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AN EXPERIENCE OF MODULARITY THROUGH DESIGN

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1 Introduction

We aim to utilise the experiences of a marine industry-based design team to determine the need for research into a modular design methodology in an industrial environment. In order to achieve this we couple the outcome of a current design project with the findings of a recent literature survey with the objectives of firstly, clarifying why a methodology is required and, secondly, defining the key elements which the methodology would have to realise or address.

The potential benefits of modularity have long been recognised in the shipbuilding industry. Many shipbuilders adopt a 'module' approach to ship construction whereby the ship structure is separated into a number of large structural 'blocks' to ease manufacture and manoeuvrability during construction. However, as understanding of the capabilities of modularity as a design tool develops there is increased interest in capitalising on the differing life phase benefits of modularity such as reduced design costs and time, increased ease of maintenance, upgrade, re-use, redesign and standardisation across individual products and product families. This is especially pertinent in naval shipbuilding where the maintenance of a class of ship requires that all previously designed ships in that class must be of similar outfitting and must be able to interface with the new ship, in terms of propulsion, weapons, communications and electronics, and thus often require some form of retrofit. Therefore, many shipbuilders are moving from viewing modularity as a purely 'manufacturing' principle to a design centred principle. However, as noted by Chang and Ward [1] 'none of the design theories or tools in the mechanical world serves as an articulate procedure for designers to follow in practising modular design'. Thus, despite the identification of a need to introduce modular principles at an earlier stage than detail design and construction [2,3], there is little aid in the form of tools, techniques and methodologies for designers in practice.

2 Research background

BAE Systems Marine Ltd, keen to maintain their status as 'world class designers' of naval ships recognised the need to research and adopt 'state-of-the-art' design, manufacture and operations principles in order to remain front runners, in both receiving and successfully fulfilling contracts. As part of BAE Systems Marine Ltd, the 'Forward Design Group' (FDG) is responsible for initial bid work and research and development. A recent project, carried out within the FDG's remit, resulted in the design of a predominantly modular artefact. A simultaneous, though separate, 're-use' based project was carried out in conjunction with the University of Strathclyde, analysed the 're-use' centred benefits achievable at BAE Systems Marine Ltd and concluded that maximum benefits were achievable through support for ‘design-for-re-use’ [4]. ‘Design for Re-use’ is the process whereby artefacts are designed to optimise their associated design activity and artefact knowledge and extract and enhance this resource to promote it’s re-use in future designs. Interestingly, the ‘re-use’ research also lead to the identification of ‘modular design’ as a potential tool on which to facilitate this ‘design-for-re-use’ process. The correlation between these two, previously separate, works became immediately apparent and induced an exploration of the design experiences from the initial ‘modular’ design project with respect to the ‘re-use’ project.

3 The marine designers concept of modularity

Through interviews and questionnaires carried out with the *mast* design team it became apparent that, despite a historical emphasis on ‘constructional modularity’, marine designers conception of modularity has changed to associate it ‘with the ability to replace and remove entire ship systems’. This shifting emphasis of modularity in the marine industry is illustrated in the development of warship designs that can accommodate a wide variety of weapon systems, sensor packages, machinery and propulsion options that the potential customer may wish to install within the overall platform. Such as the F2000 frigate design at BAE SYSTEMS Marine Ltd, which can be configured to undertake a number of diverse roles dependent on the customer requirement. At the ship systems level the development and adoption of modular missile launch systems that allow the launching of a large variety of missile types (anti-submarine, anti-air, land attack, etc.). This offers the naval customer an inexpensive, minimum refit, role re-configuration option as the fleet undertakes different campaigns in different warfare situations. An example of which is the Lockheed Martin Mk 41 Guided Missile Launching System [5]. Similarly, the proposed future surface combatant (FSC) requirement for the United Kingdom Royal Navy, will have to exhibit a greater degree of role flexibility through the application of modular design principles than previous general purpose warships (e.g. the Royal Navy Type 22, Broadsword Class Frigates [6].). For example recent missions carried out by the Royal Navy have included, drug interdiction, disaster relief, evacuation of British nationals, and resolution of regional conflicts such as Sierra Leone.

All these aspects of modularity above, were examined both to consolidate the design teams conception of the potential application of modular design principles and to aid in initial analysis of the potential for modular design to adequately support a research and development project concerning the design and manufacture of a ‘technology *mast* concept demonstrator’.

4 The design project

The concept for the BAE Systems ‘marine technology *mast*’ originated from the need to support 4 fixed phased array radar antennas as the main radar sensors for a concept corvette known as “The Warship”. This requirement changed as the targeted platform became a destroyer sized multi-role warship and the antenna requirements became the more onerous two phased array rotating design. The project aim was to design and construct an advanced technology *mast* to demonstrate the utility of the design concept, within project objectives of:

1. Supporting the specified antenna (also under research and development).
2. Reducing the warship’s radar signature.
3. Reducing the number of external aerials.

4. Improving maintenance and equipment availability.
5. Improving the performance of incorporated sensors

The project itself resulted in a highly flexible modular structure, which successfully fulfilled the above objectives, and proved the feasibility of the design concept. Figure 1a shows a 3D visualisation of the technology demonstrator, which was constructed full scale (approx. height 11m, width 7.5m). Figure 1b shows a 3D visualisation of a 'modularised sensor' replacement being hoisted into position through the internal structure and figure 1c shows the centre column which supports the main radar and the external framing to which the exterior panels are fastened.

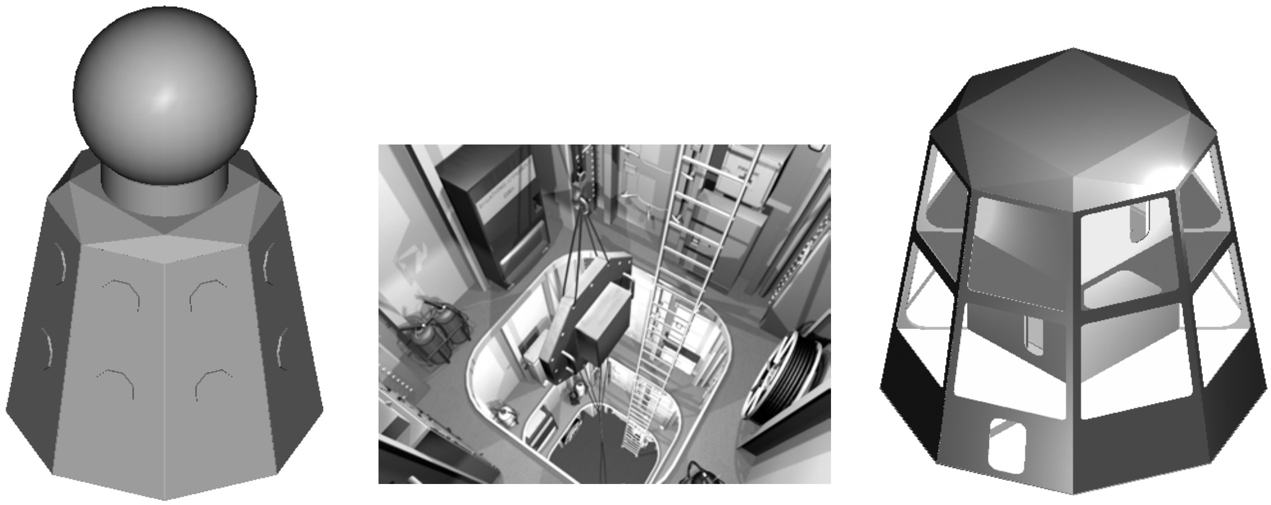

Figure 1(a) – Mast Demonstrator (b) – Replacing a 'Modular Sensor' (c) External Panels and Structure

The decision to focus on producing a predominantly modular structure was influenced by a number of factors including:

- Distribution of Involved Business Groups – the teams would have to undertake design tasks in remote locations, across the UK, whilst ensuring integration with the overall system design and specification.

- Tight Timescales – the teams would have little chance to test the compatibility of designed components and tight delivery schedules meant many components would not be physically together in one location until the final assembly phase.

- Improved Maintainability Requirement – a key objective in the design concept that meant related issues of removal, replacement, and accessibility of components of varying technologies required to be addressed.

- Rapid Response to Repair of Battle Damage – a key requirement of the concept was the ability to rapidly reconfigure and replace sensors based on various battle damage scenarios.

Thus, the application of modular design to overcome such issues became a practical solution as the principle is synonymous with developing products with distinct detachable modules to support rapid product development, efficient upgrades and reconfiguration [7].

5 The mast design process

No formal procedure or process was available to the design project to support modularisation. Through formalising and rationalising the activities undertaken the overall process has been modelled as sown in Figure2. The initial stage of allocation of tasks and constraint definition was carried out as a single design team. The detail design of each modular unit was carried out in individual remote design teams. The tools/techniques are intended as a representative sample of those employed at differing stages of the process and not an exhaustive list.

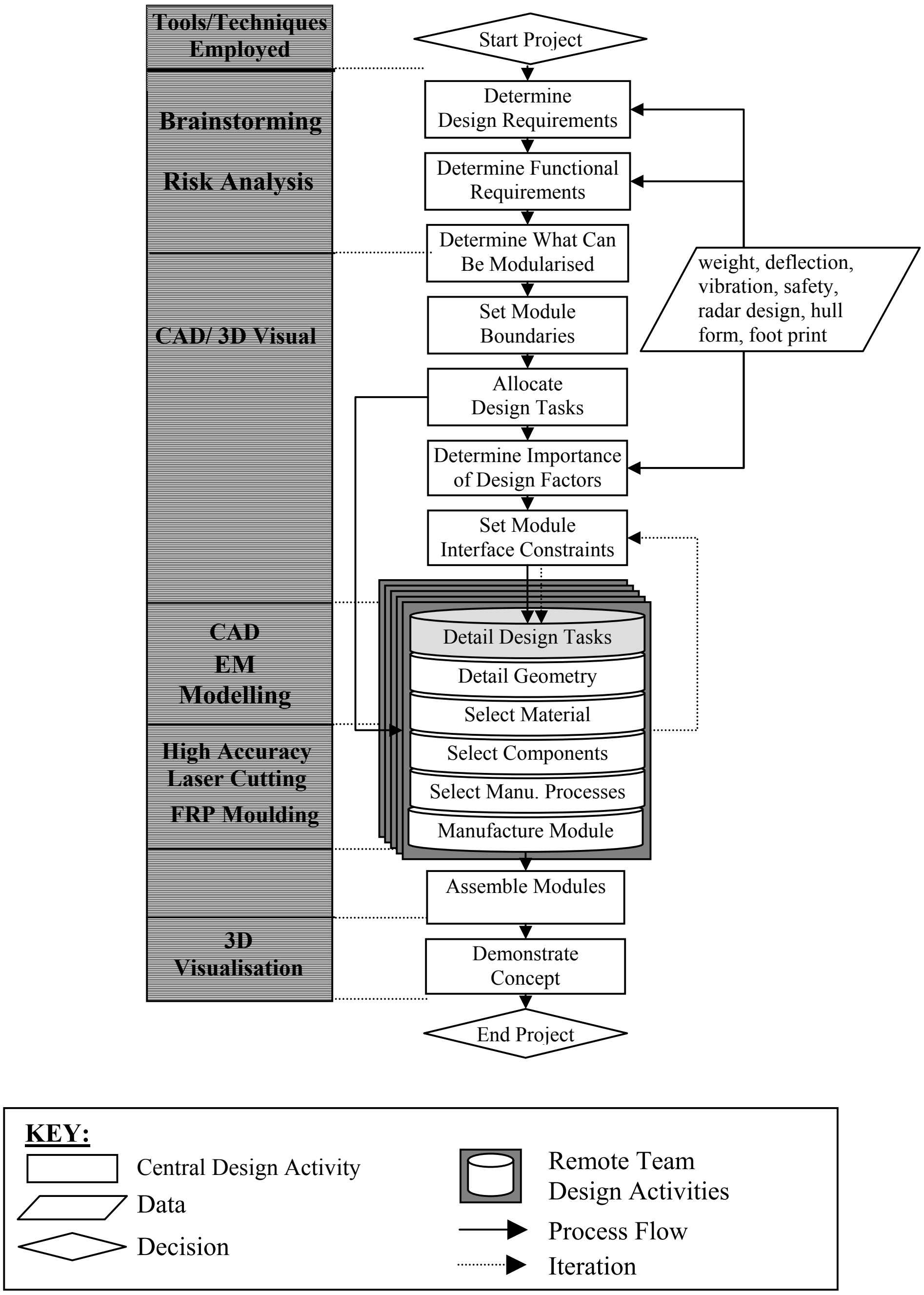

Figure 2 - The Design Process Illustrating Tools/Techniques Employed

We can see from Figure 2 that the earlier phases of the process lack the support of any formalised tools or techniques. Here, the designers had to rely on personal experience and a common sense approach to the determination of module boundaries and the allocation of design tasks to individual teams. Thus, despite an increasing recognition of modularity as a design principle, problems of awareness, availability and/or understanding of formal tools or techniques contributed to a lack of support for the earlier modular design stages. The team felt these stages, where the control of interfaces, their dimensions and constraints are determined, were of vital importance to the realisation of a successful design solution. The importance of supporting these stages is illustrated when we consider that their realisation required a series of iterative 'manpower intensive' reviews to determine these control parameters and ensure the robustness and integrity of the rapidly evolving modular solutions (illustrated by the iterative loop shown in Figure 2). Such experiences highlight the need for the promotion of 'modular design' in industry as a process, rather than a philosophy, to both raise designer awareness and support designers in their drive to implement effective modular design.

6 Design experiences – issues and outcomes

The following considers some of the main experiences of one of the distributed teams, the Forward Design Group (FDG) BAE Systems Marine Ltd, Scotstoun, who were responsible for the structural design, manufacture, final *mast* assembly and general project management.

Signature Reduction Constraints – The objective to reduce the ship radar signature places constraints on both the sensor selection and structure design. These included the introduction of flat panel technology and also the requirement for a taper in the structure (more significant directional changes lead to a bigger signature i.e. right angles). Initially this raised issues as it was at odds with the introduction of a modular solution i.e. due to the taper not all decks/tiers could be made of the same (dimensional) module. This was overcome by assigning a modular importance factor to the components. For instance the sensor's modularity was factored as the highest importance due to ease of maintenance and replacement requirements followed by the frame structure and then panel (due to material and ease of manufacture trade-offs). Thus, as can be seen from Figure 3 the design has been made as modular as possible with the sensor being completely interchangeable whilst the panels are tier specific but can be fixed to any side of the structure.

Control of Interface Constraints – Although the modular principle was a natural choice, given the technologies being implemented in the *mast* design, the determination of the constraints on sensor and ship interfaces raised a number of issues. The teams quickly realised the importance of adequate constraint control to the timely realisation of the project objectives but required significant investigation and an iterative series of resource intensive reviews between the teams to set, define and manage these effectively.

Technology Integration – The integration of hardware and software raised a number of issues for the design teams. Although in the demonstrator the sensors are all physically interchangeable once fitted they require further programming to be fully functional within the on-board command control system. The software/hardware conflict remains an issue for further research to improve and develop flat panel technology and the flexibility of combat system software.

Material and Manufacturing Choice Constraints – The material and manufacturing method choice presented the designer with a series of issues and trade-offs. On beginning detailed design it became apparent that requirements such as the need for gas-tight seals between the components and the vibration and deflection requirements would have a significant impact on materials, manufacturing and as a consequence the control constraints between the modules. Thus, a need to further prioritise module design parameters was raised. Due to deflection and vibration requirements the sensor and frame tolerances were prioritised. For instance, the frame is manufactured from high grade steel by high accuracy laser cutters form CAD data to provide precision tolerances whilst the panels are manufactured utilising Fibre Reinforced Plastic (FRP) with a sufficient tolerancing allowance to compensate for any differences and provide towards the seal requirement. Similarly, the fasteners are embedded into the panel to assist with this compensation. The sensor to panel fixing, although not implemented in the demonstrator, is envisaged as a sleeve, with sufficient internal tolerancing to fit precisely around the sensor, but with external tolerancing compensation to accommodate dimensional variations in the panel.

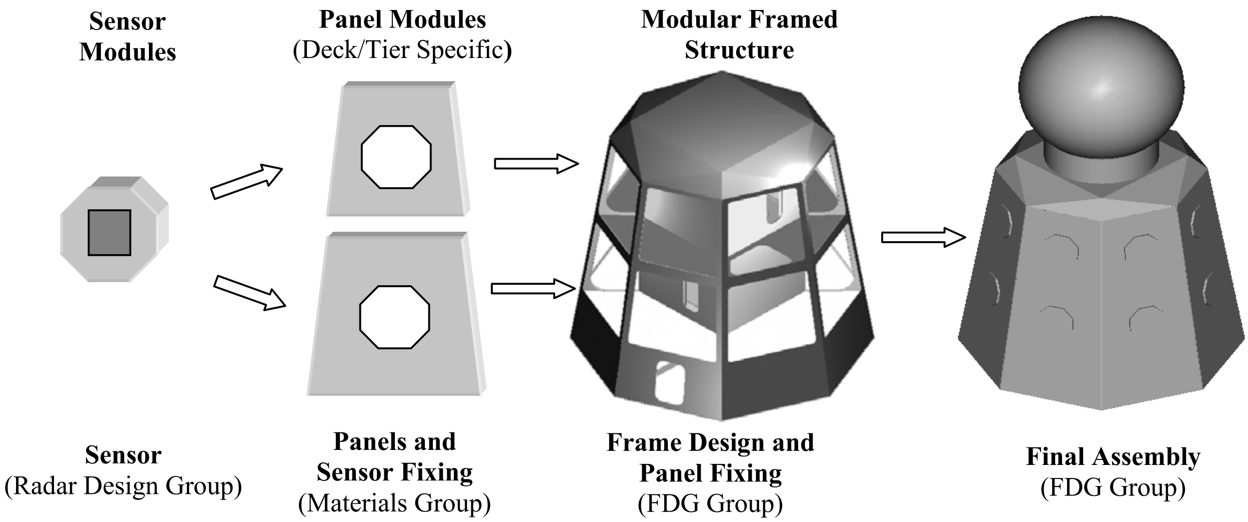

Figure 3 - Technology Demonstrator Mast - main components illustrating group responsibilities

Potential Cost Increases – Issues were raised concerning potential cost increases due to the marginal increase in material (steel). However, due to the simplicity of the structure, over current masts, significant savings are gained through a reduction in production hours, labour requirements and rework that negate these concerns.

Footprint– Initial concerns that the *mast* 'footprint' size would be adversely affected as a result of modularity of the structure were not realised through the construction of the technology *mast* demonstrator (which had a footprint relative to that of a conventional structure carrying out the same function). However, the designers recognise that as the required dimensions of the mast structure is highly dependant on the function and design of the 'antenna sensor fit' and this 'footprint concern' may be an issue on other platforms.

We see here that the design team successfully overcame the majority of issues that the introduction of modularity presented. However, there was a notable lack of support to the evolution of this modular solution with the designers relying on experience and a trial and error approach. Support for the determination of module boundaries, defining design task boundaries and setting module and task constraints may have saved resources, time, cost and design rework. Such experience highlights the need to research the potential for developing mechanisms to better support the determination, definition, design and configuration of modular solutions to design problems. Though these points only cover the recurring or most significant issues raised through interviews with the FDG *mast* team designers they serve to illustrate the need for industry based research for successful transference of 'modular design tools' from academia into industrial practice.

7 Methodology requirements

The designers identified both through past experiences and those gained from working on the technology *mast* project a number of criteria, which they deemed as important requirements to be addressed by any industry based design methodology/tool. These include:

- **Generic Approach** – A key requirement was that the methodology/tool be of a generic nature. This arose from a need to support the application of modular design across a wide variety of design scenarios. In addition, the designers perceived that a tool developed for a specific application area would have limited value beyond that niche due to the nature of marine contracts (one-offs, batches, made to order individual ship systems design, etc.). Thus they felt a generic tool would be easier to justify in terms of application benefits over cost of development.

- **Complementary Approach** – A major issue involved the perception that formal approaches were restrictive in nature. Thus, the designers felt that any methodology/tool developed for the purpose should not restrict design to the extent that it automatically excludes design solutions nor narrows the solution search space. Thus, it must be capable of harmonising with and complementing the working practice of design so as to maintain creativity and flexibility.

- **Life-cycle Approach** – The team felt that a methodology that could be incorporated from project inception and applied throughout the design cycle would be of greater advantage over one supporting a 'specific design phase'. The reasoning for this was a need to involve, understand and manage manufacturing, process engineering and product life-cycle requirements and trade-offs throughout design.

- **Technology Integration Capabilities** – Due to the diverse nature of the systems incorporating into marine design the team felt any modular methodology should have the capability to aid in the development of a modular solution which required integration of a range of hardware, software technologies and incorporate human factors design. This need arose form the complications of modularising the physical geometry and software requirements of the different sensors.

- **Warship Market Capabilities** – A common concern was that due to the often specialised one-off nature of products, in the warship industry, the cost reduction benefits of modular design gained through creation of variety would be negated. Consequently, the designers perceived a methodology which supports modular design of relatively small batch sizes whilst realising its associated benefits through other means (re-use, ease of manufacture, ease of maintenance, refit minimisation, etc.) would be of greater applicability to the industry.

- **Decision Support** – A widespread opinion was that although the designers felt confident in allocating individual design tasks based on colleagues/teams past experience the grouping of functions/concepts/solutions principles into modules to successfully realise the project objective was less clear. Thus, they felt a successful modular design methodology should provide a mechanism to aid in the determination and definition of module boundaries to support the designer/design team's decision process.

All involved parties felt that a 'modular design methodology' which could facilitate the above requirements would be of significant benefit to the practice of modular design in the marine industry.

8 Conclusion

The project itself was a success in that it resulted in the design and production of a modular structure that met the defined project objectives. As the outcome of the project was to produce a concept demonstrator there are still a number of specific issues that require further research in order for the designed technology *mast* to be integrated into a warship platform.

Although, the predominantly modular structure was developed without the aid of a formal methodology the experiences of the design team in overcoming issues and problems associated with producing a modular structure suggest a requirement for further research of this principle in this industry. The *mast* design team noted a lack of tools and technologies to support earlier design stages and indicated that their experiences highlighted these stages as highly important to the successful realisation of the overall solution. Thus, indicating a need to research and develop techniques to support the designer throughout the modular design process.

Further, the study resulted in a list of requirements for a modular design methodology to support the practice in industry, based on the experiences gained of a practicing design team within the remit of a technology *mast* design project.

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