The Network Block Approach Applied to the Initial Design of Submarine Distributed Ship Service Systems

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ABSTRACT

The paper follows on from a recent IJME paper and summarises a new early-stage ship design approach. This is termed the Network Block Approach (NBA) and combines the advantages of the UCL 3D physically based ship synthesis Design Building Block (DBB) approach and the Virginia Tech originated Architecture Flow Optimisation (AFO) method for distributed ship service systems (DS3). The approach has been applied to submarine DS3 design and utilises: a set of novel frameworks; and Qinetiq's Paramarine CASD suite features. The proposed NBA enables the development of a submarine concept design to different levels of granularities. These range from modelling individual spaces to locating various DS3 components and system routings. The proposed approach also enables the designer to balance the energy demands of a set of distributed systems. This is done by performing a steady-state flow simulation and visualising the complexity of the submarine DS3 in a 3D multiplex network configuration. The potential benefits and limitations from such a 3D based physical and network synthesis are presented. The paper concludes with a discussion of the Network Block Approach comparing it to previous applications of network theory which have been to surface ship design. It concludes that it would be possible to better estimate DS3 weight and space inputs to early-stage submarine design and also enable radical submarine configurations and DS3 options to be reflected in early stage submarine design for better concept exploration and requirement elucidation. Finally, further work on the sensitivity of the approach to designer inputs will be addressed in future papers.

1. INTRODUCTION

As a Physically Large and Complex Systems (PL&C), the submarine design process encompasses various design phases which may be conducted by different organisation entities. The design phases comprise concept, assessment or feasibility, followed by contract or project definition to fix price and check that the selected design remains balanced. This especially applies to the buoyancy and stability balance, even it is more demanding in submarine design than for surface ships, which needs to be done before proceeding to detailed design (Andrews 1994). However, in the initial sizing of complex vessels, where recourse to type ship design is overly restrictive, one crucial set of design features has traditionally been poorly addressed. This is the estimation of the weight and space demands of the various distributed ship services system (DS3). DS3 is a collection of connected components that provide a service from one or multiple sources to multiple users, via connections throughout the ship, directed towards defined functions, supporting specific operations of the vessel (Mukti et al. 2021). Such a type ship approach not only inhibits the ability of the concept designer to consider the impact of DS3 options with distinctly different styles but also ignores the opportunity (or necessity) to undertake Requirements Elucidation, more specifically for DS3 (Andrews 2018).

Given there is a need to consider DS3 in a better manner than a scaling based parametric approach, this does not mean the Concept Phase must 'bottom out the preferred design' for DS3 synthesis. Recent papers by the authors (Mukti et al. 2019; Mukti et al. 2021) presented an early version of DS3 synthesis where design flexibility was achievable utilised a tool for DS3 "Submarine Flow Optimisation" (SUBFLOW), which was combined with the UCL Design Building Block approach (Andrews et al. 1996). That implementation revealed the technical issues when integrating the network-based sizing approach with the whole submarine design synthesis using SURFCON Paramarine (Mukti et al. 2022). A significant amount of effort was required using both approaches and this inhibited the exploration of DS3 options in ESSD. Thus, this paper presents a novel approach that addresses this issue and provides a more believable DS3 synthesis than the 'type ship' or 'rule of thumb' scaling approach, yet is not too detailed as full DS3 design appropriate later in the process.

The paper commences with the novel approach in the context of previous approaches to initial submarine design. Following this, the recent network theory-based studies for the design of distributed systems are discussed, that have been applied by the researchers to naval surface vessels, and the new approach is then outlined. The remainder of the paper is taken up with an application of the proposed approach to early-stage design (ESD) for a typical conventional powered submarine. The paper concludes by discussing the advantages presented to the submarine designer by this approach with the potential of

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such a concept design being more DS3 information rich and fostering a more exploratory design approach to DS3. Finally, the focus of current UCL research using the proposed approach to submarine studies is briefly presented.

2. APPROACHES TO EARLY STAGE SUBMARINE DESIGN

ESSD for complex vessels, has been described by Andrews (1994) as three overlapping stages, which are focused on the task of Requirement Elucidation: Concept Exploration; Concept Studies; and Concept Design. Concept Exploration is a wide-ranging exploration of potential solutions to meet the initial and very broad outline requirements. Such an exploration could be based on a nominal design solution space, which Andrews (2018) suggests could have three main axes of investigations: capability; packaging; and technology. Then a nominal baseline should be e developed in sufficient level of detail to conduct Concept Studies to investigate issues that are likely to be significant size or cost drivers in the design, see Andrews (2018). Finally, Concept Design is conducted to working up the selected baseline design or possible two distinct competing options by performing trade-off studies of cost-capability and highlighting design risks. The following three subsections discuss the main approaches to submarine ESD.

2.1 DECISION MAKING PROCESS OF COMPLEX VESSELS

Given many important submarine design decisions are made either consciously or unconsciously in the Concept Phase, the issue is that such major design decisions are often not questioned nor acknowledged by design stakeholders. Furthermore, such decisions should be subject to investigation in a properly conducted Requirement Elucidation process (Andrews 2018). Andrews (2018), in turn, has long proposed the whole ship design process is best summarised in Figure 1, which does not just list sequential tasks in the ship design process but also encapsulates major decisions the designer must take often by default, to undertake those tasks, see Figure 1 from (Andrews 2018). This series of specific decisions for a conventional powered submarine are given in Figure 6 of Andrews (2021) and the unique nature of the submarine design process summarised in Section 8.4 of (Andrews 2018). The first nine steps in the 'decision making' approach summarised in Figure 1 cover the ESD scope of the paper. The next subsection discusses design approaches that could potentially accommodate both the synthesis of the whole submarine as well as that for the various DS3. This leads to a discussion of the selection of the synthesis model type, which is step 6 in the 'decision making' approach.

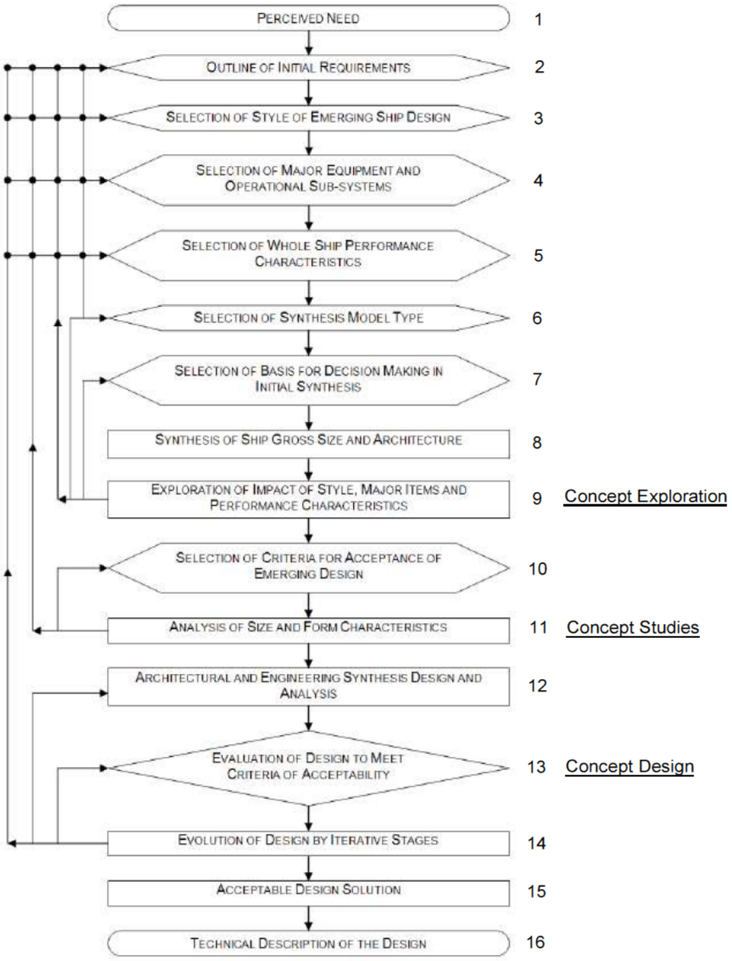


Figure 1: The decision making sequence for complex vessels outlined in detail in Figure 4 and Appendix A of (Andrews 2018) in a similar manner to the submarine example in Figure 4 of (Andrews 2021)

2.2 TRADITIONAL NUMERICAL SYNTHESIS

The approach to initial submarine synthesis used at UCL for the annual post-MSc submarine design and acquisition course (SDAC) (UCL 2021) was adopted from a sequential design procedure given by Burcher & Rydill (1994). The procedure, as is shown in Figure 2, begins with an initial set of broad requirements to initiate the process. From these initial requirements, a set of payload equipment can be selected, which then gives a first numerical indication of likely submarine size. As such it can then be used to parametrically estimate the size of component design features based on mathematical relationships with coefficients suggested by Burcher and Rydill (1994). This may be developed based upon 'rules of thumb' drawn from their hands-on submarine design experience within the UK Royal Navy, suggesting such rules of thumb are likely to be different from navy to navy (e.g., US Navy (Arentzen and Mandel 1960) and MIT professional summer programme (Jackson 1992)). This, in turn, implies the 'traditional' characteristic of the procedure. The term 'numerical' here refers to a 'crude' (or 'gross') initial estimation of weight and space (budget) of the submarine design, which does not reflect necessary the architectural realities (see Purton (2016)). Thus, this first numerically balanced design implies the longitudinal moment and vertical balance have yet to be addressed. It was considered that the adoption of just this procedure was insufficient. The submarine design needs to incorporate the 'architectural' or the configurational aspect of the submarine to enable the physical models of DS3 to be considered early in the design process, as is discussed in the next subsection.

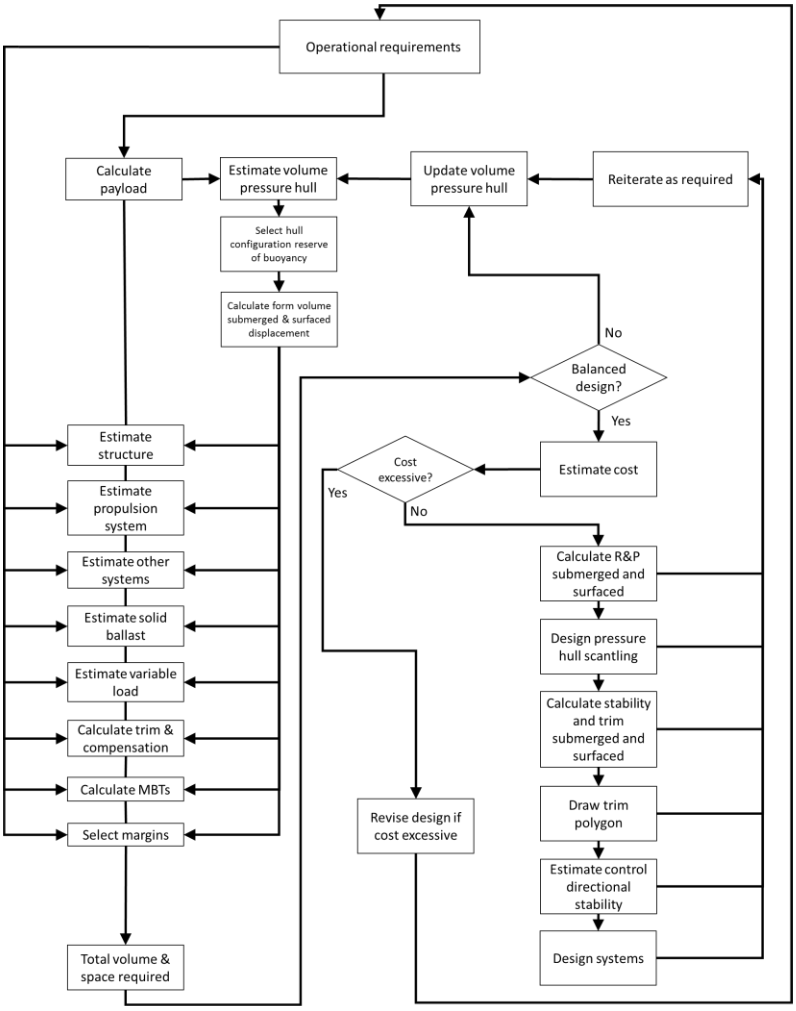


Figure 2: A generic submarine design procedure, redrawn from Burcher & Rydill (1994)

2.3 THE UCL DESIGN BUILDING BLOCK APPROACH

The limitation of the traditional numerical synthesis in addressing requirements elucidation was first raised by Andrews (1981), who then demonstrated an architecturally driven ship synthesis (Andrews 1984), which was subsequently fully integrated to the submarine case with the architecture and weight organised functionally, (e.g., Fight, Move, Float, and Infrastructure) as opposed to the traditional weight breakdown structure (Andrews et al. 1996). This approach, known as the UCL Design Building Block (DBB) approach (Andrews and Dicks 1997), is now a proven design method and was implemented as the Surface Concept (SURFCON) module (for both surface ships and submarines) in the sophisticated fully three-dimensional (3D), commercially available naval architectural Computer-Aided Design (CAD) software Paramarine™ (QinetiQ 2019), coded by Graphic Research Corporation (GRC) (Andrews and Pawling 2003).

However, there were several drawbacks in implementing such a sophisticated (fully 3-D), high-fidelity, high-capability Computer-Aided Design (CAD) modelling tool in ESSD, such as the difficulties due to effort in modelling or creating each of the numerous features and placing them individually. The latter can be considered laborious and demanding, especially if detailed modelling must be carried out after each design change and iteration (Andrews et al. 2009). Such modelling effort can be referred as to the Gulfs of Execution and Evaluation (see Figure 3), which highlights the overall effort required in making a system perform the desired task correctly (Norman 2013). Therefore, the 3D based synthesis was then reduced by the UCL ship design research team to be what is called ‘2.5D’ to allow a simpler architecturally oriented design tool to be developed in-house, for specifically, surface ship research and education, referred as to the UCL JavaScript layout exploration tool (Pawling et al. 2015; Kouriampalis et al. 2021). In the current paper, an alternative solution was developed without creating a further separate or standalone design tool like the UCL JavaScript tool. That tool sacrificed many advantages of using 3D based synthesis and 3D informed dialogue, which Paramarine facilitated and was seen to be necessary for exploring the submarine DS3 in ESSD.

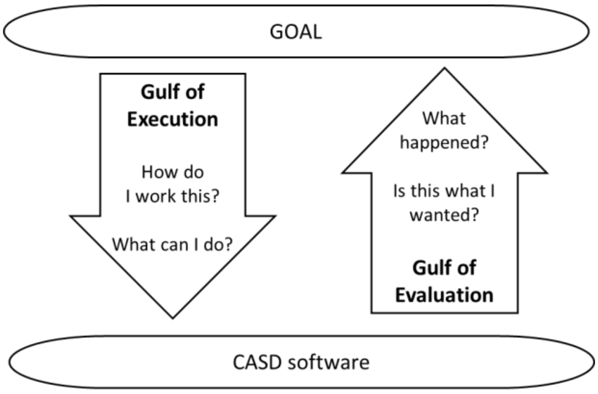


Figure 3: Gulfs of Execution and Evaluation for CAD Development, after Norman (2013)

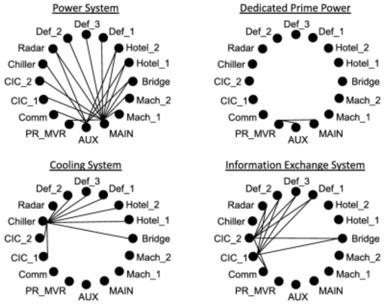
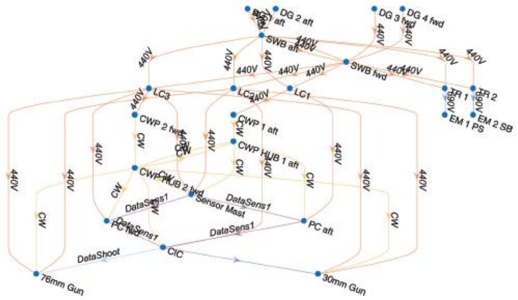
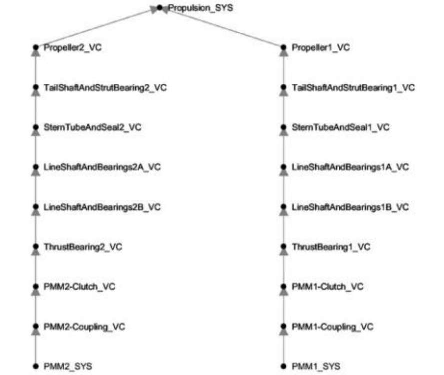
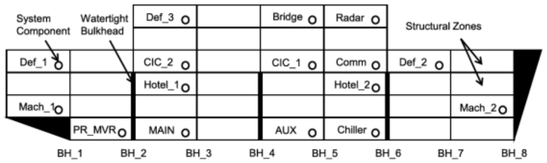
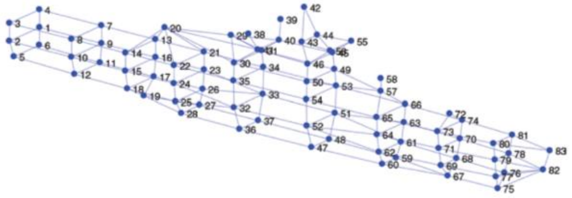
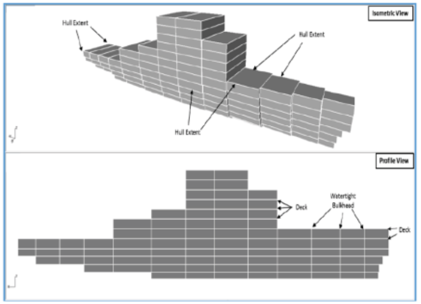
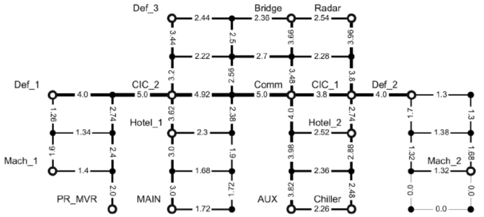
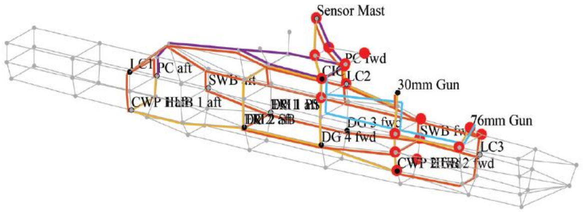
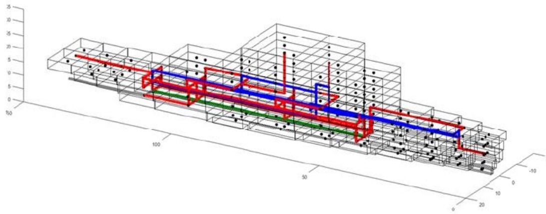
Although the synthesis of the whole submarine design could have been developed using the sophisticated 3D based synthesis UCL DBB approach, it was seen to be sensible to consider in the next section design issues and existing approaches specific to designing DS3. Some of these were seen as aiding the designer in developing DS3 beyond physically descriptive models in ESSD.

3. SYNTHESISING DISTRIBUTED SYSTEMS ISSUES AND APPROACHES IN EARLY STAGE DESIGN

Designing DS3 is quite complex and relevant information may not be addressable during initial submarine sizing (Burcher and Rydill 1994), furthermore, each DS3 technology may require different design methods. Sizing from the first principles or detailed sizing may give a more accurate design than a traditional numerical or parametric approach (Stapersma and de Vos 2015), however, it can be time consuming. More importantly, the detailed component design information may not be available at the earliest design phases and quite distracting from the essence of ESSD requirements elucidation (Andrews 2018). Lying between detailed DS3 sizing and the traditional numerical approach is the use of network theory. This requires fewer assumptions than detailed sizing but is seen to be better than a parametric approach when applied to distributed ship service systems. DS3, as already defined in the beginning of this paper, is an assembly of connected individual components and thus appropriate to be studied using what is called a network or graph. A network is a collection of points connected by lines usually known as arcs or edges (Newman 2010). Modelling connected entities as in a DS3 as a network has been considered as a means to new insights (Newman 2004). Not only can a DS3 be modelled as a network, but also relationships between spaces within a ship arrangement (Pawling and Andrews 2018; Gillespie 2012), as well as variables within design algorithms (Collins et al. 2015).

Given network theory specific to submarine systems had not been applied, applications of network theory to surface ship design were also investigated. Table 1 summarises and provides a high-level comparison of how network theory has been applied to naval surface ship distributed systems design. Table 1 also indicates that all the current approaches require different architectures as the main input (e.g., logical architecture, how DS3 components are connected each other; physical architecture, how DS3 components are located on the vessel (Brefort et al. 2018)). A network of the ship can model the spaces within a ship (physical architecture) while nodes in the distributed system’s logical architecture can be assigned to those nodes in the physical architecture. Each approach used a different optimisation technique for systems routing, which range from the shortest path algorithm (Dijkstra 1959) to the Network Flow Optimisation (Trapp 2015), discussed further in the following Subsections 3.1 to 3.4.

Table 1: Summary of network theory applications to ship service distributed systems, taken from various sources as specified in the header of the table

	(A) The L-PAT approach (Shields et al., 2017)	**(B)** The early routing approach (Duchateau et al., 2018)	**(C)** The Architecture Flow Optimisation approach (Robinson, 2018)
1	System model for the L-PAT algorithm application (total of five logics including personnel movement) (Shields et al., 2017)	Power system network as the input of the early routing approach (Duchateau et al., 2018)	Mechanical plex logical architecture that provides a list of components required for a specific distributed system (Brown, 2020)
Logical Architecture			
2	System model nodes (1A) are assigned to vessel arrangement (Shields et al., 2017)	Routing adjacency network for a naval vessel compartments and superstructure defining the decks and hull envelope (Duchateau et al., 2018)	Subdivision Block of a generic naval combatant produced from Synthesis Model of the Virginia Tech where the blocks are defined by decks, watertight bulkhead, and hull extent (Robinson, 2018)
Physical Architecture	 Label: main (MAIN) and auxiliary (AUX) machinery, prime mover (PR_MVR), defence system component (Def) (e.g., radar, bridge, combat information centre (CIC)), mechanical component (Mech/Mach) (e.g., hotel load centre, chiller, and communications centre (Comm)		
3	The output of the L-PAT approach in 2D representation showing different routing densities (0 to 5): 0 indicates no connection; 5.0 means the connection contains all systems in 1A (Shields et al., 2017)	The output of the early routing approach showing power (orange and blue), cooling (yellow), and data (purple and light blue) for a generic naval combatant (Duchateau et al., 2018)	The output of the Architecture Flow Optimisation approach showing mechanical (grey), electrical (red), chill water (blue), and seawater (green) for a generic naval combatant (Robinson, 2018)
Physical Solution			

3.1 PHYSICAL SOLUTION APPROACH

The research produced by the University of Michigan's Advanced Naval Concepts Research (ANCR) group has applied network theory (Newman 2010) to naval ship design general arrangements (Gillespie and Singer 2013), and a better understanding of the relationship between DS3 and ship's arrangements (Rigterink et al. 2014). The Logical-Physical Architecture Translation (L-PAT) algorithm was proposed to provide the designer with knowledge of physical solutions using network approaches (Shields et al. 2017). In this approach (see Table 1 (A)), DS3 routing was developed from logical architecture, via simplex (Shields et al. 2017) and multiplex network (Gomez et al. 2013), which could be said to be similar to a multislice network (Mucha et al. 2010) representation. The L-PAT tool from the University of Michigan could give insights into a DS3 physical solution (routing), by indicating wherein the vessel the DS3 physical solution could be located without requiring detailed physical modelling. However, the process behind making the minimum input information (such as the size of DS3 major components and the vessel's physical architecture) for such analysis in the first place remains questionable and thus was not seen to be very helpful in understanding the starting process for synthesising DS3 components for submarines.

3.2 EARLY STAGE ROUTING AND AUTOMATIC TOPOLOGY GENERATOR TOOL

As shown in Table 1 (B), TU Delft has undertaken DS3 related work using an extension of Delft's automated bin packing approach (van Oers 2011). TU Delft used a genetic algorithm (GA) (Deb et al. 2002) and Pareto Front representation to reduce the number of solutions in design space explorations of DS3 in ESSD. Using these two methods, the Automatic Topology Generator (ATG) was created to assist a system designer in the decision making in the early design of a ship's DS3 (de Vos 2018). The TU Delft's ATG has shown that the routing of DS3 could be done using an automated and optimisation-based approach, where many options could be explored using a network representation. However, the optimisation is done only at the logical architecture level of abstraction. Furthermore, particular ship's systems must be known before ATG can function, as the number of components is a chosen input to be made before the ATG can be run. This would seem to be a process like University of Michigan's L-PAT tool, which is more suitable for outside-in ship design approaches (see Andrews (2018)). The output of ATG was seen to only explore the number of connections and thus was considered not sufficiently sensitive to varying DS3 component choice for (say) for redundancy as part of a more style driven approach (Andrews 2018).

3.3 ARCHITECTURE FLOW OPTIMISATION APPROACH

The Network Flow Optimisation (NFO) approach combines network theory and linear programming (Trapp 2015). In the NFO approach, nodes and arcs are modelled as a set of mathematical variables describing the necessary constraints, bounds, and objective functions for linear programming to be undertaken. The NFO approach (called Non-Simultaneous Multi-Commodity Flow (NSMCF)) was applied to model shipboard Integrated Engineering Plant (IEP) by Trapp (2015) via Mixed-Integer Linear Programming (MILP). A follow up to this was the development of Non-Simultaneous Multi-Constraint Parallel-Commodity Flow (NSMCPCF) or Architecture Flow Optimisation (AFO) by the research team at Virginia Tech led by Brown (Robinson 2018). Since then, AFO has been significantly enhanced and developed to be the Dynamic AFO (DAFO) and Vulnerability AFO (VAVO) (Parsons et al. 2020). Unlike a semantic network (Sowa 1983), AFO was used to model the actual physical objects representing a total ship, all systems (~500 DS3 components and ~1200 connections) in a putative large and complex naval combatant (Parsons et al. 2019). Although this is not feasible without recourse to a significant Machinery Equipment List, i.e., equipment database (Parsons 2021), AFO allows a direct representation of decisions made for different DS3 style choices in a ship design. AFO can provide numerical data, such as power, which can then be used to scale the size of baseline DS3 components (Stinson 2019), Thus, unlike other network applications, AFO has been applied to design and size distributed naval ships systems. Such conversion to space and weight input for the relevant DS3 was only possible provided that the power to weight ratio and power to volume ratio were known or assumed, which means the approach is also dependent on the quality of the database of DS3 components.

Instead of tracking various commodities in the network flow, as was done using Trapp's NSMCF approach (Trapp 2015), AFO only tracks energy flow in a steady state condition, using pre-defined plexus. This simplification allows the inclusion of multiple DS3 for a ship through linear programming optimisation in ESSD. The approach in using the AFO tool is that the definition of the wider system's (the vessel) physical architecture should be kept as simple as possible (Robinson 2018). This also applied to the approaches from the University of Michigan (Table 1 (2A) and TU Delft (Table 1 (2B)) and thus the volume of a space, such as a typical ship's compartment, is represented by a single node. This enables such a network tool to be easily used without the need for physical modelling including some detailed ship arrangement, as in the UCL DBB approach. However, the AFO process has been devised to work specifically with the Virginia Tech's ship design process, which is different from the inside-out UCL DBB approach (Andrews 2018). The surface ship applications of AFO were limited to ship procurement cost and survivability formulation and thus as they stood were not considered applicable to submarine's DS3 ESD without further work. Hence, this paper presents an alternative approach in applying the Network Flow Optimisation approach to submarine DS3.

3.4 SMART SHIP SYSTEMS DESIGN

As summarised in the 2018 IMDC state of the art report on design methodology (Andrews et al., 2018), the Electric Ship Research and Development Consortium (ESRDC) (ONR-ESRDC 2018) focused on future electric surface warships using high-energy weapons (Chalfant et al. 2017). That consortium has developed a collaborative analysis tool called Smart Ship Systems Design (S3D) (Smart et al. 2017). This enables specialist engineers to be involved much earlier in the design phase (Langland et al. 2015). Further relevant work has provided specific ship design inputs from the simulation-based environment to evaluate thermal cooling system design (Babaee et al. 2015), machinery (Jurkiewicz et al. 2013), and power distribution system (Chalfant and Chryssostomidis 2011). Nevertheless, the collaboration between specialist engineers in designing ship systems can result in excessive design detail at ESSD, which was considered inappropriate. This is because, as Andrews argued, one should not fix large portions of the design since the overall design should still be subject to big decisions as part of Requirement Elucidation and hence undertaking detailed design is either nugatory or curtailing choice (Andrews 2013).

The applications of network theory to the design of distributed ship service systems were considered to fit between these two extremes, i.e., it is more accurate than the type-ship or rule of thumb scaling approach, yet not too detailed as the collaborative systems modelling. Most importantly, the proposed approach, which is outlined in the next section, aimed to capture of the complexity of interrelated DS3 both in terms of logical and physical architectures.

4. DESCRIPTION OF THE NETWORK BLOCK APPROACH

The implementation of the UCL Design Building Block approach in Paramarine with its SURFCON (DBB) module is highly flexible and so specifically useful for DS3 synthesis. The algorithms and assumptions were part of the input and thus the implementation of the UCL DBB approach in Paramarine was not a black-box process. However, such a ‘glass box’ approach is demanding in the expenditure of time for developing a new design. Furthermore, integrating the network-based sizing approach with the submarine design process, using SURFCON Paramarine, exacerbated the Gulfs of Execution and Evaluation (Figure 3) and this could inhibit exploring DS3 options in ESSD.

Therefore, an approach termed the Network Block Approach (NBA) was proposed. The NBA consisted of frameworks, methods, and design tools that employed a strategy to ‘intercept’ data flow, before being inputted to Paramarine, and utilised a set of spreadsheet Excel inputs. The main objective of the development of the NBA was to create an integrated design procedure that incorporated SUBFLOW and the UCL Design Building Block approach. Unlike the previous SUBFLOW in a recent paper by the authors (Mukti et al. 2021), the current SUBFLOW, part of the Network Block Approach (NBA) was not used to optimise DS3 design nor the overall submarine design. Thus, compared to other network-based approaches (see Sections 3.1 to 3.3), the optimisation technique in SUBFLOW was only used to solve the energy balance through linear programming, rather than (questionably) ‘optimise’ the whole submarine design.

On one hand, SUBFLOW requires design data at a specific level of design granularities (see (Mukti 2022)). On the other hand, the UCL DBB approach facilitates the development of a new design *ab initio* at a level of design granularity required for DS3 synthesis. Therefore, the architecture of the NBA must consider the two distinct design philosophies. To merge the advantages of both approaches, the NBA was developed based on DevOps software practice that is a blend of two different activities, ‘Development’ and ‘Operations’ (Hüttermann 2012). In this case, the ‘Development’ represents the implementation of the UCL DBB approach in Paramarine and the ‘Operations’ represents the DS3 synthesis using SUBFLOW in MATLAB. This leads to an infinity loop diagram presented in Figure 4, which represents the iterative nature and can be terminated once the design is considered naval architecturally balanced.

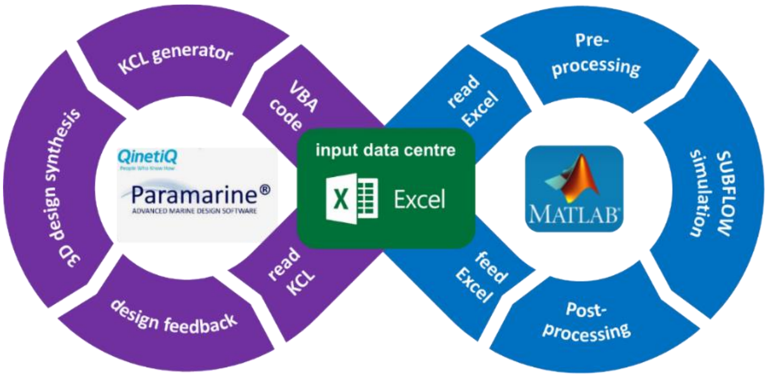


Figure 4: The logic of the proposed Network Block Approach showing a high level process of Physical Loop method in purple and Logical Loop method in blue

Figure 4 shows centrally the Excel spreadsheet, where the design data can be stored, and is termed the ‘input data centre’. The design data dealt with the design concerns appropriate to ESSD, such as space and numerically defined gross weight, as well as creating DS3 components and connections, including their attributes required for the SUBFLOW network analysis. The NBA consisted of what was termed as the 'Physical Loop' method in purple and the 'Logical Loop' method in blue in Figure 4. The Physical Loop method focused on the task to synthesise the submarine design and the DS3, in terms of the physical architecture, which was done through the interaction between a spreadsheet and Paramarine using Visual Basic Applications (VBA) based programming language (Microsoft 2021). The Logical Loop method makes use of MATLAB codes to perform the development of a DS3 network by pre-processing, analysis, and post-processing through SUBFLOW to enable energy based DS3 sizing and DS3 energy flow simulation at a logical level of abstraction.

The input data centre consisted of several programs, summarised in Figure 5. Each program was developed as a worksheet with its distinct cells layout, which could be read both by Paramarine for rapid modelling of objects and by MATLAB for automatically generating codes to perform SUBFLOW. With this approach, the designer could focus and readily manipulate the architecture of the vessel and perform SUBFLOW simulation without needing to address the Gulf of Execution (Figure 3) in Paramarine and MATLAB.

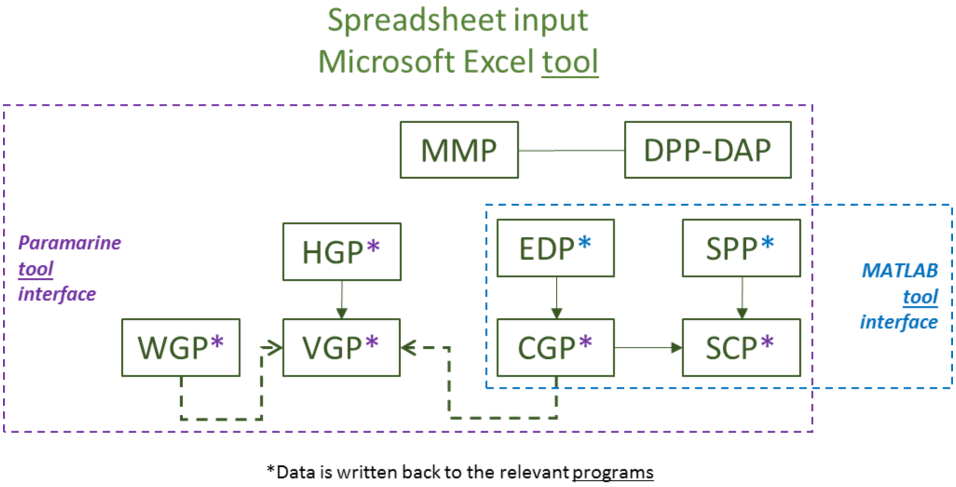


Figure 5: The detailed breakdown of the input data centre, showing multiple programs in green, Paramarine interface in purple and MATLAB interface in blue

The top part of Figure 5 shows the Main Menu Program (MMP), which is a menu to execute all the programs listed in Table 2 through a 'single click'. MMP was also connected to Design Preamble Program (DPP) and Design Analysis Program (DAP). The DAP is a hardcoded KCL script for automatically setting up the analytical capability available in the Paramarine system, including the audit function. As shown in the purple dashed box in Figure 5, all programs work with Paramarine but only four programs in the blue dashed box work with MATLAB. The application of the programs in Table 2 within the Physical Loop and Logical Loop methods is discussed in next two subsections.

Table 2: Summary of programs in the Network Block Approach (Mukti et al. 2022)

Program	Description	Function
MMP	Main Menu Program	Execution menu to compile all programs
DPP	Design Preamble Program	Hardcoded design setup
DAP	Design Analysis Program	Hardcoded analysis setup
HGP	Hull Granularity Program	Input for hull size
VGP	Volume Granularity Program	Input for spaces
WGP	Weight Granularity Program	Input for weight
EDP	Equipment Database Program	Input for equipment data
CGP	Component Granularity Program	Input for DS3 components for arrangement and SUBFLOW
SPP	System Preamble Program	Input for DS3 connections
SCP	System Connection Program	Input for DS3 connection and SUBFLOW

4.1 DESCRIPTION OF THE PHYSICAL LOOP METHOD

Fundamentally, the structure of the Physical Loop method consisted of two major stages: a coarse stage and a fine stage. In the coarse stage, the design could be developed *ab initio* to define the weight and space models for the architecturally centred submarine synthesis using three programs: Hull Geometry Program (HGP); Volume Granularity Program (VGP); and Weight Granularity Program (WGP). The coarse stage produced a design with the level of granularities that was normally considered sufficient for submarine concept. However, as the research explored greater detail necessary for DS3, the design needed to be developed to the fine stage in the Physical Loop method.

Therefore, in the fine stage, four programs: Equipment Database Program (EDP); Component Granularity Program (CGP); System Preamble Program (SPP); and System Connection Program (SCP) were produced to develop the submarine design to a sufficient level of design detail necessary for DS3 synthesis. The logic of these two major stages is depicted in Figure 6. The NBA is not just an Excel tool, it comes with extensive frameworks. Three main frameworks are discussed in turn.

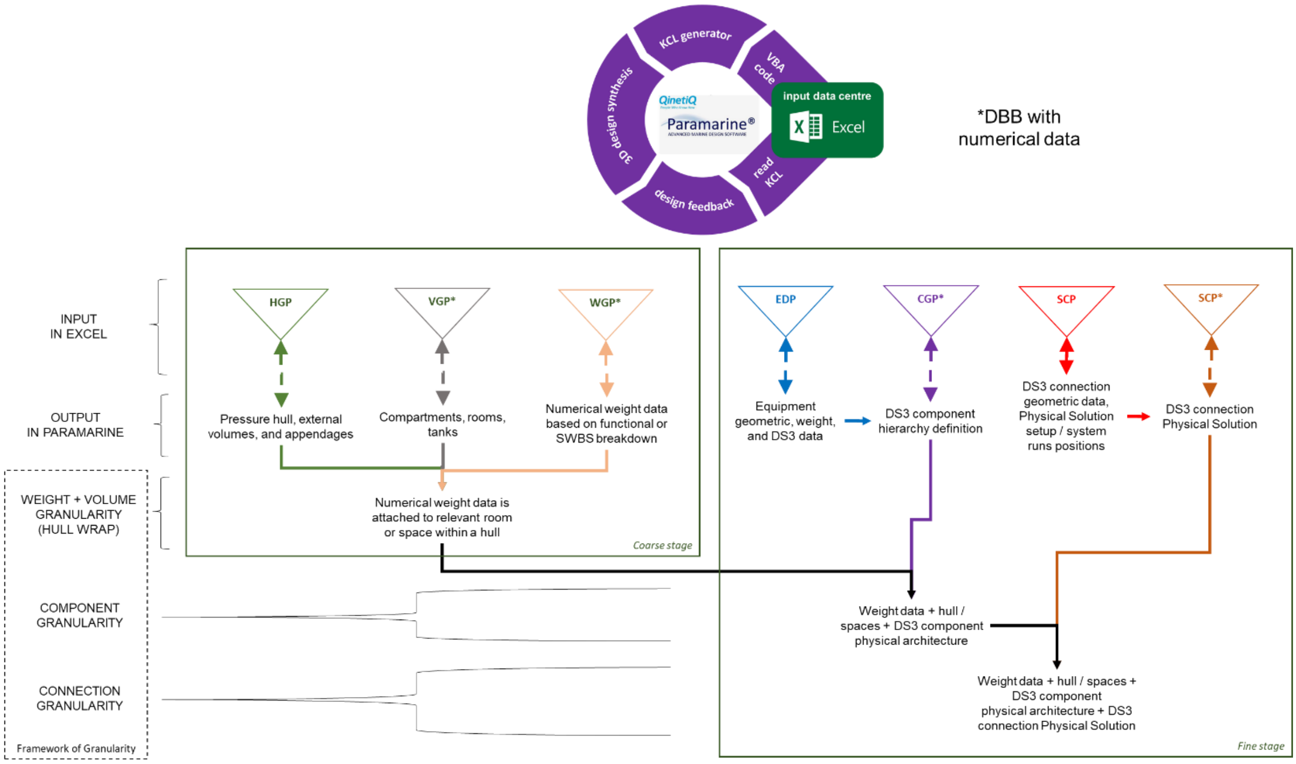


Figure 6: The structure of the Physical Loop method with various frameworks (see the following subsections)

4.1.1 Design Granularity and Design Fidelity

To make the Physical Loop method possible, different design granularities needed to be considered. A framework was proposed to aid the designer to understand what level of detail was considered necessary for DS3 synthesis. The proposed framework, as shown in Figure 7, distinguishes design granularity and design fidelity. These are illustrated as the two main axes in Figure 7. A design can progress from just weight and space definition to include DS3 components and connections. Thus the X-axis represents the design granularity. Concurrently, the design can also be more detailed, decomposing models to a more detailed definition, quantified by the design fidelity given in the Y-axis. The highly flexible UCL DBB phases aim to explore both axes until a sufficient level of detail is achieved to inform the Requirement Elucidation and thus is adopted in this framework.

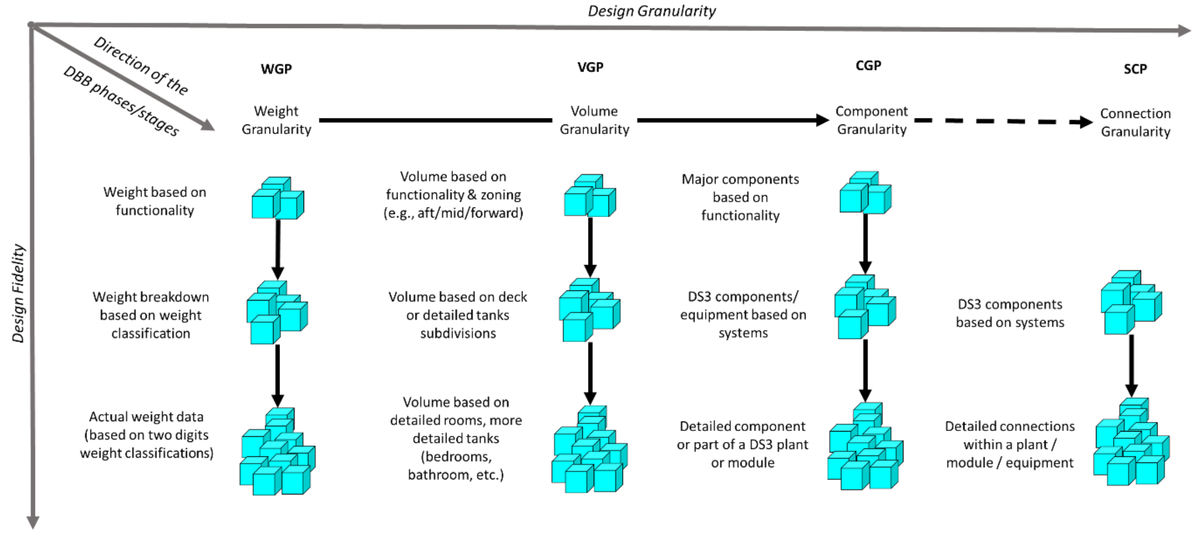


Figure 7: Framework of design granularity and fidelity

4.1.2 Types of Building Block Objects

The use of design building block objects in Paramarine could be split into two types: a building block for organisation (that is descriptive) and a building block with numerical data (Pawling 2007). The descriptive design building blocks could be based on the functionality or zonal (spatial) definition. An example of building block functionality was the UCL DBB functional grouping (i.e., Fight, Move, Float, and Infrastructure). Examples of a building block zonal used in submarine design could be a watertight compartment zone (dry spaces), an external Main Ballast Tanks (wet spaces) or a free flood space (hull appendages). The numerical data for DBB object in this approach can be weight data; volume data; equipment data (length, beam, and height); or connection data (length, diameter (for cross sectional area), and weight). Using different numerical data, the DBB objects could be organised based on various design granularities, starting at the first level and going to the third level of granularity as explained earlier. Thus, building blocks with numerical data were divided into those giving individual weight data, those with geometric volume data, those describing DS3 components, and those identifying DS3 connections. These building blocks were defined using the Volume Granularity Program (VGP), Weight Granularity Program (WGP), Component Granularity Program (SGP), and System Connection Program (SCP).

4.1.3 Design Building Block Hierarchical Breakdown

Although the development of the DBB model in the Paramarine was intuitive, it was limited to a single view of hierarchy (Mukti et al. 2021). Hence, to organise building block objects based on both functionality and spatial definition would have required many descriptive DBB objects. This did not include more detailed DBB objects that could reach the fifth level, which meant chasing a particular DBB object could be a daunting task. To avoid this, while using the DBB hierarchy, an alternative hierarchy was developed. The hierarchy in this approach still retained functional, packaging, and spatial or zonal information but it was categorised based on the types of DBB objects as discussed in Subsection 4.1.2, which was weight data, volume data, DS3 components data and DS3 connections data. Therefore, the proposed approach did not mix different types of DBB objects under the same parent organisational DBB object, except for the Master Building Block (MBB) which is essentially the whole submarine characteristics (Andrews and Pawling 2003). With this approach, commonality with those DBB objects with numerical data could be achieved. This enabled the designer to manage the design data more effectively, especially in a design where there were hundreds of DBB objects with numerical data.

4.1.4. Distributed Systems Routing Model

Paramarine can be used to model systems routing or connections that were not exploitable in the previous UCL DBB research at a PhD level (Pawling 2007; Purton 2016). In this research, the issue with the DS3 modelling, more specifically, DS3 routing in Paramarine has been investigated, which led to two different systems routing frameworks. The first framework employed automatic routing in Paramarine that was termed as the ‘point to point’ framework in the current research. However, if, for instance, the designer wanted to model a more detailed routing, a framework termed ‘highway’ framework, combining automatic routing and a highway, consisting multiple longitudinal system runs, could be used.

4.1.5 Naming Convention for Design Building Block Objects

As the submarine design needed to be developed to component granularity to enable a DS3 synthesis, the number of DBB objects with numerical data at component granularity escalated to more than 100 objects. Thus, a naming convention was applied to ease the Gulf of Evaluation (Figure 3) by making the design data easier to be tracked, revised and developed using consistent, chronological, and descriptive names (Stanford University 2021). The DBB objects with numerical data were identified by an alphabet designation system separated by some underlines or underscores. Thus, the programs within the Physical Loop method were able to automatically read and write thousands of items of design data back and forth to the Paramarine model. Generally, each of the naming conventions consisted of several two-digit alphabetic designation systems, giving the information contained in an object’s name. The object name started with ‘BB’ (building block), indicating the object was included in the ‘MBB’ (master building block) hierarchy. This was followed by the first level of identification system showing the level of granularity, such as ‘NL’, which stands for numerical (for weight granularity, ‘VL’, which stands for volume (for space or volume granularity), and ‘DB’, which stands for database (for DS3 equipment or component granularity). In this approach, an ‘NL’ object was meant to describe a building block object without any physical entity, which can be weight data or power data. If the building block contained a physical entity, it was ‘VL’ or ‘DB’.

4.2 DESCRIPTION OF THE LOGICAL LOOP METHOD

The Logical Loop method covers the SUBFLOW process that provides a network-based sizing for various types of DS3. Generally, any type of DS3 could be sized directly using the SUBFLOW network with a derived length to weight or length to volume ratio for various types of DS3. The SUBFLOW network with flow response simulation adds an early steady-state flow response simulation appropriately to submarine ESD. Since SUBFLOW assumes the relationship between energy and the size of DS3 to be linear, the early steady-state flow response simulation could then be used to size a set of DS3 that is network flow dependent, such as for a heat removal system. This means some DS3 could be sized directly using the

SUBFLOW network without the need to perform the flow response simulation (see Table 3). The more detailed DS3 network definition, the lesser design margin is required.

Table 3: Two possible ways of using SUBFLOW, as part of the Logical Loop method

Stage	DS3 Sizing	Notes
SUBFLOW Network	Length to weight and volume ratios	Less effort but not sensitive for sizing DS3, which is network flow dependent, for example heat removal systems
SUBFLOW Network + Flow Response Simulation	Power to weight and volume ratios	Energy balance and heat removal systems can be calculated but require more effort

The Logical Loop method consisted of three general tasks that could be treated as a loop for a given operating condition. The objective of the general tasks was to automate the routine tasks in the Logical Loop method and thus the designer could go back to work on the Physical Loop method simultaneously. The general tasks consist of pre-processing, the use of the solver (CPLEX in MATLAB (IBM 2014)), and the post-processing task. The pre-processing task read the input the designer defined in the Component Granularity Program (CGP) and System Connection Program (SCP), while the post-processing task wrote the results back to two programs (Equipment Database Program (EDP) and System Preamble Program (SPP)). Once the results were in the spreadsheet, the designer could individually justify the size of each arc dependent on the different types of DS3 technologies. The inputs required in modelling the DS3 network for SUBFLOW simulation are briefly outlined in the following subsections.

4.2.1 SUBFLOW Network Model

The type of nodes selected for SUBFLOW was simplified for the early-stage design application. There were only two types of nodes, a terminal or a hub node. These were the input required to be defined using the Component Granularity Program (CGP). Another input in the same program was the node type, defined in terms of physical definition. Hence, in terms of granularity, a node can be either numerical 'NL' or physical 'DB' while in terms of SUBFLOW a node can be a terminal or a hub node. Meanwhile, an arc can be numerical or physical in terms of granularity, but in terms of SUBFLOW, the arc is organised due to their technology, i.e., the type of commodity carried by that DS3 physical connection.

4.2.2 SUBFLOW Operational Matrix

In this approach, only continuity constraints were hardcoded into the SUBFLOW network model. The other SUBFLOW constraints, such as lower and upper bounds of each node and arc could be adjusted in the CGP and SCP (Table 2). Furthermore, the CPLEX toolbox in MATLAB (2019) was used instead of using the IBM ILOG CPLEX (2014). This enabled user intervention in the network formulation code for CPLEX using MATLAB programming language, i.e., a matrix-based computation. This, in turn, could minimise any black-box tendencies of linear programming formulation, by revealing the interaction between objective function, constraints, and bounds in the form of several matrices constituting a single large matrix. Such a large matrix is referred as to the Operational Matrix framework (see (Mukti et al. 2021) for example).

4.2.3 SUBFLOW Multiplex Visualisation

Unlike a previous SUBFLOW network visualisation (Mukti et al. 2021), in this approach, the SUBFLOW network clustered various DS3 technologies like the 3D multiplex network but nodes were manipulated in the Z-axis so they would not overlap in the X-Y view. The SUBFLOW DS3 network was inspired by the London underground tube map (Elliott and Deasley 2007), which shows the tube network not to scale but has the sense of directions (east-west, north-south, etc). Therefore, the SUBFLOW DS3 logical network was devised to maintain the spatial aspect of the vessel (e.g., forward-aft, upper-lower, port-starboard) but also adopted a node shape differentiation as well as colour coding, which represented different types of DS3 technologies.

5. SUBMARINE CASE STUDY

To test whether the new approach could capture the style choices of DS3 at component granularity level and could be validated with available data, a case study was developed with the payload and style choices akin to the ocean-going 2500 tonne generic submarine. This design was extracted from the database used in the annual UCL submarine design exercise (UCL-NAME 2014) and is summarised in Table 4.

Table 4: The realisation for submarine case study following the decision making sequence for complex vessels outlined in detail in Figure 4 and Appendix of (Andrews 2018) in a similar manner to the submarine example in Figure 4 of (Andrews 2021)

Process Step	Selection Decision / Realisation for Submarine Case Study	
Perceived need	Demonstrate the application of the Network Block Approach (NBA)	
Outline of initial requirements	Initial SSK key parameters desired (capabilities)	
	Payload equipment in Table 5	
	Initial Performance	**Value**
	Complement	46 personnel
	Operational environment density range	1-1.025 te/m^3
	Deep Diving Depth	250 m
	Patrol length	49 days
Selection of style of emerging ship design	**Style Level**	**Choice**
	Macro Level	Non nuclear (SSK)
	Main Level	Diesel-electric power plant
		Medium size ocean-going submarine
		Single hull with casing
		Three watertight bulkheads
	Micro Level	Detailed DS3 styles
Selection of major equipment and operational sub-systems	DS3 configurations (see (Mukti 2022))	
Selection of whole ship performance characteristics	**General Performance**	**Value**
	Sprint speed	20 knots (2 hrs)
	Submerged speed	5 knots (17 hrs)
	Snort speed	6.5 knots (5 hrs)
	Indiscretion ratio (Burcher and Rydill 1994)	22 %
	Sub Level	**Value**
	For DS3	See the following subsections
Selection of synthesis model type	The Network Block Approach (NBA)	

Table 5: Baseline submarine payload equipment based on the broad specifications of a typical submarine (UCL-NAME 2014)

Payload Equipment	Description	Unit/Set
600 mm tubes (OD)	Torpedo tubes to eject the torpedo from the submarine	6
Spearfish-UK	Torpedo reloads as the anti-ship or anti-submarine weapon	18
Air turbines	Air turbine pump torpedo discharge system	2
Bandfish-UK	Countermeasures to distract, decoy or destroy incoming torpedoes	2
SPA4 RFOM-81	Sonar systems (1 cylindrical Bow Passive Sonar (BPS), 6 Passive Ranging Sonar (PRS), and 2 Flank Array Sonar (FAS))	1
R3 RFOM-100	Radar mast non-penetrating telescopic	1
EW4 RFOM-72	Submarine Electronic Warfare	1
C5 RFOM-53	Communications fit, which operate across the frequency spectrum	1
CMS7 RFOM-85	Combat Management Systems	1

5.1 DESIGN DEVELOPMENT

Figure 8 shows the logic of the approach for the submarine case study, which consists of several steps and is iterative. This used various programs that are listed in Table 2.

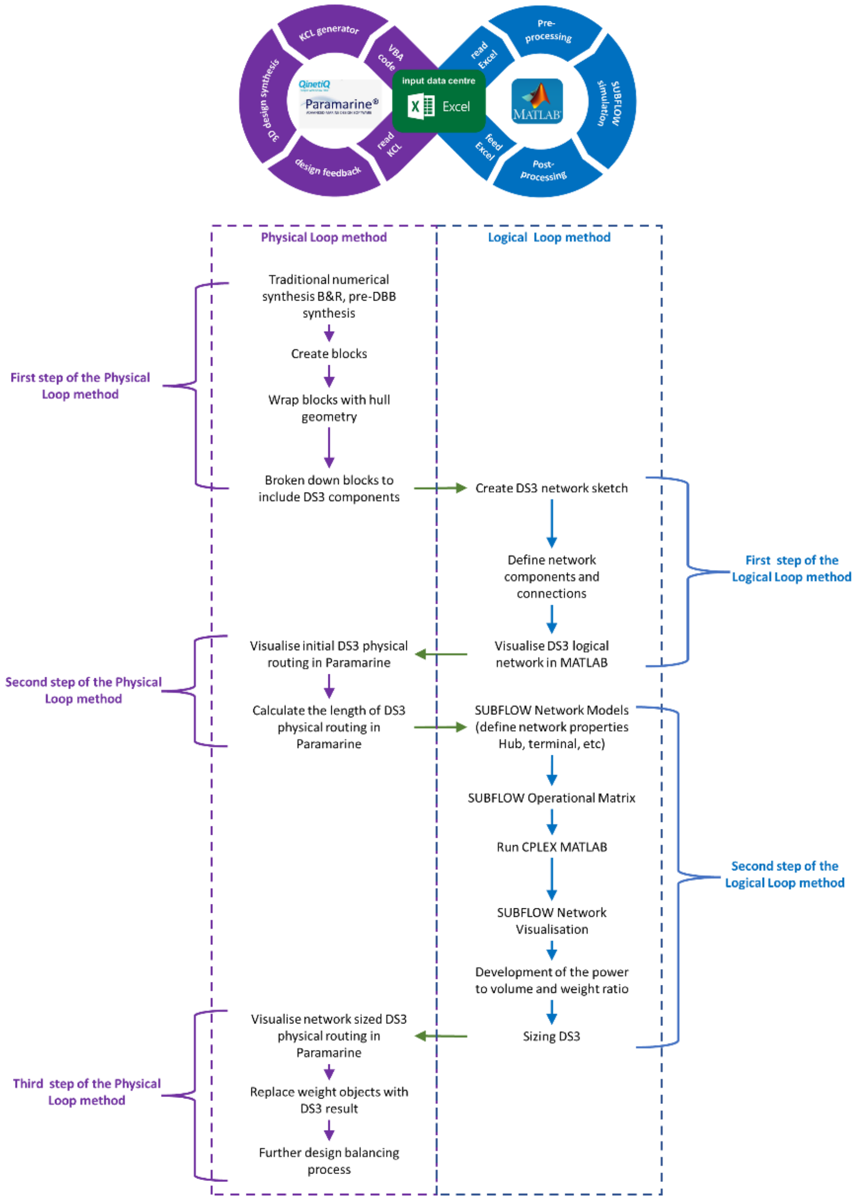


Figure 8: The logic of the proposed Network Block Approach (NBA) to DS3 synthesis for submarine design ESD (see Subsection 4.2.2 for CPLEX MATLAB)

The process began by inputting the numerical synthesis data into the Volume Granularity Program (VGP) and the Weight Granularity Program (WGP). At this point, the design would have had implicit DS3 styles, since it would have been sized using the gross weight-displacement based algorithms. Using the two programs, the designer created volume blocks as shown in Figure 9 (top). These 21 volume blocks not only represented spaces within the submarine but also 181 items of weight data which were attached to the volume blocks as attributes. At this coarse stage, some weights that were distributed throughout the submarine, such as DS3, were allocated at the longitudinal centre of the pressure hull with assumed z coordinates, based on the previous submarine data (UCL-NAME 2014).

The volume blocks were then be included within the hull using the Hull Geometry Program (HGP) to obtain an initial indication of longitudinal balance. This then resulted in a more refined volume due to additional data being estimated, as well as obtaining the weight of the total fluids in the tanks, as is shown in Figure 9 (middle). Some of the major equipment components, such as the diesel engines, propulsion motor, escape towers, and torpedo tubes could also be modelled at this point to aid sizing volume objects when using the Component Granularity Program (CGP). This is given in Figure 9 (bottom). This is the first step of the Physical Loop method as shown in Figure 8.

The level of design granularity shown in Figure 9 (middle) or even in Figure 9 (bottom) was considered sufficient for typical submarine concept level design. However, since this research concerned DS3 synthesis, it was decided that the design should be developed beyond this level of granularity. Some DS3 style choices subject to spatial definition, such as zoning for electrical systems, could only be investigated once the design progressed to this level of design granularity. Therefore, the procedure to develop various DS3 technologies is discussed after this section to cover the second step of the Logical Loop method as well as the third step of the Physical Loop method (see Figure 8).

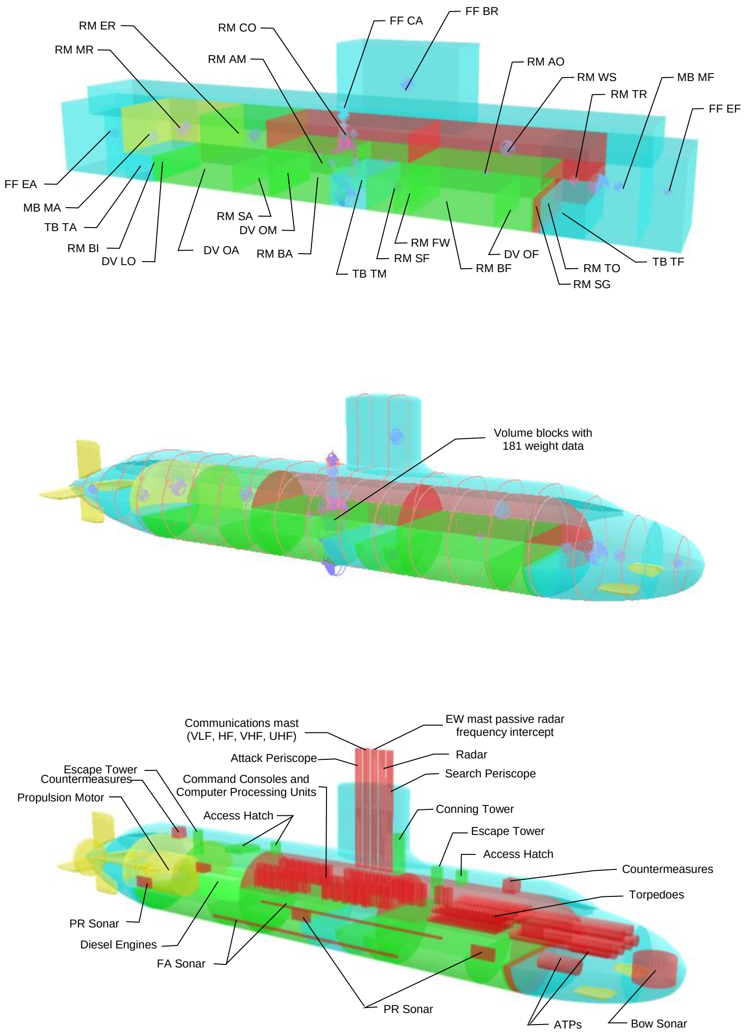


Figure 9: Design progress of submarine case study showing (top) volume blocks and weight data, (middle) and included in the hull, (bottom) concurrent with placement of major components (see acronyms for payload items in Table 5) Items named in top diagram by four letters are individually identified in (Mukti 2022)

5.2 DS3 SYNTHESIS

Although major design decisions are listed in Table 4, there were many detailed decisions made in order for the submarine design to progress the physical and logical DS3 synthesis much earlier in the design process than traditionally. These decisions were dependent on the nature of different DS3 technologies, many of which are discussed later in this chapter. Thus, for this case study, the following different DS3 were considered to test the applicability of the new approach: fuel oil (FO) system; electrical (EL) system; mechanical (ME) system, as part of the propulsion system; heat removal (HV) systems; water distribution or trim and ballast (TB) systems; high-pressure air (HP) system; low-pressure (LP) air system; hydraulic (HY) systems, and important data (DT) systems. The development of each DS3 network required an understanding of the individual DS3 technologies and how the physics drove a different formulation for the network models. The architecture of each DS3 was also dependent on detailed system types, technology changes and styles of redundancy at the component or connection level.

As the development of the DS3 network was not intended to 'bottom out the preferred design' i.e., it required to be open to revision, simplifying assumptions were made for each DS3 technology. This kept the network simple for ESSD application while avoiding the loss of sufficient DS3 complexity. Therefore, although each DS3 network was developed based on the relevant system line diagram, some nodes were modelled as 'DB' but without yet having geometric data. They were produced to complete the network structure and to aid the DS3 routing decisions. Furthermore, the detailed components, which were not explicitly modelled in this network, were accommodated using typical design margins. This input could be manually adjusted using the System Connection Program (SCP) and the Component Granularity Program (CGP) (Table 2). In this case study, different DS3 technologies, ranging from cables to piping for transporting either gas or liquid were developed. There were 231 nodes and 468 arcs. Figure 10 shows the DS3 network as multiplex, with the fuel 'FO' as the source of energy being transferred to various DS3 demands (bottom to top), ranging across data 'DT', electrical ‘EL’, mechanical ‘ME’, heat removal ‘HE’, hydraulics ‘HY’, trim and ballast ‘TB’, high-pressure, and low-pressure air systems ‘HP’ & ‘LP’. Table 6 provides the colour coding for network arcs for the various DS3 technologies.

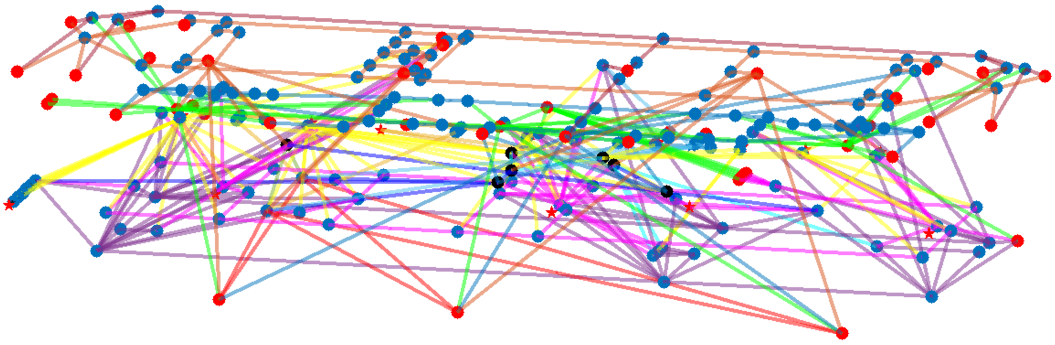


Figure 10: Multiplex 3D network of the overall DS3 for submarine case study showing each layer for a specific type of DS3, see Table 6 for the description of the colour coding used for different arcs for various DS3 technologies and see Mukti (2022) for the description of the colour coding used for different nodes

Table 6: Colour coding and description of arcs for various DS3

No	Service Commodity	DS3 Name	Colour Coding
1	Fuel oil	FO	🟥
2	Electrics	EL	🟪
3	Data	DT	🟪
4	Mechanical	ME	⬛
5	Trim and ballast SW (cooling)	SW TB	🟦
6	High pressure air	HP	🟧
7	Low pressure air	LP	🟥
8	Hydraulics	HY	🟩
9	Air intake	HVIN	🟦
10	Air heat	HVHE	🟨
11	Air exhaust	HVEX	🟧
12	Chilled water	CW	🟦
13	Lubricant oil	LO	🟩
14	Freshwater (cooling)	FW	🟦

5.3 INITIAL DS3 ROUTING

Once the DS3 logical network was firm, the indication of the overall DS3 network logic in Figure 11 could also be translated into physical definition rapidly by the new programs (Table 2) as part of the second step of the Physical Loop method (Figure 8). This was done by first assigning the DS3 components to the volume blocks, as shown in Figure 9. As this step occurred before the network-based sizing, some simplifications in the inputs for the Component Granularity Program (CGP) and the System Connection Program (SCP) were made just for the visualisation, enabling the designer to simultaneously develop the DS3 design both physically and logically. Firstly, the program was set to employ point to point, which meant the 468 connections overlapped each other. Secondly, the size of all connections was adjusted so they can be reasonably visible in the 3D model. Thirdly, the 231 DS3 components were assigned at the centroid of each object’s volume, which are modelled as simple spheres. These simplifications resulting in a visualisation of all 14 DS3 routings are given in Figure 11.

Beyond the second step of the Physical Loop method of Figure 8, the mathematical models for the SUBFLOW could be defined in the Component Granularity Program (CGP). This consisted of three categories of input: the type of nodes; the (Sankey) energy coefficient input of each DS3 component; and the calculation of power demand of user components. Therefore, if there were 230 components, as in this submarine case study, this meant a total of 690 additional inputs for the SUBFLOW on top of the (181) weight data to be defined in the second step of the Logical Loop method.

Before the power information from SUBFLOW could be translated into DS3 space and weight input for ESSD, the power to volume and weight ratios of each node needed to be derived. The derivation of these ratios also requires an understanding of what information that node represented in the design. As discussed in Section 4.1, only nodes that were marked as 'DB' could be translated into space and weight input. However, some 'DB' nodes were modelled to aid the DS3 routing and thus may not have sufficiently consequential spatial geometry, such as DB nodes representing valves in the air intake or exhaust system.

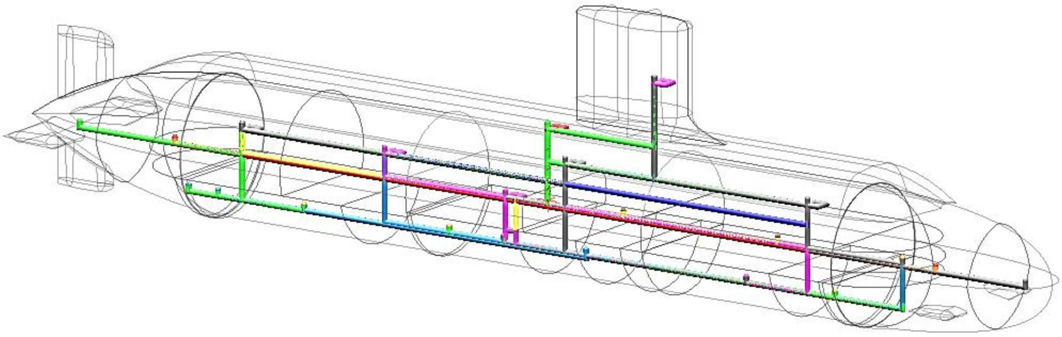


Figure 11: Initial routing in the second step of the Physical Loop method (Figure 8) showing DS3 components situated at the centre of each volume space, which had been defined using Component Granularity Program (CGP), System Preamble Program (SPP), and System Connection Program (SCP) (Table 2)

In the third step of the Physical Loop method of Figure 8, a more refined Paramarine model was produced to demonstrate the applicability of the NBA in terms of physical routing. As shown in Figure 12, this was done using the graphical interface in Paramarine by arranging each DS3 component, compartment by compartment. Thus, 230 unique x, y, z locations for the DS3 components could be identified and stored in the Component Granularity Program (CGP). Furthermore, the appropriate system highways could be added as additional inputs to the existing 698 items of DS3 data in the System Connection Program (SCP).

5.4 REFINED DS3 ROUTING

The refined overall submarine model is given in Figure 13, showing gradual steps in manipulating DS3 components in the 3D layout. Starting from major components based on the FMFI breakdown as in Figure 13 (top), followed by the electrical 'EL', mechanical 'ME', and data 'DT' systems in Figure 13 (middle), and finally, the rest of the systems listed in Table 6 were arranged, as shown in Figure 13 (bottom).

There was a total of 170 hub nodes and 500 equality constraints in this case study. Such constraints could be generated automatically in the Logical Loop method to ensure the continuity in the SUBFLOW simulation. The network solutions produced using SUBFLOW showed the energy balance on the vessel has been achieved with a specific set of flow paths. This set is akin to the energy balance chart, which serves as an insight for the designer to understand how the energy flow comes in and out from the submarine. As arcs between systems in SUBFLOW were explicitly modelled, the energy transfer between systems could be observed visually

Furthermore, the NBA allowed the designer to evaluate and manually justify the size of each node and arc in the input data centre (Figure 4). This means the designer could add, duplicate, or increase the power calculated by the network and this implies that any optimisation technique used in this approach would not directly constrain the size of the DS3. For example, arcs for the fuel forward are zero because the "optimisation" only chooses the fuel aft node to supply the energy to the diesel nodes. This is not necessarily always true because the forward fuel node could be used when there is no available fuel left from the fuel aft tank. However, the power information at the fuel aft arcs represents the maximum power flow when a fuel tank is used. Therefore, the designer could use this information for sizing the fuel aft arcs in the System Connection Program (SCP).

5.5 WEIGHT AND SPACE SIZING RESULTS

The DS3 weight inputs for this case study calculated using the network approach are compared to the fictitious yet not unrealistic submarine design data in Table A1. In summary, the network could be used to give about 50 weight and space inputs to the design. However, there was no available data to compare individual volume results and thus only weight was compared in the study.

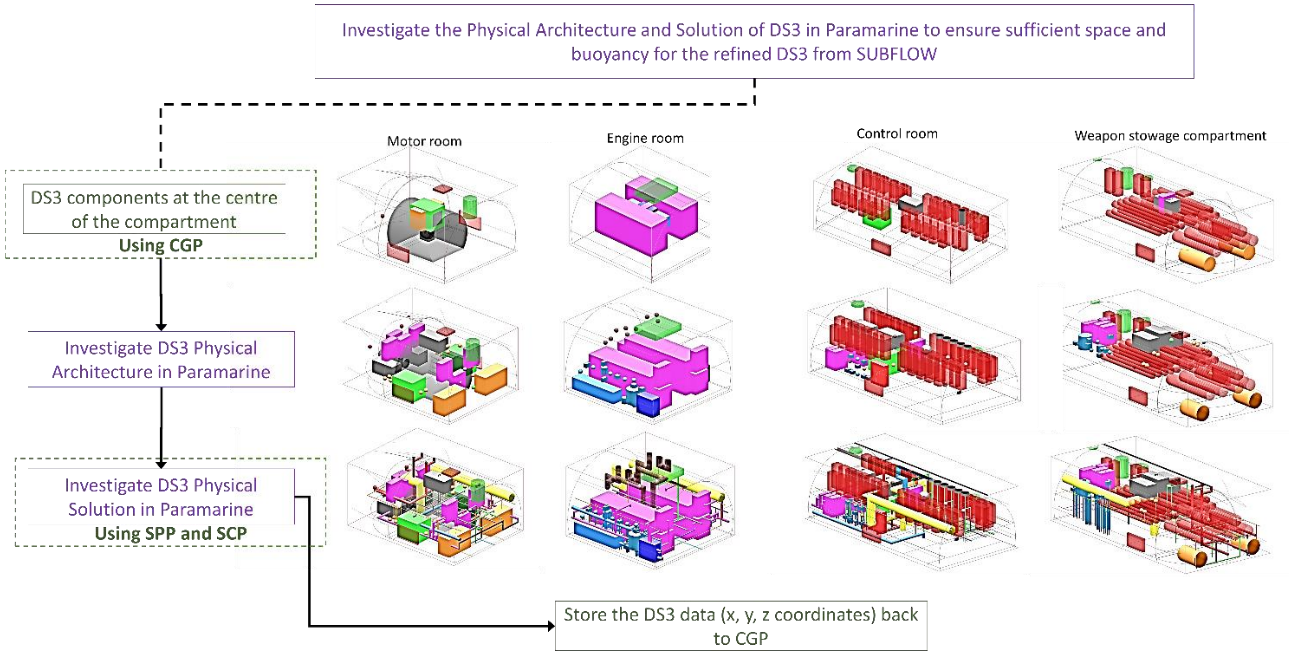


Figure 12: The schematic of performing 3D layout arrangement of DS3 at ESSD fine stage, showing gradual step by step arrangement of procedure compartment by compartment using the Component Granularity Program (CGP), the System Preamble Program (SPP), and the System Connection Program (SCP)

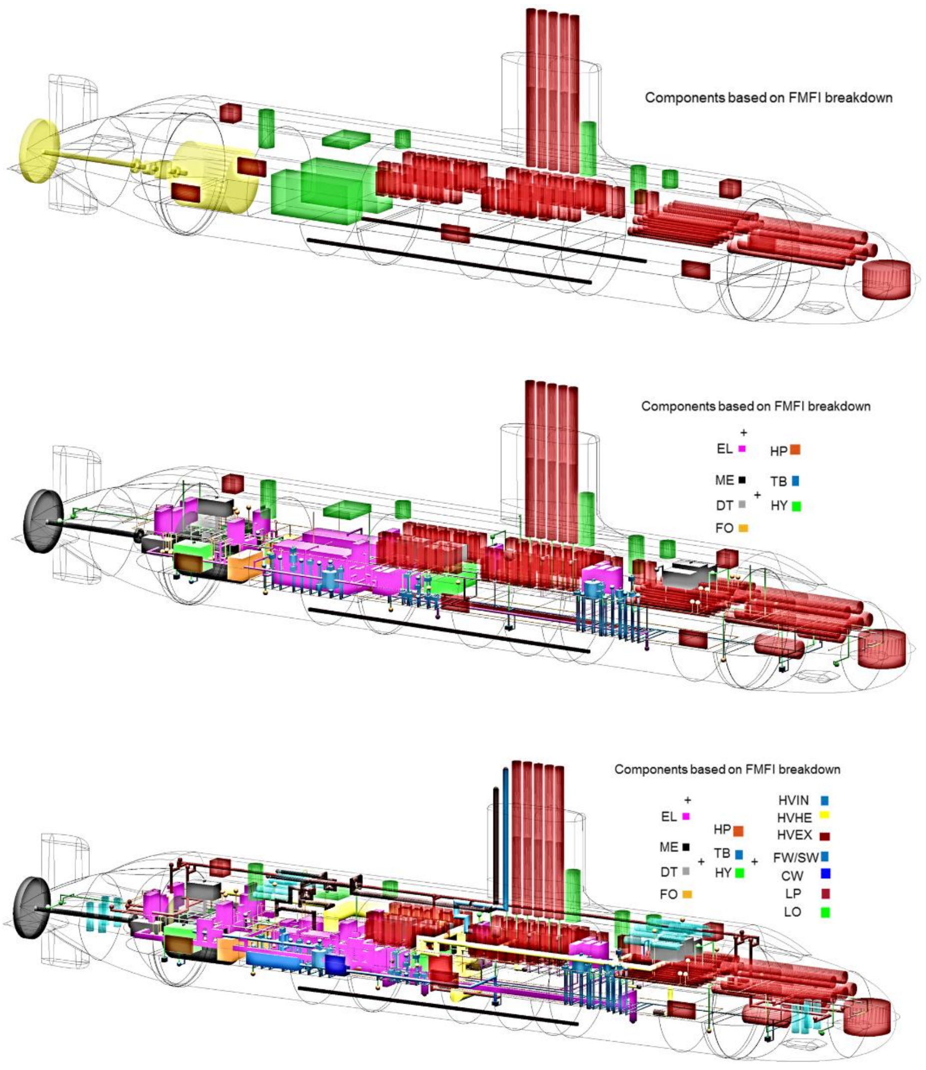


Figure 13: Refined DS3 model in the third step of the Physical Loop method showing the progress of placing DS3 system by system in the 3D layout. There were 365 design building block objects at component granularity and 472 design building block objects at connection granularity level. The latter shows 14 DS3 top level routings

The Weight Group 2 classification system used at UCL-NAME mostly contains the mechanical ‘ME’ system. Since the power to weight ratio for these components was derived from the UCL submarine data (UCL-NAME 2014), the difference between the NBA/SUBFLOW sizing and the data should have been small. Initially, there were no significant differences except for the main batteries and the propulsion motor, which were about 5% different from the Weight Group 2 data. The difference in the size of the batteries was due to the energy losses modelled in the overall DS3 network for the submarine case study that then demanded a slightly higher power source to account for these losses. After introducing a numerical node to allow the heat to escape into the environment, the difference was reduced to 0.7%. Meanwhile, although the electrical ‘EL’ system in the network used more recent components, such as the Power Converter (PC) or bus nodes (ND), the overall weight of the electrical system in the Weight Group 3 shows a relatively good agreement with the UCL 2500 data in that it only differed by some 4.8%. For Weight Group 4, the power to weight ratio data for the payload equipment was developed from the UCL submarine design data and thus there was also no significant difference from that for Weight Group 2 (~3 tonnes). Although in percentage terms, the difference was likely to be higher, at 9.3 %.

Essentially, the majority of DS3 components are likely to be in Weight Group 5 where it was found that the results from network sizing was lower than the UCL submarine data by 20.7% or 15 tonnes. This was presumably due in some degree to many detailed ‘DB’ nodes, such as valves and junctions that had not been modelled explicitly in the network case. However, another reason might be the style decision of each DS3 in the submarine case study not exactly matching the style decision made in the fictitious UCL 2500 submarine design. It would be possible to reduce the difference by increasing the design margins of each DS3 in the relevant programs, where these were initially assumed to be about 20% each.

Although the size of the fuel tanks could be determined by simple numerical calculation, the fuel nodes could be used to refine the size of the fuel tanks. The derivation of the power to volume of the fuel nodes required more input, such as the specific fuel consumption (SFC) and fuel weight density. A similar reason seemed to arise in the electrical ‘EL’ system size, where the difference in Weight Group 9 was about 7.1%. Overall, the difference in the weight between UCL 2500 data (UCL-NAME 2014) and the network sizing based SSK was only 18 tonnes or less than 1% overall submerged displacement. As discussed above, the major contributor to such difference was Weight Group 5.

6. CRITIQUE OF THE NETWORK BLOCK APPROACH APPLIED TO A SUBMARINE STUDY

It might be argued that a parametric coefficient for disparate DS3 styles could be sufficient for a quick estimation in ESSD. For example, a ring main electrical system might have an additional factor relative to the existing scaling algorithm. However, the DS3 style influencing the selection of relevant design algorithms and that various DS3 can be significantly different from submarine type to submarine type. Thus, it was concluded that a few design parameters would not be able to capture the complexity and interrelated interactions between various DS3.

As already discussed in Section 3, the 3D based synthesis was reduced to be what is called ‘2.5D’ to allow a simpler architecturally oriented design tool and more sophisticated network analyses. However, a 2.5D design tool has to sacrifice many advantages from using a 3D based synthesis. This then raised the question as to whether a submarine design approach needs to be 3D based and what might be the advantages identified of using such a 3D based synthesis in concept design?

Given the case study, more specifically, Figure 13, submarine DS3 arrangement and physical routing are reasonably complex. Thus, any 2.5D design tool will be unlikely to be able to capture overlapping DS3 routing due to different highways being on the same deck. Furthermore, the physical interactions of DS3 components are going to be scattered in a 3D space within a compartment and, without a 3D representation, consideration of accessibility to those DS3 in the confines of a crowded compartment would be hard to address. The identification of such 3D related issues early in the design process would help ensure the selected DS3 design could be integrated into the submarine design beyond compartment or packing densities assumptions (such as (Purton 2016)) that need to be based on previous designs. Furthermore, given the advances in computer graphics, not utilising such technology to create a 3D based synthesis was seen to be not taking advantage of CAD developments. The issue is seen rather to be how to make the 3D based synthesis execution process as simple as possible so that the designer can readily be able to manipulate the 3D architecture of the vessel and focus on important architecturally driven decision making in ESSD.

As the proposed approach could facilitate an improved quality of the 3D based DS3 synthesis, this then raised a question as to whether such detail is needed at the concept. The submarine concept is unlikely to go into such detail every time, but this research has demonstrated the potential advantages and shown that such detail could be done in the Concept Phase using the proposed approach. This would particularly be the case if there is seen to be a need to investigate uncertainty in DS3 synthesis, such as the adoption of new DS3 technology or totally different overall submarine DS3 style configuration where simple algorithms with a small set of submarine parameters would be suspect.

Given the naval vessel is the “engineering’s greatest compromise” (Purvis (1974), the SUBFLOW outlined in Section 4 was not used to optimise the submarine design nor the various DS3 designs. Pursuing all possible scenarios applicable to a complex vessel into a set of optimisation setups in ESSD was seen to be prohibitive and highly questionable (Andrews 2018), especially, since the impact of many unknowns only arises once designs have been worked up into more detail in subsequent design phases. Thus, SUBFLOW was used for simulating the energy balance on the submarine. This also demonstrated that the proposed approach employed network analysis as little as possible, commensurate with the needs of Requirement Elucidation. Further complicated network optimisation analysis was seen as inappropriate to be applied in ESSD.

As discussed in Subsection 4.2, the development of each DS3 required an understanding of the individual DS3 technology and thus it was found that not all submarine DS3 could be sized solely using energy flow. For example, the derivation of power to weight and volume ratio for the part of the heat removal systems requiring heat exchangers must include the consideration of Deep Diving System Test Pressure (DDSTP), as they would have to be tested to such pressure. Similarly, one of the drivers for the emergency blow system part of the 'HP' system and the 'hard' trim and ballast 'TB' systems was the DDSTP requirement rather than energy flow. Another example was that the power to weight and volume ratio for hydraulic system connection was derived based on a triple redundancy style as well as the required capacity to provide actuation of various DS3 components on the submarine. A further energy-based formulation of such submarine specific systems was considered to have made the formulation of SUBFLOW too complicated to be applied in ESSD, given the aim was to provide an improved sizing in a practical time manner. Therefore, it was concluded that the energy-based sizing was only applicable to components that require power 'EL' to operate and thus other remaining DS3 could be sized directly from deriving relevant weight or volume to DS3 length assumptions.

Despite the limitation of the energy flow-based sizing, the use of a logical network in SUBFLOW was found to assist the designer to facilitate the development of DS3 design *ab initio*. This was demonstrated in the submarine case study where modelling trim and ballast 'TB' system directly in Paramarine was seen to be questionable, given the complexity of piping due to the incorporation of the chosen unidirectional pumps. This meant the DS3 synthesis approach required consideration beyond physical models or the DS3 physical architecture. SUBFLOW was also found to guide the designer to size DS3 by calculating the weight and space of DS3 components and connections that should be best reflected in the SUBFLOW network. Still, to accommodate uncertainty, margins could be used in the Network Block Approach, specifically in the Component Granularity Program (CGP) and the System Connection Program (SCP).

7. CONCLUSIONS ON THE NETWORK BLOCK APPROACH

It was considered that none of the existing approaches was able to achieve an integrated DS3 synthesis that works well across different architectures, and specifically, address both physical and logical architectures (Brefort et al. 2018).

The sophisticated 3D based synthesis that the UCL DBB approach provides (Andrews 2018), when using the SURFCON module in the Paramarine CASD system, enables the designer to model DS3 physical architecture to whatever level of detail is deemed necessary. However, it was found to be limited in capturing the overall set of DS3 logical architectures. In contrast, most of the current network theory applications to surface ship distributed systems, including the AFO and its variants (Parsons et al. 2020), are focused on performing optimisation while keeping the DS3 physical architecture as simple as possible (2.5D).

The novel Network Block approach in this paper is seen to close the gap, by combining the advantages of the 3D physical based synthesis of the UCL DBB approach with the network based AFO type synthesis for DS3 when applied to the demanding complexity of submarine DS3 design. If the designer wants to integrate a potentially different DS3 style into a submarine design or new DS3 technology into the new design, the Network Block Approach (NBA) is considered to provide a means of assessing the impact of a new style in submarine ESD. It must be emphasised that the NBA is only a guide to a first estimate of vital DS3, but it is clearly a help to have a starting point that is more reliable than the parametric approach. Having demonstrated the application of the Network Block Approach (NBA) to a generic and very conventional SSK study, it was necessary to undertake DS3 sensitivity analyses exploiting the NBA capability. This will be presented in future papers.

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APPENDIX A

Table A1: Weight results for the 2500 data vs Network Block Approach via SUBFLOW

Weight Group	Item	Network Name	2500 Data (te)	NBA/SUBFLOW Sizing (te)
2	Shafting	(SCP)_ME	7.4	7.4
	Thrust block	ME_TT_BK	3.2	3.1
	Stern seal	ME_ST_SL	1.8	1.7
	Propeller, rope guard & cone	ME_PR_NE	7.2	8
	Main motor	ME_PM_DC	83	84.9
	Propulsion switchgear	EL_SG_PM	4.5	6
	Main batteries	EL_SE_BD	269	263
	Machinery Control & Console (MCC)	DT_MC_DC	3.3	3.3
	Total WG 2 Classification		379.4	376.6
3	Cabling	(SCP)_EL	19.5	10
		(SCP)_DT		3.7
	140 kW 60 Hz motor generators	EL_PC_(ALL)	10.7	6
	1.4 MW diesel generators	EL_PG_DG	37.9	43.4
	DG lubricant oil system	(SCP)_LO	1.5	0.1
		LO_PT_HX		1.3
	DG fuel oil system	(SCP)_FO	1.1	0.1
	Diesel exhaust system	(SCP)_HVEX	12.6	4
	Main battery breakers	EL_PD_(ALL) EL_ND_(ALL)	3	11 7.9
	Distribution equipment 440 V 60 Hz		1.1	
	Distribution equipment 115 V 60 Hz		2.3	
	Distribution equipment 200/115 V 400 Hz		0.1	
	Distribution equipment main DC		1	
	Distribution equipment 24 V DC		1	
	Total WG 3 Classification		91.8	87.5
4	Periscopes	DT_SA_DC	4	2.2
		DT_AK_DC		1.9
	Ship Control Console (SCC)	DT_SC_DC	0.8	0.8
	Miscellaneous control & instrumentation	DT_DD_(ALL)	2	1.8
	Wireless mast & hoist	DT_CN_DC	1.5	1.5
	Radar mast and hoist	DT_RA_DC	2.5	2.5
	EW mast and hoist	DT_EW_DC	2.7	2.7
	Main passive sonar dome	DT_SO_DC	3.6	4
	Sonar processing & display	DT_CO_AC	7.5	5.2
	Data handling computer & display	DT_PU_AC	3.5	3
	Total WG 4 Classification		28.1	25.6
5	Snort induction system	(SCP)_HVIN	4.2	1.1
	Ventilation trunking	(SCP)_HVHE	3.5	1.6
	Ventilation fans control	HV_HE_(ALL)	1.3	7.9
	Vent valves and filters		1.3	
	Vent heaters		0.1	
	Chilled Water (CW) plants	(SCP)_CW	5.1	0.5
		CW_PT_HX		1.6
	Chilled Water (CW) system	(SCP)_SW	3	11
	Ships Saltwater (SW) cooling system	FW_SW_HX	12.3	2.8
	Trim, bilge & ballast system	(SCP)_TB	8.8	3.7
		TB_VV		4.8
	Trim pumps & starter	TB_P (ALL)	0.4	2.5
	HP bilge pump & starter		1.5	
	LP bilge pump & starter		0.2	
	HP ballast pump & starter		1.5	
	Ships Fresh Water (FW) cooling system	(SCP)_FW	2.9	2.2
	HP air compressors	HP_CM_(ALL)	5	5.4
	HP air system	(SCP)_HP	3.9	0.6
	Direct blow system		2.1	
	Auxiliary vent & blow system		3.6	
	LP blower	LP_BR_(ALL)	1.8	2
	LP blow system	(SCP)_LP	4	3.4
	Main hydraulic system	(SCP)_HY	4.5	4.7
	External hydraulic system		2.3	
	Steering & hydroplane control system		1.4	
	Steering & diving hydraulic plant	HY_(ALL)	2.8	10
	Main hydraulic plant		1.6	
	External hydraulic plant		1.5	
	Total WG 5 Classification		80.6	65.8