Do Modular Bridge Fins have the potential to Optimise a Submarine during Build and In-Service?

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1. SYNOPSIS

Advances in engineering design and modelling have enabled modular build to play an important part in accelerating production of recent classes of submarine. However, this is typically limited to large structural modules (such as Pressure Hull sub-units) or partially outfitted internal rafted modules that are not designed to be removed upon completion of build. Capability upgrades through life generally require significant modifications within maintenance periods which increase maintenance programmes and negatively impact availability of assets. Platforms with fully outfitted modules that can be readily attached and detached through life could open the door to a host of additional maintenance and overhaul options to increase efficiency, reduce cost and improve and diversify capability.

The Bridge Fin is a critical part of the submarine design, linking the internal environment with the external world. The Bridge Fin structure provides protection for a wide variety of systems, allowing the crew to maintain situational awareness and capability whether surfaced or submerged.

Due to the complex nature of the systems within the Bridge Fin, the structure and equipment within requires frequent survey, maintenance and upgrade. Coupled with increasing demand on hydrodynamic efficiencies and a reduction in Bridge Fin spatial envelopes means that designs are becoming more complex with increased build and supportability burdens. There is also an increasing trend towards Bridge Fins supporting diver operations such as in the Israeli Dolphin II Class (Sutton, 2022) and German Batch II 214 Class (Sutton, 2020) .

At both build and in-service points there are increasing issues with accessibility for installation and repair of both structure and systems. This paper explores whether there are potential benefits associated with a modular Bridge Fin design throughout the build and in-service phases in both current and future submarine designs.

Keywords: Bridge Fin, Modular, Submarine.

2. CAVEAT

The views and opinions in this paper are those of the author and should not be construed as the official view of Babcock International.

3. INTRODUCTION

Modular design is increasingly common in both surface ship and submarine design. Several contemporary submarines are built using a modular approach such as the USA Virginia Class where both Electric Boat and Newport News Shipbuilding initiated a parallel modular construction process to optimise the build cycle (Beam, 2015). The Virginia Class demonstrates many of the benefits associated with modular build such as modules being fully tested prior to insertion into the Pressure Hull, to the point that 81% of the first Virginia Class submarine was complete prior to the Pressure Hull being completed (RAND, 2011).

There are a number of different definitions for the term "module" ranging from structural pressure hull sections and pre-outfitted pressure hull sub-assemblies to compartment level modules and smaller modular equipment packages. For the purposes of this study the term "module" refers to pre-outfitted segments of submarine, pressure hull or superstructure, capable of being fully manufactured away from the main assembly hall.

0Within the UK, the Astute Class was built using a modular approach to both Pressure Hull sub-unit fabrication and the outfitting of internal modules. However, to date has been limited drive for the use of modules to support through life maintenance activities.

Babcock International funded an internal R&D task to understand if modular fins could have an overall positive benefit. The aim of this study was to investigate whether there are benefits associated with being able to modularise the Bridge Fin; allowing it to be built offsite and integrated with the platform to enable technology insertion or increase availability. Modularisation may open up opportunities for enhanced maintenance through life allowing the Bridge Fin to be removed from the submarine, either whole or in parts and taken to a separate facility where access can be improved, and maintenance activities undertaken in parallel with the rest of the platform.

This paper will explore and highlight both the benefits and challenges associated with a modular approach.

BIOGRAPHY

Ben White is a qualified Naval Architect and Chartered Engineer currently in the position of Principal Engineer at Babcock in Bristol, UK. His work is primarily concerned with in-service maintenance, structural design and assessment of submarines.

4. THE BRIDGE FIN

The Bridge Fin is a critical part of the submarine design, providing a link between the internal environment and the external world. The structural envelope of the Bridge Fin provides protection for the myriad of systems contained within as well as providing freeboard for the main access hatch. In addition, it allows a conning position for manoeuvring on the surface and an outer hydrodynamic form to mitigate the negative drag implications.

The Bridge Fin plays host to a number of safety and mission critical systems including sonar, radar, communications, visual masts, navigational equipment, exhaust and intake masts and associated supporting systems. Due to the life of platforms, a number of these systems will require frequent upgrade to maintain operational capability resulting in a high supportability burden throughout the life of the submarine.

Over time advances in mast design and the move from hull penetrating masts to external self-contained "cassette" designs has allowed Bridge Fin designs to evolve, resulting in a trend towards smaller internal volumes with reduced access for survey and maintenance.

5. THE CASE FOR A MODULAR BRIDGE FIN

It is commonly accepted that with complex assets such as naval platforms the upfront procurement cost is a relatively small percentage of the total life cycle cost.

The UK National Shipbuilding Strategy (UK MoD, 2017) highlighted that the economic service life of naval assets is increasing beyond the original design life and therefore the ability to upgrade capabilities must be considered as a critical capability. The National Shipbuilding Strategy Refresh suggests that complex systems are more likely to be delivered in a modular nature in the future giving potential to simplify the host platform whilst retaining flexibility and providing adaptability to enable the assets to outpace evolving threats and capitalise on emerging technology (UK MoD, 2022).

Submarine availability is an increasingly complex and critical aspect of operating a modern submarine fleet. It must be considered not only as part of the in-service phase of the life cycle but also during the design and build phases where decision making can have significant effects on the submarine's operational life. To date modularisation of submarines has focused on the build benefits with little attention paid to the benefits or disadvantages through life.

Major characteristics such as the through life cost, are set relatively early in the procurement of a complex asset such as a submarine. Traditionally during the time of most opportunity, in-service support has had limited influence and by the time that in-service support effects are being felt the ability to influence the design is lowest and the support characteristics are set. In the context of modular design, the best time to insert modules is during build, however it is important that the modules are not only designed to benefit the build programme but also support through life aspects.

During build, the Bridge Fin is typically manufactured as a structural module before being outfitted at the boat. Whilst this simplifies the structural assembly phase by allowing optimisation of processes in a factory environment there are still inefficiencies associated with outfitting the space. A significant number of systems then require installation and testing within a restricted spatial envelope, alongside other competing workstreams, which could be further optimised through additional modularisation.

Similarly, through life a significant amount of maintenance and survey is required around the Bridge Fin envelope such as:

- Capability upgrades;
- Structural survey and maintenance; and
- System survey maintenance.

The Bridge Fin requires support equipment such as staging to access the outer and upper areas and access to cranage is necessary to remove large items such as mast cassettes. Coupled with this, the Bridge Fin provides one of the primary access points to the submarine via the main access hatch, which can cause conflict with maintenance requirements.

6. REQUIREMENTS

A number of design parameters were set at the beginning of this study to ensure that the resulting modular Bridge Fin design met the core requirements. Whilst this paper predominantly addresses the application of a modular Bridge Fin to an existing submarine design, any of the requirements would be equally valid for new designs.

The following are the key requirements considered:

1. Be modular, so that it can be fabricated, repaired, or upgraded independently from the platform.
2. Modules shall be land transportable and shall be capable of being lifted within current dockyard crane limits.
3. Design is to be based on a baseline Bridge Fin design, specifically housing typical equipment, maintaining access and conning points, having similar structural requirements.
4. The Bridge Fin shall be designed with survey through life in mind, improving access over the baseline design.
5. Equipment interfaces with the pressure hull shall be demonstrated to be appropriate in terms of integrity and ease of connection and removal, during build and maintenance.
6. Supportability (maintainability) shall be improved over existing fin arrangements.

7. THE BASELINE

The study was based on a generic submarine Bridge Fin design utilising non-pressure hull penetrating masts with the following systems, masts and access points included:

- Diesel Exhaust Mast;
- Snort Induction Mast;
- Mission Systems Mast #1;
- Mission Systems Mast #2;
- Mission Systems Mast #3;
- Communications Mast #1;
- Communications Mast #2;
- Starboard electro-optronic periscope;
- Port electro-optronic periscope;
- Navigation Mast; and
- Conning Tower.

In addition to the above systems, a lock out chamber was included to capture the trend towards supporting diver operations from the Bridge Fin.

8. CONCEPT DEVELOPMENT

Due to the number of mechanical, electrical and mission systems associated with the Bridge Fin the concept development has been addressed under the following headings:

1. Structural;
2. Mission Systems;
3. Mechanical; and
4. Electrical.

8.1. Structural

Modularisation of the structural elements forms the backbone of the modular concept to meet the key requirements of being fabricated, repaired, or upgraded independently from the platform. To investigate the feasibility of a modular structural design three philosophies were considered:

1. Fully Modular;
2. Partial Modular; and
3. System Modular.

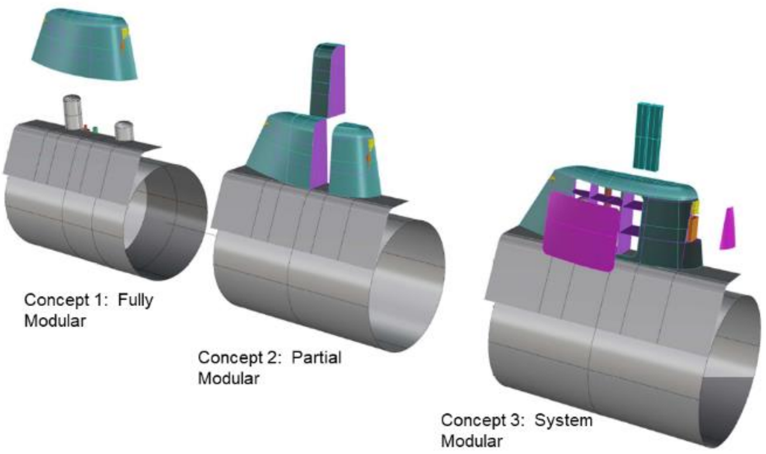

Figure 1 - Structural Concepts

For the purposes of this study the system boundary for the Bridge Fin has been taken as the interface with the upper surface of the casing superstructure.

Concept 1 consists of a single module for the Bridge Fin, with an internal structural arrangement broadly unchanged from the baseline design. Where traditionally the structure would be fully welded to the submarine structure, there would be a bolted interface to rigid seats mounted off the Pressure Hull structure. Preliminary assessments show that stiffener section increases would be required to compensate for the loss of continuous stiffening between the Bridge Fin and casing structure. Based off the baseline design the estimated total mass would likely prohibit this size module from being lifted using available cranage.

Concept 2 consists of a smaller Bridge Fin module encompassing the majority of the masts up to the forward end of the Bridge Fin, excluding the snort and diesel exhaust masts. In this arrangement the bulk of the mission systems fit is removable to allow off board build and outfit. Similar to Concept 1 the welded connections at the base of the bulkheads and skin plating would be replaced with bolted connections. Removal of the module allows for improved access of the mission systems for build and upkeep through life as well as improving access to the remaining Bridge Fin sections. Reducing the overall size of the module from Concept 1 also brings it within typical crane limits. Similar size sections have previously been seen in Russian submarine design as escape pods in a number of classes (Sutton, 2020). In those examples the outer shells of the Bridge Fins are angled to provide an auto-aligning feature for escape pods.

Concept 3 is to have a removable section of the Bridge Fin skin to allow access to the internal systems during maintenance periods. This could be a GRP panel to reduce weight, secured with bolts to a stiffened framework. Initial assessments show that a 7m by 3.4m panel, 25mm thick GRP could be a 30% weight saving over an equivalent steel panel (noting that some additional weight will be required to compensate for the opening). Similar to Virginia Class submarines which have a large number of removable Bridge Fin panels placed for access to internal systems (Gardiner, 2012).

8.2. Mission Systems

For the purposes of this study the mission systems within the baseline design have been assumed to remain constant. However, it must be demonstrated that there is ease of upgrade through life. The key systems that are considered were:

- Mast Raising Equipment (and associated mast equipment);
- Forward Sonar; and
- Stern Sonar.

Mast raising equipment (MRE) can be classified as either hull penetrating or non-hull penetrating. For the purposes of this study non-hull penetrating masts are assumed, based on the available design by L3Harris™ (L3Harris, 2022). Non-hull penetrating masts are typically a self-contained cassette design consisting of either a hydraulic or electrically actuated raising element and an upper mast payload.

8.3. Mechanical

The Bridge Fin houses a significant number of complex mechanical systems which require a different design philosophy to be considered to enable a modular approach to be taken. As this was a high-level study a proof of concept approach has been taken where a small number of systems have been assessed on the basis that similar constraints and issues will be equally relevant to all. Potential systems within the Bridge Fin for consideration were:

- Radar mast;
- Visual mast; and
- Lock in Lock out system.

The systems have a number of issues associated with modularisation such as the introduction of semi-permanent connections, system cleanliness and contamination concerns and alignment of interfaces across modules, to name a few. Systems required for masts run from Pressure Hull penetrations through the Bridge Fin to their destination. Pipework is generally formed 'at ship' and are connected using Swagelok type fittings. This leads to potential alignment issues across the fleet as the pipe runs and connector fittings will be non-standard. In addition, blanking caps will be required to ensure adequate system protection and cleanliness standards when disconnected on both ends of the pipework. Several options for mechanical connections were looked at, ranging from permanent welded joints, Swagelok® (Swagelok, 2022) and Staubli connectors (Staubli, 2022). Alignment issues are commonly resolved using flexible hoses however this would introduce a significant additional survey and maintenance requirement so was not preferable. Therefore, a common datum point in the form of a connector plate (Figure 2) is proposed to co-locate system pipework, this will remove potential issues with commonality of modules across a class.

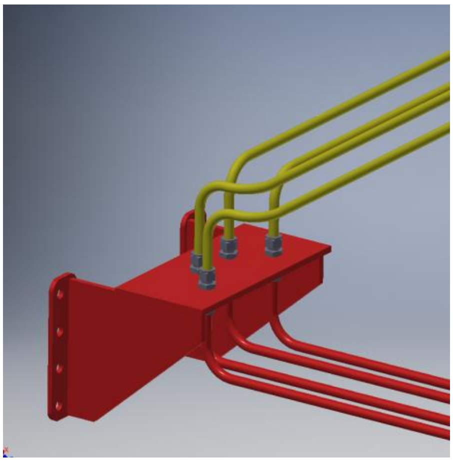

Figure 2 - Connector Plate

Since the connection types proposed are already used within the systems the test and certification requirements for mechanical systems will not be significantly different. However, there will likely be an increase in connections resulting in additional test and maintenance activities.

8.4. Electrical

Electrical cabling typically runs from Pressure Hull gland penetrations through the Bridge Fin to the individual equipment items. Cables tend to be routed to a splice box prior to being split out to equipment items. These splice boxes are already fitted with connector, allowing detachment of cables at the splice boxes. Modularising the Bridge Fin will likely result in an increase in connections where cables cross modules therefore it would be preferable to avoid crossing modular boundaries where possible. Any increase in the number of splice boxes should be avoided as they will introduce an additional weight to the Bridge Fin which is not desirable. For systems which span multiple modules the preferred solution would be to have a central cable run under the casing to feed each module. Similar to the mechanical connections this would allow cable connections to be contained to a single region per module rather than having multiple crossing points. Alignment is of limited concern with electrical cabling as long as sufficient slack and bend radius is provided to account for variations between modules and platforms.

9. CONCEPT DOWN SELECTION

From the main structural concepts outlined above a multi-criteria decision analysis method (Roszkowska, n.d) was used to assess the three options against the requirement set. Using this approach solutions are ranked in terms of geometric distance from the ideal solution. This showed that against the defined requirement set, the partial modular concept scored highest compared to the fully modular and system modular approaches. Through subsequent critical review of the concepts, it was concluded that whilst the partial modular approach scored highest there were further optimisations which could be made by merging the three concepts together to create a hybrid or evolved partial modular approach (Figure 3).

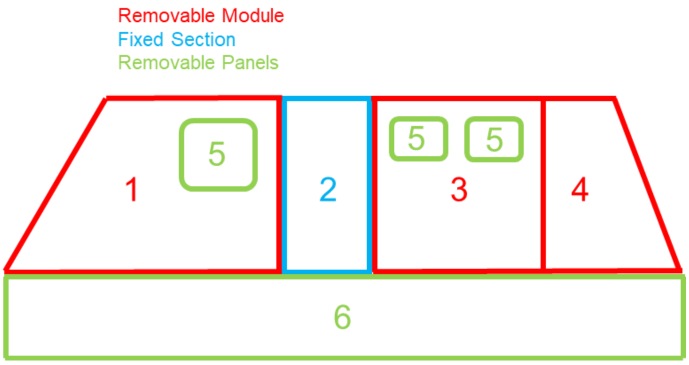

Figure 3 - Evolved Partial Modular Concept

In Figure 3 the Bridge Fin has been split into a series of modular sections, fixed sections, and removable panels to provide a multitude of opportunities for removal dependant on the maintenance activities being undertaken. Figure 4 to Figure 9 shows the proposed module characteristics based on the baseline Bridge Fin design.

Module 1 – Removable Aft Section				
Systems	**Material**	**Structural Connections**	**Frequency of Removal In-Service**	**Proposal Benefits**
Lock Out Tower Stern Array Nav Lights System pipework	Steel	Welded	Deep maintenance only (1-2 times during life)	Additional access to the Pressure Hull during extended maintenance

Figure 4 - Module 1 Characteristics

Fixed Section 2 – Diesel System Section				
Systems	**Material**	**Structural Connections**	**Frequency of Removal In-Service**	**Proposal Benefits**
Diesel Exhaust Snort Induction System pipework	Steel	Welded	N/A	Diesel systems availability maintained

Figure 5 - Fixed Section 2 Characteristics

Module 3 – Combat Section				
Systems	**Material**	**Structural Connections**	**Frequency of Removal In-Service**	**Proposal Benefits**
Combat Mast #1 Combat Mast #2 Combat Mast #3 Comms Mast #1 Comms Mast #2 Stbd periscope Port periscope System pipework	Steel	Bolted with alignment pins	Base maintenance periods	Repair by replacement of combat systems during routine maintenance periods.

Figure 6 - Module 3 Characteristics

Module 4 – Forward Section				
Systems	**Material**	**Structural Connections**	**Frequency of Removal In-Service**	**Proposal Benefits**
Conning Tower Forward Array Navigation Mast Nav Lights Conning Positions Bridge Comms Voice Pipe System pipework	Composite	Bolted with lugged joints	Base maintenance periods	Removal improves access to the platform through the conning tower, whilst moving maintenance away from the platform or allows repair by replacement.

Figure 7 - Module 4 Characteristics

Removable Panels 5 – Bridge Fin Panels				
Systems	**Material**	**Structural Connections**	**Frequency of Removal In-Service**	**Proposal Benefits**
All systems	Composite or Steel	Bolted	Base maintenance periods	Improved access to internal areas

Figure 8 - Removable Panels 5

Removable Panels 6 – Casing Panels				
Systems	**Material**	**Structural Connections**	**Frequency of Removal In-Service**	**Proposal Benefits**
Hull Valves System Pipework Mast Connections	Composite or Steel	Bolted	Base maintenance periods	Improved access to internal areas

Figure 9 - Removable Panels 6

10. MODULE CONNECTIONS

With multiple removable modules, one of the key elements to be considered is the attachment and detachment of each module and the structural connections required to ensure that the structural integrity of the Bridge Fin is maintained and not degraded. To demonstrate the benefits of modular design it is required that the modules can be removed and fitted in a safe and time efficient manner. Removal of modules to take maintenance away from the dockside will only be beneficial if it does not tie up dockside cranes for an extended period of time and does not increase the critical path in terms of maintenance activities within the work package.

Each module must align correctly with the platform structure and the other modules as well meeting the design strength and stiffness requirements. The key Bridge Fin load cases which must be considered are sea slap, internal drain down forces, naval shock, hydrodynamic forces as well as ice breaking forces (Wikipedia, 2022). For the majority of these load cases the modular design will not have a significant impact on the strength of the Bridge Fin framing or plating and therefore this study has not focused on this area. Rather the novel area of the modular connections has been investigated to demonstrate that it is feasible to achieve. The key requirements for the connections are broken down as follows:

- Minimise opportunities for error during attachment and detachment of modules;
- Minimise the number of loose parts;
- Minimise the time required to install, remove and inspect; and
- Use non-permanent joints to allow for multiple assembly/disassembly evolutions.

The concepts investigated during this study were:

- Bonded joints (adhesives or welding);
- Mechanical fastening;
- Hybrid Bonded-Mechanical fastening; and
- Mechanical interfaces.

During the course of the study, it was proposed that Module 1 would likely only be removed one or two times in-service in conjunction with the lock out trunk to create a larger shipping envelope during deep maintenance. On this basis it is proposed that the lock out trunk would be a bolted attachment to the Pressure Hull and the surrounding Bridge Fin module would be normally welded and cut away during maintenance. To re-attach the module the structure would be re-welded in place.

The fixed section 2 would be fully welded at build and not be intended to be removed through life. There would be limited benefits in removing the diesel exhaust and intake system, and it is more beneficial to be able to maintain the operability of the system during build and maintenance periods. Access for maintenance would be provided by removal of the surrounding modules as dictated by the build and maintenance schedules.

Module 3 consists of a simple shape with no complex double curvature therefore it lends itself to steel fabrication to reduce costs and complexity of the design. This steel fabrication is also good for the mechanical interfacing points around the MREs and shutters. It is proposed that this module would be removed most frequently for capability upgrades and associated maintenance, providing a drop in capability for different mission system fits. Due to the sensitivity of these systems to alignment the module will require accurate placement and a system of alignment pins is proposed for attachment of the module base to the Pressure Hull (rather than the casing structure).

Module 4 is the forward section of the Bridge Fin which plays host to a number of sensors. It is proposed that this smaller section is manufactured from composites which will allow the complex shape to be moulded rather than formed from steel. This would also allow the hydrodynamic “cusp” at the forward edge of the Bridge Fin to be cast as part of the module. Manufacturing this section from composites would also likely introduce a weight saving which could be used to offset the additional weight introduced through modularising the Bridge Fin. There would also be benefits in terms of making this section lighter weight and easier to remove during routine maintenance periods to improve access to the conning tower for entry to the submarine. Consideration would need to be taken regarding the ice breaking capability of this section if this is a requirement for the platform. It is proposed that a lugged joint system is used here to minimise the number of bolts and aid in more regular removal of the module. Due to the systems fitted in this module there are no strict mechanical alignment requirements other than maintaining the hydrodynamic form. To eliminate movement or wear in the joint a novel solution such as the Nordlock Expander (Nord-lock Group, 2022) could be used.

The proposed set of casing panels (Panel 5 and Panel 6) would be bolted to the casing framing and could be GRP or steel depending on the weight and strength requirements.

11. ASSOCIATED IN-SERVICE BENEFITS

The following points are considered to be of benefit in-service:

- Removable skirts will provide a significant improvement to access hull glands under the casing. For new submarine designs this arrangement would allow pressure hull penetrations to be arranged at the outer edges of the casing for easier access;
- NDE within the modules could be performed in segregated areas away from the platform reducing the impact on concurrent work;
- Significant impact in damage recovery if spare modules are available for replacement;
- Potential to distribute maintenance work across multiple sites to reduce burden on maintenance teams during deep maintenance;
- Removes maintenance from traditional maintenance periods with repair by replacement philosophy using a spare Bridge Fin and conducting maintenance over a longer period of time;
- Reduces working in restricted spaces or potentially confined spaces and reduces competition for access and improves casing egress;
- Maintaining the fixed diesel exhaust and snort section ensures that diesel systems can be sustained during maintenance;
- Removal of Module 4 improves access to the platform by opening the conning tower for cranage and access;
- Removal of Module 1 would allow the lock out trunk to be made removable during maintenance to add an additional access route into the platform, reducing reliance and congestion around the main access routes. The lock out trunk could also be maintained while off the platform; and
- Reduces requirement for dockside working at height and support equipment such as staging alongside. Working from height can be conducted in a better controlled environment.

12. FURTHER AREAS OF INVESTIGATION

The following areas are considered to merit further investigation:

- Development of build and supportability metrics to measure benefits of modular approach;
- Added complexity during the design process due to the structural connections and modular system arrangements;
- Increase in the number of connections and associated testing which must be carried out during build. This may be balanced by the ability to parallel build and remove a significant number of connections from the main build process;
- Increased weight due to increase in structure and system components. Negative impact on platform stability. Could be mitigated by use of composites where appropriate. Potential to gain weight savings by enabling a more compact Bridge Fin design due to improved access as a result of modularisation;
- Increased survey and maintenance requirements as a result of modular attachment for both structure and systems; and
- Increased requirements on cranage for removal of modular items. This would need to be reviewed to ensure that any increase in cranage is offset against a reduction in other cranage such as MRE removal. Methods of attachment would also need to be designed in a way that lifting equipment can be removed at the earliest opportunity once the module is seated and secured.

13. ASSOCIATED BUILD BENEFITS

There could be a number of perceived build benefits associated with the proposed modular Bridge Fin design. These would be predominantly associated with optimising the build schedule by decoupling the Bridge Fin build and outfit from the Pressure Hull build. Maintaining the fixed section for the diesel exhaust and snort induction masts would allow the completion of the diesel system prior to the outfit and attachment of the main Bridge Fin. This would allow advanced testing and trials to be undertaken whilst the Bridge Fin is still being outfitted away from the main build.

Integration of the modular Bridge Fin elements at a later stage of the build process could provide a multitude of benefits, such as:

- Potential to allow tighter packaging of Bridge Fin equipment to improve hydrodynamic form and reduce drag and target echo strength, as a result of improved external access to Bridge Fin;
- Improved access to under casing areas during build;
- Reduced risk of damage to critical systems during build;
- Potential for continued development of the mission systems during build;
- Reduced Non-Destructive Examination (NDE) of welds at boat; and
- Allows split production strategy to be used, increasing industry involvement in the build process to optimise scheduling.

The use of modular sections during build could also enable the ability to incorporate engineering changes developed for later boats of class onto the earlier platforms through removal and replacement of individual modules.

14. CONCLUSIONS

This paper has considered whether modular Bridge Fins have the potential to optimise both build and in-service evolutions. During the conduct of this study a baseline design was developed to define the envelope and systems within the Bridge Fin. A series of concepts and proposals have been explored to determine whether there is a feasible application for a modular Bridge Fin.

The study has shown there are significant benefits to be realised through modularisation of the Bridge Fin. These benefits have the potential to exist throughout the asset life cycle and therefore benefit availability of assets in terms of optimising build and reducing effort during in-service maintenance. The benefits realised could be greater still for a new Bridge Fin design based on a modular concept from the beginning, where additional weight and hydrodynamic opportunities may be realised.

15. ACKNOWLEDGEMENTS

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17. GLOSSARY

GRP – Glass Reinforced Plastic
MRE – Mast Raising Equipment
NDE – Non-Destructive Examination
TOPSIS – Technique for Order of Preference by Similarity to Ideal Solution