*
Stowage/Handling	1	Overhead Crane System - Trolley	6	5
Launch	2	Stern Ramp	1	2
	3	Crane	1	4.5
	4	Crane	1	4.5
Mission Theatre	5	Sea Space	∞	180
	6	Sea Space	∞	150
Refuel and Ordnance On-Station	7	Refuel and Ordnance Hub Type 01	10	25
	8	Refuel and Ordnance Hub Type 02	10	15
Malfunction at Sea	9	Sea Space	∞	50
Mission Theatre	10	Sea Space	∞	100
	11	Sea Space	∞	100
Recovery	12	Stern Ramp	1	3
	13	Crane	1	6
	14	Crane	1	6
Handling/Stowage	15	Overhead Crane System - Trolley	2	5
	16	Overhead Crane System - Trolley	4	5

Node Name	Node Number	Node Service Area		
		Facility/Server Type	Facility/Server Levels *	Facility Service Time (min)*
Maintenance/Refueling and Rearming	17	Ship Spaces - Complement - Service Facilities (e.g. Pump Type 01)	4	25
	18	Ship Spaces - Complement - Service Facilities (e.g. Pump Type 02)	8	20
Handling/Stowage	19	Overhead Crane System - Trolley	2	5
	20	Overhead Crane System - Trolley	4	5
* The values of the facility levels were speculative and based on the candidate's engineering judgement, while the processing times were based on the broad specifications resulted from relevant references and discussions with BAE Systems representatives, further discussed in Chapter 7				

Table 30: Description of the inputs to the nodes of the queueing network that models the mission bays of the baseline USV mothership

The queueing network model represents two mission bays that integrate the systems shown in Table 31. The model provides information on:-

- The mission bay space demands required for the service facilities and the incurred queueing effects;
- The resultant LAR capability.

The service facilities are listed in Table 31, while the incurred queueing spaces are shown in Table 32.

Mission Bay	
Amidships	Stern
Stowage Area	
Stowage System	
Vehicles Type "B"	Vehicles Type "A"
Handling Systems	
LAR Area	
Side Cranage Systems	Stern Ramp
	Winches
Maintenance Area	
Storage (maintenance packs, toolboxes, spares, ready-use ammunition)	
Fuel Systems (pumps)	
Working Spaces	
Handling Systems	

Table 31: Mission bay systems for the baseline USV mothership design

Node	Service	Service Facility		Mission Bay	Queueing Spaces
		System	No.		
2	Launch	Stern Ramp	1	Stern	3
3	Launch	Side Crane	1	Amidships	7
4	Launch	Side Crane	1	Amidships	7

Table 32: On-board queueing effects at mission bays of the baseline USV mothership design

Taking into account the overall space demands indicated by the fitted service facilities and the incurred queueing requirements, while also allowing for clearances, two mission bay arrangements (i.e. amidships and stern) were proposed, as seen in Figure 58 and Figure 59. These configurations were then integrated into the baseline USV mothership design already presented in Chapter 5.

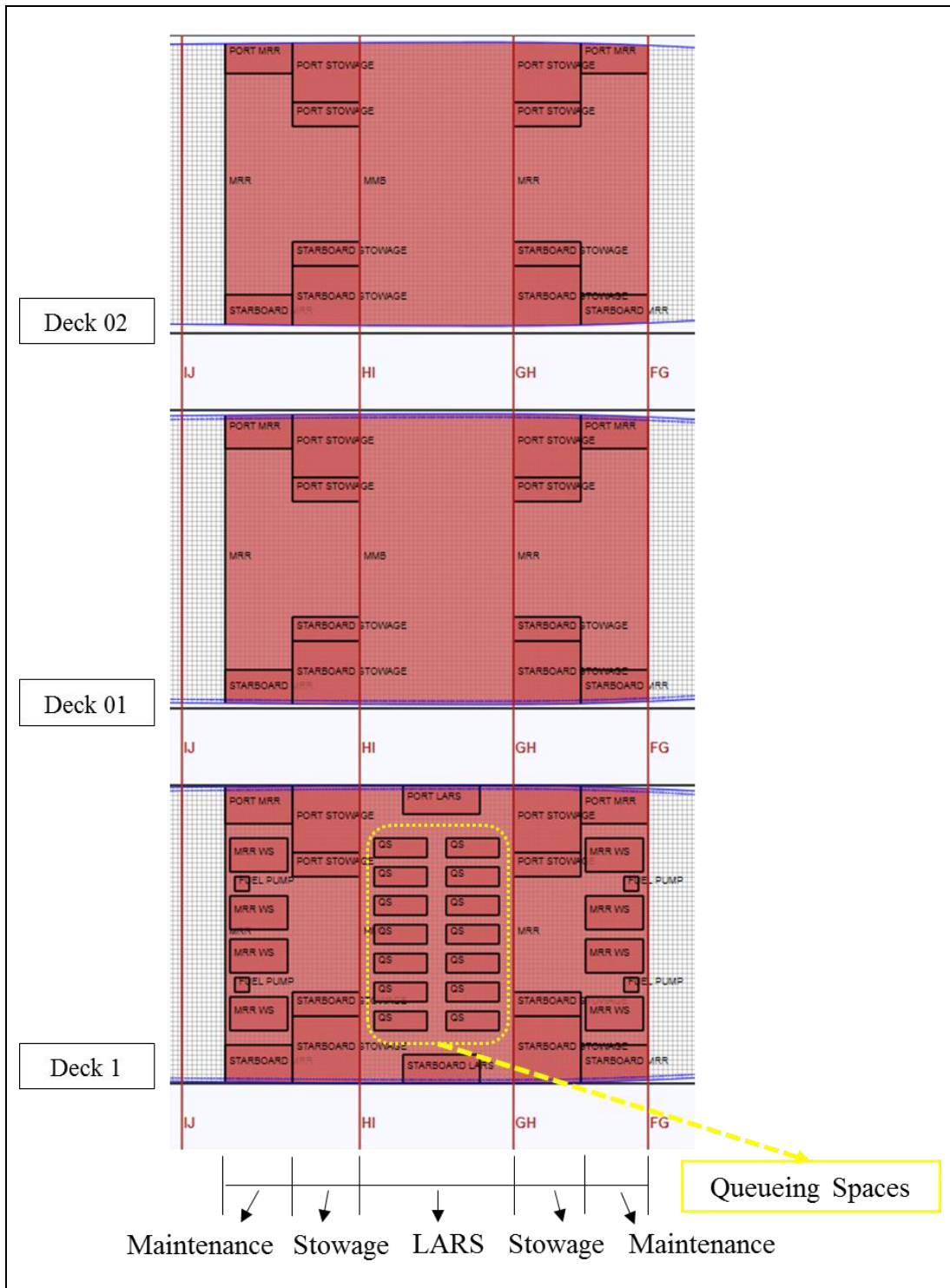


Figure 58: Proposed amidships mission bay arrangement (baseline USV mothership design)

6.3 Queueing Network Application to Mothership Design Variants

The following sub-sections present the results from investigating the two baseline USV mothership design variants, summarised in Figure 60. The incremental variant (i.e. mothership Design Variant "1") is an enhancement of single mothership LAR capability, where twice the number of LARSs are fitted in the mission bays compared to those of the baseline USV mothership. In the step-change design variant (i.e. mothership Design Variant "2") the USVs fleet was split in two identical mothership designs, where each one of them incorporates in the mission bays the same number of LARSs as the baseline USV mothership design.

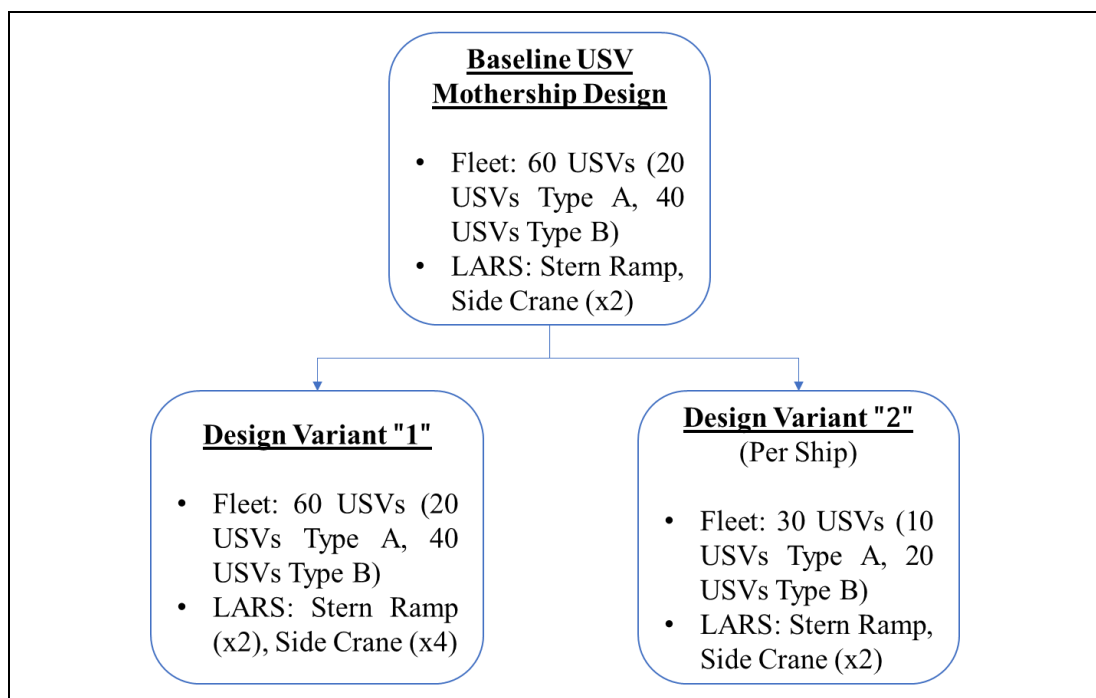


Figure 60: Description of USV mothership design variants

6.3.1 Enhancement of Single Ship Launch and Recovery Capability

Following the procedure described in the previous section for the baseline USV mothership design, the mission bay arrangements for the mothership Design Variant "1", were configured, as well as defining the resultant LAR capability of the ship. This design variant integrates an increased number of LARSs, as a means to enhance the LAR capability compared to that of the baseline USV mothership. The queueing network model, described in previous section, was investigated for twice the number of LARSs, i.e. two ramps fitted in the stern mission bay and four side cranes installed in the amidships mission bay. The resulting queueing spaces are presented in Table 34

and were also compared to the resultant queueing effects of the baseline mothership design, demonstrating an expected reduction, due to the increased number of LARs fitted in the mission bays.

Node	Service	Service Facility		Mission Bay	Queueing Spaces			
					Design Variant "1"		Baseline	%
		Server	No.		Per Server	Total		
2	Launch	Stern Ramp	2	Stern	0	0	3	-100
3	Launch	Side Crane	2	Amidships	1	2	7	-71
4	Launch	Side Crane	2	Amidships	1	2	7	-71

Table 34: On-board queueing effects at mission bays of the USV mothership Design Variant "1", also compared to those of baseline design

The overall space demands for the service facilities fitted, as well as the queueing requirements were reflected in the proposed amidships and stern mission bay arrangements, shown in Figure 61 and Figure 62, respectively. These were subsequently integrated into the mothership Design Variant "1" already presented in Chapter 5.

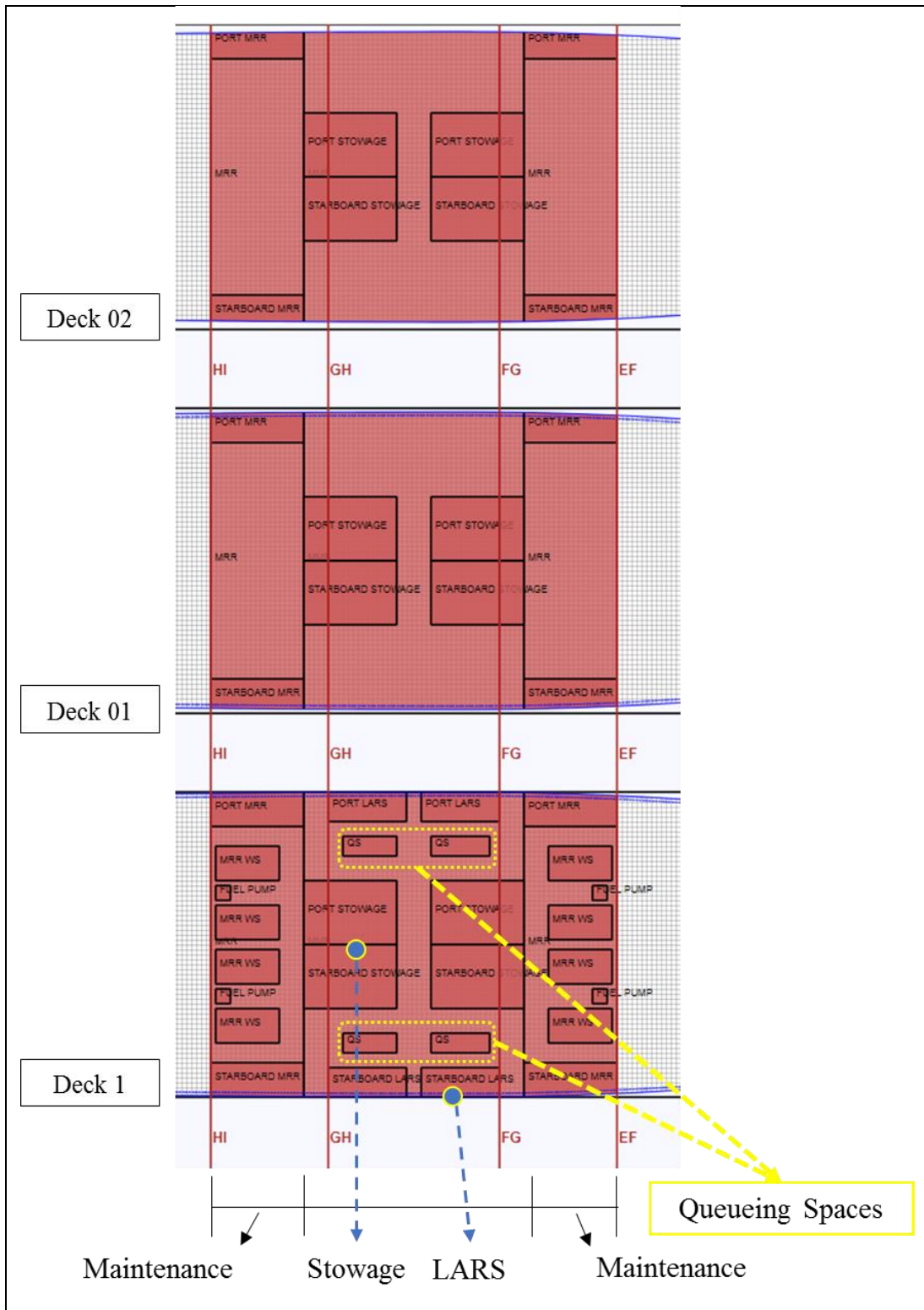


Figure 61: Proposed amidships mission bay arrangement integrated in mothership Design Variant "1"

independent smaller USV mother vessels. A multi-mothership solution would be equivalent to a single large mother vessel, as in both cases the operations of the identical fleet of USVs can be supported. Such a solution would provide enhanced flexibility during a mission, since it would enable the smaller motherships to operate in unison and perform LAR activities concurrently, additionally the ships could be positioned in different locations nearby the theatre of operations. Moreover, such an option is seen as a less vulnerable solution, reducing the risk of losing all of the USV capability in a single hit. In this design variant, the USVs fleet is equally split and distributed in two identical mothership design options, i.e. Design Variant "2". Hence each mothership accommodates a fleet of 30 USVs, where 10 USVs of Type "A" are hosted in the stern mission bay, while 20 USVs of Type "B" are hosted in the amidships mission bay. The queueing network model described in Section 6.2 was investigated for a fleet of 30 USVs, where a single ramp and two crane LARSs were respectively fitted in the stern and amidships mission bay of each one of the two USV motherships. The mission bay arrangements (i.e. amidships and stern) for each mothership design were configured, accounting for the space requirements allocated for the fitted service facilities and the likely queueing effects. The queueing effects for each Design Variant "2" are shown in Table 36, and are compared to those of the baseline mothership design. The analysis showed that the queueing demands ahead of each LARS would be reduced, when compared to those of the baseline USV mothership, because of the number of USVs to be served from each LARS is halved.

Node	Service	Service Facility		Mission Bay	Queueing Spaces		
					Design Variant "2"	Baseline	%
		Server	No.		Per Ship		
2	Launch	Stern Ramp	1	Stern	1	3	-67
3	Launch	Side Crane	1	Amidships	2	7	-71
4	Launch	Side Crane	1	Amidships	2	7	-71

Table 36: On-board queueing effects at mission bays of the USV mothership Design Variant "2", also compared to those of baseline design

Taking into consideration the space demands defined by the service facilities fitted and the queueing requirements incurred, the mission bay spaces were arranged, as

proposed in Figure 63 and Figure 64, which were then integrated in the mothership Design Variant "2", as already presented in Chapter 5.

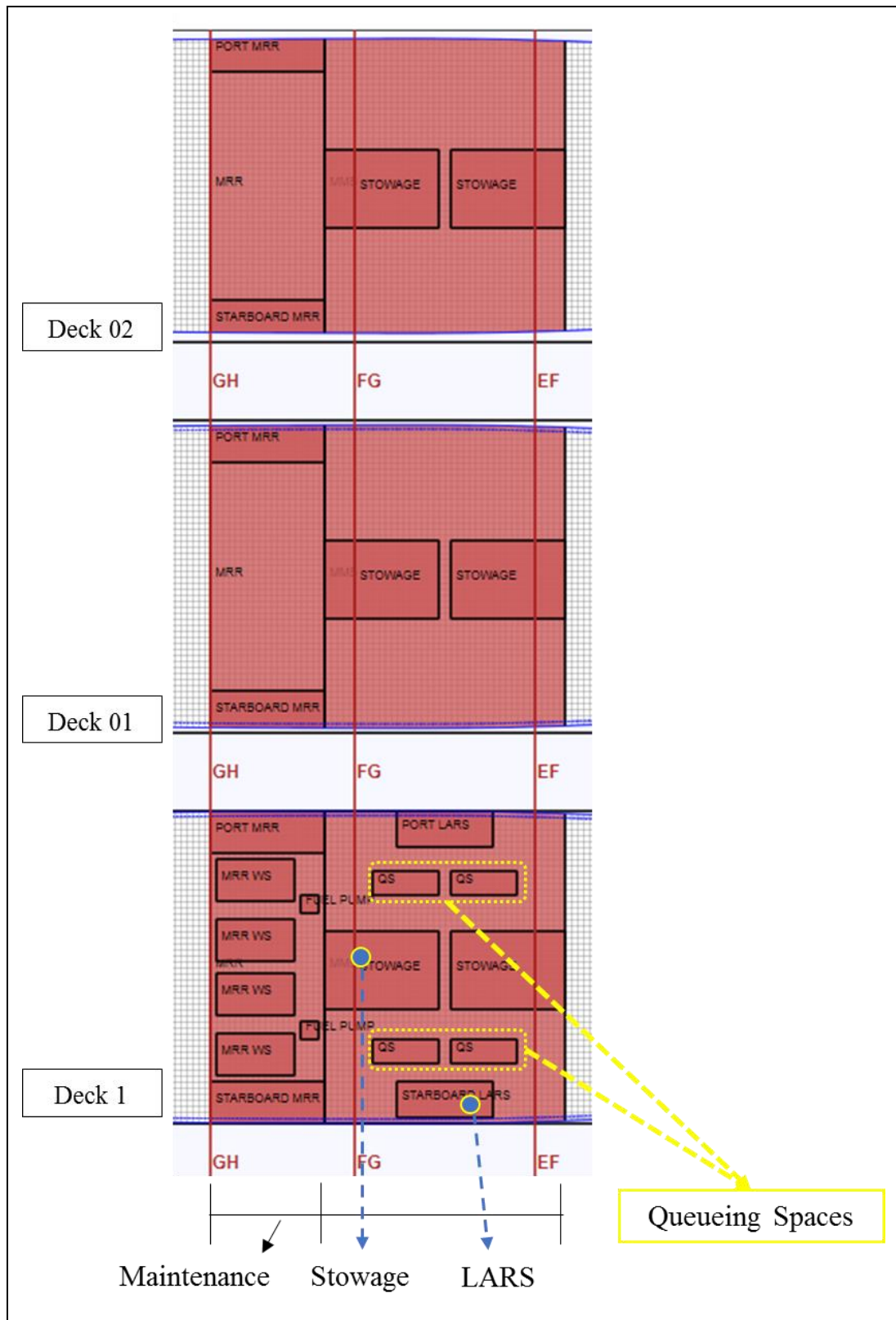


Figure 63: Proposed amidships mission bay arrangement integrated in mothership Design Variant "2"

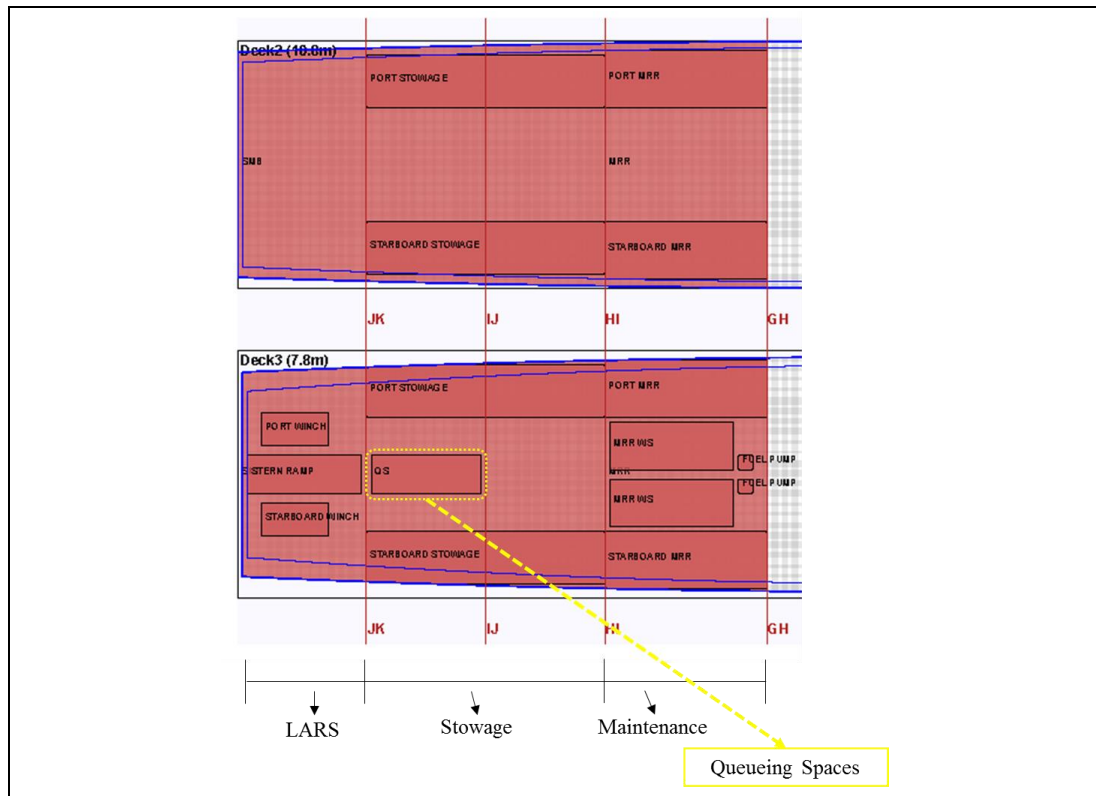


Figure 64: Proposed stern mission bay arrangement integrated in mothership Design Variant "2"

The resultant LAR capability for each of the second design variants is presented in Table 37. It suggests that in comparison to the baseline USV mothership design, the proposed measure of LAR capability was improved, since the two smaller USV motherships can operate together and perform concurrently LAR activities thus deploying and retrieving the same fleet of USVs in shorter times, i.e. 53% and 60% reduction for launching through the stern ramp and each side crane, respectively, whereas the total recovery times were reduced by 55% and 63% for the stern ramp and each side crane, respectively.

Node	LARS	USVs to Serve	Baseline		Design Variant "2"			
			Total Time		Total Time (Per Ship)			
			Launch	Recovery	Launch	%	Recovery	%
2	Stern Ramp	20 ^{*1}	47 min	76 min	22 min	-53	34 min	-55
3	Side Crane	20 ^{*2}	131 min	205 min	53 min	-60	76 min	-63
4	Side Crane	20 ^{*3}	131 min	205 min	53 min	-60	76 min	-63

^{*1, 2, 3} In 2nd design variant the vehicles served per LARS per ship is 10 (thus 60 USVs in total)

Table 37: USV mothership Design Variant "2" LAR capability, also compared to that of the baseline design

6.4 Cost and Operational Effectiveness Analysis Comparison Review of the Proposed Mothership Design Options

To enable a more cost effective comparison between the baseline USV mothership design and the two variants, the LAR capability results are summarised in Table 38, along with a number of major ship design characteristics, namely displacement, gross volume, density and UPC, where all the values were normalised to the baseline design.

		USV Mothership Designs				
		Baseline	Design Variant "1"	Comparison to Baseline (%)	Design Variant "2"	Comparison to Baseline (%)
LAR Capability (overall ^{*1})						
Launch	A	1.00	0.85	-0.15	0.47	-0.53
	B	1.00	0.70	-0.30	0.40	-0.60
Recovery	A	1.00	0.80	-0.20	0.45	-0.55
	B	1.00	0.61	-0.39	0.37	-0.63
Displacement (Per Ship ^{*2})		1.00	0.99	-0.01	0.78	-0.22
Gross Volume (Per Ship ^{*2})		1.00	0.98	-0.02	0.75	-0.25
Density (Per Ship ^{*2})		1.00	1.00	0.00	1.00	0.00
U P C	Per Ship ^{*2}	1.00	0.99	-0.01	0.81	-0.19
	Overall ^{*1}	NA	NA	NA	1.62	0.62
^{*1} Overall comparison refers to full fleet support, where in the case of Design Variant "2" the fleet is supported from the two identical USV motherships, i.e. overall LAR capability for Design Variant "2" is considered when the two ships operate concurrently, while the overall UPC for Design Variant "2" addresses the total cost for the two identical ships, where the fleet is distributed to ^{*2} Per ship capability refers to each ship's characteristics						

Table 38: Comparison of LAR capability with major ship design characteristics, produce for the baseline USV mothership design and its variants

UPC along with the mothership LAR capability measure allow the comparison of potential mothership options, supporting the same fleet of USVs, on a COEA basis. This was enabled through the combination of queueing network modelling and DBB approach to mothership design, as shown in Figure 65. Thus:-

- The mothership LAR capability was assessed and compared between the various mothership design options through the QT tool, i.e. total time to deploy and retrieve the USVs fleet;
- Design implications were visually presented, technically assessed and compared for performance and cost. The ship design layouts produced, using the DBB approach, such that the mission bay arrangements were informed by the service facilities and queueing effects, themselves analysed via queueing network modelling;
- Costing of the potential mothership options was performed using UCL UPC costing procedure.

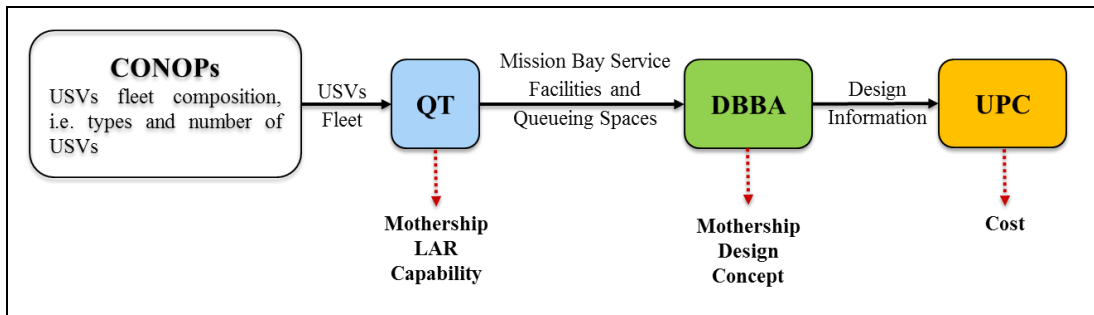


Figure 65: Information exchanged through the proposed USV mothership design approach

It could be concluded from the results presented in Table 38 that a considerable LAR capability improvement could be achieved through either small (i.e. incremental), or greater (i.e. step) changes in major ship design characteristics. Hence, when comparing to the baseline USV mothership design, in the case of the USV mothership Design Variant "1", the LAR capability of the ship was noticeably improved for less ship UPC, whereas for the USV mothership Design Variant "2", the ship's LAR capability was significantly enhanced for a significantly increased total ships' UPC. A more comprehensive discussion of these results is provided in Chapter 7.

Chapter 7: Discussion of Approach to the Design of a Mothership Supporting a Fleet of Uninhabited Vehicles in the Early Stage Ship Design

7.1 Introduction

This chapter consists of two main sections. The first section provides a more comprehensive discussion of the results presented in Chapters 5 and 6, as well as considering the wider ship design implications of the results in terms of the research's objectives. The second section discusses the proposed UXV mothership evaluation approach and if this has achieved the research aim described in Chapter 1 and also whether it has addressed the knowledge gap revealed in Chapter 2. The chapter concludes by discussing the research assumptions and limitations, as well as raising the areas that are seen to merit further investigation.

7.2 Analysis of the Mothership Design Evaluation Results

This section discusses the results from evaluating the USV mothership design options proposed in Chapter 5. These design options resulted from integrating the mission bay arrangements, proposed in Chapter 6, which were informed by the appropriate queueing network modelling and analysis, also demonstrated in Chapter 6. Hence, the results discussed in this section include the assessment of the proposed ship's LAR capability measure, the incurred ship's UPC, as well as general design observations that emerged throughout the USV mothership design investigations.

7.2.1 Assessment of the Incremental-Change Design Variant

The results from assessing the impact of increasing the number of the LARSs employed on the mission bay arrangements and the resulting USV mothership design, demonstrated that an increase of the service facilities provide the means of enhancing the deployment and retrieval of the USVs fleet for the case of an assumed mission scenario. Such an enhanced mothership design, referred to as the USV mothership Design Variant "1", can be seen as an incremental design change from the baseline design, which integrates mission bays with twice the number of LARSs into the mothership. This first design variant allowed an improved ship LAR capability, thus leading to a faster launching and recovering of the given USVs fleet, as seen in Table 38 in Section 6.4. This is to be expected, because the Design Variant "1" enables the concurrent LAR activities of the same USVs fleet (when compared to the fleet operated from the baseline USV mothership design), through the increased number of LAR service facilities able to be operated independently of each other. When compared to the baseline mothership design, such an improvement of the ship's LAR performance measure can be linked to a better operational effectiveness "score" (i.e. using the proposed proxy measure of operational effectiveness achieved through the proposed USV mothership design variant). This assumes an improvement in a specific military situation could be achieved from faster LAR. The major ship design characteristics, namely displacement, enclosed volume, density and UPC were comparable for the USV baseline design and Design Variant "1" (Table 28 in Section 5.3.1). Despite the similarities in the overall design characteristics, the LAR capability performance achieved in the baseline design and the first design variant was noticeably

different. Moreover, it was observed that the integration of the appropriate mission-oriented spaces resulted in distinct mothership design configurations. This was due to the integration of different number of LARSs, resulting in different configurations for the mission bays and thus for the overall mothership design arrangement, including the passageway arrangement and the arrangement of the crew accommodation spaces, for the first design variant (Sub-Section 5.3.1).

The proposed mission bay configurations integrated in the first mothership design variant were smaller to those of the baseline design, despite increasing the number of LARSs fitted (see Sub-Section 6.3.1). This is attributed to the increased number of LARSs installed in the mission bay areas, resulting in considerably less queueing (see Table 34 in Sub-Section 6.3.1). The amidships mission bay was significantly reconfigured, since the need of queueing spaces ahead of the port and starboard cranes LARSs, had been significantly reduced. Therefore, the spaces that were initially used to account for the queueing effects in the amidships mission bay of the baseline USV mothership design, could then be employed for stowage space, resulting in the proposed amidships mission bay configuration in the first design variant. Moreover, the resultant stern mission bay configuration of the Design Variant "1" has no queueing space demands, hence the queueing space compartment in the baseline design is no longer required in this first design variant, resulting in a smaller stern mission bay arrangement. Such area demand reductions were shown in Table 39 for both the amidships and stern mission bay arrangement of the baseline mothership design and its incremental-change design variant (i.e. the Design Variant "1") and compared. For simplicity of the appropriate area calculations, they mission bays were assumed to be approximately rectangular.

Mission Bay	Dimensions (L x W)		Area		Comparison
	Baseline Design	Design Variant "1"	Baseline Design	Design Variant "1"	
Amidships	44 x 31 m	41 x 31 m	1364 m ²	1271 m ²	-7%
Stern	71 x 30 m	57 x 30 m	2130 m ²	1710 m ²	-20%

Table 39: Mission bay comparison between baseline USV mothership design and Design Variant "1"

Since the resultant stern mission bay arrangement fitted in the first mothership design variant was smaller in length, this readily enabled a double sided and athwartships passageway arrangement within comparable overall ship design characteristics (i.e.

displacement, gross volume and overall length), as seen in as seen in Table 28 in Sub-Section 5.3.1. This was considered to be plausible due to the space made available in the first mothership design variant (i.e. the Design Variant "1") through integrating a smaller stern mission bay. It is noteworthy that the overall beams (i.e. 31 m) of both the baseline USV mothership design and its first design variant were driven by the size of the proposed mission bay arrangements. Given the maximum ship's beam, a double sided and athwartships passageway arrangement might be desirable, necessary to ease accessibility (i.e. enhanced routeability, given a degree of passageway redundancy) throughout the main passageway decks, also noting possible structural considerations arising from such an arrangement that might need further consideration. Such issues, as the arrangement of openings (i.e. uptakes, downtakes, hatches and other openings), would need addressing to avoid implications to the ship's longitudinal strength. Normally this would mean concentrating openings away from the garboard strake, as the garboard strake (i.e. plating that connects the side shell to the upper deck) is more highly stressed than that nearer the centreline [Chalmers, 1993]. With the extensive stern mission bay integrated in the baseline USV mothership design, a double passageway arrangement was likely to have resulted in a bigger ship. This did not arise with the first design variant, due to a smaller stern mission bay arrangement.

Given the smaller stern mission bay integrated in the first USV mothership design variant (Design Variant "1"), a more flexible arrangement was possible with regards to the accommodation spaces. The available space, due to the shorter stern mission bay, meant the accommodation spaces could be pushed further aft in the ship. This could prove to be a more attractive solution for laying out the accommodation spaces, given wave-induced ship motions are likely to be less in the central portion of the ship.

It was also observed that the mothership Design Variant "1" ought to achieve a noticeably better LAR capability, as seen in Table 38 in Section 6.4, with an estimated cost (UPC) that is comparable to that of the baseline USV mothership design, i.e. it was estimated to be 1.1% cheaper than the baseline UPC. This comparison indicated that the LAR capability of the mothership should be noticeably improved for almost the same major ship design characteristics and assessed UPC.

7.2.2 Assessment of the Step-Change Design Change Variant

The concept of splitting equally the assumed fleet of USVs, and distributing it between two identical smaller motherships, was considered as an interesting second alternative to the baseline USV mothership design. Compared to the option of a single USV mothership design, the second design variant allows for an enhanced redundancy, given the USVs fleet is distributed in two independent hulls. Thus, in the scenario of a single hull lethality hit the whole USVs fleet's capability would not be lost and part of the capability would still be deployable.

The proposed measure of the mothership's LAR capability for the assumed mission scenario was found to significantly improve for the Design Variant "2", when compared to the baseline design, as seen in Table 38 in Section 6.4, with a much faster LAR arrangement for the given USVs fleet. Such an overall LAR enhancement was expected, due to the decrease of the number of USVs operated from each of the second variant mothership designs, since each one of them accommodated two mission bays, namely a stern mission bay with a single ramp and an amidships mission bay with two side crane LARSs. This design option is referred to as the USV mothership Design Variant "2" and could be seen as a step design change from the baseline USV mothership design. In such a design option, the overall USV capability was maintained, but it was accommodated and independently supported by the two identical motherships with distinct major ship design characteristics and configuration outlined in Sub-Section 5.3.2. Furthermore, these two motherships could independently transit towards a potential theatre of operations and concurrently deploy their USV capability to meet that mission.

The reduced mission bay size, consequent on a reduced number of USVs operated by each ship, as well as the decrease of the accommodation space needs attributed to the lower personnel requirements (given the reduction of USVs fleet per ship and the smaller ship size), resulted in a noticeably smaller ship design solution than the baseline option, as seen in Table 29 in Sub-Section 5.3.2. Hence, when compared against to the baseline design, the integration of the resultant mission-oriented arrangements into the mothership design resulted in a different ship design option in both the major ship design characteristics and internal arrangement aspects. The mission bays (i.e. amidships and stern) were reconfigured, as displayed in Sub-Section

6.3.2, based on the appropriate reduced stowage demands and the reduced queueing effects, giving smaller and noticeably different arrangements to those of the baseline design, with a reduced maximum beam requirement of 26 m, which subsequently drove the overall beam of the resultant USV mothership Design Variant "2" (i.e. maximum beam 16% smaller to that of the baseline design). The proposed general arrangement of the second USV mothership design variant, shown in Figure 56 in Sub-Section 5.3.2, follows the generic deck plan arrangement adopted in both the baseline design and the first design variant, i.e. double-bottom, two machinery decks, two main passageway decks and superstructure. However, the second design variant adopted a single central passageway arrangement.

The two motherships of Design Variant "2" can overall achieve a significantly enhanced LAR capability, since the two ships can simultaneously deploy and retrieve the fleet of USVs, as seen in Table 38 in Section 6.4. However, it was concluded that the overall UPC to acquire the two smaller identical USV motherships is increased by 62% when compared to the single bigger baseline design option, given the procurement of two ships.

7.2.3 General Mothership Design Assessments

From the investigation of the impact of the given USVs fleet on the design of a mothership, through applying the proposed mothership design evaluation approach to the ship design case studies displayed in Chapter 5, the following ship design related points emerged:

- The resultant USV mothership design options, proposed in Chapter 5, are quite large relative to typical naval combatants. This was due to the voluminous mission bay arrangements, having to be integrated into the ship design, arising from the requirement to accommodate and support a "fleet" of USVs. The proposed mission bay arrangements were sized based on the operational requirements, arising from applying queueing network modelling. This led to space demands for the installed service facilities, the incurred queueing effects, as well as providing excess space for accessibility and operations inside the mission bays. It was observed that the overall beam of each USV mothership design was driven by the arrangement of the mission-oriented spaces.

Additionally, the mission bay spaces were seen to drive the configuration of the overall ship.

- The stowage arrangement adopted for the USVs was spread in various locations inside the mission bays. Such an arrangement might be seen to be of enhanced flexibility, since it allows the concurrent handling of multiple vehicles towards launching during deployment and stowage after recovery. Moreover, although the scenario of a single hit might cause a complete damage to the mission bays, it was speculated that by distributing stowage systems in those spaces might also enable the protection of a part of the USVs capability, compared to all vehicles being stowed in a single part of the mission bay.
- For the USV mothership design option (i.e. Design Variant "1"), where two ramps were fitted in the stern mission bay, it might be likely that the stern width might be excessive. Although the design implications of installing two stern ramps were assessed, the implications of a double ramp fitted in the stern of a ship are seen as likely to entail further investigation, due to the speculative nature of the LARSs employed in the research.
- The USV mothership design options that integrate a stern mission bay with a single stern ramp were equipped with an extra winch, where in the case of a malfunctioned winch, the USVs Type "A" would still be deployable through incorporating the extra installed winch. The same duplication concept could apply through the use of a double stern ramp in the first design variant (Design Variant "1"), as well as through fitting more than one side crane LARS in the amidships mission bay of all the proposed mothership design options.
- Cranes can be relatively readily mounted on the ship, whereas stern ramps have to be built into the ship's hull structure. Therefore, cranes, unlike the built-in stern ramps, might be regarded as modularised systems, which are relatively easier to be replaced with enhanced future systems. Given a ship has a longer life cycle than that expected for the operated vehicles, it might be necessary for the ship to be able to operate more than one generations of vehicles. However, this might prove problematic regarding the stern ramp, since stern ramps are normally customised to operate specific types of vehicles and refits of different stern ramps in a given ship could prove more challenging. Therefore, systems having a major impact on the design of a ship, such that of

a stern ramp, should be taken into account in the early stages of the ship design process.

- A ramp fitted in the stern of a ship is an opening on the ship's hull structure is exposed to the sea water, possibly affecting the ship's resistance and also causing local dynamic problems. When LAR operations do not take place, such effects can be mitigated by fitting stern doors. However, while deploying and retrieving vehicles through a stern ramp at higher sea states, the extent of sloshing effects caused, since the ramp is open to the sea, might cause local dynamic phenomena that may hinder such operations. Generally, although project LAURA's goal is to develop LARSs for successfully performing LAR activities from naval combatants up to Sea State 6 [Knight, 2013], launching is normally seen as an easier procedure than recovery operations, which in higher states (i.e. beyond Sea State 6) may not be achievable. Moreover, in the case of a double stern ramp, each ramp should be separated to the adjacent one with an in-between hull structure (i.e. wall), which would then mitigate the likely sloshing effects.
- The USV-related maintenance spaces were located on the side of the proposed mission bay arrangements, so as they would not interfere with the stowage and LAR parts of the mission bays.
- The concept mission bay arrangements proposed by Knight (2013) and illustrated in [Figure 66](#) were intended to accommodate and facilitate operating a small number of UXVs. The vehicles in those mission bays have been stowed ahead of the LARSs, i.e. side crange LARSs in the amidships mission bay and ramp in the stern mission bay. However, such a stowage arrangement would have incurred significant space demands to accommodate a fleet of UXVs, such as that investigated in this research, leading to even bigger mission bays and subsequently larger and more costly ships than those demonstrated in the current investigations. Therefore, the USVs in the mission bay arrangements proposed in Chapter 6 are stowed at dedicated parts of the mission bays in rack structures, where the vehicles would be positioned ahead of the pertinent LAR points using appropriate handling systems. It can be observed that the proposed USV mission bay arrangements have an intermediate space, where necessary, between the stowage spaces and the LARSs, which meets the queueing effect

space demands, suggested by the appropriate queueing network modelling. Such intermediate spaces can be seen as the equivalent to the stowage parts of the concept mission bay arrangements, suggested by Knight (2003).

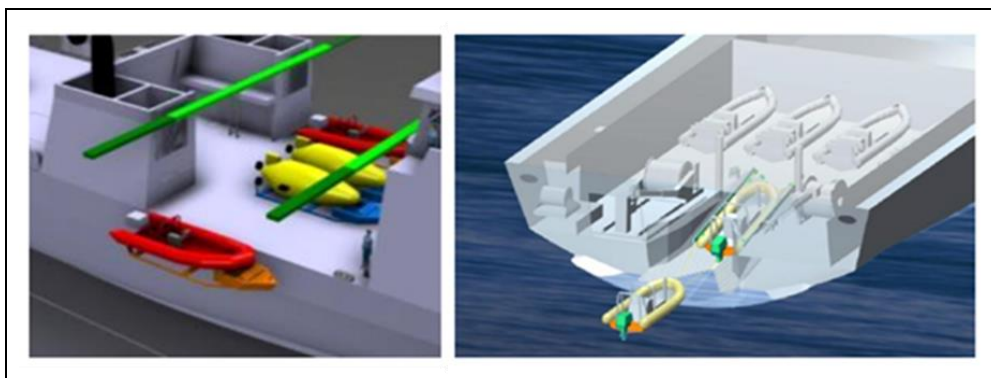


Figure 66: Concept UXV mission bay arrangements proposed by Knight (2013): left: amidships mission bay; right: stern mission bay

- Given the reduction in buoyancy at the stern of the proposed USV motherships, due to the ramp structure fitted in the hull, buoyancy chambers might need to be fitted on both sides of the ramp to account for potential damage stability scenarios, with further ship design implications.
- In all USV mothership design options, the position of the ship's mast was unavoidably located in the forward part of the ship, which was due to the extensive amidships mission bay arrangements. Thus, the mast had to be placed ahead of the engine exhausts, in order for the fumes not to interfere with the C3 and navigation systems mounted on it.
- Such a mast has to be structurally supported, due to the total loading conditions it is likely to be subjected to (i.e. point loads), including the heavy weight of the systems mounted on it and potential dynamic loads (e.g. wind, blast and ship motions). This is normally achieved by employing dwarf bulkheads (extending one or two decks below), or deep girders, at one or more sides of the mast (depending on the extent of the structure and mounted equipment, requiring local stiffening of the structure), resulting in increased structural weight and impacting ship's structural cost.
- Any local loads arising in the voluminous mission bay arrangements, due to the equipment fitted, would have to be taken into account. For instance, crane systems inside the mission bays need structural support. For that reason, in the early stages of ship design such additional structural seatings were allowed for in additional weight. To protect the ship's USVs capability

against small arms, the mission bay spaces could be reinforced with Kevlar. However, this would add to the total weight and cost of the ship.

- For the size of the USV mothership design options, described in Chapter 5, a double passageway arrangement might have been considered to be a more sensible choice. However, such arrangement would have driven the size of both the baseline mothership design and the second design variant (i.e. Design Variant "2") even higher. Moreover, in the case of the baseline USV mothership design, the incorporation of a single central passageway arrangement facilitated the demonstration of a double passageway in the first design variant (i.e. Design Variant "1"). This was possible, due to the smaller stern mission bay arrangement integrated in this first variant, thus providing space for incorporating a double passageway, while the resultant overall ship configuration was then of a comparable size to that of the baseline design.
- The USV mothership design options presented, were not seen as definitive ship design solutions. The ship design case studies were seen as a means to demonstrate the proposed mothership design method for assessing the impact of a fleet of UXVs on the design of a mission bay, as well as indicating how such spaces might drive the overall ship design configuration and determine the ship's LAR capability. However, the mothership design options produced were balanced (i.e. in weight and space) solutions and assessed against basic naval architecture aspects (i.e. resistance-powering and intact stability), with the proposed internal arrangements meeting key typical relationships for ship general arrangement, with location and adjacency guidance for various ship spaces, as proposed by UCL DRC's design experience.

7.3 Research Review

7.3.1 The Need for an Approach to Evaluate the Impact of a Fleet of Uninhabited Vehicles on the Design of a Mothership

The design of a UXV mothership able to accommodate and support a fleet of UXVs throughout a set of potential mission scenarios is seen as an imminent technology to which navies seem to be interested. UXV capability has to date been limited to the operation of a small number of UXVs from surface vessels, such as the procurement of Frigate Type 26 in U.K. and the LCS versions (i.e. monohull and trimaran) in U.S. UXV technology would enable reductions in force personnel and costs, since the vehicles do not have to provide space, life support and special threat protection for the needs of humans [Canning, 2005]. Given the immature nature of the envisaged ship's UXVs fleet capability, there would be a need to explore the likely implications of this new technology on the design of a support surface ship at the ESSD, since early design decisions set the "skeleton" upon which the detailed design would be subsequently based, and hence they have a significant impact on the design outcomes. Therefore, it is important for the likely major ship design drivers to be identified at the early, yet formative and flexible, design stages [Andrews, 1993, 2003 a].

The design of a mothership to host and provide support to the operations of a substantial fleet of UXVs is a multi-layered problem, and subsequently a considerable number of issues ought to be investigated. From the state of the art review on the employment of UXVs in naval operations supported from surface ships (Chapter 2), it was concluded that certain aspects relevant to the design of a potential mothership have already emerged as issues. In particular the research areas listed below have been addressed to some extent in current naval ship designs:-

- The development of various UXV types, which are driven by the capabilities they need to bring into the theatre of operations, according to a mission scenario requirements (i.e. mission-oriented design), thus determining the UXVs' payload demands, as well as the vehicle design characteristics, including speed and range;
- The investigation, development and testing (i.e. simulation modelling, physical models) of LAR methods and systems for the deployment from and retrieval

to surface vessels of various UXVs. These LARSs have had the aspiration of minimising the risks to operating personnel and to the vehicles when exposed during LAR operations up to Sea State 6. Such investigations have been part of a wider UXV technology exploration, such as that under the U.K./Netherlands LAURA project, which investigates concepts of UXV LAR methods and their implications on the design of the UXVs, as well as on the direct design of a ship, on which such systems might be mounted on [Knight, 2013]. The LAURA project has considered:- (i) the structural interfaces at loading conditions imposed during LAR; (ii) hydrodynamic and seakeeping issues (i.e. relative motions and accelerations at the LAR interfaces); (iii) storage and handling solutions of UXVs within the mothership; (iv) adaptability considerations of LARSs to different UXV types, via exploring generic LAR concepts. This latter item facilitates the operations of a wider variety of UXVs and likely future vehicles via common LARSs, with the intention to limit the need to frequently modify ships to operate in different UXV scenarios, which is seen to be expensive [Knight, 2013];

- Plausible solutions that would allow C3 of UXVs by the mothership, while deployed in a mission, have been investigated by the U.S. Navy, which proposed employing the United States Navy (USN) "FORCEnet" C3 platform [Committee on Autonomous Vehicles in Support of Naval Operations, 2005];
- Given the risks a mothership would be exposed to, as well as the time to recover the UXV on-board the mothership, every time a UXV has to refuel or rearm, options for replenishment (i.e. refuel and ordnance) on-station have been explored [Galway, 2008 a][Lebans et al., 2012] [Mullens et al., 2004] [Petersen et al., 2012, 2015].

However, potential operational aspects when deploying and retrieving a considerable number of UXVs (i.e. fleet concept) from a mother vessel have yet to be investigated. This is in part due to the absence of structured and numerical means to address such design related aspects in ESSD. Particularly, the likely implications of such LAR operations on the design of a dedicated ship's mission-oriented spaces, from which the UXVs would be operated and the ship's capability to LAR as fast as possible. Such operational considerations (especially in high sea state) along with the mission bay support systems, including the employed LARSs, are likely to drive the configuration

of the mission bay spaces and beyond. Furthermore, the integration of such spaces into a mothership design would have significant impact on the overall ship design characteristics and ship's performance requirements (i.e. ship dynamic stability for successful LAR activities), as well as may also have further implications on the personnel-accommodation space demands and the ship service requirements (e.g. power installation). Complicated issues, like the consideration of LAR operational aspects and their likely effects on the ship design, will need to be explored in the early design stages. In the infancy of ship design process, any significant design novelty has to be investigated, while the design is still fluid and options could be explored [Brown, 1986], as these are likely to identify ship design drivers.

Since ship design process cannot be described by a set of directly solvable equations [Gale, 2003] and warships ought to be considered as architecturally-driven, any exploration of a UXVs fleet carrying mothership concept must incorporate configurational modelling alongside the numerical synthesis, where the ship's size (i.e. weight and volume) is determined [Andrews, 2003 b]. Given the impact of a UXVs fleet on the arrangement of potential mission bays and their integration in the overall mothership design would significantly impact the ship's layout, such investigations should be fed into a configurationally-oriented approach to ESSD. The DBB approach was originally developed at UCL [Andrews, 1985] [Dicks, 1999], and was subsequently implemented through the SURFCON module [Andrews and Pawling, 2003] in the commercially established QinetiQ GRC's Paramarine CASD suite, enabling the interfacing of appropriate naval architectural analytical tools with ship architectural modelling in ESSD. However, due to the demandingly high learning overheads before efficient using of such a sophisticated 3D CAD modelling tool (SURFCON), the need to focus on the clear ship design drivers of the UXV facilities on board the UXV mothership, and the Pre-Concept nature of the current research, it was considered that such a sophisticated tool was not necessary in the investigations of this research. Therefore, an alternative UCL-originated tool to meet the DBB logic, which was developed using JavaScript environment, could produce the mothership design case studies undertaken in this research.

7.3.2 The Proposed Mothership Design Approach

The development of the UXV mothership design evaluation approach, proposed as part of this research, was carried out to address the impact of operating a UXVs fleet from the mothership on the design of the ship. Given the architectural nature of modern warships, the development of the proposed approach evaluating the impact of a UXVs fleet on a mothership was focused on the ship's architectural aspects. To execute the DBB approach, the UCL JavaScript concept ship design tool was employed to explore the UXV implications through several design case studies of the mothership concept. The ship design tool allowed the definition of potential mission bay arrangements driven by the number and type of LARSs fitted within, which drove the overall mothership design, at a level of detail appropriate for the Pre-Concept nature of the ship design. Using the JavaScript tool, the very high software learning overheads associated with more sophisticated tools, like Paramarine, can be avoided, thus allowing a relatively faster (considering the low learning overheads) exploration of mothership design options.

To enable the exploration of the USV implications on the arrangement of the mission bays, a comprehensive set of representative activities the USVs fleet might perform throughout a mission scenario was modelled in the form of queueing network, where the vehicles are modelled as customers that seek service from certain equipment, namely the UXV stowage, handling and LARS service facilities. The appropriate equipment and system specifications (e.g. space demands), including stowage, handling systems, maintenance equipment and LARSs, were speculative given the immature nature of UXVs technology. The proposed mothership design approach relied on such data, in order to demonstrate how the integration of such systems would influence the arrangement and the size of the mission bays, which thereafter drove the design of the mothership. Although such estimates might seem rather crude, they were considered appropriate given the difficulties of predicting developments in the field, due to the very early stages of UXVs technology. This is consistent with the high level design information available during in ESSD, sufficient to assess "what-if" architectural design implication scenarios. Given the generic structure of the queueing network modelling tool, a range of service facilities could be modelled, thus enabling the assessment of the impact of such facilities on the mothership design. Therefore,

concept mission bay systems, such as those illustrated in Appendix 2, could be sufficiently detailed (i.e. space requirements and LAR times per vehicle) to be assessed for the ship design implications.

The difficulty of quantifying operational effectiveness metrics has been addressed by employing a number of indicative (i.e. proxy/indirect) measures. The total time it takes to deploy and retrieve a given fleet of UXVs from a mothership was considered to be an indication of mission effectiveness that might be achieved by the engagement of the particular mothership into the mission. Hence, from the mothership's perspective a mission can be accomplished more effectively, should the vehicles be deployed in the mission theatre and recovered on-board once the mission is completed, as promptly as possible.

The proposed UXV mothership design approach, i.e. combination of QT tool with the architectural-oriented ship design, provides a more holistic mothership design approach. Such an approach could be employed in an actual Concept Phase in collaboration with mission specialists on mothership design studies. Thus, various potential ship design solutions could be investigated in terms of technical feasibility and affordability, and result in refining the user requirements captured through requirements elucidation. Since most of the major decisions are made in the initial stages of a ship design, an early consideration of the implications of a fleet of UXVs for the design of a mothership could be essential. Therefore, such an approach, as undertaken in these mothership studies, could be seen as appropriate towards the investigation of a UXVs fleet impact on the design of a mothership. However, due to the immature nature of UXVs technology, the proposed mothership design case studies were considered as a means to demonstrate the capabilities of the proposed mothership design evaluation approach, rather than the initiation of a full concept design. Consequently, the proposed mothership design options were not considered as definitive solutions, but indicate how comparative assessments of different design options, informed by queueing network modelling, could aid early work on UXVs fleet like concepts.

The purpose of this research was to devise a plausible approach for exploring the implications of deploying a fleet of UXVs on the design of a potential mothership, able to host such assets on-board and support their operations during naval mission

scenarios. Thus, incremental and step design changes were undertaken to a sufficient level of detail appropriate to the Pre-Concept nature of this research. The research investigated ship's capabilities to accommodate and support a fleet of USVs, emphasising on the impact of LARS on the design of a mothership, due to the critical role of such systems within the overall UXV operational issues. Since the design of a UXV mothership is a multi-layered problem, as discussed in Sub-Section 7.3.1, the proposed approach is broad-brush, and it can be considered as informing UXV operational impacts on the mission bay configurations and hence the overall configuration of a potential UXV mothership. Although the mothership evaluation approach is a proposal, the application and utility were demonstrated through its application on the demonstrated ship design case studies, which provided insights regarding the USV implications on the mothership design solution space. Since UXV technology moves fast, the research aim was to scope the problem of a UXVs fleet scenario supported by a mother vessel, while providing reasonable and believable results (since the results demonstrated anticipated trends, i.e. decrease of total LAR time and less queueing effects, when more LARSs were employed - 1st design variant, or when fewer vehicles were supported - 2nd design variant).

7.3.3 The Appropriateness of Queueing Network Modelling to the Design of a Mothership

The design of a UXV mothership is a multifaceted problem, where a number of interrelated issues have been identified and discussed in Sub-Section 7.3.1. However, from the state of the art review on the employment of UXVs in naval operations, supported from surface ships (i.e. Chapter 2), a knowledge gap was revealed. This had to do with the operational issues that are likely to occur when deploying a large number of UXVs (i.e. a "fleet"), since to date operating UXVs has been limited to a small number (~ typically less than 5) of UXVs. Furthermore, current UXV capable combatants can only launch and recover one vehicle at a time, consistent with the limited number of LARSs installed on such vessels. Should there be a much larger number of vehicles ("fleet") to be deployed, this would then create a queueing problem. Since the concept of a fleet of USVs is currently speculative, then the related mothership design implications have yet to be addressed.

Given the driving ship design issue for such a mothership would be the deployment of a large number of USVs, recourse to a numerical and structured approach for assessing the impact of such operating conditions was devised. Network theory seemed to provide the basis of modelling the fleet of UXVs when operated from a mothership, due to the set of tasks the UXVs would have to undertake would be in a certain predefined sequence. This sequence could be assumed to meet a generic flow of activities in the order of: launch (i.e. mission initiation); mission activities and appropriate support during a mission scenario; and recovery (i.e mission completion). Consequently, a network system of UXV-related activities was devised, where those activities taking place on-board the mothership, including LAR operations, would be likely to significantly impact the design of a ship. By adopting network theory as the means to describe the likely operational issues necessary when deploying a fleet of UXVs, queueing theory applied to network systems was seen to provide a coherent means of capturing such effects, as discussed in Section 3.2. The other two options for analysing networks (i.e. Distance Networks and Capacitated Networks), also discussed in Section 3.2, were seen as less likely to capture the likely operational effects of a fleet of UXVs on a host ship. This is because, the on-board support ship systems can be represented as the facilities providing an appropriate service to each UXV, and thus queueing network theory can capture the relevant operational steps. Therefore, the information that can be outputted from queueing network theory can define the likely queueing effects incurred. The latter is due to the limited number of service facilities likely to be available on a ship and the large number of UXVs to be processed through the deployment procedures. Additionally, the queueing network model could be used to quantify a mothership's LAR capability, as a proxy measure of USV fleet's mission effectiveness. This then provided a means to compare different mothership design options. With the addition of comparative UPC estimates, it was possible to undertake some COEA like conclusions.

Applying QT to network systems is a mathematical modelling approach that approximates the behaviour of a real process. One alternative to QT in modelling network systems would be to use a simulation software package that would mimic the behaviour of the system more realistically than simple numerical models (such as based on QT). This would provide more accurate representations of the deployment of a fleet of USVs from a surface ship, as well as further potential insights through

(for example) animations, as discussed in Section 3.6. However, such software would be computationally demanding and would probably still be preferable to adopt a combination of both numerical modelling and simulation techniques. This is because numerical modelling (such as QT) enables an abstraction of the problem, revealing its underlying structure, and the cause and effect relationships inside the system. While more extensive simulations could refine subsystem options, when a technology is still developing (as with UXVs in naval operations) the problem of producing believable simulations could make the simulations debatable. Consequently, at this very early stage investigation of deploying a fleet of USVs from surface ships, the use of queueing network theory was seen to be more appropriate with the top-level available in Pre-Concept.

Furthermore, QT modelling of appropriate network systems allows relatively fast exploration of various options, which was seen appropriate given the Pre-Concept nature of this research, and thus the need to investigate different UXVs fleet compositions and mothership support systems. This was enabled by the fact that the code (implementing queueing network theory) was developed with a built-in flexibility, reading data from an input file, thus allowing queueing network system variations to be modelled with simple modifications to the tool. The QT tool's capabilities have been discussed in Chapter 4, while its applicability to naval ship design practice has now been demonstrated through discussing the specific mothership design case studies presented in Chapters 5 and 6. Limitations of queueing network theory in modelling operational aspects of a fleet of UXVs have also been identified and discussed in Sub-Sub-Section 7.3.5.2. Thus, information extracted from the queueing network modelling could size and arrange the mission bay spaces. This information gave number and types of facilities and systems required inside the mission bay, as well as queueing space demands incurred. The QT tool directly interfaced with the architecturally-based ESSD procedure, enabling the configurations of the mission bay spaces, to then drive the overall mothership design, through integrating these large compartments into the ship.

This research was able to explore various options rather than produce definitive mothership design solutions. This was appropriate given the fact that UXV technology is rapidly developing (such as UXV capabilities, control systems and automation in handling of UXVs from surface ships). Thus, interfacing the QT tool with the ship

design process can provide a means to explore "what-if" mission bay/LARS options as UXV technologies develop. The information required by the QT tool and concept ship design software, regarding the UXVs fleet composition, as well as the number and types of on-board the mothership equipment and support systems, could be input to the proposed approach, allowing different systems to be assessed. The proposed combination of QT and the UCL DBB approach could directly enable exploration of both processes and arrangements for handling different UXV-related developments on-board a mothership. The QT tool could provide meaningful investigation into the impact of potential tasks to be undertaken by a fleet of UXVs, addressing the design of mission bays, which are clearly key to any such mothership design options. It can be concluded that a QT-based numerical tool in combination with an architectural-based ship concept design approach would be appropriate investigating ship design issues associated with deploying a large number of USVs from a mothership. The following sub-sections consider the limitations of the undertaken research, as well as the assumptions employed in this research and how the uncertainties incurred from such assumptions might be addressed in further works.

7.3.4 Research Limitations

The mothership design case studies were developed based on the UCL warship design procedure and database [UCL, 2014 a and b], which do not precisely match the U.K. MoD's practices and data, but are broadly representative of current U.K. warship design practice (although the research is directed towards midterm future UXV fleet fits). Moreover, despite the capabilities and low learning overheads of the UCL JavaScript concept ship design tool, such design tool could not assess certain ESSD aspects of the potential mothership options. These include the designs' seakeeping performance, which is key in any successful LAR operation, given that the more dynamically stable a ship would be the less susceptible it would be to wave-induced motions. Additionally, given the limited capability of the JavaScript tool to model certain naval architecture analyses, such that of intact and damage stability, were not precisely captured. Consequently, the GZ curve produced using the procedure developed by Ali (2003) was not able to take into account the part of inflection point ($\sim 25\text{-}30^\circ$) at deck edge immersion. This means that the tangent fitted through the GZ curve to estimate the metacentric height (GM) was likely to be overestimated.

There were also significant uncertainties in the UCL parametric costing models used to estimate the UPC of the USV mothership design studies. Such uncertainties include assumptions regarding the material and equipment costing (e.g. gas turbine, diesel generators, electric motors, combat system equipment), the labour and shipyard hourly rates, as well as the purchasing overhead factors, which were all based on historical U.K. monohull warship data. Therefore, those data cannot be considered to be representative of innovative design solutions and new technologies, such as that of UXVs. Consequently, the estimated UPC values could only be used in a comparative sense. Moreover, TLC estimations were not carried out as part of developing the ship design case studies. This is because the evaluation of TLC according to UCL procedure would be even more simplistic (i.e. multiples of UPC). Furthermore, such estimates were considered unlikely to provide meaningful information on the impact of UXVs on the mothership configurations, not least because the complementing estimates were also no more than comparatively accurate.

The mothership design case studies developed as part of this research consisted of a baseline monohull USV mothership design and two monohull variations, namely incremental-change design variant, where an increased number of LARSs were fitted in the ship's mission bays, and step-change design variant, where the initial USVs fleet was equally split and distributed in two identical hulls. However, other ship design styles, such as different monohull configurations and multihull design options, further discussed in Sub-Section 7.3.5, were not investigated. When compared to monohull mothership design options, it is worthwhile mentioning that unconventional hullforms, such as twin-hullform and trimaran technology, might provide more flexible mission bay configurations. This is because unconventional mothership design types would allow greater overall ship beam configurations, which subsequently could enable the integration of a greater number of LARSs, thus entailing improved design solutions, i.e. deploying and retrieving UXVs concurrently and subsequently in less time than the equivalent monohull option. Furthermore, multihull options could achieve improved ship's stability and seakeeping performances, which might be seen as appropriate for successful LAR operations. However, any concept UPC estimates are likely to require greater uncertainty margins, so potential advantages might be seen to be accompanied with higher cost risks.

7.3.5 Issues Revealed from Applying the Proposed Uninhabited Vehicle Mothership Design Approach and the Ship Design Case Studies

The current sub-sections addresses the assumptions employed in this research, which can be grouped in those that were design related and those of operational nature.

7.3.5.1 Design Assumptions

Accommodating a UXVs fleet is likely to have additional implications on the ship design, including the complement and ship services. So accommodation spaces, as well as the ship spaces dedicated to pertinent services are likely to demand more weight and space. Given the limited information available at this very early stage investigations, such estimates selected had to be accepted in this research. Given the Royal Navy's trend towards personnel reductions and thus mitigation of ship's TLC, as well as from discussion with staff from the industrial sponsor (BAE Systems), it was assumed that a one crew-member would be required per USV, while the rest of the personnel demands were assumed as typical to run the ship operations. However, given the increased number of LARSs in the USV mothership Design Variant "1", increased personnel requirements would be likely for undertaking LAR operations. Moreover, in the second design variant, where the USVs fleet was equally split in two identical mothership designs, it was assumed that the personnel dedicated to USVs would be also reduced per ship according to the number of USVs accommodated, i.e. 30 persons per ship to handle the USVs. Moreover, given the second design variant resulted in smaller ships, it was also assumed that the personnel dedicated to ship's operations was accordingly reduced based on second variant's gross volume reduction compared to the baseline USV mothership design (i.e. ~ 30% gross volume reduction of ship Design Variant "2" compared to that of the baseline design). In addition, although indicative power demands the USVs could have on the proposed mothership design options were taken into account, load charts were not produced. Further power demands might be demanded to integrate extra LARSs, or additional personnel. Hence, such assumptions regarding the ship's resources, i.e. personnel and power requirements, may be overestimated and could warrant further investigations in any follow-up work.

The assessment of the seakeeping performance of the mothership design case studies was limited to assuming that bigger ships are likely to have a better seakeeping performance. Although such an assumption may have a merit, it is rather crude, and any further work should include assessment of the impact of sea conditions on the LAR operations. It is worth mentioning that the LAURA project's main objective was to develop robust methods and systems able to perform fast (~ 5 min per vehicle) LAR operations of USVs from surface ships up to Sea State 6 [Knight, 2013]. In addition to this, literature, including Sheinberg et al. (2003), Kimber (2012) and Chun et al. (2012), reference existing ship design solutions integrating LARSs, including stern ramps and crange systems with wave compensating systems, able to perform fast and successfully LAR up to Sea State 6 in typical naval combatants (i.e. small vessels than the USV fleet mothership studies). Those referenced LAR times vary within different LAR types and LARSs, i.e. from stern ramps to cranes, or within ramps (or cranes) of different technology, respectively, as well as within different operational conditions (i.e. sea states, speeds and headings) and overall ship design characteristics (e.g. length). Normally, launch times are shorter than the recovery, as at recovery a connection point needs to be established between the mothership and the vehicle. Typical values up to Sea State 6, for stern deployment and retrieval are less than 60 seconds [Sheinberg et al., 2003] [Chun et al., 2012] [Kimber, 2012], while cranes with wave compensating systems achieve LAR within approximately 5 mins. Based on the literature review, it was assumed that the LARSs fitted in the proposed mission bays of the USV mothership design case studies, would be able to perform successfully up to Sea State 6, without any significant implications to the accomplishment of LAR activities and the LAR time duration per vehicle. Consequently, it was also presumed that Sea State 6 is the limit for successful and safe LAR operations from surface ships. A more detailed discussion on the LAR operations and the impact of sea state on such operations is provided in the operational assumptions listed in the following sub-sub-section.

7.3.5.2 Operational Assumptions

The proposed mothership design approach can be seen as a preliminary investigation into the implications of potential UXVs fleet activities during a mission, on the design of a mothership. The generic structure of queueing network tool allows for different

UXVs fleet compositions and technology, mission bay systems and ship types (i.e. multihull option) to be assessed, by varying the inputs to the proposed mothership design approach, such as the specifications of vehicles and systems (e.g. space demands and time to launch and recover for a LAR system). The queueing network models that were analysed for the proposed mothership design case studies, comprised a set of representative activities likely to take place during a mission scenario for a typical USV fleet deployment. Furthermore, appropriate UXV specifications and systems were modelled based on researched literature. However, the accuracy of any model that represents a process, is restricted by the assumptions employed and available data (i.e. rubbish in-rubbish out). The assumptions used in this research, related to UXV operations, are listed:

- To model a "fleet" of USVs, a number of 60 USVs was assumed, consisting of two distinct types, namely 20 USVs of Type "A" and 40 vehicles of Type "B". Different vehicle types were assumed to be employed, to provide an extent of mission adaptability and flexibility, since different vehicle types bring distinct payload and capabilities in a mission theatre. Moreover, different types of USVs are likely to have distinct demands for mission bay systems and equipment, including LARSs. Such vehicle variation also demonstrated the queueing network tool's capability to handle different types. However, for a comprehensive Concept Phase the composition of a fleet of UXVs, including number and type of vehicles, would be the outcome of CONOP studies. The latter would address potential mission scenarios, allowing for UXV adaptability to the variety of mission scenarios considered. Although the USVs fleet composition, i.e. number and types, of vehicles was speculative, such information was necessary for the proposed mothership design approach. However, the QT tool could readily model different UXV compositions (since such information is input to the tool).
- The specifications of vehicle types and the mission bay support systems were obtained with reference to existing UXVs technology, since such data were required in the arrangement and sizing of the mission bays, and subsequently the configuration of the proposed USV mothership design options. However, the proposed mothership design evaluation approach could readily consider different types of vehicles and equivalent mission bay support systems, since

the QT tool is not dependent on UXVs technology (i.e. variation of values to QT tool inputs can represent different technologies, with implications for ship design assessed through the DDB method).

- Although it was assumed that a number of 60 USVs would be required for a range of mission scenarios, and thus would be operated by a mothership design option, in reality different mission scenarios may have distinct demands in the number and mix of vehicles that need to be deployed and engage to the mission. Although the QT tool allows different UXV compositions to be assessed, the ship's LAR capability was just assessed assuming the most demanding scenario, where the full fleet of USVs was deployed.
- Operational uncertainties, such failure of LARSs, could not be captured by the proposed queueing network tool, since it assumes that service facilities would be available constantly. Hence, ship's LAR capability was assessed with all LARSs are available. However, all the proposed USV mothership design options provide a degree of redundancy in that the amidships crane LAR arrangement had more than one crane fitted in the relevant mission bays. But only the first design variant (Design Variant "1", see Sub-Section 5.3.1) had a degree of redundancy, given that the stern mission bay had two stern ramps. However, in the occurrence of a LARS failure, the LAR capability of a ship would be affected. With the number of LARSs decreased for the same number of demands (i.e. vehicles), then the total LAR time to serve the vehicles would increase.
- Another operational uncertainty would be the number of vehicles that are likely to be disabled during a mission, and thus either have to be replaced with spare vehicles stowed on-board the mothership, or restored (depending on the extent of damage), having first been recovered on-board, maintained and then relaunched. However, in the case of repair by exchange (i.e. disposable vehicles) extra stowage space would be needed, whereas in the case of maintenance damaged vehicles while in mission, on-station deficiencies would incur without back-up vehicles.
- On-board activities and particularly those referring to launch and recovery of vehicles are likely to be affected by uncertainties regarding the operating conditions, i.e. sea state, ship speed and human factors. Although it is to be

considered that the manufacturer of such LARS would provide a mean LAR time per vehicle a particular LARS could achieve, any further specifications are likely to quantify such performance against operating conditions. Moreover, the recent LAURA project work suggests that Sea State 6 would be the threshold beyond which LAR operations would be problematic. For the purpose of this research, the LAR time per vehicle for the employed LARSs were assumed based on literature suggestions, as already discussed in Sub-Sub-Section 7.3.5.1. Stern ramps normally have shorter LAR times than side crane systems, since the vehicles can slide down the ramp under their own weight and drive up using their own propulsion, whereas lifting the vehicle in and out of the water is a more tedious procedure [Eriksson and Ringman, 2010]. Development of LAR technologies, such as latching mechanisms for cranes and extendable stern ramps for maintaining an appropriate level of sill depth required for recovery, aim towards safe and fast recoveries [Galway, 2008 b] [Kimber, 2012]. Therefore, given the lack of a method for assessing the impact of such operating conditions on the LAR times (per vehicle), the service times of the LAR service facilities were taken as suggested by the literature, while providing a safety margin ($\sim 10\%$) to account for such uncertainties that might affect the LAR service times. The assumption for the current work was that LAR operations would be undertaken up to Sea State 6. This assumption can be justified, given the envisaged automation of UXVs technology and LAURA's aim to perform LAR operations as fast, safe and successfully up to Sea State 6 [Knight, 2012]. Thus, LAR times per vehicle were considered to not vary significantly, due to operating conditions, up to that sea state threshold specified for LAR. Furthermore, LAR operations normally take place at low ship speeds (i.e. 3-6 kts) [Sheinberg et al., 2003], to avoid excessive hydrodynamic phenomena at the relevant LAR interfaces, which could subsequently either delay or impede such operations (i.e. particularly recovery). However, the LAURA project's aim has been to develop methods and LARSs able to perform successfully with mothership speeds up to 12 kts during such operations [Knight, 2013]. As remarked in Section 5.2 on seakeeping, the mothership was likely to have a waterline length greater than 150 m. This was borne out by the actual studies and hence investigating seakeeping performance during LAR operations was not

considered necessary. However, further seakeeping studies would merit investigation in the concept design phase.

7.3.6 Future Work

The ESSD UXV mothership design evaluation approach, proposed in this research, suggests the following further investigations:

- To obtain more realistic results regarding the UXV-related requirements for personnel/accommodation spaces and ship's services, including power demands, the implications of a UXVs fleet, as well as the relevant support systems and equipment on those ship design aspects should be further investigated.
- The investigation of different types of motherships. Other ship design styles, such as unconventional ship types (i.e. multi-hullforms) should be investigated to assess whether equivalent-to-monohull multi-hull options could enable enhanced LAR capability.
- Different monohull configurations are worthy of investigating. For instance, different types of LARSs, such as a well dock, should be explored, since it would be expected to allow improved (i.e. faster) LAR capability. However, such LARSs are likely to have extensive implications on the mothership configuration.
- JavaScript tool could be further expanded to include important ESSD analyses, such as damage stability and seakeeping, in order to obtain more believable and informative results.
- UPC estimation method should be based on more realistic data (since UPC estimation was based on parametric relationships for a frigate that is representative of fourth vessel of a class of twelve ships), in order to attain more accurate results, albeit UPC was employed as a comparative measure (not absolute) in this research between the several USV mothership design options, where cost sensitivity was not really an issue.
- In reality the duration of LAR activities per vehicle is likely to be affected by endogenous (i.e. human factor-how fast does the crew do their jobs, ship speed) and exogenous (i.e. sea state and headings-ship motions) factors. The LAURA project has been investigating probabilistic methods for describing LAR

operations, in order to quantify those factors. Such investigations are based on ESSD experience, simulations (i.e. seakeeping, model testing), LAR research, probabilistic and risk-based design research, as well as feedback from operators involved in LAR operations. Thus, the proposed UXV mothership design evaluation approach could be used to interface with such models, providing insights regarding the impact of uncertainties, due to endogenous and exogenous factors, on LAR. Such investigation would inform the LAR service times per vehicle modelled in the proposed queueing network tool, since more realistic data/modelling would then be available.

- Simulation techniques, although computationally more expensive. These could inform a more accurate analysis of queueing networks. A mathematical model, such the queueing network tool developed as part of this research, is essentially an approximation of a real process [Bhat, 2008]. However, computer simulation programs can mimic the behaviour of a system more realistically than numerical models, providing more accurate modelling of the behaviour of the system under study. Moreover, some computer simulation programs enable animations to better understand the behaviour of a modelled system. The proposed mothership design evaluation approach can be seen to provide an early investigation of the implications of a fleet of UXVs on the configuration of a mothership, since it allows a relatively fast (depending on the complexity of the network system under study) exploration and comparison of different mothership design options against cost-LAR capability criteria. Favourable design options that might emerge through such comparative studies, could be explored using simulation techniques, since they can provide more accurate results on the vehicles' operations supported from the ship.
- The implications of the assumption on disabled vehicles not interfering with the deploying process (Section 4.2) could be further investigated, but was not pursued in this research.

Chapter 8: Conclusions

The main aim of this research was to propose and demonstrate a novel UXV mothership design approach to identify and evaluate the implications of a fleet of UXVs operated from a mothership throughout a mission scenario, in the early, but crucial, stages of ship design. Overall, the research aim was met, i.e. a new quantitative and structured approach was proposed and implemented to capture, at early stage design, the implications on the naval ship design of rapidly deploying from and retrieving a fleet of UXVs to a surface vessel. Some significant conclusions are presented below.

It was demonstrated through the ship design case studies that the proposed approach was able both to differentiate between design options, and to diagnose why they were different. This difference centred on the choice and use of the numerical metrics extracted from the QT model, acting as abstracted measures of UXV mothership capability, as well as assessing the impact of UXV operations on the mission bay arrangements. Hence, distinct mothership design options in terms of size, configuration and performance were produced by integrating the various proposed mission bay arrangements into a new overall ship design solution. The mothership options were assessed against meaningful criteria, which were extracted from the output obtained using the proposed design approach. Thus, UPC and LAR capability acted jointly as a proxy measure of operational effectiveness in the absence of direct mission performance indicators. Although specific down-selection methods were not considered as part of this research, COEA can be seen as a framework to assist decision-making process, but only on a comparative basis, rather than in absolute values, in judging the various potential options forming the available solution space.

The UPC were estimated through parametric cost data and empirical relationships that describe the cost of each weight group of the ship design solutions [UCL, 2014 a], which were visualised and assessed using the JavaScript concept ship design tool. Although unconventional (i.e. multihull types) mothership variations ought to be explored, the various LAR options were limited to monohull mothership topologies, given the JavaScript concept ship design tool being currently limited to monohull configurations. LAR capability was quantified through the developed queueing

network tool, in the form of the total time required to deploy and retrieve a given fleet of UXVs. Since the QT tool was capable of assessing the performance of a UXV network system relatively rapid, the ESSD tools and methods used need to be capable of exploiting this. Thus, exploration models at Pre-Concept level were employed, in order to investigate and develop the various design options at an appropriate balance of detail.

Given that motherships are architecturally-constrained, the development of the proposed evaluation approach was focused on the architecturally identifiable aspects of integrating a UXVs fleet into the design of a mothership and how these would affect the overall ship design. Therefore, the advantages of the implementation of the architecturally-oriented UCL DBB approach to ESSD through the JavaScript tool were realised during the development of the ship design case studies to which the proposed mothership evaluation approach was applied. Such advantages included the ability to generate high level design information relatively fast, focusing on the mission bay spaces that were of most interest, as well as the easy implementation of major configurational changes and the efficient location and audit of areas and volumes of critical spaces. Consequently, the UCL-originated DBB approach to ESSD allowed the visualisation and investigation of the effects of a UXVs fleet and the relevant support systems and equipment on the ship's configuration, in the early, but formative stages of the design process. At this design stage the expenditure of design resources are negligible when compared to the whole programme. Furthermore, the ship design is still fluid and amenable to likely modifications at manageable costs, unlike the later more detailed stages, where design adjustments entail costly (or impossible) reworks.

However, several limitations emerged throughout the development, implementation and application of the proposed UXV mothership design approach in ESSD. Such aspects merit further investigation, in order to improve the proposed evaluation approach, and are discussed in sub-sections 7.3.5, 7.3.5 and 7.3.6. Despite those issues, it is considered that this research has shown the extent of how information resulting from numerical modelling techniques can be fed into the early and formative stages of complex, diverse and highly integrated engineering systems, such as motherships.

In conclusion, the integration of QT tool with a ship design tool would provide the ship designer with insights into the space demands, which are incurred by a UXVs fleet composition. Additionally, the number and types of on-board facilities, the ship's performance requirements (i.e. S⁵ plus combat systems capability) and the appropriate configuration for a mothership to successfully carry on-board and support the operations of a given fleet of UXVs could be assessed. Furthermore, QT modelling could act as a means for assessing a mothership's capability as an indication/measure of the operational effectiveness that can be achieved by the engagement of a potential UXV mothership into a mission scenario. Thus, believable and informative concept solutions can be produced.

References

Aeronautics Defence Systems Ltd. (2015). "Sea Star: The Unmanned Surface Vehicle". Brochure Specifications, 2015.

Ali H. (2003). "GZ Curves of Warships from Form Parameters". Naval Architecture MSc Thesis. University College London, London, U.K. 2003.

Alkire B., Kallimani J. G., Wilson P. A. and Moore L. R. (2010). "Applications for Navy and Aircraft Systems". National Defence Research Institute. Santa Monica, CA, U.S.A. RAND Corporation. 2010.

America's Navy (2016 a). "USS Independence". URL: http://www.navy.mil/view_image.asp?id=83741 (accessed 09.09.2016).

America's Navy (2016 b). "USS New York". URL: http://www.navy.mil/view_image.asp?id=84391 (accessed 09.09.2016).

Andrews D. J. (1981). "Creative Ship Design". Transactions of RINA, 123, pp. 447-471. 1981.

Andrews D. J. (1984). "Synthesis in Ship Design". Naval Architecture PhD Thesis. University College London, London, UK. 1984.

Andrews D. J. (1985). "An Integrated Approach to Ship Synthesis". Transactions of RINA, 128, pp. 73-91. 1985.

Andrews D. J. (1992). "The Management of Warship Design - The MoD Warship Project Manager's Perspective". Transactions of RINA, 134, pp. 1-24. 1992.

Andrews D. J. (1993). "Preliminary Warship Design". Transactions of RINA, 135, pp. 37-55. 1993.

Andrews D. J. (1998). "A Comprehensive Methodology for the Design of Ships (and Other Complex Systems)". Proceedings of Royal Society A, 454, pp. 187-211. January, 1998.

Andrews D. J. (2000). "Future warship design and the prospects for trimaran warships". Proceedings of RINA International Conference of R.V. Triton: Trimaran Demonstration Project. Southampton, U.K. April, 2000.

Andrews D. J. (2003 a). "Marine Design - Requirement Elucidation Rather Than Requirement Engineering". Proceedings of International Marine Design Conference (IMDC). Athens, Greece. May, 2003.

Andrews D. J. (2003 b). "A Creative Approach to Ship Architecture". International Journal of Maritime Engineering, 145, pp. 229-252. RINA. 2003.

Andrews D. J. (2011). Marine Requirements Elucidation and the Nature of Preliminary Ship Design. International Journal of Maritime Engineering, 153, pp. 23-29. 2011.

Andrews D. J. (2012). "Art and Science in the Design of Physically Large and Complex Systems". Proceedings of Royal Society A, 468, pp. 891-912. 2012.

Andrews D. J. (2013). "The True Nature of Ship Concept Design - And What it Means for the Future Development of CASD". Proceedings of the International Conference on Computer and IT Applications in the Maritime Industries (COMPIT). Cortona, Italy. May, 2013.

Andrews D. J. (2018). "Choosing the Style of a New Design - The Key Ship Design Decision". International Journal of Maritime Engineering, 160, pp. 71-90. 2018.

Andrews D. J. and Brown D. K. (1982). "Cheap Warships are not Simple". Proceedings of SNAME Symposium: Ship Costs and Energy. New York, NY, U.S.A. 1982.

Andrews D. J., Cudmore A. C., Humble P. and Wilson D. (1996). "SUBCON - A New Approach to Submarine Concept Design". Proceedings of Warship Conference 1996. RINA. London, U.K. June, 1996.

Andrews D. J. and Dicks C. (1997). "The Building Block Design Methodology Applied to Advanced Naval Ship Design". Proceedings of International Marine Design Conference (IMDC). Newcastle, U.K. June, 1997.

Andrews D. J., Keane R. G., Lamb T., Sen P. and Vassalos D. (2006). "State of the Art Report on Design Methodology". Proceedings of International Marine Design Conference (IMDC). Michigan, MI, U.S.A. May, 2006.

Andrews D. J., Papanikolaou A., Erichsen S. and Vasudevan S. (2009). "State of the Art Report on Design Methodology". Proceedings of the International Marine Design Conference (IMDC). Trondheim, Norway. May, 2009.

Andrews D. J., McDonald T. P. and Pawling R. J. (2010). "Combining the Design Building Block and Library Based Approaches to improve Exploration during Initial Design". Proceedings of International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT). Gubbio, Italy. April, 2010.

Andrews D. J., Percival V. and Pawling R. J. (2012). "Just How Valid is the Ship Design Spiral Given the Existence of Cliffs and Plateaux?". Proceedings of International Marine Design Conference (IMDC). Glasgow, Scotland. June, 2012.

Andrews D. J. and Pawling R. J. (2003). "SURFCON - A 21st Century Ship Design Tool". Proceedings of International Marine Design Conference (IMDC). Athens, Greece. May, 2003.

Andrews D. J. and Pawling R. J. (2004). "Fast Motherships - A Design Challenge". Proceedings of Warship 2004: Littoral Warfare and the Expeditionary Force. RINA. London, U.K. June, 2004.

Andrews D. J. and Pawling R. J. (2006). "Innovative Ship Design for High Speed Adaptable Littoral Warfare". Proceedings of Warship 2006: Future Surface Warships. RINA. London, U.K. June, 2004.

Andrews D. J. and Pawling R. J. (2007). "Concept Studies for a Joint Support Ship". Proceedings of the Warship: The Affordable Warship. RINA. Bath, UK. June, 2007.

Andrews D. J. and Pawling R. J. (2008). "A Case Study in Preliminary Ship Design". International Journal of Maritime Engineering, 150. 2008.

Andrews D. J. and Pawling R. J. (2009). "The Impact of Simulation on Preliminary Ship Design". Proceedings of International Marine Design Conference (IMDC). Trondheim, Norway. May, 2009.

Arena M. V., Blickstein I., Younossi O. and Grammich G. A. (2006). "Why Has the Cost of Navy Ships Risen? " National Defence Research Institute. RAND Corporation. 2006. Santa Monica, CA, U.S.A.

Ashdown I., Blackford H., Colford N. and Elsey F. (2010). "Common HMI for UXVs: Design Philosophy and Design Concept". BAE Systems 2010. Version 3. June, 2010.

Austin R. (2010). "Unmanned Aircraft Systems UAVs Design, Development and Deployment". Wiley. Sussex, U.K. 2010.

Autonomous Surface Vehicles (ASV) Ltd. (2016). "C-Hunter: Semi-Submersible". URL: <http://asvglobal.com/product/c-hunter/> (accessed 26.08.2016).

Autonomous Surface Vehicles (ASV) Ltd. (2016). "C-Stat: Semi-Submersible". URL: <http://asvglobal.com/product/c-stat/> (accessed 26.08.2016).

Bhat U. N. (2008). "An Introduction to Queueing Theory - Modelling and Analysis in Applications". Birkhauser Boston. New York, NY, U.S.A. 2008.

Bhatt A. and Arsenie N. A. (2017). "Hybrid Car Technology Adopted in Next Generation M-Frigates". Militaire Spectator 186, 3, pp. 114-124. 2017.

Benjamin M. R., Schmidt H., Newman P. M. and Leonard J. J. (2010). "Nested Autonomy for Unmanned Marine Vehicles with MOOS-IvP". Journal of Field Robotics 27, 6, pp. 834-875. August, 2010.

Bluefin Robotics (2016). "Bluefin-12S". URL: <http://www.bluefinrobotics.com/assets/Downloads/Bluefin-12S-Product-Sheet.pdf> (accessed 28.08.2016).

Bolch G., Greiner S., de Meer H. and Trivedi S. K. (1998). "Queueing Networks and Markov Chains. John Wiley and Sons". 2nd Edition. Hoboken, NJ, U.S.A. 1998.

Bose K. S. (2002). "An Introduction to Queueing Systems". Springer Science + Business Media. New York, NY, U.S.A. 2002.

Braithwaite C. R. (2013). "A Group System Approach to Naval Warfare - The UXV Mothership Concept". Proceedings of Warship 2013: Minor Warships. RINA. Bath, U.K. June, 2013.

Brefort D., Colin S., Jansen H. A., Duchateau E., Pawling R., Droste K., Jasper T., Sypniewski M., Goodrum C., Parsons A. M., Kara Y. M., Roth M., Singer J. D., Andrews D., Hopman H., Brown A. and Kana A. A. (2018). "An Architectural Framework for Distributed Naval Ship Systems". Ocean Engineering, 147, pp. 375-385. 2018.

Broadbent C. and Binns S. (2006). "A Vision for an Affordable Flexible UXV Enabled Versatile Surface Combatant". Proceedings of Warship 2006: Future Surface Ships. RINA. Bath, U.K. June, 2006.

Brown D. K. (1986). "Defining a Warship". SNAME Naval Engineers Journal, 98, 2, pp. 31-40. March, 1986.

Brown D. K. (1993). "Naval Architecture". SNAME Naval Engineers Journal, 105, 1, pp. 42-50. January, 1993.

Brown D. K. (2004). The Eclipse of the Big Gun: The Warship 1906 - 1945. London, U.K. Conway Maritime Press, 2004.

Brown D. K. and Andrews D. J. (1980). "The Design of Cheap Warships". Proceedings of International Naval Technology Expo. Rotterdam, Netherlands. June, 1980.

Brown D. K. and Tupper C. E. (1988). "The Naval Architecture of Surface Warships". Transactions of RINA, 131, pp. 29-56. 1988.

Bruell C. S. and Balbo G. (1980). "Computational Algorithms for Closed Queueing Networks". London, U.K. North Holland Elsevier Inc. 1980.

Button R. W., Kamp J., Curtin T. B. and Dryden J. (2009). "A Survey of Missions for Unmanned Undersea Vehicles". National Defence Research Institute. Santa Monica, CA, U.S.A. RAND Corporation. 2009.

Canning J. S. (2005). "A Definitive Work on Factors Impacting the Arming of Unmanned Vehicles". Naval Surface Warfare Centre. Dahlgren, VA, U.S.A. May, 2005.

Carreyette J. (1977). "Preliminary Ship Cost Estimation". Transactions of RINA, 120, pp. 129-155. 1977.

Chalmers D. W. (1993). "Design of Ship's Structures". H. M. Stationery Office. London, U.K. 1993.

Cheng S. (2008). "Rapid Deployment UAV". Proceedings of IEEE Aerospace Conference. Big Sky, MT, U.S.A. March, 2008.

Chun H. H., Kim C. M., Lee I., Kim K., Lee K. J. and Jung H. K. (2012). "Experimental Investigation on Stern-Ramp Deployment System and Operability for Korean Coast Guard Ship". International Journal of Naval Architecture and Ocean Engineering, 4: 488-503. 2012.

Clapper J. R., Young J. J., Cartwright J. E. and Grimes J. G. (2007). "Unmanned Systems Roadmap 2007-2032". Department of Defence U.S.A. Washington, DC, U.S.A. December, 2007.

Committee on Autonomous Vehicles in Support of Naval Operations, National Research Council (2005). "Autonomous Vehicles in Support of Naval Operations". The National Academies Press. Washington, D.C. 2005.

Cooper B. R (1981). "Introduction of Queueing Theory". 2nd Edition. Elsevier North Holland INC. London, U.K. 1981.

Deb K. (2001). "Multi-Objective Optimisation using Evolutionary Algorithms". Wiley. Chichester, U.K. 2001.

Defence Industry Daily (2016). "LCS: The USA's Littoral Combat Ship". URL: <http://www.defenseindustrydaily.com/the-usas-new-littoral-combat-ships-updated-01343/> (accessed 12.09.2016).

Depetro A. and Hoey R. (2011). "Rapid Generation and Optimisation of Ship Compartment Configuration Based on Life Cycle Cost and Operational Effectiveness". BMT Design and Technology. Melbourne, Australia. 2011.

Dicks C. A. (1999). "Preliminary Design of Conventional and Unconventional Surface Ships Using a Building Block Approach". Naval Architecture PhD Thesis. University College London, London, UK. 1999.

Eaton M., Ambrose G. and Pass D. (2014). "The Integration of Launch and Recovery Systems into the Mission Compartment". Proceedings of ASNE Launch and Recovery Symposium. Linthicum, MD, U.S.A. November, 2014.

Eriksson M. and Ringman P. (2013). "Launch and Recovery Systems for Unmanned Vehicles Onboard Ships. A Study and Initial Concepts". Centre of Naval Architecture. KTH Royal Institute of Technology in Stockholm. 2013.

Esbati S. (2018). "Design for Support in the Initial Design of Naval Combatants". Naval Architecture PhD Thesis. University College London, London, UK. 2018.

Evans H. J. (1959). "Basic Design Concepts". ASNE Naval Engineers Journal 71, 4, pp. 147-156. 1959.

Ferrier B., Duncan J. M., Belmont M. R., Christmas J. T. and Duncan J. "All Weather Ship Operational Prediction Using Simulation - Technology Developments and Results From a Dedicated Royal Navy and Related Sea Trials". Proceedings of International Conference on Computer Applications in Shipbuilding (ICCAS). Singapore. September, 2017.

Gale P. A. (2003). "The Ship Design Process". Chapter 5 - Ship Design and Construction. Thomas Lamb (Edited). SNAME. Jersey City, NJ, U.S.A. 2003.

Galway R. J. (2008 a). "Autonomous Refuelling of Unmanned Vehicles at Sea". Naval Surface Warfare Centre. Proceedings of ASNE Launch and Recovery of Manned and Unmanned Vehicles from Surface Platforms. Annapolis, MD, U.S.A. May, 2008.

Galway R. J. (2008 b). "Design considerations for Autonomous Launch and Recovery of Unmanned Surface Craft". Naval Surface Warfare Centre. Proceedings of ASNE Launch and Recovery of Manned and Unmanned Vehicles from Surface Platforms. Annapolis, MD, U.S.A. May, 2008.

Galway R. J. and Harris D. B. (2010). "Unmanned Sea Surface Vehicle (USSV) Motion Data and Refuelling Equipment Design". Naval Surface Warfare Centre. Proceedings of ASNE Launch and Recovery Symposium. Arlington, VA, U.S.A. December, 2010.

Garcia-Diaz A., Phillips T. D. and Hicks I. (2011). "Network Theory: Concepts and Applications". Wiley Encyclopaedia of operations Research and Management Science. January, 2011.

Gates J. (2016). "Is the SSBN Deterrent Vulnerable to Autonomous Drones? ". The RUSI Journal, 16, 6, pp. 28-35. 2016.

General Atomics Aeronautical (2016). "Predator B RPA". URL: <http://www.ga-asi.com/predator-b> (accessed 26.08.2016).

Gerdemann G., Kuramochi N. F., Mooshage O., Puppe D. and Rudio M. (2012). "VORGES - A Comprehensive Approach for the Planning of Future Naval Vessels". Proceedings of Warship 2012: The Affordable Warship. RINA. Bath, U.K. June, 2012.

Han K., Graham D. and Ochieng W. (2018). "M20/A20 Congestion Prediction with Post-Brexit Border Delays". Center for Transport Studies, Imperial College London. London, U.K. 2018.

Harris D. B. and Galway R. J. (2012). "Launch and Recovery of Small Unmanned Surface Vehicles at Sea". Proceedings of ASNE Launch and Recovery Symposium. Linthicum, MD, U.S.A. November, 2012.

Heather R.G. (1990). "Preliminary Design Considerations for Fast Warships". Proceedings of Warship 1990: The Future for Surface Warships. RINA. London, U.K. June, 1990.

Henry G., Cox I., Crossland P. and Duncan J. (2009). "Virtual Ships: NATO Standards Development and Implementation". Systems Engineering and Assessment. Beckington, U.K. 2009.

Hewish M. (2004). "Littoral Warfare by Remote Control". Jane's Navy International. October, 2008.

Hillier S. F. and Lieberman J. G. (2001). "Introduction to Operations Research". McGraw-Hill. 7th Edition. New York, NY, U.S.A. 2001.

Hockberger W. A. (1996). "Total system Ship Design in a Supersystem Framework". Naval Engineers Journal, 108, 3, pp. 147-167. May, 1996.

Hockberger W. A. (1999). "Determining the Level of Ship Protection". Naval Engineers Journal, 111, 3, pp. 335-345. May, 1999.

Holtrop J. and Mennen G. G. J. (1982). "An Approximate Power Prediction Method". Journal of International Shipbuilding Progress, 29, 335, pp. 166-170. 1982.

Holtrop J. (1984). "A Statistical Re-Analysis of Resistance and Propulsion Data". Journal of International Shipbuilding Progress, 31, 363, pp. 272-276. 1984.

Hydroid (2016). "Remus 100". URL: <https://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/D241A2C835DF40B0C12574AB003EA6AB?OpenDocument> (accessed 26.08.2016).

Irani R. and Spencer W. (2014). "Mission Bay Handling System for Launch and Recovery of Manned and Unmanned Systems". Proceedings of ASNE Launch and Recovery Symposium. Linthicum, MD, U.S.A. November, 2014.

Keeney R. L. (1981). "Measurement Scales for Quantifying Attributes". Behavioural Science, 26, 1, pp. 29-36. 1981.

Keeney R. L. (1982). "Decision Analysis: An Overview". Operations Research, 30, 5, pp. 803-838. 1982.

Kiick D. M. (2012). "Unmanned Vehicle Mission-Level Autonomy Applications to the Littoral Combat Ship". John Hopkins Apl Technical Digest, 31, 175-178. May, 2012.

Kimber C. A. (2006). "Future Ship Concepts for Repair and Maintenance at Sea". Proceedings of World Maritime Technology Conference. London, U.K. March, 2006.

Kimber C. A. (2012). "Boat Launch and Recovery - A Key Enabling Technology for Flexible Warships". Proceedings of Pacific Conference. Sydney, Australia. February, 2012.

Knight S. (2012). "LAURA Joint Industry Project". Proceedings of ASNE Launch and Recovery Symposium. Linthicum, MD, U.S.A. November, 2012.

Knight S. (2013). "LAURA Joint Industry Project: Offshore Patrol and Security". Portsmouth, U.K. 2013.

Koenig C. P., Nalchajian D. and Hootman C. J. (2008 a). "Ship Service Life and Naval Force Structure". Proceedings of ASNE Symposium: Engineering the Total Ship. Tysons VA, U.S.A. September, 2008.

Koenig C. P., Czapiewski M. P. and Hootman C. J. (2008 b). "Synthesis and Analysis of Future Naval Fleets". Taylor and Francis. Journal of Ships and Offshore Structures, 3, 2, pp. 91-89. May, 2008.

Kouriampalis N., Pawling J. R. and Andrews J. D. (2017). "The Implications of Uninhabited Vehicle Technology on Naval Fleet Structures and Naval Ship Design". Proceedings of International Conference on Computer Applications in Shipbuilding (ICCAS). Singapore. September, 2017.

Lagershausen S. (2013). "Performance Analysis of Closed Queueing Networks". Springer-Verlag. Berlin. 2013.

Lebens G., Spencer B., Robb M. and Webb G. (2012). "Leveraging Offshore Oil and Gas Technology for Handling and Refuelling Unmanned Vehicles from Surface Combatants". MARI-TECH. April, 2012.

Lester G. (2007). "REMUS Launch and Recovery Systems". International Symposium on Unmanned Untethered Submersible Technology. Durham, NH, U.S.A. August, 2007.

Lockheed Martin (2016). "Marlin Mk3". URL: http://auvac.org/uploads/platform_pdf/Marlin-brochure.pdf (accessed 28.08.2016).

Manley J. E. (2008). "Unmanned Surface Vehicles, 15 Years of Development". OCEANS. Quebec. September, 2008.

Marin (2016). "JIP LAURA". URL: <http://www.marin.nl/web/JIPs-Networks/Archive-JIPs-public/LAURA.htm> (accessed 05.09.2016).

Messineo S. and Serrani A. (2009). "Offshore Crane Control Based on Adaptive External Models". Elsevier, 45, pp. 2546-2556. September, 2009.

Michigan Aerospace (2016). "Littoral Combat Ship (LCS) Launch and Retrieval System". URL: <http://www.michiganaerospace.com/experience/earth/> (accessed 07.09.2016).

Ministry of Defence, DE&S (2012). "Type 26 - The Shape of Things to Come". Desider. Issue 52. Bristol, U.K. September, 2012.

McTaggart K., Roy A., Steinke D., Nicoll R. and Perrault D. (2012). "Simulation of Small Boat Launch and Recovery from a Ship with a Crane". Proceeding of Launch and Recovery of Manned and Unmanned Vehicles from Surface Platforms. ASNE. Linthicum, MD, U.S.A. November, 2012.

McTaggart K., Henry G., Oakey S. and Spengen V. J. (2018). "Naval Platform Simulation Using the NATO Virtual Ships Standard". Proceedings of Symposium on Multinational Interoperability: Agility for Military Training and Operational Applications, Innovation in Enterprise Level Consortiums and M&S Technology Development. Ottawa, Canada. October, 2018.

Molland A. F., Turnock S. R. and Hudson D. A. (2011). "Ship Resistance and Propulsion: Practical Estimation of Ship Propulsive Power". 2nd Edition. Cambridge University Press, New York, U.S. 2011.

Mullens K., Burmeister A., Wills M., Stroumtsos N., Denewiler T., Thomas K. and Stancliff S. (2004). "Automated Launch, Recovery and Refuelling for Small Unmanned Aerial Vehicles". Proceedings of SPIE. San Francisco, CA, U.S.A. December, 2004.

Naval Drones (2016 b). "RQ-2 Pioneer". URL: <http://www.navaldrones.com/pioneer.html> (accessed 26.08.2016).

NRAC Committee (2012) (Naval Research Advisory Committee). "How Autonomy Can Transform Naval Operations". NRAC Committee Report. October, 2012.

Naval Undersea Warfare Centre Division Newport (2016). "Manta". URL: <http://auvac.org/platforms/view/180> (accessed 26.08.2016).

Naval Today (2016). "USA: LCS Remote Mine hunting System Finishes Developmental Testing". URL: <http://navaltoday.com/2013/12/13/usa-lcs-remote-minehunting-system-finishes-developmental-testing/> (accessed 09.09.2016).

Northrop Grumman (2016). "Fire Scout". URL: <http://www.northropgrumman.com/Capabilities/firescout/Pages/default.aspx> (accessed 26.08.2016).

Office for National Statistics (2017). "Inflation and Price Indices". 2017.

O'Rourke R. (2016). "Navy Littoral Combat Ship (LCS)/Frigate Program: Background and Issues for Congress". Congressional Research Service. June, 2016.

Page J. (2011). "Flexibility in the Early Stage Design of US Navy Ships: An Analysis of Options". MSc Thesis in Engineering and Management and Naval Engineering. Massachusetts Institute of Technology. Cambridge, MA, U.S.A. June, 2011.

Piperakis S. A., Gaspar M. H., Pawling J. R. and Andrews J. D. (2018). "An Online Application of the Design Building Block Approach to Preliminary Ship Design". UCL. 2016 (1st draft - To be published).

Pawling R. J. (2015). "Relationships in General Arrangement Design". UCL Department of Mechanical Engineering. UCL. London, U.K. April, 2015.

Pawling R. J. and Andrews D. J. (2009). "The Ship Design Challenge of Naval Unmanned Aerial Vehicles". Proceedings of Warship 2009: Air Power at Sea. RINA. Bath, U.K. June, 2009.

Pawling R. J. and Andrews D. J. (2013). "Large Unmanned Vehicles and the Minor War Vessel". Proceedings of Warship 2013: Minor Warships. RINA. Bath, U.K. June, 2013.

Pawling R. J., Andrews D. J., Piks R., Singer D., Duchateau E. and Hopman H. (2013). "An Integrated Approach to Style Definition in Early Stage Design". Proceedings of International Conference on Computer and IT Applications in the Maritime Industries (COMPIT). Cortona, Italy. May, 2013.

Pawling R. J., Piperakis A. S. and Andrews D. J. (2015). "Developing Architecturally Oriented Concept Ship Design Tools for Research and Education". Proceedings of International Marine Design Conference (IMDC). Tokyo, Japan. May, 2015.

Pawling R. J., Kouriampalis N., Esbati S., Bradbeer N. and Andrews D.J. (2017). "Expanding the Scope of Early Stage Computer Aided Ship Design". Proceedings of the International Conference on Computer and IT Applications in the Maritime Industries (COMPIT). Cardiff, U.K. May, 2017.

Petersen S. M., Galway R. J., Michelon L. J. and Harris D. B. (2012). "The In Situ Replenishment System ". Launch and Recovery of Manned and Unmanned Vehicles from Surface Platforms. Proceedings of ASNE Launch and Recovery Symposium Linthicum, MD, U.S.A. November, 2012.

Petersen S. M., Harris D. B. and Galway R. J. (2015). "Remote Autonomous Replenishment Buoy for Sea Surface Craft". U.S.A. Patent. February, 2015.

QINETIQ (2018). URL: <http://paramarine.qinetiq.com/solutions/warship-solutions.aspx> (accessed 12.09.2018).

Randles I. (2012). "Designing for the Future: The Type 26 Global Combat Ship Mission Bay". International Naval Engineering Conference and Exhibition (INEC). Edinburgh, U.K. May, 2012.

Rauch G. C., Purcell J. M., Austin T. and Packard J. G. (2008). "Ship of Opportunity Launch and Recovery System for REMUS 600 AUV's". Proceedings of IEEE Aerospace Conference. Oceans Conference. Kobe, Japan. April, 2008.

Rawson K.J. (1973). "Towards Economic Warship Acquisition and Ownership". Transactions of RINA. 1973.

Rehman U. F., Nardiello R. N., Grenda D. and Orji J. (2014). "Landing Platform Dock". MSc Ship Design. UCL. London, U.K. 2014.

Robertazzi G. T. (1994). "Computer Networks and Systems. Queueing Theory and Performance Evaluation". Springer-Verlag. Second Edition. New York, NY, U.S.A. 1994.

Roberts G. N. and Sutton R. (2006). "Advances in Unmanned Marine Vehicles". IET Control Engineering Series, 69. The Institution of Electrical Engineers. 1st Edition. London, U.K. 2006.

Rolls Royce (2018 a). URL: <https://www.rolls-royce.com/products-and-services/marine/about-marine/market-sectors/naval.aspx> (accessed 01.04.2018). "MT30 Gas Turbine Brochure".

Rolls Royce (2018 b). URL: <https://www.rolls-royce.com/products-and-services/marine/product-finder/generating-sets/diesel-generating-sets.aspx> (accessed 20.03.2018). "The Bergen Marine Engine and Propulsion Portfolio 2017".

Rudius M. (2012). "Approaches to Cost Risk Analysis in Naval Shipbuilding". Proceeding of Warship 2012: the Affordable Warship. RINA. Bath, U.K. June, 2012.

Savitz S., Blickstein I., Buryk P., Button R. W., DeLuca P., Dryden J., Mastbaum J., Osburg J., Padilla P., Potter A., Price C. C., Thrall L., Woodward S. K., Yardley R. J. and Yurchak J. M. (2013). "U.S.A. Navy Employment Options for Unmanned Surface Vehicles (USVs)". National Defence Research Institute. Santa Monica, CA, U.S.A. RAND Corporation. 2013.

Schietekat S., Wall D. A. and Gopaul G. K. (2016). "Validation and Verification of a Bayesian Network Model for Aircraft Vulnerability". Proceedings of 12th INCOSE SA Systems Engineering Conference. Pretoria, South Africa. June, 2016.

Sheinberg R., Minnick V. P., Beukema G. T., Kauczynski W. Silver L. A. and Cleary C. (2003). "Stern Boat Deployment Systems and Operability". Word Maritime Technology Conference. San Francisco, CA, U.S.A. October, 2003.

Smith T. C. Timothy (2008). "Launch and Recovery Model Testing Approaches". Launch and Recovery of Manned and Unmanned Vehicles from Surface Platforms. Annapolis, MD, U.S.A. May, 2008.

Stoer J. and Bulirsch (2002). "Introduction to Numerical Analysis". 3rd Edition. Springer. New York, NY, U.S.A. 2002.

Suri R., Sahu S. and Vernon M. (2007). "Approximate Mean Value Analysis for Closed Queueing Networks with Multiple-Server Stations". Proceedings of Industrial Engineering Research Conference. Pittsburgh PA, U.S.A. 2007.

Think Defence (2016). "Unmanned Mine Countermeasures Update". URL: <http://www.thinkdefence.co.uk/2014/04/unmanned-mine-countermeasures-update/> (accessed 09.09.2016).

Thomsen J. E. (2007). "The Navy Unmanned Surface Vehicle (USV) Master Plan". U.S.A. Department of the Navy. Washington, DC, U.S.A. July, 2007.

Tupper E. C. (2013). "Introduction to Naval Architecture". 5th Edition. Butterworth-Heinemann. Oxford, UK. 2013

UCL (2007). "Surface Ship Structural Design and Grillage Design Notes". MSc Naval Architecture. London, U.K. July, 2007.

UCL (2014 a). "Ship Design Procedure". MSc Naval Architecture. London, U.K. April, 2014.

UCL (2014 b). "Ship Design Data Book". MSc Naval Architecture. London, U.K. April, 2014.

U.K. Defence Journal (2017). "Queen Elizabeth Class Aircraft Carrier: A Guide". URL: <https://ukdefencejournal.org.uk/queen-elizabeth-class-aircraft-carrier-guide/> (accessed 02.04.2019).

U.K. MoD (2000). "Defence Standard 02-109 - Stability Standards for Surface Ships". U.K. MoD, London, U.K. 2002.

U.K. MoD (2002). "The Acquisition Handbook". U.K. MOD. Bristol, U.K. January 2002.

Unmanned Systems Technology (2016). "RQ-4B Global Hawk UAV". URL: <http://www.unmannedsystemstechnology.com/2013/03/northrop-grumman-successfully-demonstrates-joint-stars-global-hawk-interopability/rq-4-block-10-global-hawk-2/> (accessed 26.08.2016).

USNI News (2016). "Navy's future Frigate Will Be Optimised for Lethality, Survivability - Will Not Retain LCS's Speed". URL: <https://news.usni.org/2015/10/15/navys-future-frigate-will-be-optimized-for-lethality-survivability-will-not-retain-lcss-speed> (accessed 09.09.2016).

VestDavit (2018). "Safe Boat Handling for Life – Unmanned Systems". URL: <https://www.vestdavit.no/mission-ease-unmanned-systems/> (accessed 09.05.2018).

Vijlee Z. S., Ouroua A., Donmaschk N. L. and Beno H. J. (2007). "Directly-Coupled Gas Turbine Permanent Magnet Generator Sets for Prime Power Generation On Board Electric Ships". Proceedings of IEEE Electric Ship Technologies Symposium. Arlington, VA, U.S.A. May, 2007.

Walsh J. A. and Smith R. M. (2004). "The Navy Unmanned Undersea Vehicle (UUV) Master Plan." Department of the Navy U.S.A. Washington, DC, U.S.A. November, 2004.

Watson D. G. M. (1998). "Practical Ship Design". Elsevier Ocean Engineering Book Series. Oxford, U. K. 1998.

Yan R., Pang S., Sun H. and Pang Y. (2010). "Development and Missions of Unmanned Surface Vehicle". Journal of Marine Science and Application, 9, pp. 451-457. September, 2010.

Yuzukirmizi M. (2005). "Finite Closed Queueing Networks with Multiple Servers and Multiple Chains". PhD Mechanical and Industrial Engineering, University of Massachusetts Amherst. February, 2005.

Appendices

Appendix 1. Launch and Recovery Methods of Vehicles from Surface Ships

UXVs	LAR Methods		
USVs	Side LARS		
	Crane	LAR	 <p>RHIB side LARS on LCS 2 (USS Independence) [America's Navy, 2016 a]</p>
	Net	Recovery	See equivalent of UUVs net LARS
	Stern LARS		
	Crane	LAR	 <p>RHIB stern LARS on LCS 2 (USS Independence) [USNI News, 2016]</p>
	Ramp	LAR	 <p>RHIB stern ramp of LCS 1 (USS Freedom) [Michigan Aerospace, 2016]</p>
	Well Dock	LAR	 <p>Well dock LARS of USS New York (LPD 21) [America's Navy, 2016 b]</p>

Table A.1. 1: USV LAR methods from surface ships





UXVs		LAR Methods	
UUVs	Side LARS		
	Crane	LAR	 <p>Hydroid REMUS 600 MCM UUV LARS on Royal Navy Hunt Class MCM Vessel [Think Defence, 2016]</p>
	Net	Recovery	 <p>Atlas Sea Fox UUV recovery net [Lester, 2007]</p>
	Stern LARS		
	Crane	LAR	 <p>UUV stern LARS on LCS 2 (USS Independence) [Naval Today, 2016]</p>
	Ramp	LAR	 <p>Seahorse UUV stern ramp LARS on Sea Fighter (FSF 1) [Chip, 2016 b]</p>
	Well Dock	LAR	See equivalent USVs well dock LARS

Table A.1. 2: UUV LAR methods from surface ships

Appendix 2. Concept Designs of Launch and Recovery Systems for Uninhabited Vehicles Operated from Surface Ships

- Design 1:

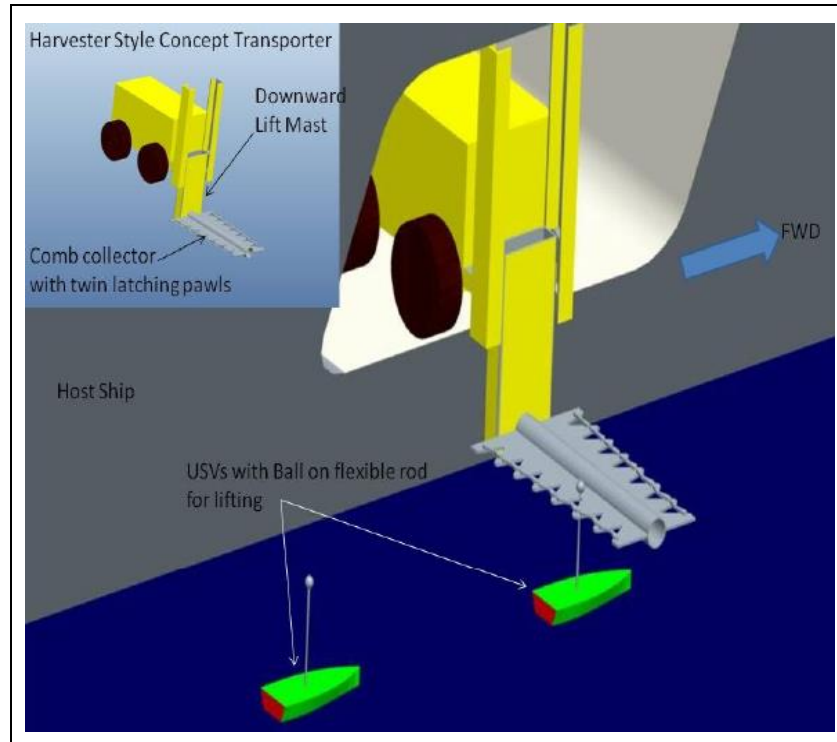


Figure A.2. 1: Harvester [Harris and Galway, 2012]

- Design 2:

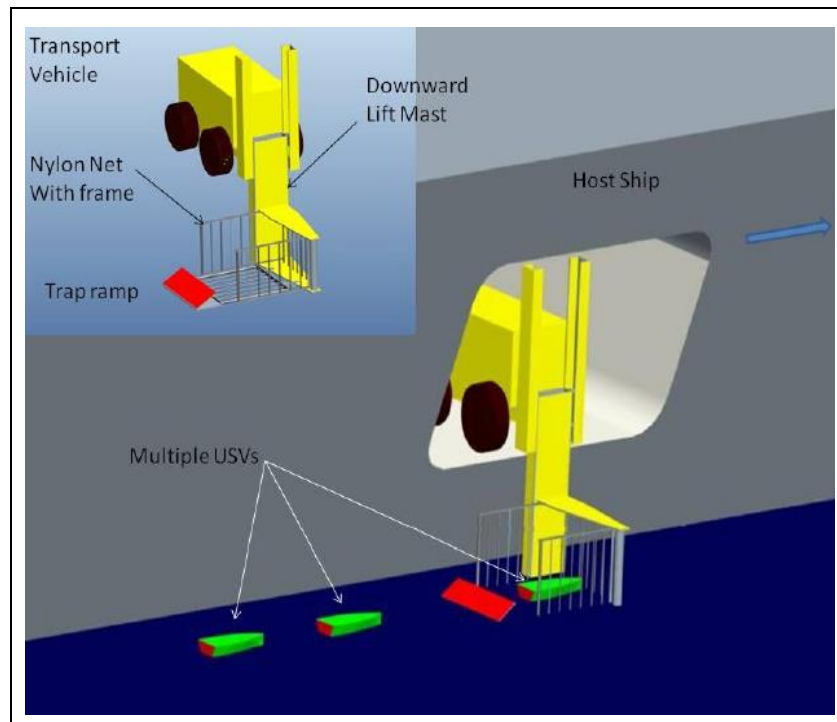


Figure A.2. 2: Ratcheting Basket [Harris and Galway, 2012]

- **Design 3:**

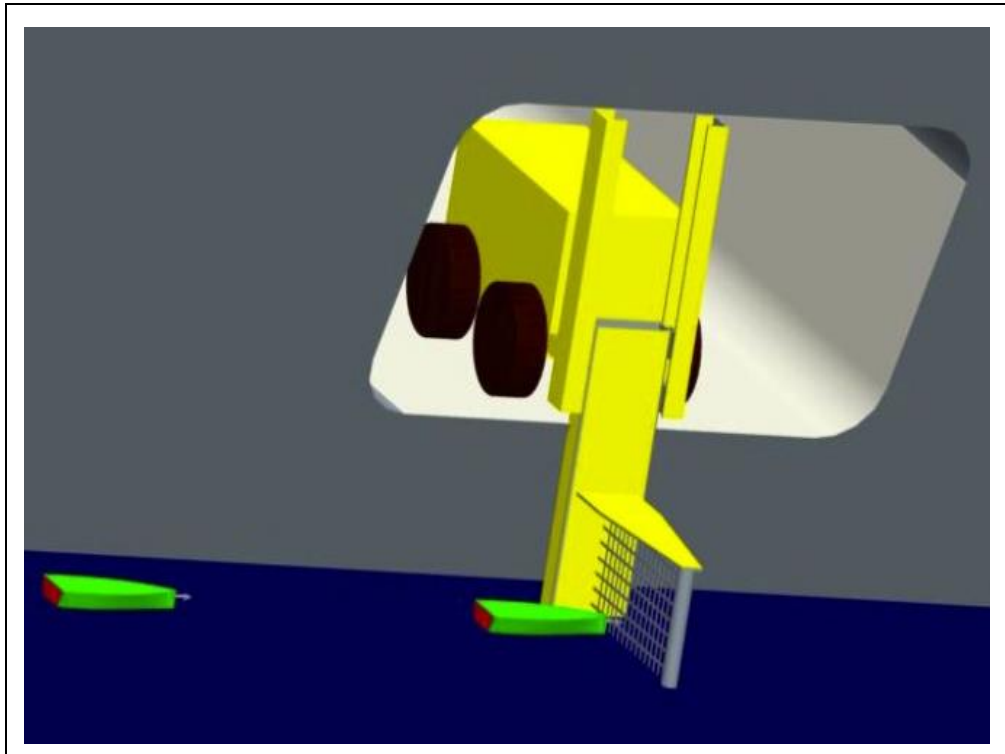


Figure A.2. 3: Barb and Net [Harris and Galway, 2012]

- **Design 4:**

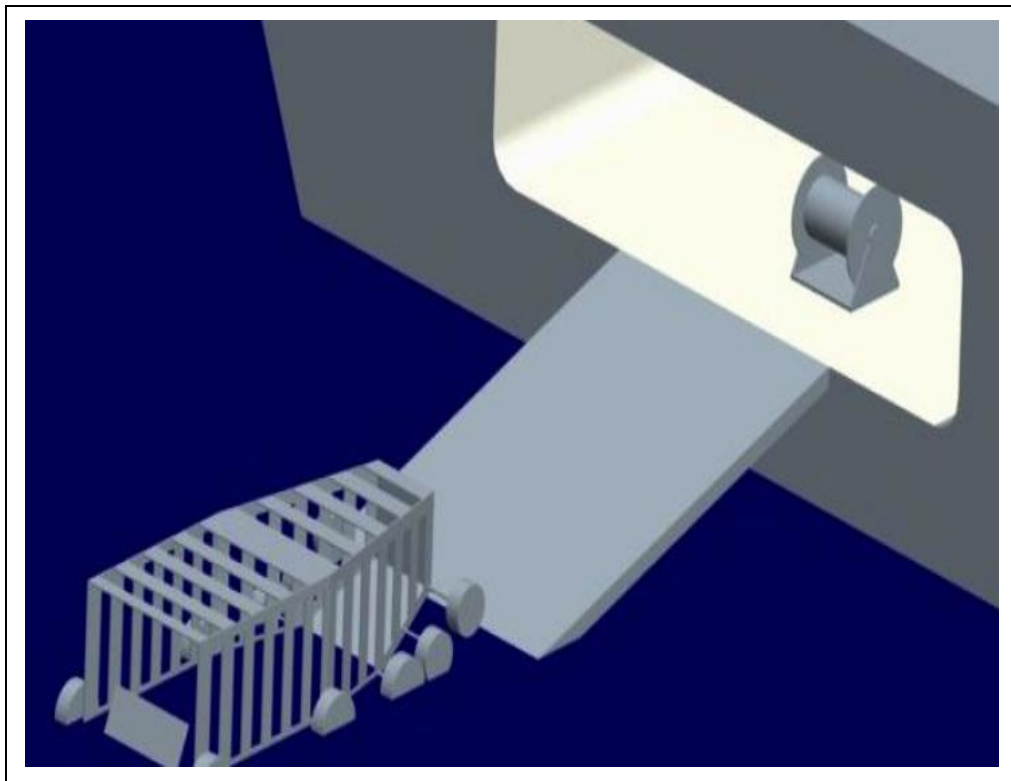


Figure A.2. 4: Ratcheting Beach [Harris and Galway, 2012]

Appendix 3. Evolution of the Aircraft Carrier Technology from Seaplane Carrier

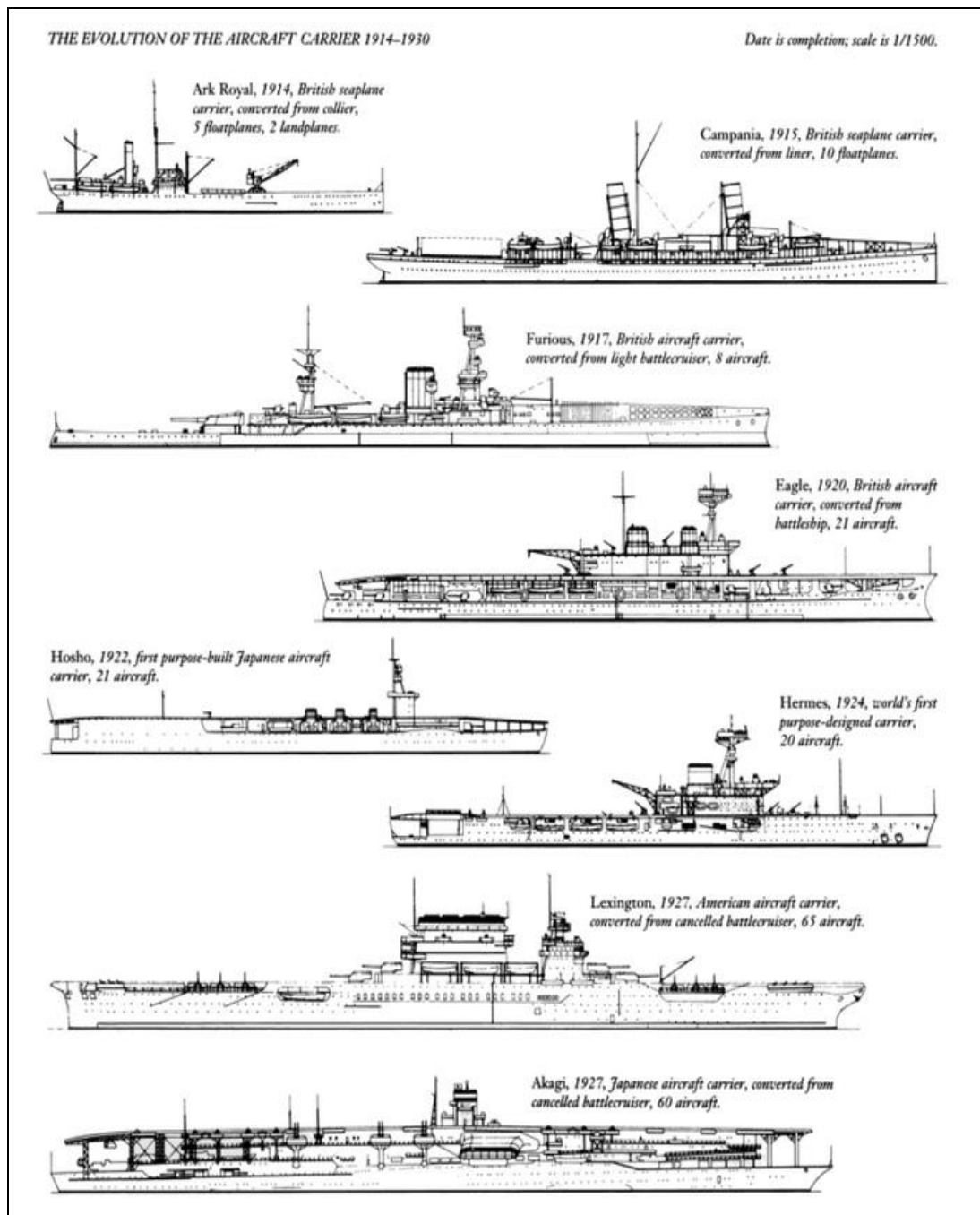


Figure A.3. 1: Seaplane and aircraft carrier evolution (I) [Brown, 2004]

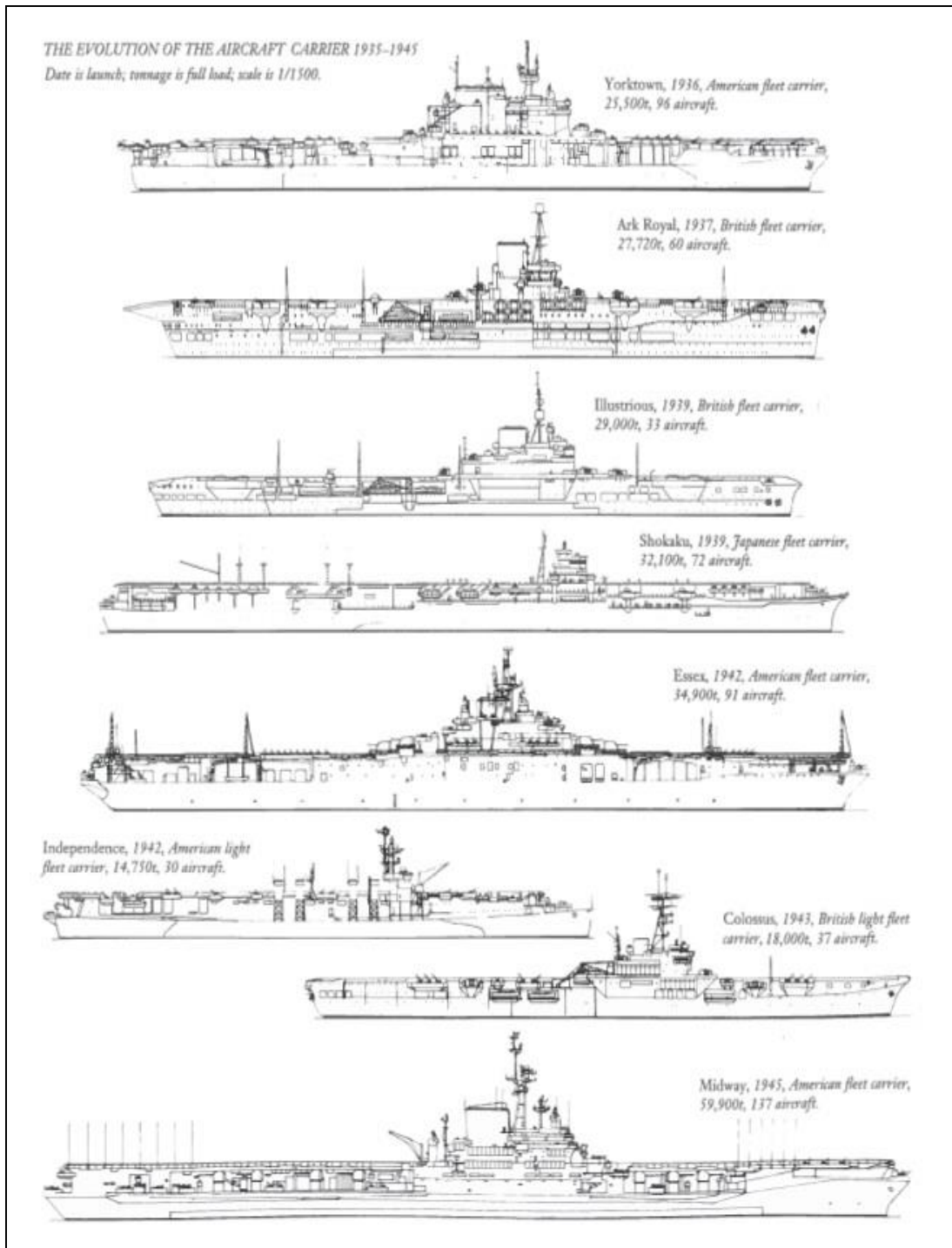


Figure A.3. 2: Seaplane and aircraft carrier evolution (II) [Brown, 2004]

Appendix 4. UCL Mothership Design Studies

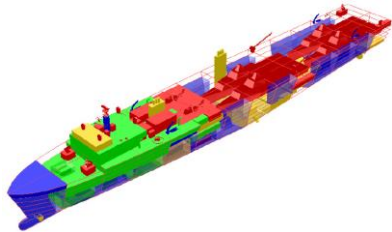
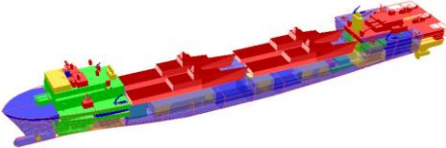
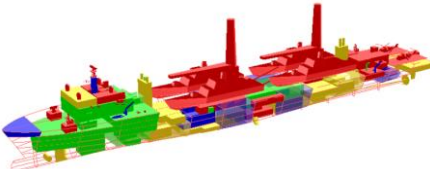
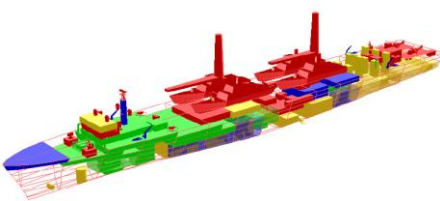
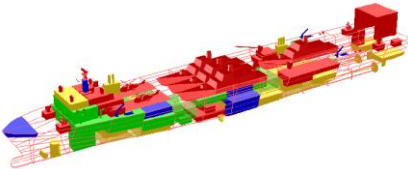
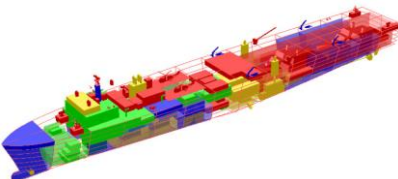
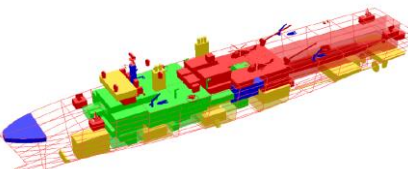
Mothership Configurations	
	Dock Ship
	Heavy Lift Ship
	Crane Ship
	Fast Crane Ship
	Stern Gantry Ship
	Deep draught Dock Ship
	SSK Dock Ship

Table A.4. 1: Mothership configurations [Andrews and Pawling, 2004]

**Appendix 5. International Conference on Computer Applications in
Shipbuilding (ICCAS) 2017**

**THE IMPLICATIONS OF UNINHABITED VEHICLE TECHNOLOGY ON
NAVAL FLEET STRUCTURES AND NAVAL SHIP DESIGN**

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Appendix 6. Mean Value Analysis Algorithm for Multi-Server Nodes

The nomenclature used in this appendix is listed, as follows [Bose, 2002]:

k: Number of nodes in the system, $k = 1, 2, 3, \dots, K$

m: Number of customers in the system, $m = 1, 2, 3, \dots, M$

C_k: Number of servers at a node "k". Servers per node are identical, thus they have equal service time

T_k: Service time per customer of each server at a node "k"

μ_k: Service rate of a node "k"

P_{zi}: Routing ratios, denoting the ratio according to a customer leaves a node "z" and enters a node "i" of the network system, $i, z = 1, 2, \dots, k$. They define the network path.

V_k: Visiting ratio, denoting the number of visits of a vehicle to a node "k" for every single visit of the vehicle to a reference node, say node 1, thus $V(1) = 1$

P_{k(j,m)}: Probability that at a node "k" there are j, $j = 1, 2, 3, \dots, m$ customers, when "m" customers are present in the entire network system (used in the estimation of the factor denoted as "S_k")

λ: System/overall throughput, when "m" customers are present in the system

λ_k: Node throughput, when "m" customers are present in the system

N_k (or j_k): Number of customers at a node "k", when "m" customers are present in the system (this includes the customers at queue and service node area)

N_{qk} (m): Number of customers waiting at queue at a node "k" when "m" customers are present in the system

W_k: Time spent by a vehicle at node "k", when "m" customers are present in the system (this includes the time at queue and service node area)

The equations employed in MVA algorithm are listed in Table A.6. 1.

MVA Equations		
	$W_k(m) = \frac{N_k(m-1) + 1}{\mu_k}$	For single-server node
Node Residence Time per vehicle (i.e. Total Time = Waiting Time + Service Time), for $k = 1, 2, 3, \dots, K$, and $m = 1, 2, 3, \dots, M$	$W_k(m) = T_k \frac{N_k(m-1) + 1 + S_k}{C_k}$	For multi-server node
	$S_k = \sum_{j=1}^{C_k-1} (C_k - j) P_k(j-1, m-1)$	
	$W_k(m) = T_k$	For IS node
System Throughput, for $m = 1, 2, 3, \dots, M$	$\lambda(m) = \frac{m}{\sum_{k=1}^K W_k(m) V_k}$	
Number of Customers at a Node $k = 1, 2, 3, \dots, K$, for $m = 1, 2, 3, \dots, M$ (Little's Law)	$N_k(m) = \lambda_k W_k(m)$	
Marginal Local Balance Theorem (by Reiser and Lavenberg), for $k = 1, 2, 3, \dots, K$, and $m = 1, 2, 3, \dots, M$	$P_k(j, m) = \frac{\lambda_k(m) P_k(j-1, m-1)}{\mu_k(j)}$ for $j = 1, 2, 3, \dots, m$ $P_k(0, m) = 1 - \sum_{j=1}^m P_k(j, m)$ for $j = 0$	
Visiting Ratios, for $k = 1, 2, 3, \dots, K$	$V_1 = 1$ $V_i - \sum_{z=1}^K P_{zi} V_z = 0, i = 2, \dots, K$	

Table A.6. 1: MVA algorithm equations [Bose, 2002]

The execution of MVA recursive algorithm is described by the following sequence of steps [Bose, 2002]:

- **Initialisation:** Set $N_k(m) = 0$ for $m = 0$, then for $k = 1, 2, 3, \dots, K$ and $j = 1, 2, 3, \dots, (C_k - 1)$, then $P_k(j, m)$:
 - $P_k(0, 0) = 1$
 - $P_k(j, 0) = 0$
- **Recursion:** Do steps (1), (2), (3), (4) successively for $m = 1, 2, 3, \dots, M$:
 - **Step 1:** Calculate $W_k(m)$ for $k = 1, 2, 3, \dots, K$:
 - $W_k(m) = \frac{N_k(m-1)+1}{\mu_k}$, for single-server nodes
 - $W_k(m) = \frac{N_k(m-1)+1+S_k}{\mu_k}$, for multi-server nodes,
 where $S_k = \sum_{j=1}^{C_k-1} (C_k - j) P_k(j - 1, m - 1)$,
 where $P_k(j - 1, m - 1)$ is updated in step 4
 - $W_k(m) = T_k$, for IS
 - **Step 2:** Apply Little's Law to obtain network system throughput $\lambda(m)$:

$$\lambda(m) = \frac{m}{\sum_{k=1}^K W_k(m) V_k}$$
 - **Step 3:** Apply Little's Law to obtain node throughput $\lambda_k(m)$ for $k = 1, 2, 3, \dots, K$:

$$\lambda_k(m) = \frac{N_k(m)}{W_k(m)}$$
 - **Step 4:** Update $P_k(j, m)$ for $k = 1, 2, 3, \dots, K$, from Marginal Local Balance Theorem:

$$P_k(j, m) = 1 - \sum_{j=1}^m P_k(j, m), \text{ for } j = 0$$

$$P_k(j, m) = \frac{\lambda_k(m) P_k(j-1, m-1)}{\mu_k}, \text{ for } j = 1, 2, 3, \dots, M$$
- **Termination:** Terminate recursion once $m = M$ is reached.

In each one of the executing recursions the following could be also calculated for each node of the network system:

- i. Queueing Delay: $QD_k(m) = W_k(m) - T_k$
- ii. Number of customers waiting at queue (from Little's Law):

$$N_{qk}(m) = \lambda_k(m)[W_k(m) - T_k]$$

The visiting ratios, employed by the MVA algorithm, for each node of the network system are calculated from the equations of flow, which are seen as the equivalent of the conservation of mass equation governing the fluid motions (i.e. continuity equation). Taking as an example a queueing network that consists of the nodes illustrated in Figure A.6. 1, where the flow through each node is passed to another node as indicated by the predefined route. In this figure the service activity is represented by a circle, whereas the queue is represented by the delay symbol [Bolch et al., 1998].

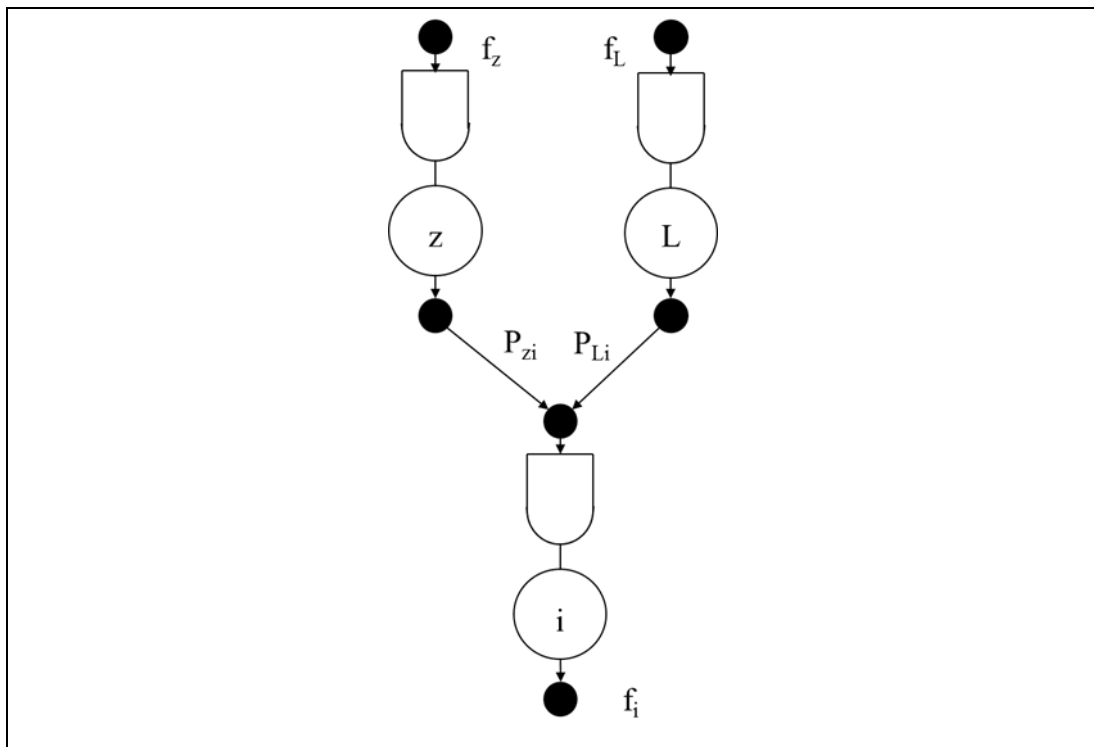


Figure A.6. 1: Flow of customers at a node in a network system [Bolch et al., 1998]

P_{zi} , $z, i = 1, 2, \dots k$, $k = 1, 2, 3, \dots K$, is identified as the routing ratio, which describes the ratio of customers leaving a node z and heading to a node i . In the case of the examined network system that represents the overall operations of UXVs, the routing ratios are deterministic (i.e. the routing ratios are defined by the user). It is noteworthy that the sum of the routing ratios describing the UXVs leaving a node must equal one, i.e. $\sum P_{zi} = 1$, thus all customers are included. To compute the flow at each node of a general network, a system of linear equations has to be constructed and subsequently solved. The value of the flow through a node i , i.e. f_i , depends on the amounts of flow provided by the preceding nodes, i.e. z and L as seen in Figure A.6. 1:

$$f_i = P_{zi}f_z + P_{Li}f_L$$

$$f_i - P_{zi}f_z - P_{Li}f_L = 0 \quad [1]$$

Equation of flow, i.e. equation (1), can be generalised to the following expression, which hold for all the nodes in a network system, i.e. $k = 1, 2, 3, \dots, K$, thus forming a system of equations:

$$f_i - \sum_{z=1}^k P_{zi}f_z = 0, \quad i = 1, 2, 3, \dots, K \quad [2]$$

The routing ratios describing all the nodes of a network system, i.e. P_{zi} , can be summarised in a matrix form, known as the routing ratio matrix, and it is summarised below:

$$P_{zi} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & \dots & P_{1K} \\ P_{21} & P_{22} & P_{23} & P_{24} & \dots & P_{2K} \\ P_{31} & P_{32} & P_{33} & P_{34} & \dots & P_{3K} \\ P_{41} & P_{42} & P_{43} & P_{44} & \dots & P_{4K} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ P_{K1} & P_{K2} & P_{K3} & P_{K4} & \dots & P_{KK} \end{bmatrix} \quad [3]$$

However, the system of equations, described by the generalised equation (3), cannot be solved directly, as there are more unknowns than the number of equations. To solve such a complex system of equations it was suggested to replace the flows " f_i " with flows relative to a node, say node one, denoted as " V_i ". Hence, setting $V_1=1$, then the set of the linear equations described by equation (2) transforms into the following system, which can thereafter provide the values of the visiting ratios " V_i " [Bolch et al., 1998] [Lagershausen, 2013]:

$$V_1 = 1$$

$$V_i - \sum_{z=1}^K P_{zi}V_z = 0, \quad i = 2, \dots, K \quad [4]$$

The above transformed system of equations (4) can be presented analytically in the following matrix form, which can be accurately solved computationally by employing the numerical method "Gauss Pivotal Elimination" [Stoer and Bulirsch, 2002]:

$$\begin{bmatrix} 1-P_{2,2} & -P_{3,2} & -P_{4,2} & -P_{5,2} & \dots & -P_{K,2} \\ -P_{2,3} & 1-P_{3,3} & -P_{4,3} & -P_{5,3} & \dots & -P_{K,3} \\ -P_{2,4} & -P_{3,4} & 1-P_{4,4} & -P_{5,4} & \dots & -P_{K,4} \\ -P_{2,5} & -P_{3,5} & -P_{4,5} & 1-P_{5,5} & \dots & -P_{K,5} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ -P_{2,K} & -P_{3,K} & -P_{4,K} & -P_{5,K} & \dots & 1-P_{K,K} \end{bmatrix} \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ \dots \\ V_K \end{bmatrix} = \begin{bmatrix} P_{1,2} \\ P_{1,3} \\ P_{1,4} \\ P_{1,5} \\ \dots \\ P_{1,K} \end{bmatrix} \quad [5]$$

$$V_1 = 1$$

Regarding the node service rate, it is a function of the number of customers present in the particular node, when $m, m = 1, 2, 3, \dots, M$, customers are present in the entire network, as well as the number of servers at the node under study [Yuzukirmizi, 2005]. This dependence is summarised by the following expression:

$$\begin{aligned} \mu(k, j(k, m), C_k) &= \min(j(k, m) / T(k), C(k) / T(k)) \\ k &= 1, 2, 3, \dots, K, j = 1, 2, 3, \dots, m, m = 1, 2, 3, \dots, M \end{aligned} \quad [6]$$

If the number of customers in a node "k" is less than or equal to the number of servers in the node, i.e. $j_k \leq C_k$, then no queue is formed. Since the server service time is considered constant (i.e. based on the manufacturer specifications for a piece of equipment, such as a LARS), then the service rate of the node increases proportionally to the number of customers present in the node, as long as the number of customers in a node, i.e. j_k , is within the range of:

$$j(k, m) \in (0, C_k], j(k, m) \in \mathbb{N}$$

Consequently, relation (6) can be analytically described as follows:

$$\begin{aligned} 1 \leq j(k, m) \leq C_k &\Rightarrow \mu(k, j(k, m)) = \min(j(k, m) / T(k), C(k) / T(k)) = \frac{j(k, m)}{T(k)} \\ 1 \leq C_k < j(k, m) &\Rightarrow \mu(k, j(k, m)) = \min(j(k, m) / T(k), C(k) / T(k)) = \frac{C(k)}{T(k)} \end{aligned} \quad [7]$$

$$k = 1, 2, 3, \dots, K, j, m = 1, 2, 3, \dots, M$$

