DISTRIBUTED SHIP SERVICE SYSTEMS ARCHITECTURE IN THE EARLY STAGES OF DESIGNING PHYSICALLY LARGE AND COMPLEX VESSELS: THE SUBMARINE CASE

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SUMMARY

In the initial sizing of complex vessels, where recourse to type ship design can be 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 Systems (DS3), which include different types of commodity services beyond those primarily associated with the ship propulsion system. In general, naval vessels are typified by extensive and densely engineered DS3, with the modern naval submarine being at the extreme of dense outfitting. Despite this, the ability for the concept designer to consider the impact of different configurations for the DS3 arrangements has not been readily addressed in concept design. This paper describes ongoing work at University College London (UCL) to develop a novel DS3 synthesis approach utilising computer tools, such as Paramarine™, MATLAB®, and CPLEX®, which provide the concept designer with a quantitative network-based evaluation to enable DS3 space and weight inputs early in the design process. The results of applying the approach to a conventional submarine case study indicate quantitative insights into early DS3 sizing can be obtained. The paper concludes with likely developments in concluding the research study.

NOMENCLATURE

[Acronym]	[Definition]
AC/DC	Alternating/Direct Current
AFO	Architecture Flow Optimisation
ASW	Anti-Submarine Warfare
BB	Building Block
DAFO	Dynamic Architecture Flow Optimisation
DBB	Design Building Block
DfDS	Design for Distributed Systems
DRC	Design Research Centre
DS3	Distributed Ship Service System
ESD/ESSD	Early Stage Design / Ship Design
GRC	Graphic Research Corporation
HVAC	Heating, Ventilation, and Air Conditioning
ISR	Intelligence Surveillance and Reconnaissance
MILP	Mixed-Integer Linear Programming
NFO	Network Flow Optimisation
NSMCF	Non-Simultaneous Multi-Commodity Flow
NSMCPCF	Non-Simultaneous Multi-Constraint Parallel-Commodity Flow
NICOP	Naval International Cooperative Opportunities Project
PG	Power Generator
PG-1-ap	PG 1 aft port
PG-2-as	PG 2 aft starboard
PG-3-fp	PG 3 forward port
PG-4-fs	PG 4 forward starboard
PM aft/fwd	Propulsion Motor aft/forward
PPS	Power and Propulsion System
SDB	Subdivision Block
SED aft/fwd	Stored Energy Device aft/forward
SUBFLOW	Submarine Flow Optimisation
VAVO	Vulnerability Architecture Flow Optimisation

1. INTRODUCTION

In the practice of engineering design, Andrews (2010) has pointed out the importance of the fact that the naval vessel is not just a complex system but also physically large. This is supported by Figure 1, taken from National Shipbuilding Research Program/American Shipbuilding Enterprise (NSRP/ASE), that shows the number of parts constituting a naval vessel (in this case a submarine) can be much larger than other complex products produced by other industries. Thus, such Physically Large and Complex Product (PL&C) require many person-hours to build (Andrews, 2011a). Furthermore, the complexity of a naval vessel is compounded by the fact that the shipbuilders must perform concurrent detailed design, constructions, and equipment procurement (Morais et al., 2018) without first producing prototypes. This can also be the case with large civil and chemical plant construction.

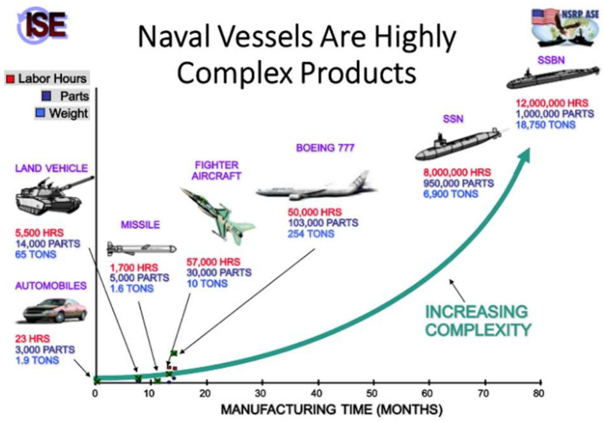


Figure 1: Naval vessels are highly complex products (Morais et al., 2018)

Naval vessels, being at the top end of the range of complex service vessels, are typified by extensive and densely engineered Distributed Ship Service Systems (DS3). DS3 is defined by authors as a collection of connected components that provide a service (commodity such as power, fluid liquid or gas) from one or multiple sources to multiple users, via a physical connection (cabling, trunking, or pipework) throughout the ship, directed towards defined functions, supporting specific operations of the vessel. The quality standards for the distributed systems of submarine are akin to those required in high performance aircraft, yet on a physically larger scale and without the advantages of several full-scale prototypes (Andrews, 2017).

The significance of the submarine's DS3 suggests a major design question. When should DS3 aspects, such as redundancy, be addressed in the overall submarine design process? Despite DS3's pivotal role in enabling the operations of the vessel to work in a hostile environment between the surface and deeply submerged, in initial sizing and ship synthesis reliance is often made on "past practice" and simple vessel displacement-based weight algorithms. This inhibits the ability of the concept designer to consider the impact of different configurations for the DS3 arrangements in Early Stage Ship Design (ESSD). This is despite the fact that the ESSD is the critical phase where decision-making has greatest impact, while the greatest uncertainty arises and minimal information is available (Andrews, 2018). Assessing whether there is sufficient redundancy needs to be addressed at this stage to avoid infeasible or overly redundant DS3 design as the design is subsequently worked up. In response to this, a new DS3 synthesis method ought to be developed if DS3 aspects are to be better addressed in ESSD.

The paper begins with a brief discussion on early-stage submarine design and DS3 issues, followed by the problem statement. After that the description of ongoing work at University College London (UCL) Design Research Centre (DRC) tackling the problem is outlined. The proposed method is then applied to a case study of a conventional submarine. This is followed by a discussion of that case study's results. Finally, conclusions are drawn and ongoing work is presented.

2. EARLY STAGE SUBMARINE DESIGN AND DS3 ISSUES

2.1 CURRENT EARLY STAGE SUBMARINE DESIGN

The approach to initial submarine synthesis used at UCL has been adopted from the sequential design procedure given by Burcher and Rydill (1994) (see Figure 2). The procedure begins with an initial set of broad requirements to initiate the process and after several steps a verification of weight and gross volume, giving a first balanced design, is produced. The work related to DS3 can be seen in the "Design System" step, which is conducted towards the end of this initial sizing process.

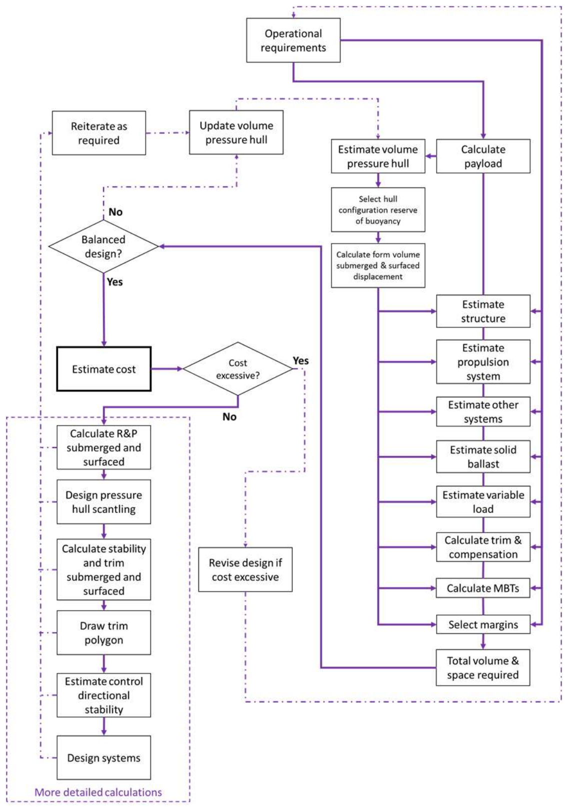


Figure 2: Traditional numerical initial synthesis for a submarine, with dash dotted lines indicating where there should be an iterative process (Burcher & Rydill, 1994)

The drawback with this traditional numerical approach is that it relies on historical based algorithms, which include implicit decisions on DS3 styles from previous selected designs. This is unable to capture different possible styles or configurations, including those for DS3. "Style" can be considered a major choice/selection in the overall design process that eventually drives the chosen solution(s) (Andrews, 2018). It was introduced by Brown and Andrews (1980) to identify those "other" aspects than the four classic naval architectural concerns in their "S^5" term for addressing the elements of naval architecture applied to ship design. Within overall style there is arrangement and part of that is the arrangement of the DS3, which itself has style decisions implicit in designing a submarine's DS3.

The limitation of the traditional numerical synthesis was addressed by Andrews, who, in the early 90s, modified his architecturally driven synthesis approach, by adopting, for the case of submarine synthesis, a functionally organised architectural description (i.e., FLOAT, MOVE, FIGHT and INFRASTRUCTURE) (Andrews et al., 1996). By focusing on the submarine's configuration, the initial hullform design and sizing incorporates the needs of the layout. This approach, known as the Design Building Block (DBB) approach, is a proven design method and was implemented as the SURFCON module (for both surface ships and submarines) in the commercial naval architectural Computer Aided Design (CAD) software, Graphic Research Corporation (GRC) – now Qinetiq – Paramarine™ (Andrews & Pawling, 2003).

The implementation of DBB in Paramarine™ (Pawling, 2007) is a top-down approach where one starts to develop a coarse model at high-level, with a few Super Building Blocks. As the design progresses, the ship model can be broken down into a more detailed definition. Other hierarchical organisation approaches exist in shipbuilding CAD/ Computer Aided Manufacturing (CAM), such as zones, modules, assembly, components, or parts, but to organise them in this distinctly functional manner is a particular feature of the UCL DBB approach. As it is designer driven, DBB is not a black box approach so it requires decisions by the designer. This makes it suitable for investigating specific aspects of submarine design like DS3.

The Design for Distributed Systems (DfDS) may be facilitated by the use of DBB approach. However, using the DBB approach alone was seen to be insufficient to develop a sufficiently workable DS3 synthesis approach. Thus, other related work on DS3, enabling quantitative measurement is discussed next.

2.2 RELATED DS3 RESEARCH

As summarised in the IMDC state of the art report on design methodology (Andrews et al., 2018), there are other projects relevant to DS3. One of them is the Electric Ship Research and Development Consortium (ESRDC) funded by the US Navy (ONR-ESRDC, 2018). This focused on future electric warships using high-energy weapons (Chalfant et al., 2017a) and has developed a collaborative analysis tool called Smart Ship Systems Design (S3D) (Smart et al., 2017) which enables specialist engineers to be involved much earlier in the design (Langland et al., 2015). However, the jump in design detail remains an issue as Andrews (2018) strongly argues, one should not get into excessive detail in ESSD as the objective is requirement.

The Naval International Cooperative Opportunities Project (NICOP), funded by the US Navy Office of Naval Research, involves the University of Michigan, TU Delft, Virginia Tech and UCL in a five-year collaborative research project started in 2015, has produced an architectural framework for DS3 (Brefort et al., 2018). This has postulated three types of architecture:

- Physical architecture giving DS3 volumes and locations, i.e. the actual definition of the system in the vessel's design layout. For DS3 it highlights the interaction of distributed systems with the spatial definition;
- Logical architecture defines the topology of the system, how the various DS3 work on ships, for example, a system line diagram or system topology. The interaction between systems is depicted by this architecture;
- Operational architecture focuses on the interaction between the human and the system over time in a specific operational scenario.

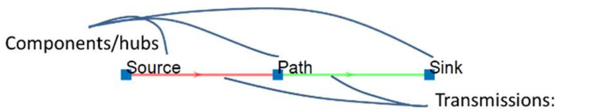
Nevertheless, there is an issue related to this framework, namely as to whether the physical architecture is that which constrains the DS3, through the architecture of the whole ship or is just describing the physical architecture of DS3 being dependant on the ship's architecture (Brefort et al., 2018).

2.3 THE USE OF NETWORK THEORY IN THE DS3 RESEARCH

Network or graph theory has been used in the related NICOP research on distributed systems. Generally, the implementation of networks in the DfDS research has been represented by the elements of DS3 within network components, as illustrated in Figure 3. There are three different types of nodes:

- Source, such as power generator;
- Path or distribution node, such as hub component (switchboard or junction);
- Sink, such as propulsion motor.

A network edge can represent the physical connection between DS3 components. As stated earlier, there are three different technologies based on types of commodities or services transported: cabling, trunking/HVAC, and pipework. It can be seen that a simple directed network can be modelled through a 3 × 3 adjacency matrix form, which enables many possible quantitative network analyses to be undertaken using numerical software, such as MATLAB® (MATLAB, 2019a).



Adjacency Matrix

	Source	Path	Sink
Source	0	1	0
Path	0	0	1
Sink	0	0	0

Figure 3: A simple illustration in modelling distributed systems as a directed network

An example of the use of network theory for exploring a range of system topologies was produced by de Vos and Stapersma (2018). Their approach utilises a genetic algorithm (GA) (Deb et al., 2002) with two opposing objective functions: demand of weight, and space requirements, costs and operability (which they call the "system claim") against robustness. Robustness is defined as "*The ability of energy distribution systems on board of (war)ships to withstand perturbations in system operation*" (de Vos & Stapersma, 2018). By improving the robustness of distributed systems, the safety of the submarine would be enhanced. Early stage routing for vulnerability reduction has been addressed by this team, (Duchateau et al., 2018).

The network flow programming approach, known as the Network Flow Optimisation (NFO) approach, combining networks and linear programming, has been implemented in many disciplines seeking solutions based on objective functions and multiple constraints (Bradley et al., 1977; Chinneck, 2018). Trapp produced a first attempt at using NFO via Mixed-Integer Linear Programming (MILP) to model shipboard Integrated Engineering Plant, which he called Non-Simultaneous Multi-Commodity Flow (NSMCF) (Trapp, 2015). This work was followed by the development of Non-Simultaneous Multi-Constraint Parallel-Commodity Flow (NSMCPCF) or Architecture Flow Optimisation (AFO) (Chalfant et al., 2017b). Since then, AFO has been significantly improved for surface ship application by Parsons et al. (2020b). This enhancement of the AFO includes the development of the operational architecture in the Dynamic Architecture Flow Optimisation (DAFO) (Shane 2021a) and the surface ship vulnerability assessment using Vulnerability Architecture Flow Optimisation (VAVO) (Parsons, et al., 2020c).

Nevertheless, none of these studies considered the synthesis of the DS3 using an architecturally-centred approach. The component arrangements were achieved assuming multiple equipment located at the centre of a geometric compartment (Duchateau et al., 2018), such as subdivision blocks (SDBs) (Robinson, 2018), and hence the arranged equipment 'overlap' each other. In addition, these studies focused on minimising cost as the main objective function. Since submarine design is different to ship design (Andrews, 2017) and, furthermore, while the safety of a submarine is of utmost importance, additional space in the pressure hull is more costly to add than in surface vessels due to the necessity of neutral buoyancy. So, considering the needs for, say, more cable redundancy meant the NICOP approach was not seen to be directly applicable and so further development was considered.

The paper presents a new DS3 synthesis approach that facilitates exploring different style decisions for submarine DS3 architecture and provides a quantitative evaluation approach as an input to an iterative requirement elucidation dialogue key to ESD (Andrews, 2011b).

3. PROPOSED DS3 SYNTHESIS METHOD

A proposed DS3 synthesis approach is shown in Figure 4. The explanation of each step is given in the following sub-sections.

3.1 DEFINING THE PROBLEM

3.1 (a) Decision-Making Process of Complex Vessels

The first step in DS3 synthesis is to determine the problem. This starts by defining a baseline submarine outline design as a case study. This requires determining major capabilities, conscious style decisions, and the initial synthesis of a submarine design solution, namely an initial concept level balanced design.

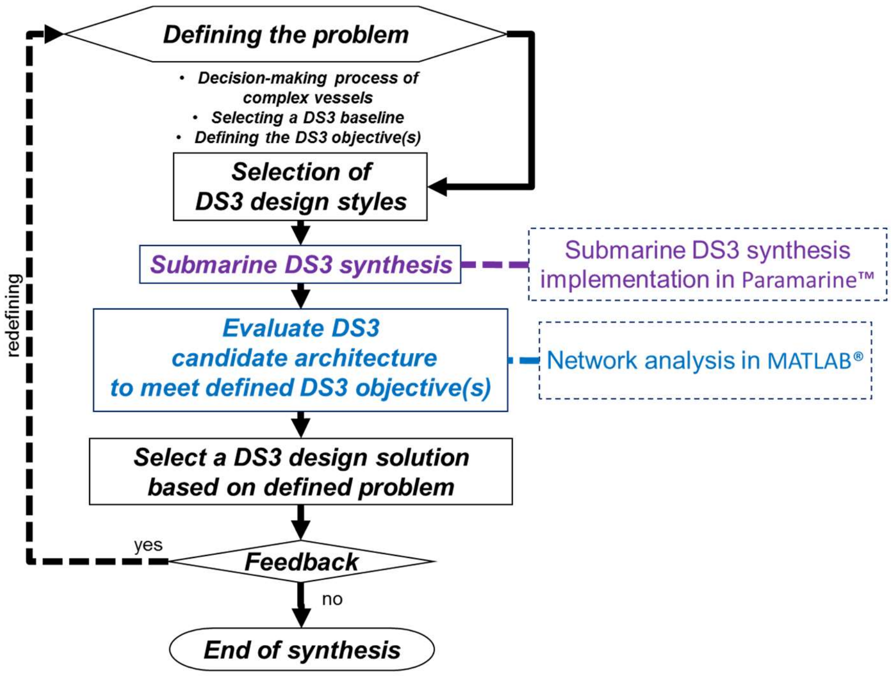


Figure 4: An overview of the proposed submarine DS3 synthesis approach - dashed line showing an iterative process where different colours indicate different tools used in the proposed approach (purple for Paramarine^{TM} and blue for MATLAB®)

The synthesis should follow the ESSD process for complex vessel seen to be part of requirement elucidation (Andrews, 2018). Thus:

- Choose outline capability and style (e.g., speed, depth, weapon, complement, endurance submerged/surface) + SSK Style;
- Choose design method (i.e., Figure 2 + DBB approach);
- Check sufficient balance in weight, space, buoyancy, stability and powering.

3.1 (b) Select DS3 baseline and Define the DS3 Objective

Next the designer determines the baseline and goals for the DS3 synthesis. These should emerge from the requirement elucidation intent. If the space required for DS3 is better estimated using the DBB approach (rather than using simple displacement-based algorithm), this enables the designer to consider some crucial design style issues in submarine ESD, especially submarine designs with significant changes of DS3 style or DS3 technology.

Therefore, from the range of DS3 on a submarine, one DS3 was selected for this synthesis. Given three distinct technologies of DS3 carrying different types of commodities, each of which have clear features (Section 2.3), electric power was selected for the evaluation step.

3.2 SELECTION OF STYLE FOR DS3

The proposed major style decisions specific to the electric power case study can be categorised as follows:

- The types of the architecture: for example, Medium Voltage DC (MVDC) architecture or AC-DC architecture for power systems;
- The physical configuration of the architecture: for example, single bus, dual bus, or a ring system;
- The redundancy of DS3 elements which could improve system robustness (de Vos & Stapersma, 2018), i.e.:
  - Components: extent of sources or sinks;
  - Connections: extent of physical connections.

3.3 SUBMARINE DS3 SYNTHESIS

Once the style aspects for DS3 had been decided, a low-level balanced submarine design layout was then developed concurrently with the selected DS3 to be synthesised (see Figure A1 in Appendix A). This ensured the selected DS3 design style was feasible within the submarine design. The system's top-level requirements (such as capacity, which is driven by the submarine's architecture and configuration) were defined. Thus, the process of DS3 synthesis can be summarised as follows:

- The definition of physical DS3 arrangements constrained by the submarine's architecture;
- The implementation of the selected configurational style for DS3, including major physical components (including redundancy) and physical connections (routing, i.e., the definition of the main highway or system runs).

3.4 EVALUATE CANDIDATE ARCHITECTURE

Up until this point, the concept designer could not be sure the synthesised DS3 architecture has met minimum levels of safety and utilised space within the hull envelope efficiently. Therefore, a structured quantitative DS3 evaluation needed to be developed.

As discussed in Section (2.3), AFO was seen to be attractive because it only tracks energy flow instead of tracking various commodities in the network flow. This simplification allows the inclusion of the total vessel, all systems (~500 DS3 components and ~1200 connections) in a large and complex naval surface combatant (Parsons, et al., 2020a). However, this is not possible without recourse to a significant machinery equipment list i.e., equipment database and Network Plexus (Parsons, et al., 2020c). These are defined as a list of system components of a distributed system and the relationship between them, which can be represented as a network. Thus, a list of components is connected in a 'MECH' plex system to disperse energy from propulsion motor to the propulsion demand in a standard operating condition (Parsons, et al., 2020a).

However, the physical architecture of these plexus is kept as simple as possible until post-AFO (Robinson, 2018). This assumes the initial equipment arrangement of the plexus is at the centre of a geometric compartment SDB (multiple equipment can be located in the same location). Such simplification allows AFO to be performed promptly without the need for 3D modelling as in the DBB implementation in Paramarine™. The volume of systems is then sized post-AFO, as outlined by Stinson (2019).

Accordingly, NSMCF with M-1 survivability by Trapp (2015) is seen to be more appropriate to be adopted with the 3D DBB approach in this evaluation step than AFO with its SDB approach. M-1 survivability by Trapp (2015) guarantees the commodity demands in the network can be satisfied, although an arc is removed from the system for a given edge loss scenario. Thus, a new NFO formulation, referred to as 'Submarine Flow Optimisation' (SUBFLOW), was devised based on the NSMCF formulation with M-1 survivability (Trapp, 2015) and the AFO energy-based sizing (Robinson, 2018). The major differences between SUBFLOW and previous network flow programming research were seen to be:-

- The objective function in SUBFLOW was derived specifically to address the nature of the selected DS3 technology (see Section 3.1 (b) and Section 3.4 (b)), not just cost minimisation as in NSMCF (Trapp, 2015) and AFO (Parsons, et al., 2020a) as well as its

variants (DAVO (Shane 2021a) and VAVO (Parsons, et al., 2020c)).
- A commodity (power) specific to the selected DS3 (PPS) was explicitly tracked to allow direct cableway sizing (volume output) from the results of the DS3 evaluation step.
- Adoption of a disparate objective function, instead of using binary variables to quantify fixed cost as in the previous research, was used to enable the concept designer to classify different standards for the size of cableways in the DS3 evaluation step.
- The evaluation step in this proposed DS3 synthesis approach has fewer steps than the AFO Execution Process (Parsons, et al., 2020a). This was due to all analysis being done in a MATLAB® environment, allowing the concept designer to avoid the cumbersome process of rewriting code to an external programming language.
- DS3 synthesis, particularly the PPS, was extracted and defined from an architecturally-driven submarine synthesis approach. This physically based synthesis enabled the DS3 physical architecture to be better defined.

The proposed DS3 evaluation process outlined below consists of several stages: pre-processing network flow analysis; network flow analysis; and post processing network flow analysis.

3.4 (a) Pre-Processing Network Flow Analysis for Selected DS3 Architecture

The pre-processing of the network flow analysis consisted of several steps:

- Provide minimum information needed for performing network flow:
  - Location and amount of maximum commodity supply from all sources;
  - Location and amount of commodity demand to all users;
- Initial routing to connect system components to the main highway;
- Labelling nodes for all physical components, including junctions, and modelling the candidate DS3 architecture as a network. This was followed by representing the network in a mathematical form, through an adjacency matrix.

3.4 (b) Network Flow Analysis

After the pre-processing for the network flow, the network-flow problem formulation commenced:

- The information provided from the pre-processing step was read;
- The objective function and the constraints of the SUBFLOW was formulated.

3.4 (c) Post Processing to Select an Aggregate Solution

This process began by storing all the results in an array, say $r \times c$ matrix A. The aggregate volume was then calculated by extracting all maximum decision variable outputs from Matrix A.

3.5 SELECT A DS3 SOLUTION (FEEDBACK AS PART OF THE REQUIREMENT ELUCIDATION)

Once the aggregate volume had been calculated using the above evaluation process, the next step was to investigate the results on the overall emergent submarine design. The results should not be used in isolation, but rather to give insight into the DS3 part of the iterative input to overall submarine requirement elucidation process.

4. DEMONSTRATION OF APPROACH FOR NOTIONAL SUBMARINE

This section outlines the ongoing work on a selected baseline submarine and DS3 design problem, as a case study.

4.1 BACKGROUND ON THE OVERALL COMPLEX VESSEL DESIGN FOR NOTIONAL SSK

To give a better understanding of the proposed DS3 synthesis method, an initial test case was developed using a notional conventional submarine (SSK). An SSK was selected based on a previous study (Mukti & Randall, 2017). Nonetheless, the proposed approach could also be applied to designing a nuclear submarine (SSN).

In this exercise, the specification for the notional SSK was drawn on to form the baseline design’s broad specification requirements set for such capabilities as Intelligence Surveillance and Reconnaissance (ISR) and Anti-Submarine Warfare (ASW). Such decisions would be part of the ESSD process for complex vessels contributing to such vessels requirement elucidation (Andrews, 2018a). Table 1 details the sequence outlined in Figure 4 and the Appendix A of Andrews (2018a) in a similar manner to the surface combatant example in Figure 30 of that paper.

4.2 BACKGROUND OF THE SELECTION OF POWER AND PROPULSION SYSTEM (PPS) AS THE DS3 CASE STUDY

The next step was to select a DS3 baseline. The first demonstration of the proposed DS3 synthesis addressed the cabling that distributes the particular commodity throughout the submarine. One of the key critical systems on a submarine is the Power and Propulsion System (PPS). If the PPS fails, the consequence could be catastrophic. Thus, the commodity produced in and demanded from this system was considered as the most vital electrical power distributed on board the submarine.

PPS, as one of the critical systems on a submarine, should be addressed more explicitly than just using the traditional numerical algorithm. To accomplish this, the PPS with a specific style was selected as the baseline of the case study and evaluated using SUBFLOW.

Table 1: The decision-making process for the concept phase of the initial test-case

Process	Decision
Perceived need	A future conventional powered submarine (SSK)
Outline of initial requirements	ISR, ASW
Selection of style	Macro level: single hull with casing and fin Main level: robustness Micro level: style for DS3
Selection of major equipment and ops sub systems	Diesel-electric propulsion system
Selection of whole ship performance characteristics	S4 (Brown & Andrews, 1980) + M-1 survivability (Trapp, 2015) for DS3 (see Section 3.4 (b))
Selection of synthesis model type	Numerical synthesis (Burcher & Rydill, 1994) and DBB approach (Andrews et al., 1996) SUBFLOW approach (based on NSMCF (Trapp, 2015) and AFO (Parsons, et al., 2020a).
Selection of basis for decision making in initial synthesis	Design for distributed systems, i.e., based on SUBFLOW formulation

4.3 STYLE CHOICE FOR THE POWER AND PROPULSION SYSTEM CONFIGURATION

The style choice for the PPS in this case study is summarised:

- Propulsion type: as specified in Table 1, a diesel powered propulsion system was incorporated;
- Distribution style: as explained in Sections 2.3 and 3.2, in this case study a ring main configuration was selected to provide redundancy in cabling port-starboard and forward-aft;
- DS3 robustness: to improve robustness (Section 2.3 and 3.2), redundancy provided to the propulsion motor (PM), Power Generators (PGs), and PPS cabling;
- PPS architecture: DC configuration (Woud & Stapersma, 2002).

4.4 POWER AND PROPULSION SYSTEM SYNTHESIS CONCURRENTLY WITH THE NOTIONAL SSK DESIGN

Based on the process above, an initial balanced submarine concept design was developed concurrently with the DS3 synthesis and based on the UCL Submarine Design Procedure (UCL-NAME, 2012) and UCL Submarine Data Book (UCL-NAME, 2014) (see Table 2 and Figure 5).

Table 2: Initial SSK principal characteristics

Initial SSK Key Parameters Desired (Capabilities)	
Complement	46 (7 officers)
Electrical Generator	4 x 1.6 MW
Propulsion Motor Power	5000 SHP (3728 kW)
Max Speed	16 knots
Snorting Speed	7 knots
Diving Depth	250 m
Hull Material	HY-80
Range	1500 nm on diesel snorting
Deployment Endurance	45 Days
Armament	4 Torpedo Tubes
Weapons Loadout	20 Torpedoes
Initial Submarine Resultant Characteristics	
Surfaced Displacement	3500 te
Submerged Displacement	3980 te
Length	85.8 m
Beam	9.5 m

Figure 5 indicates an initially feasible PPS architecture. It consists of two Propulsion Motors (PMs), four Power

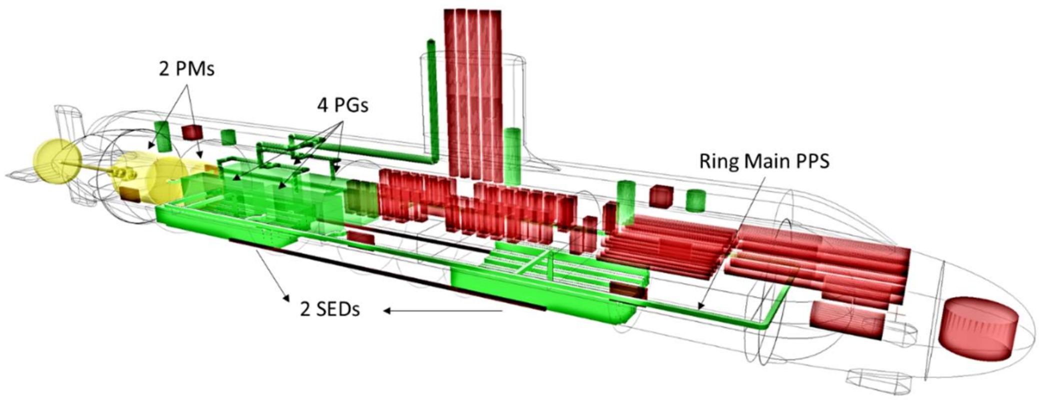


Figure 5: Initial SSK design using Paramarine™ showing PPS elements

Generators (PGs), and two Stored Energy Devices (SEDs)/batteries and a ring-main connection.

An actual PPS system would, however, include many more detailed components, such as switchboards or rather many more service load users with different voltages. The number of PPS components in this initial case-study was limited and was considered sufficient to demonstrate the essence of the applicability of the proposed DS3 synthesis method. However, the approach could be used to whatever level of detail deemed necessary for any particular set of DS3s at the concept level.

The early routing was attempted in this step using Paramarine™. However, it was found that the ability to show routing was limited. Paramarine™ could perform automatic routing as long as the route of the main system highway was provided and the location of the relevant system components known. It requires some detailed connection properties, such as the definition of the cabling shape and minimum bend radius. Paramarine™ then employs a shortest-path algorithm to connect the components via defined highways. However, the automatic routing algorithm ignores or violates others BB volumes, as shown in Figure 6 (circled in red).

Such routing clash can be avoided by adding more inputs to Paramarine™. However, it can be time consuming, labour-intensive, and the information required to generate the model (all complete locations of users, hub, and suppliers must be known) will not be available early in the design phase.

In the ESSD, the interest is more about estimating the size of the DS3 and the impact of selecting a certain DS3 option on the overall submarine design, since the design would still be fluid, as it would need to be if it is to influence the requirement elucidation dialogue.

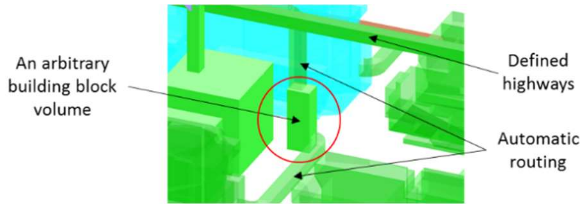


Figure 6: Cable routing for initial SSK synthesis using Paramarine™

4.5 EVALUATION OF THE INITIAL CONFIGURATION OF THE POWER AND PROPULSION SYSTEM

While the PPS and the submarine architecture may have been numerically balanced, however, there remains the need to measure whether the candidate PPS architecture provides an assumed level of safety and is satisfactorily routed throughout submarine. Hence, the following subsections are devoted to explaining how such assurance was numerically obtained.

4.5 (a) Pre-Processing Network Flow Analysis for Selected PPS Architecture

Information extracted from a 3D DBB synthesis using Paramarine™ is given in Table 3. The cable routing was revisited to get a better estimation of length for the selected DS3 style routing as in Figure 7.

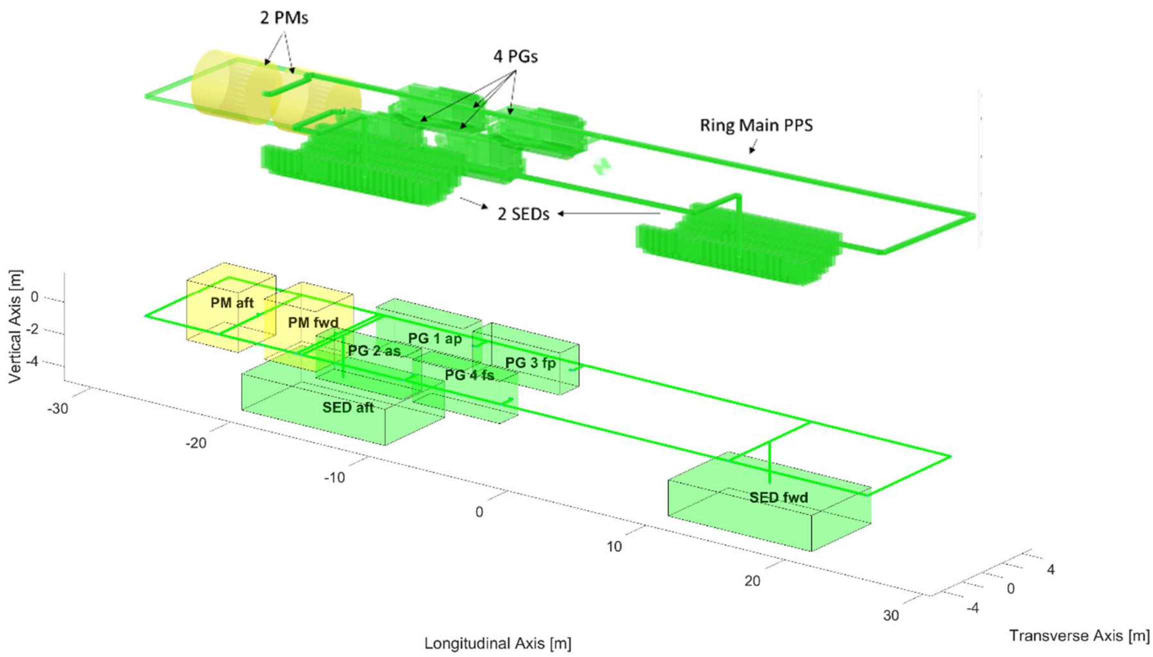


Figure 7: PPS architecture displayed in Paramarine™ (top) translated into MATLAB® for evaluation step (bottom)

Table 3: The physical architecture properties of PPS for the case study SSK extracted from Paramarine™

System Component	Centroid Location (m)			Dimension (m)		
	X	Y	Z	L	B	H
PM aft	-23.6	0	0	3.7	3.7	3.7
PM fwd	-18	0	0	3.7	3.7	3.7
PG 1 ap	-11.5	3	0	6.3	1.8	2.6
PG 2 as	-11.5	-3	0	6.3	1.8	2.6
PG 3 fp	-4.5	3	0	6.3	1.8	2.6
PG 4 fs	-4.5	-3	0	6.3	1.8	2.6
SED aft	-15.5	0	-3.7	6.3	5.9	2.2
SED fwd	15.3	0	-3.7	6.3	5.9	2.2

The PPS was re-modelled in MATLAB® then an adjacency matrix for a network representation of the candidate PPS architecture was created. The PPS was modelled as a 32×32 adjacency matrix, with 32 nodes and 36 edges (see Figure 8 for node labelling and Table B1 in Appendix B for the adjacency matrix of this PPS network).

4.5 (b) Network Flow Analysis for Selected PPS Architecture

This analysis commenced by reading all the information provided from the pre-processing step (Section 4.5 (a)). The important procedure in this step was the network flow formulation. To formulate the key space and safety concerns, the following assumptions were made:

The novel objective function in SUBFLOW, Equation (1), was devised to evaluate the PPS candidate architecture so that it uses the least amount of cabling and takes up the least amount of space.

$$\sum_{(i,j)\in E} \left(\alpha\, \delta_{i,j} + \beta\, \delta_{i,j} + \lambda_{i,j}\, P_{i,j}\right) \tag{1}$$

Equation (1) could also be used to produce two direct cable sizing approaches. The first one was termed as the 'binary variables' approach that minimise DS3 connection space using coefficients α and β. These coefficients categorise arcs in a DS3 network to a certain standard edge component via binary decisions of $\delta_{i,j}$. The second approach was the 'integer variables' approach which also minimise the value of multiplication between power to volume ratio $\lambda_{i,j}$ and power $P_{i,j}$. Power to volume ratio $\lambda_{i,j}$ quantifies power $P_{i,j}$ for each set of arcs E connecting node i and node j into a discrete volume.

As the required power $P_{i,j}$ and/or the distance between nodes of an edge increase, it will require more volume to achieve the necessary physical connection i.e., the volume of a Distributed Ship Service System's physical connection is characterised by its length and capacity.

The length is calculated by finding the physical distance (using the *Manhattan Distance*) between two adjacent nodes. Let say $r \times c$ matrix N consist of three values x, y, and z, arranged in column c of a pair of nodes n, i and j allocated in row r. Therefore, the *Manhattan Distance* L between nodes i and j is defined as:

$$L(i,j) = \sum_{c=1}^{3} \left|N_{ic} - N_{jc}\right| \tag{2}$$

However, this was not enough to quantify the discrete volume from the power capacity $P_{i,j}$. The derivation of the variable area per unit power capacity $P_{i,j}$ flow capacity, for the chosen cable routing is outlined below.

The study assumed the maximum capacity flow between nodes, P_{wire} of 4800 kW. If the highest possible voltage V_{wire} for sprint was assumed to be 1000VDC and the number of cables N_{wire} were three, this gave 1.6 kA current flow I_{wire} per cable (see Equation (3)). Each of the three rows consist of a positive and a negative DC cable.

$$P_{wire} = I_{wire} \times V_{wire} \times N_{wire} \tag{3}$$

A reference from US DoD cable comparison military handbook (U.S. Department of Defense, 1989) gave an estimation of the diameter required for accommodating such current. A 1.63 kA ampacity was selected for this case study. The diameter of the cable for the current rating was given as ~56 mm. By assuming the spacing allowance

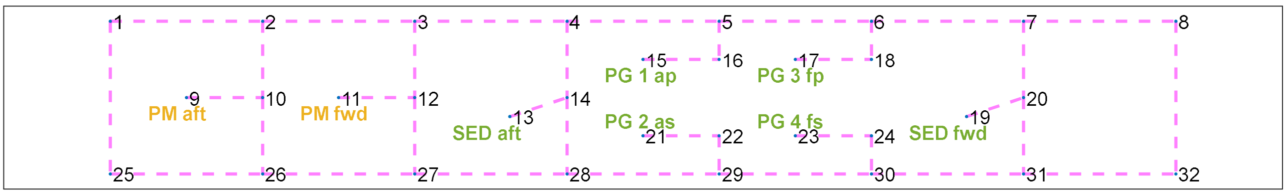


Figure 8: Nodes labelling to the PPS architecture in MATLAB® (not to scale) with purple dashed line indicating the power commodity is tracked in the PPS cabling network

between cables is 25 mm, the W (188 mm) and H (270 mm) could then be calculated (see Figure 9). The cableway support for the system runs or main highway was based on US naval design practice (U.S. Department of Defense, 2009). The cableway support, typically threaded stud steel, is installed between frames, welded to the inside of pressure hull, and penetrates hull insulation as illustrated in Figure 9.

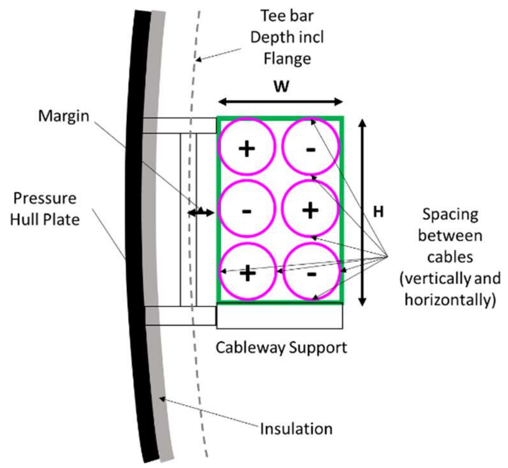


Figure 9: A sketch of the cableway arrangement

It was assumed that the area A_{ij} needed would linearly increase with power capacity P_{ij}, the calculated value of power to volume ratio ratio, $\lambda_{i,j}$ (multiplication between A_{ij} and L_{ij} see Equation (2)) in Equation (1) for this investigation being given by Equation (4).

$$\lambda_{i,j} = \frac{A_{ij}}{P_{ij}} L_{ij} = \frac{1.04 \times 10^{-5} m^2}{kW} L_{ij} \quad (4)$$

In this case study, to define variables α and β in the overall equation (1), there were two assumed standard edge components. The first one was a cable with 0.467 kA ampacity, the second one had 1.63 kA ampacity. Based on the cableway arrangements, the first category α could accommodate a maximum capacity of 1.4 MW power and the second category a maximum β of 4.89 MW power.

This completed the coefficients for the objective function (Equation (1)). SUBFLOW did not just seek the minimum space, but also satisfied several constraints, given in Equations (5 to14). In these constraints, k is an indexed scenario within the set of scenarios K.

The first constraint, Equation (5), is the basic NFO formulation that ensures the flow variable or flow path x entering and leaving a node n within a set of nodes N is equal to the amount of commodity γ at that node n and is preserved throughout the edges E, except at the relevant sources and sinks.

$$\sum_{(i,j)\in E}^{k} x_{i,n}^{k} - \sum_{(i,j)\in E}^{k} x_{n.j}^{k} = \gamma_n^k \qquad (i,j,n) \in N \quad (5)$$

Equation (6), which is based on the NSMCF (Trapp, 2015), allows a bidirectional flow path $x_{i,j}$ to be 'rolled up' and converted to power capacity flow $P_{i,j}$ as the decision variables in SUBFLOW.

$$\left|x_{ij}^{k}\right| \leq P_{ij}^{k} \qquad (i,j) \in E, (k) \in K \quad (6)$$

Equation (7) defines the lower bound and the upper bound of the amount of commodity γ produced by a source node s within the set of nodes N to be equal or less than the source capacity Y_s. The source nodes in the PPS study were the PGs i.e., nodes 15, 17, 21, 23 (see Figure 8).

$$\sum_{(s)\in N}^{k} \gamma_s^k \leq \sum_{(s)\in N}^{k} Y_s^k \qquad (k) \in K \quad (7)$$

Equation (8) allows modelling of path nodes p, where the commodity γ at a path node p within the set of nodes N is bounded to the source capacity Y_s. The examples of path nodes in the PPS study were nodes 1, 2, 3, etc (see Figure 8).

$$\sum_{(p)\in N}^{k} \gamma_p^k \leq \sum_{(s)\in N}^{k} Y_s^k \qquad (k) \in K \quad (8)$$

Equation (9) confirms that the required power P_{ij}, as the decision variables in SUBFLOW formulation, is always positive.

$$P_{i,j}^{k} \geq 0 \qquad (i,j) \in E, (k) \in K \quad (9)$$

Equation (10), which is adopted from the AFO (Robinson, 2018), captures the aggregate solution $P_{i,j}$.

$$P_{i,j} = \max_{(k)\in K}\left(P_{i,j}^{k}\right) \qquad (i,j) \in E \quad (10)$$

Equation (11) is based on the M-1 survivability by Trapp (2015) (see Section 3.4), which is a scenario to find out the flow path x when an edge in the DS3 is assumed to be lost in a damaged or edge loss scenario m within the set of scenarios M.

$$P_{i,j}^{k,m} = 0 \qquad (i,j) \in E, (k) \in K, (m) \in M \quad (11)$$

The δ in Equation (12) serves as the binary decision to classify a capacity of an edge i to j to achieve certain standards for an edge component (type α and β, see Equation (1))

$$\delta(i,j) \in \{0,1\} \quad (12)$$

For evaluating the system components redundancy, a pair of constraint Equations (13) and (14) was needed to state the system requirement capacity of sink Y_t in an operational scenario k. Equation (13) applied to PMs while Equation (14) was the hard constraint for the SED charging demand. Therefore, in the PPS study, the sink nodes t were PMs and SEDs (nodes 9, 11, 13 and 19 in Figure 8).

$$\sum_{(t)\in N}^{k} \gamma_t^k = Y_t^k \qquad (i,j) \in E, (k) \in K \quad (13)$$

$$\gamma_t^k = Y_t^k \qquad (t) \in N, (k) \in K \quad (14)$$

Then the commodity required from the source Y_s^k and sink Y_t^k in the Equations (7), (13), and (14) had to be defined from design requirements, i.e., the demanded power was based on the baseline SSK design, as outlined in Table 4.

Table 4: The summary of the power commodity during snorting and transit

System Component	Supply Y_s (kW)	Demand Y_t (kW)	Node (Figure 8)
PM aft	-	346	9
PM fwd	-		11
PG 1 ap	1600 (max)	-	15
PG 2 as	1600 (max)	-	21
PG 3 fp	1600 (max)	-	17
PG 4 fs	1600 (max)	-	23
SED aft	-	2930	13
SED fwd	-	2930	19

In this study, only the scenario for snorting and transit (battery charging) was considered, where the SEDs become the highest load in the PPS network letting $k = 1$. Propulsion demand for snorting speed (7 knots) was calculated automatically in Paramarine™ as 346 kW (shaft efficiency included).

Total power demand Y_{SED} being 5.8 MW was calculated from the UCL Submarine Design Procedure (UCL-NAME, 2012) to meet the desired indiscretion ratio (ratio of time snorting to time submerged (Burcher & Rydill, 1994)) as well as estimates for hotel load (392 kW), energy loss due to conversion, and margins. (The latter were assumed to be 10%.)

For a very small, simple network flow problem, it is possible to solve the problem manually. However, for a large problem, i.e., involving many nodes and edges, a robust commercial solver is needed, such as the one used by Trapp, CPLEX® (Trapp, 2015) or MATLAB® toolbox for MILP called *intlinprog* (MATLAB, 2019b). Rather than using *intlinprog* from MATLAB®, CPLEX® provides a toolbox that can be incorporated directly into MATLAB® (IBM, 2014). This streamlines the evaluation step to be done fully in MATLAB® without requiring a rewrite of the code from MATLAB® to CPLEX® and vice versa.

Most importantly, the use of the CPLEX® toolbox in MATLAB® enables user intervention in the simplex (network) formulation code for CPLEX®. This, in turn, could minimise any black-box tendencies of SUBFLOW by revealing the interaction between objective function, constraints, and bounds in several matrices constituting a large matrix modelling the constraint equations (Equations 5 to 11) as in Figure B1 given in Appendix B.

Such a matrix could be used as the pseudocode in MATLAB® and was referred as the 'operational matrix' because it was driven by the operating conditions of PPS components. Therefore, the constraints (Equations (5 to 11) were encoded into six different group of matrices listed in Table 5 and the operational matrix shown in Figure B1.

Table 5: Constraints allocation to different matrices used in the evaluation step

Matrix	Description	Equation
Aeq	Double matrix for linear equality constraints	5 13-14
beq	Double column vector for linear equality constraints	
Aineq	Double matrix for linear inequality constraints	6
bineq	Double column vector for linear inequality constraints	
lb	Double column vector of lower bounds	7-8
ub	Double column vector of upper bounds	

It can be seen from Figure B1, to ensure flow continuity (Equation (5)) for the DS3 synthesis, rules were invoked for interpreting commodity flow direction. Firstly, any flow going into the node is positive and vice versa. Secondly, sequencing was based on the order of the edge. For example, edge 1 to 2 is positive but edge 2 to 1 becomes negative. Thirdly, the sign of the nodes was always negative, except for the supplier. Although the initial flow was defined, this could change as the network-flow would find the best routing for the power flow.

Besides continuity, the formulation of Aeq and beq, as in Table 5 and Figure B1, included designer input in formulating the operational scenario. Thus, the requisite number of minimum PMs was required to be online in an operational scenario k. Bidirectional ability in the network was achieved by implementing Equation (6) to the matrices Aineq and bineq. They also needed to be used to

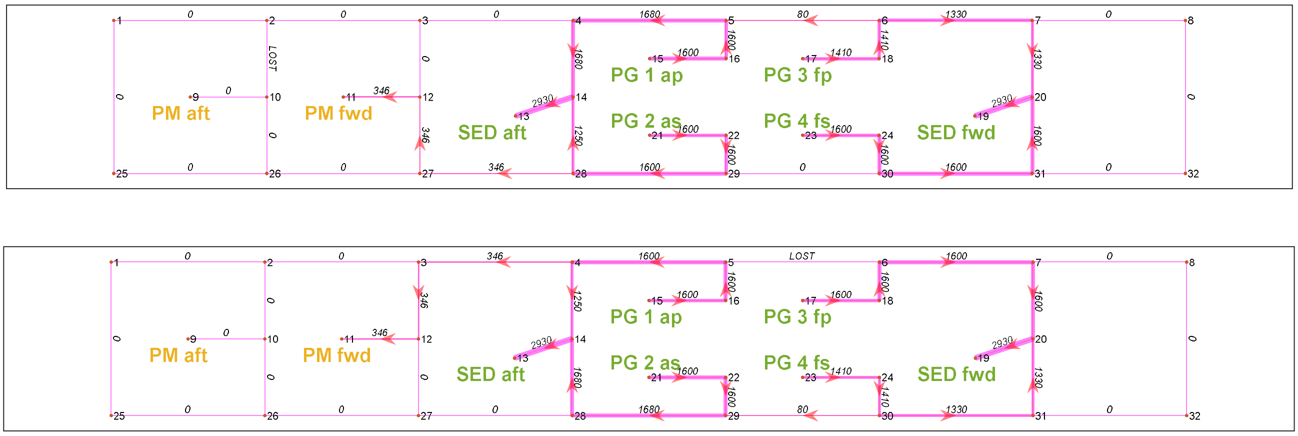


Figure 10: Flow configuration of edge lost (2,10) (top) and (5,6) (bottom) (not to scale)

couple the binary decisions $\delta_{i,j}$ and variable decisions $P_{i,j}$ in the Equation (1). Lastly, Equations (7-8) had to be implemented in matrices lb and ub (see the operational matrix in Appendix B, Figure B1).

With all constraint equations modelled in the mathematical form (summarised in Figure B1 in Appendix B), quantitative analyses were made to the candidate PPS architecture. The following procedure implemented a basic survivability metric to the network (M-1) (Trapp, 2015) (see Section 3.4 (b)). This was done by simply setting the value of specific flow $P_{i,j}$ in matrix ub to zero as a constraint to mimic a scenario of losing one edge $(i,j) \in E$ in the PPS network (see Equation (11)).

4.5 (c) Post Processing to Select an Aggregate Solution

Storing each simulated result into an aggregate array matrix "A" was the first step in post-processing. It was followed by two parts of data extractions. Firstly, all variable decisions were captured giving an estimation of the volume size of the PPS; secondly, binary decisions were extracted from the aggregate solution to categorise different size of cabling used in the PPS architecture (see Section 3.4(b)).

There was a total of 28 results from the edge lost scenario. A representative result has been chosen here to show a unique flow configuration (Figure 10-14). The discussion of these results is given in Section 5.

5. DISCUSSION OF DEMONSTRATION OF DS3 SYNTHESIS

5.1 DAMAGE SCENARIO RESULTS

In a scenario (Figure 10 (top)), a unique power distribution was created. From the PPS components, summarised in Table 3, PG-2-as was dedicated to supply power to PM-fwd to meet the system requirements for shaft power during snorting. From Table 4 the commodity supplied by PG-2-as was found to be insufficient to meet the power demand for the SED-aft. As a result, PG-1-ap was used to meet the residual commodity demand of SED-aft. Again, this was not enough to meet the system requirements for SED-aft during snorting, hence SED-aft received another 80kW power from PG-3-fp.

Interestingly, since the formulated objective function was to find minimum space for routing, rather than fully using all the remaining PG-3-fp power supply for SED-fwd (1.52 MW), PG-4-fs was used to do so. As a consequence, the distribution edge (5,6) was unused and so PG-3-fp had

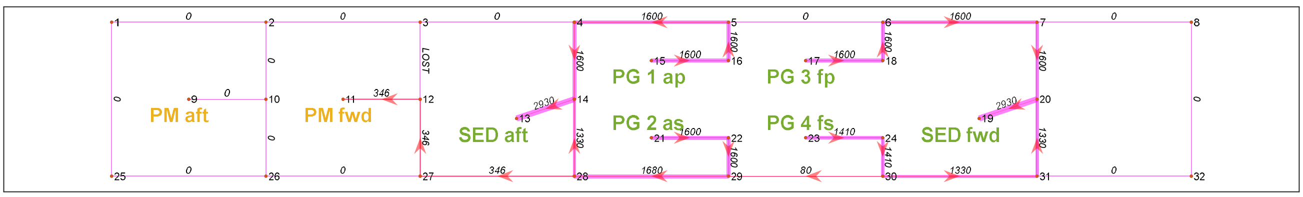


Figure 11: Flow configuration of edge lost (3,12) (not to scale)

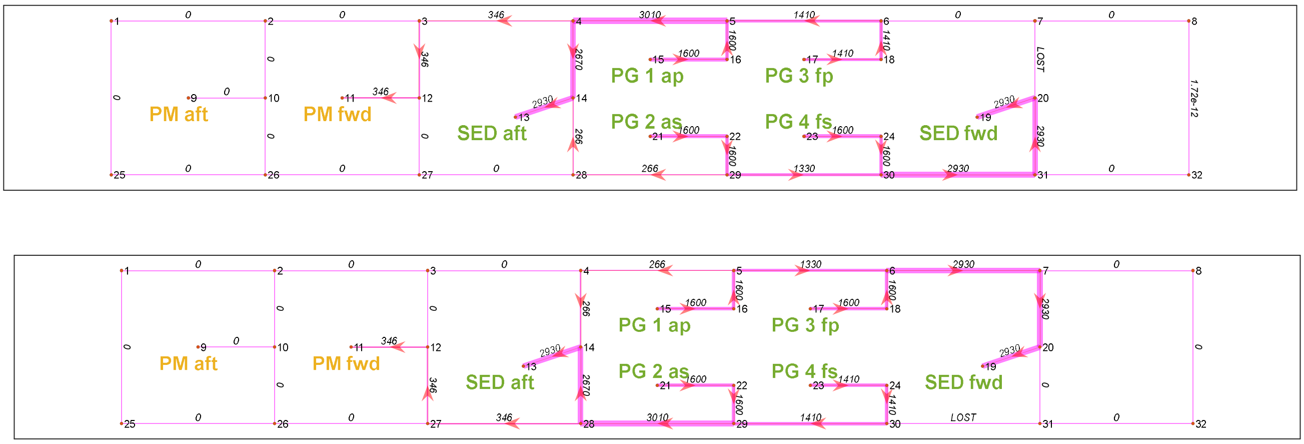


Figure 12: Flow configuration of edge lost (7,20) (top) and (30,31) (bottom) (not to scale)

a 186 kW power margin in the PPS architecture. This damage scenario produced the same configuration with the scenario of edge lost (1,2), (1,25) (2,10), (9,10), (11,27), (25,26), (27,28), (29,30). This was due to the application of the M-1 survivability (Trapp, 2015) (Section 3.4 (b), Equation (11)), which showed the PPS configuration was still able to satisfy the system requirements without the presence of those edges.

The redundancy for this type of configuration was found when the edge (5,6) had been assumed to be unavailable. The routing used edge (29,30) as the only edge left. This type of configuration can be found in scenario of edge lost (2,3), (5,6), (7,8), (8,32), (10,26), and (31,32) as in Figure 10 (bottom).

Similarly, as shown in Figure 11, when either distribution edges (3,4) or (3,12) are not available, then PG-2-as is used to supply power to PM-fwd. The reason for this is that the shortest path was chosen to transport power directly from PG-2-as to PM-fwd. The combined power from PG-1-ap and PG-4-fs was utilised for charging SED-aft.

The configuration above is significantly changed when the distribution edge adjacent to SED-fwd is damaged. Thus, when edge (6,7) and (7,20), as in Figure 12 (top) is unavailable, the power margin is transferred to PG-3-fp instead of PG-4-fs. PG-2-as and PG-1-ap are fully employed in producing the power commodity at 2.9 MW for SED-fwd and 266 kW through distribution edge (28,29) in fulfilling the deficit supply for SED-aft. The “mirror” of this case is to be found in the scenario where edges (7, 20) or edge (30,31) (Figure 12 (bottom)) are lost.

Interestingly, when one of the main (port side or starboard side) distribution edges (4,5), as in Figure 13, is unavailable the (top) edge is assumed to be offline. So, the deficit supply from the combination between PG-2-as and PG-4-fs would be gained, either from PG-1-ap or PG-3-

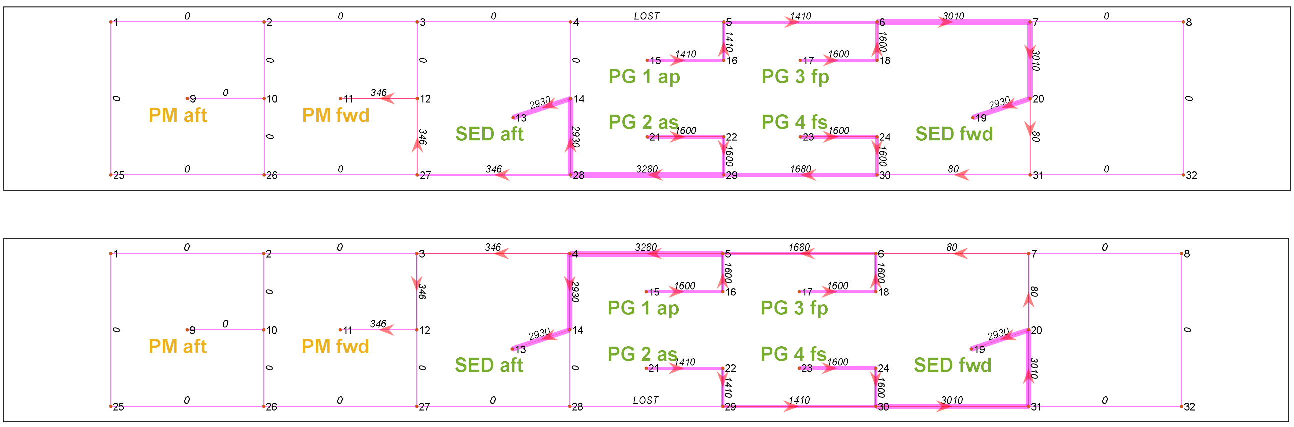


Figure 13: Flow configuration of edge lost (4,5) (top) and (28,29) (bottom) (not to scale)

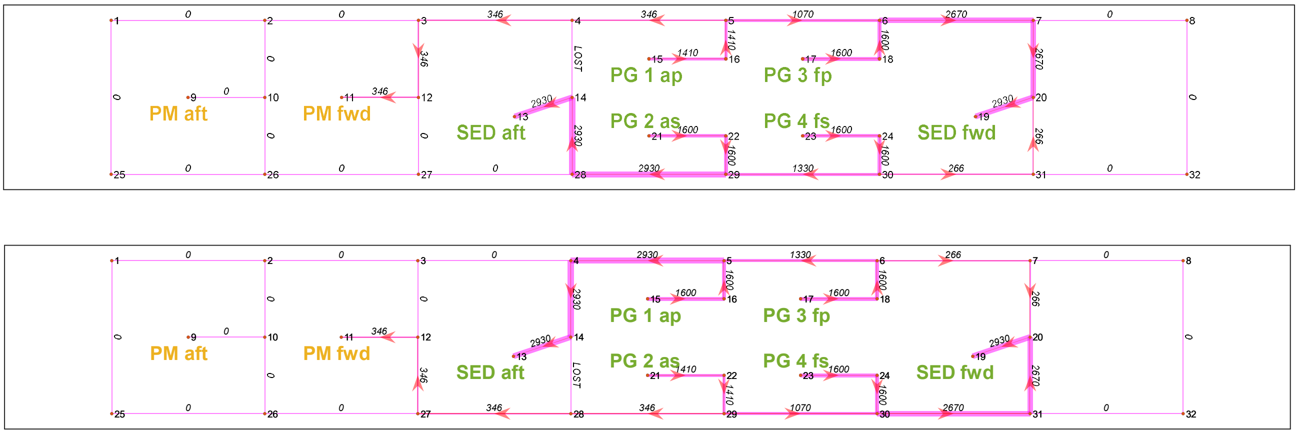


Figure 14: Flow configuration of edge lost (4,14) (top) and (14,28) (bottom) (not to scale)

fp. This means the power commodity flow direction had to continue after edge (7,20). The inverse of this case is found to be in the scenario where edge (28,29) is lost (Figure 13 (bottom)).

Another unique flow distribution was found when edge (4,14) (Figure 14 (top)) or (14,28), as in Figure 14 (bottom), was assumed to be damaged. As these provide the only route available for distributing service flow to SED-aft, they would receive supplies at: ~1 MW from PG-1-ap; 1.6 MW from PG-2-as; and 279 kW from PG-4-fs.

However, the power combination between powers available left from PG-3-fp and PG-4-fs being inadequate would then meet the demand from SED-fwd. Thus, a 13 kW supply would have to be received from PG-2-as, as shown in Figure 14 (bottom).

Since the objective function seeks the minimum space needed for routing, PM-fwd was used in an undamaged scenario. However, when this component is offline, with edge (11,12) lost, the PM-aft (as the redundant system component) has then to be used.

5.2 SELECTION OF A DS3 SOLUTION (FEEDBACK AS PART OF THE SSK REQUIREMENT ELUCIDATION)

Given different possible configurations have been considered in Section 5.1, the aggregate solution can be extracted by selecting the highest possible power flowing through an edge (i,j).

The aggregate solutions in Figure 15 (middle and bottom) reveal the outer arcs became zero, but the arc in the middle has an average flow of 4.8 MW while the arc in the bottom diagram has a series of different flow solutions ranging from 300 kW to 3 MW. This occurred due to the binary formulation providing an alternative sizing option by classifying power flow either to arc categories α or β. This was quite different to the integer formulation given in Section 4.5 (b). Table 6 delineates the edges in the PPS architecture (see Figure 8), which are categorised by two different standard edge components (α and β).

Conversely, the top diagram in Figure 15 shows a conservative solution which preserved an all-ring configuration style, where the power $P_{i,j}$ of all arcs was homogenous at 6 MW, given by the maximum power available from the four PGs. These various flow solutions gave insights to the designer, which could then be used to obtain the volume of the PPS connections using the power to volume ratio, as outlined in Section 4.5 (b).

Since there were found to be three possible approaches, the designer was able to choose the between "optimised solutions" (3m^3 and 5m^3) or the conservative solution (10m^3) for the PPS arcs input sizing (see, by way of illustration, Figure 15 and Table C1 Appendix C).

Table 6: The summary of standard edge component results

Standard Edge Component	Edges
Edge Type α	(2,3), (2,10), (3,4), (3,12), (9,10), (11,12), (12,27), (27,28)
Edge Type β	(4,5), (4,14), (5,6), (5,16), (6,7), (6,18), (7,20), (13,14), (14,28), (15,16), (17,18), (19,20), (20,31), (21,22), (22,29), (23,24), (24,30), (28,20), (29,30), (30,31)

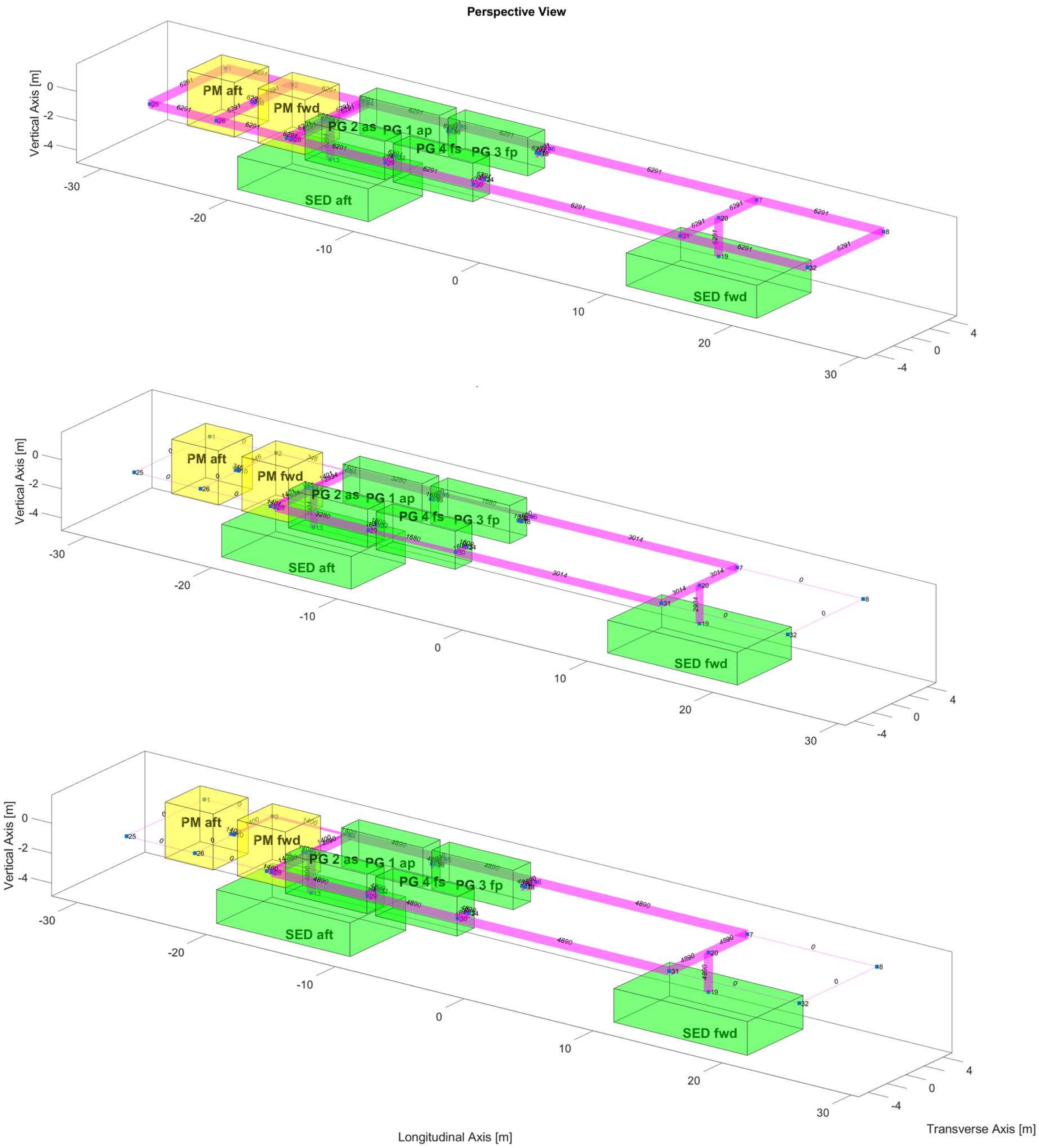


Figure 15: Visualisation of the PPS arcs sizing results: conservative approach (top); integer variables approach (middle); and binary variables approach (bottom) for the SSK case study

The main merit of the evaluation step in the DS3 synthesis process is to create a structured quantitative measurement of the selected candidate architecture. Without an evaluation it is possible to arrive at an arrangement with many redundancies either of DS3 components or routing configuration. This would mean the system would require more space, more weight of equipment and more demanding DS3 architecture.

5.3 LIMITATION OF THE CASE STUDY

The results examined in Sections 5.1 to 5.2 are driven by the formulation of the constraints and the range of damage scenarios examined. In this case study, the damage scenario used was limited to M-1 survivability from Trapp (Trapp, 2015) (Section 3.4 (b), Equation (11)). It can be seen that the M-1 survivability alone could not capture the contribution of outer ring (edge (1,25) and edge (8,32)) to PPS survivability. To do this requires a greater variety of survivability and other relevant SSK's operational scenarios. A set of further iterations would be sensible to be consistent with requirement elucidation intent.

The PPS (at a low-level of detail, commensurate with ESSD) was selected as an example of DS3 technology (main power cable), however the DS3 synthesis method used here could also be applied to other types of cabling (cabling includes a range of power cable and range of data cables, including fibre optics, and even substantial de-gaussing cabling). It could also be applied to other DS3 technologies (trunking and pipework). This could be achieved provided that the power to volume ratio $\lambda_{i,j}$ (for Equation 1) can be derived specifically for these various DS3 technologies.

6. CONCLUSIONS AND FUTURE WORK

This paper has presented progress on ongoing work at UCL to develop a novel integrated DS3 synthesis method for complex vessels in ESSD. It outlines the current limits on a concept designer assessing the impact of different DS3 options on the design input to requirements elucidation and how they could be tackled for a conventional submarine by the proposed DS3 synthesis method.

The case study has demonstrated that a DS3 synthesis is possible as part of an overall DBB based submarine synthesis. This is because the DBB approach enables the consideration of the submarine's architecture early in the design synthesis. Using DS3 information, such as, obtaining the location of DS3 components in a 3D layout much earlier in the design process, is facilitated by the use of the architecturally centred approach. The case study is part of the "Proof of Concept" in the application of the DBB based design synthesis to DS3.

The results from the SSK PPS case study also demonstrate how a network science approach can be used to give a quantitative insight into DS3 sizing. The use of network programming in the evaluation step can aid the designer in obtaining a DS3 routing with reduced weight and space yet meeting system requirements and specific survivability capabilities.

The application of this DS3 synthesis method can facilitate whatever level of detail is deemed necessary for DS3 concept design. Therefore, it can not only enable the concept designer to consider different configurations of DS3, but also evaluate the designer's style choices with regard to architectural aspects of DS3.

To date, the further work on the project has focused on four major aspects, which will be presented in future publications:

- Reducing routine task modelling in Paramarine™ to gain full advantages of architecturally-centred approach for rapid DS3 synthesis in 3D;
- Streamlining the process between Paramarine™ and MATLAB® to allow other DS3 explorations beyond PPS cabling, such as, trunking and pipework technologies;
- Defining a comprehensive network modelling procedure that allows different levels of granularity in DS3 synthesis, as well as the use of explicit arcs for different Plexus. This would greatly aid the concept designer to grasp the energy transfers between Plexus.
- Further SSK sensitivity studies will be performed to show how the new method could reveal insights on the impact of different DS3 stylistic decisions to the whole boat performance early in the design process, when the design is still fluid.

7. ACKNOWLEDGEMENTS

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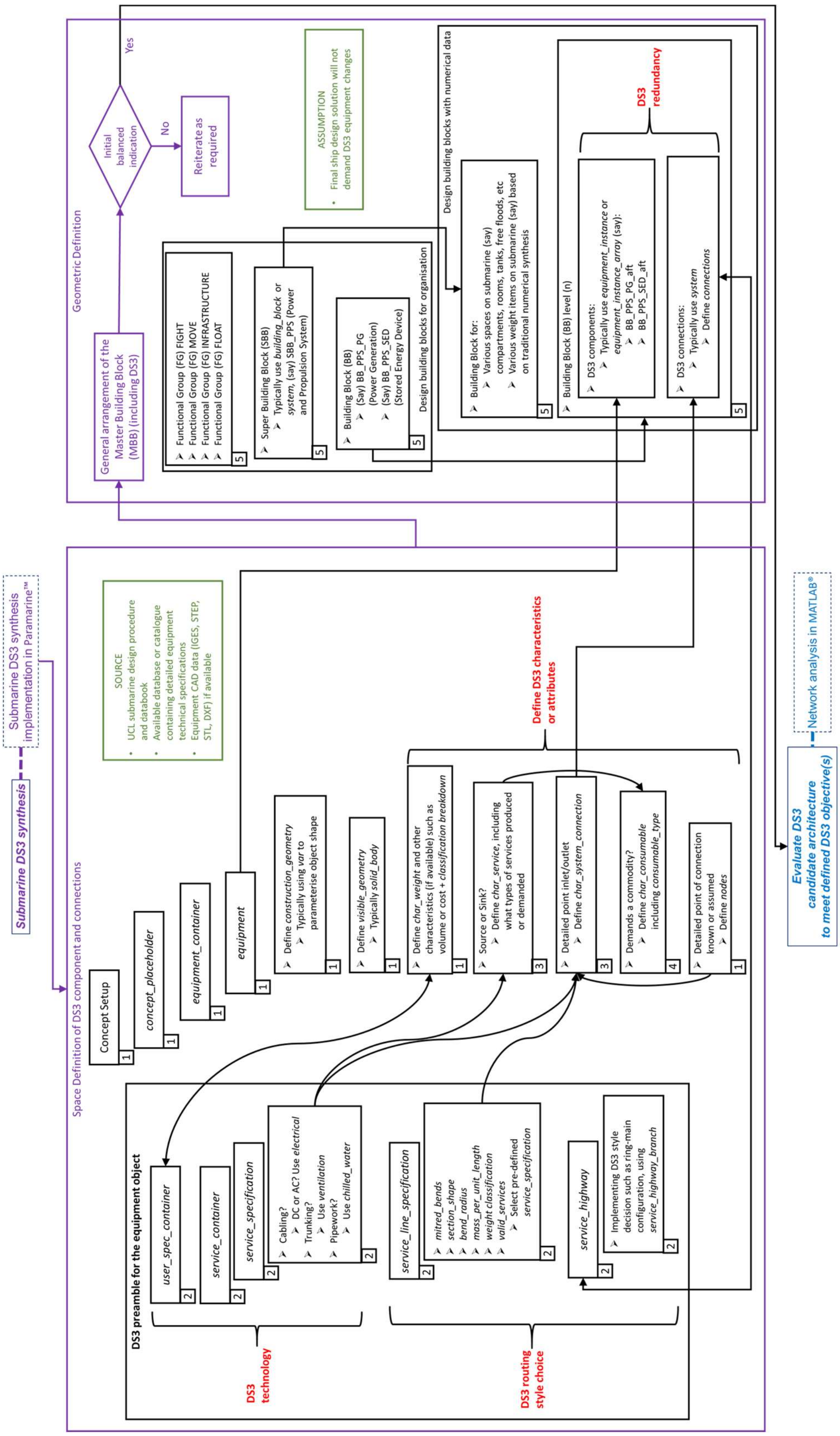
APPENDIX A - DEVELOPMENT OF DS3 SYNTHESIS IN PARAMARINE



Submarine DS3 synthesis implementation in Paramarine consisting of five detailed steps:
step 1 is to create objects for modelling a DS3 component in Paramarine, shown in italic, such as 'concept_placeholder', 'equipment_container', etc (QinetiQ, 2019). DS3 equipment physical size including creating objects to host possible the connection point (x,y,z) of the equipment;
step 2 to setup the DS3 connection(s) of a DS3 component adding more objects in Paramarine, such as 'user_spec_container', 'service_container', etc (QinetiQ, 2019);
step 3 is to provide input for DS3 component as source or sink and define what relevant DS3 connections could be connected to the DS3 component in terms of DS3 technology;
step 4 is to define the numerical commodity demand of the equipment (if applicable);
step 5 is to perform DS3 modelling using SURFCON module in Paramarine, which consists of creating building block objects that is descriptive (or for organisation (Pawling, 2007))

Figure A1: The logic of implementation of the UCL DBB Approach in Paramarine™ for submarine DS3 synthesis, see the first author's PhD thesis for more detail

APPENDIX B - DETAILED SETUP FOR THE SUBFLOW

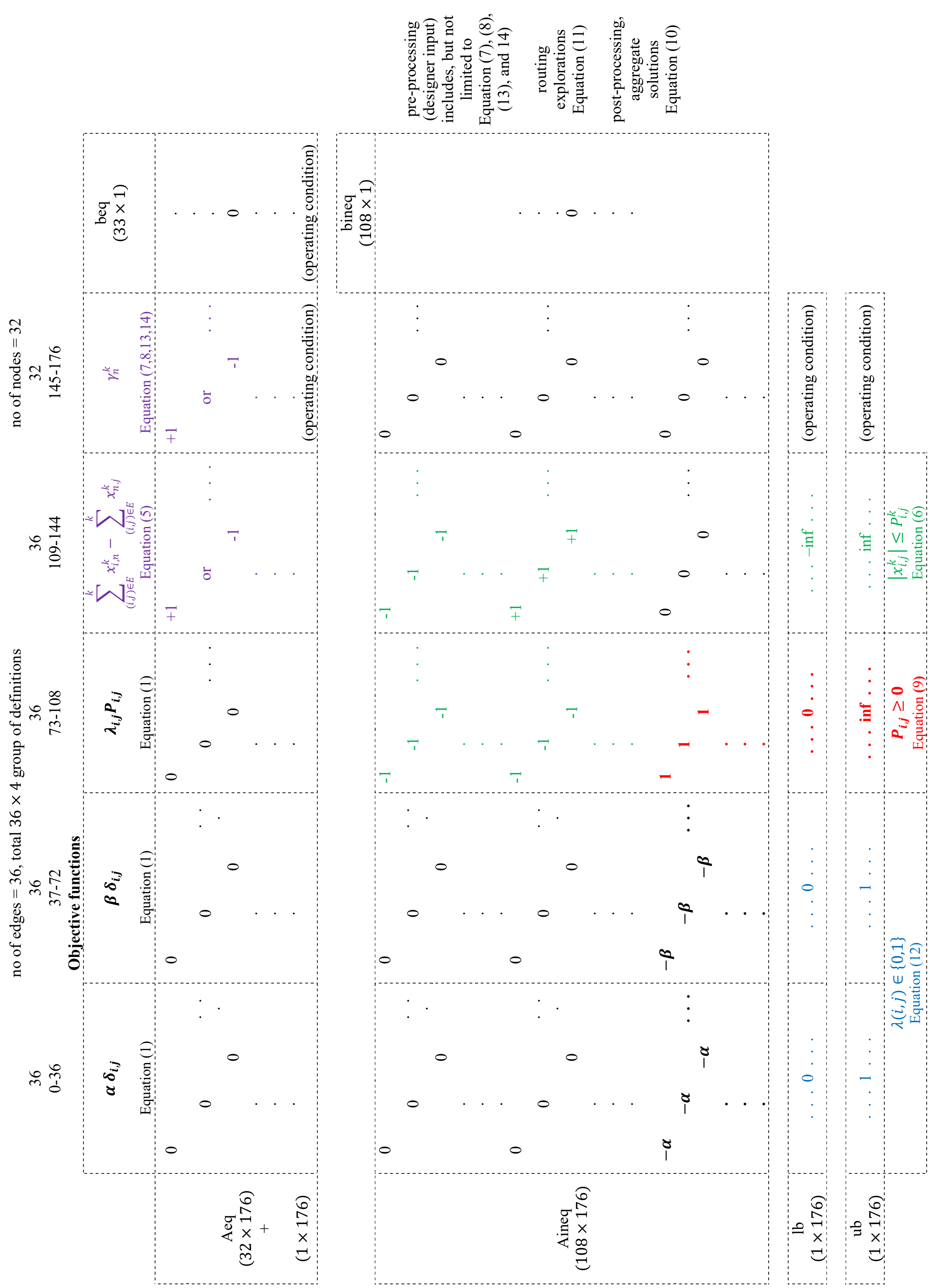


Figure B1: Pseudocode for constraints matrices of the case study, showing different colours for different constraints

Table B1: The adjacency matrix of the case study (undirected network)

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
2	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
25	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1
32	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

APPENDIX C – THE RESULT FROM THE SUBFLOW APPROACH

Table C1: Sizing results of the PPS study for the SSK case study

Arc No	Node i	Node j	Power to volume ratio $\lambda_{i,j}$ (m³/kW)	Conservative Approach Power $P_{i,j}$ (kW)	Conservative Approach Volume $V_{i,j}$ (m³)	Integer Variables Approach Power $P_{i,j}$ (kW)	Integer Variables Approach Volume $V_{i,j}$ (m³)	Binary Variables Approach Alpha α	Binary Variables Approach Beta β	Binary Variables Approach Power $P_{i,j}$ (kW)	Binary Variables Approach Volume $V_{i,j}$ (m³)
1	1	2	5.52E-05	6291	0.347	0	0.000	-	-	0	0.000
2	1	25	8.68E-05	6291	0.546	0	0.000	-	-	0	0.000
3	2	3	5.84E-05	6291	0.367	346	0.020	yes	-	1400	0.082
4	2	10	4.31E-05	6291	0.271	346	0.015	yes	-	1400	0.060
5	3	4	4.02E-06	6291	0.025	1401	0.006	yes	-	1400	0.006
6	3	12	4.31E-05	6291	0.271	1401	0.060	yes	-	1400	0.060
7	4	5	7.72E-05	6291	0.486	3280	0.253	-	yes	4890	0.378
8	4	14	4.31E-05	6291	0.271	2934	0.127	-	yes	4890	0.211
9	5	6	7.30E-05	6291	0.459	1680	0.123	-	yes	4890	0.357
10	5	16	1.18E-05	6291	0.074	1600	0.019	-	yes	4890	0.058
11	6	7	1.71E-04	6291	1.076	3014	0.515	-	yes	4890	0.836
12	6	18	1.18E-05	6291	0.074	1600	0.019	-	yes	4890	0.058
13	7	8	1.05E-04	6291	0.660	0	0.000	-	-	0	0.147
14	7	20	4.31E-05	6291	0.271	3014	0.130	-	yes	4890	0.211
15	8	32	8.68E-05	6291	0.546	0	0.000	-	-	0	0.121
16	9	10	2.61E-06	6291	0.016	346	0.001	yes	-	1400	0.004
17	10	26	4.36E-05	6291	0.275	0	0.000	-	-	0	0.000
18	11	12	2.61E-06	6291	0.016	346	0.001	yes	-	1400	0.004
19	12	27	4.36E-05	6291	0.275	1401	0.061	yes	-	1400	0.061
20	13	14	2.74E-05	6291	0.172	2934	0.080	-	yes	4890	0.134
21	14	28	4.36E-05	6291	0.275	2934	0.128	-	yes	4890	0.213
22	15	16	2.61E-06	6291	0.016	1600	0.004	-	yes	4890	0.013
23	17	18	2.61E-06	6291	0.016	1600	0.004	-	yes	4890	0.013
24	19	20	2.74E-05	6291	0.172	2934	0.080	-	yes	4890	0.134
25	20	31	4.36E-05	6291	0.275	3014	0.132	-	yes	4890	0.213
26	21	22	2.61E-06	6291	0.016	1600	0.004	-	yes	4890	0.013
27	22	29	1.24E-05	6291	0.078	1600	0.020	-	yes	4890	0.060
28	23	24	2.61E-06	6291	0.016	1600	0.004	-	yes	4890	0.013
29	24	30	1.24E-05	6291	0.078	1600	0.020	-	yes	4890	0.060
30	25	26	5.52E-05	6291	0.347	0	0.000	-	-	0	0.000
31	26	27	5.84E-05	6291	0.367	0	0.000	-	-	0	0.000
32	27	28	4.02E-06	6291	0.025	1401	0.006	yes	-	1400	0.006
33	28	29	7.72E-05	6291	0.486	3280	0.253	-	yes	4890	0.378
34	29	30	7.30E-05	6291	0.459	1680	0.123	-	yes	4890	0.357
35	30	31	1.71E-04	6291	1.076	3014	0.515	-	yes	4890	0.836
36	31	32	1.05E-04	6291	0.660	0	0.000	-	-	0	0.147
Total Volume					**10.865**		**2.723**				**5.243**