

Reliability constraints in the topology generation of ship architecture

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ABSTRACT

Ship design involves the integration of numerous subsystems, with potential interconnections and constraints that make identifying a suitable architecture increasingly challenging as the number of components grows. A tool for the topology generation of the ship architecture for the early stage design has been developed to facilitate this conception phase. Apart from specific requirements (propulsion, hotel load or heating), one important point in the ship architecture is its reliability, i.e its ability to ensure these tasks in a degraded mode (with one or several down components). Some constraints about redundancies have been introduced in a logic programming approach to construct reliable ship architecture topologies. It can either affect the number of each component or each connection to enhance the ship architecture's resilience to defects during the early stages of the design process. The global reliability of the ship architecture is calculated with the different failure rates for components in series or in parallel. Two numerical cases are computed (with or without heating requirements) to illustrate the versatility of the algorithm. The ship architecture reliability is compared with different options such as no redundancy, redundancy of each function path, redundancy of all connections or all components. The results are analyzed based on the trade-off between reliability and the complexity of the architecture, defined by the number of components and connections.

Keywords: ship energy system; architecture topology generation; constraint programming

1 Introduction

In engineering design, a complex system involves many components and can be difficult to apprehend at early stage in a project. In ship design it is particularly critical with the different constraints involved (cost, environmental impact, maintenance) along with the ship requirements (propulsion, hotel load and heating) among others [Frangopoulos \(2020\)](#). In addition to these tasks based on the ship mission profile, one important aspect for the ship architecture is its reliability or survivability [Batra et al. \(2023\)](#). It is defined here as the possibility to fulfill a function after one or several defects (component or connection failure). The different leverages enhancing the reliability include components or connections redundancy along with different spatial repartition of subsystems [de Vos and Stapersma \(2018\)](#). When such measures are considered, it can go against other objectives in ship design (minimum cost, weight, emissions, maintenance time) so it has to be investigated carefully to minimize additional complexity induced by the reliability constraints.

The reliability of the ship electric system architecture has been investigated in [Trapp et al. \(2015\)](#), where a network flow optimization process is used to find alternative routings for energy distribution

after damage to the architecture. The basic theory in [Trapp et al. \(2015\)](#) is also applied in [Robinson et al. \(2018\)](#); [Parsons \(2021\)](#) to assess for the ship energy system survivability. However, these works rely on predefined topologies with limited possibilities to increase the reliability if necessary. In addition, all possible topology options can be manually gathered in a superconfiguration ([Dimopoulos et al. \(2008\)](#); [Sakalis and Frangopoulos \(2018\)](#)) but it can become cumbersome for a large list of components. The state-of-art will then focus on modifications applied in the topology generation algorithm for the ship architecture to increase its reliability.

Nest, [Dubey and Santoso \(2017\)](#) enhance the reliability of a ship’s electrical network by iteratively adding connections until a target reliability value is achieved. For efficiency purposes, the selected connection at each iteration is the one that maximizes the network availability. The effect of different characteristics topologies (ring bus, breaker-and-a-half and double-bus double-breaker) in the network reliability is investigated in [Dubey and Santoso \(2016\)](#). Also, the availability of the primary distribution system is improved by modifying the equipment locations within the ship architecture. In [de Vos and Stapersma \(2018\)](#), ship architectures with additional rings (connections between nodes that distribute energy) were selected using a genetic algorithm to improve the global system’s reliability. However, this approach still relied on a fixed set of components.

In this work, we aim to integrate reliability constraints into the topology generation algorithm, with a flexible number of components and connections. Our methodology is based on the previous work of the authors [Dugast et al. \(2023\)](#), leveraging constraint programming in Prolog to enforce various design constraints. Two cases are computed involving a ship energy system with or without heating requirements. In both applications, the effect on the system reliability is investigated for different constraints: redundancy of function paths, connections or components. The reliability is calculated based on the failure rates of each component. The topology generation algorithm is presented in Section 2 and the associated results in Section 3.

2 Method

The ship architecture is constructed based on the components listed in Table 1. Two cases will be considered in this study : Case 1 (electrical or mechanical propulsion and hotel load with diesel engines or gas turbines) and Case 2 (Case 1 + heat recovery system and heat generation). More details about the calculation of the component reliability will be given later in this article. First, elementary chains are created following the methodology explained in [Dugast et al. \(2023\)](#). They represent the different options to achieve a function (propulsion, hotel load or heating). An example of the elementary chains for Case 1 is shown in Figure 1.

2.1 Determination of the number of components and connections

After the creation of elementary chains, the number of components W and connections X is determined depending on the constraints on ports connections and also on redundancy requirements (minimal number of components or connections). The set of connections is based on the ones involved in the elementary chains. The different constraints are :

1. For all components C_i in Table 1, with the number of possible connections for the corresponding inlet port being $N_{C_i}^p \in [1, +\infty[$ the relationship between the number of connections and components is written as :

$$\frac{1}{N_{C_i}^p} \leq \frac{W_{C_i}}{\sum_{j=1}^{n_x} X_{C_i^p - C_j^q}} \leq 1 \quad (1)$$

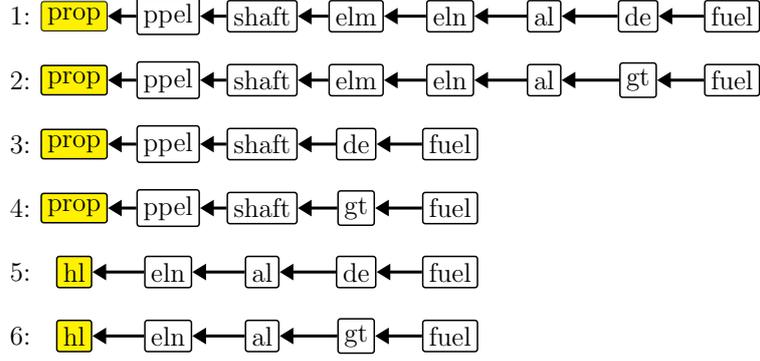


Figure 1: Case 1 : Elementary chains

Full name (shortname)	Input ports	Output ports	Min	Max	Reliability
Propulsion (prop)	1.[prop,inf,[]]	1.[]	1	1	1.0
Hotel load (hl)	1.[elec,inf,[rel]]	1.[]	1	1	1.0
Propeller (ppel)	1.[meca,1,[shaft]]	1.[prop,1,[]]	1	4	0.98
Shaft (ppel)	1.[meca,inf,[]]	1.[meca,1,[he]]	1	4	0.98
Elec. motor (elm)	1.[elec,inf,[rel]]	1.[meca,1,[]]	1	4	0.9396
Elec. network (eln)	1.[elec,inf,[]]	1.[elec,inf,[]]	1	4	0.9888
Gas turbine (gt)	1.[fuel,inf,[]]	1.[meca,1,[]] 2.[heat,1,[]]	1	4	0.7236
Diesel engine (de)	1.[fuel,inf,[]]	1.[meca,1,[]] 2.[heat,1,[]]	1	4	0.8922
Alternator (al)	1.[meca,1,[]]	1.[elec,inf,[]]	1	4	0.9229
Fuel tank (fuel)	1.[]	1.[fuel,inf,[]]	1	2	0.99
Heating (heat)	1.[heating,inf,[]]	1.[]	1	1	1.0
HRSG (hrsg)	1.[fuel,inf,[]] 2.[heat,inf,[]]	1.[steam,inf,[]]	1	2	0.9672
Auxiliary boiler (ab)	1.[fuel,inf,[]] 2.[water,inf,[]]	1.[steam,inf,[]]	1	2	0.5322
Steam turbine (st)	1.[steam,1,[]]	1.[meca,1,[]]	1	4	0.9020
Water tank (water)	1.[]	1.[water,inf,[]]	1	2	0.99

Table 1: Components list for Case 1 and Case 2 (ports and components in bold)

with n_x the number of possible $X_{C_i^p-C_j^q}$ connections, where p and q represent the ports for C_i and C_j respectively. The same equations are also used for outlet ports where $X_{C_i^p-C_j^q}$ is replaced by $X_{C_j^q-C_i^p}$.

- The occurrence of each component in the ship architecture is constrained by minimal and maximal values according to Table 1:

$$W_{C_i,\min} \leq W_{C_i} \leq W_{C_i,\max} \quad (2)$$

- For all connections represented in the elementary chains $\Omega = X_{C_i^p-C_j^q}$, having $X_{C_i^p-C_j^q} \geq 1$ may not be enough to satisfy the design constraints, regardless of redundancy requirements. Multiple identical connections could be necessary to construct the elementary chains presented in Figure 1 if several components of a chain have a constraint on the maximal number of connections at their ports. In general, this calculation is given by :

$$\bar{W}_{C_j} = \begin{cases} \frac{1}{N_{C_j}^q} \sum_k \bar{W}_{C_k} & \text{if } X_{C_k^p - C_j^q} \in \Omega \\ 1 & \text{if } N_{C_j}^q = \infty \\ 1 & \text{if } X_{C_k^p - C_j^q} \notin \Omega \end{cases} \quad (3)$$

At the end the minimum number of connections is given by :

$$X_{C_i^p - C_j^q} \geq \max(\max(\bar{W}_{C_i}, \bar{W}_{C_j}), n_R) \quad (4)$$

where \bar{W}_{C_i} is also obtained with (3) by checking the inlet connections of the component C_i . The number n_R is a user-defined variable to enforce some redundancies in selected connections.

4. The maximum number of connections is also related to the number of components with the following equation:

$$X_{C_i^p - C_j^q} \leq W_{C_i} \times W_{C_j} \quad (5)$$

These different constraints are solved with the *clpfd* library from Prolog. Although several solutions to this problem exist, the one that minimizes the number of connections and components is selected using solver options.

2.2 Determination of the components connections

Multiple ship architectures (list of components connections) can be represented by one set of number of components and connections. Appropriate architectures are determined with the following constraints:

- Constraint 1 : the number of connections to one component port is inferior or equal to the maximal number of connections allowed for this port,
- Constraint 2 : all elementary chains are present at least once in the architecture structure,
- Constraint 3 : all components are used,
- Constraint 4 : the minimal number of connections is equal to X .

In this problem, one component C_i defined earlier can have several instances, where each instance is defined by $C_{i,k}$. As a consequence, the connections are now written $X_{C_{i,k}^p - C_{j,l}^q}$. Two types of unknown are used in this system of equations : Y for the presence/absence of a connection and Z for the presence/absence of a component on an elementary chain e . In general, the relationship between Y and Z is given by:

$$\sum_e Z_{C_{i,k},e} \times Z_{C_{j,l},e} \begin{cases} = 0 & \text{if } Y_{C_{i,k}^p - C_{j,l}^q} = 0 \\ \geq 1 & \text{if } Y_{C_{i,k}^p - C_{j,l}^q} = 1 \end{cases} \quad (6)$$

for $X_{C_{i,k}^p - C_{j,l}^q} \in \Omega$. The equality constraint in (6) is set to be optional in the solver because it can happen that two components are present in the architecture without being connected together. A minimization of the number of constraint violations is used to enforce this constraint whenever possible. The expressions for Constraints 1 to 4 are written as :

$$\text{Constraint 1: } \sum_{j,l} Y_{C_{i,k}^p - C_{j,l}^q} \leq N_{C_i}^p \quad \text{and} \quad \sum_{i,k} Y_{C_{i,k}^p - C_{j,l}^q} \leq N_{C_j}^q \quad (7)$$

$$\text{Constraint 2: } \sum_k Z_{C_{i,k},e} \geq 1; \quad \text{Constraint 3: } \sum_e Z_{C_{i,k},e} \geq 1 \quad (8)$$

$$\text{Constraint 4: } \sum_{k,l} Y_{C_{i,k}^p - C_{j,l}^q} \geq X_{C_i^p - C_j^q} \quad (9)$$

These constraints are solved by the *or-tools* library in Python. Given the multitude of solutions to this problem, the solver is configured to select the solution that minimizes the number of connections. Note that this objective can enter into conflict with the minimization of constraint violations introduced earlier. A higher weight is applied on the minimization of constraint violations to make it a priority compared to the number of connections.

2.3 Reliability calculation

The reliability function for a component is written as [Tsekouras and Kanellos \(2016\)](#):

$$R_{C_i}(t) = \exp \left[- \int_0^t \lambda_{C_i}(t) dt \right] \quad (10)$$

where λ_{C_i} is the failure rate of the component C_i . For a simple example, the reliability of a component is set constant with two assumptions : a constant failure rate and the calculation of the reliability for a specific time (t=1000 hours). The failure rates are extracted from the OREDA database. For unknowns values, the value is set to 0.99 for the fuel and water tanks, and 0.98 for the shaft and the propeller. The reliability for each component is given in [Table 1](#). Then the reliability for the global system is calculated based on the parallel or serial arrangement of components with the following formula [Tsekouras and Kanellos \(2016\)](#):

$$R_{\text{series}} = \prod_{i=1}^n R_{C_i} \quad \text{and} \quad R_{\text{parallel}} = 1 - \prod_{i=1}^n (1 - R_{C_i}) \quad (11)$$

with n the number of components involved in the serial or parallel arrangement.

3 Results

The reliability of the ship architecture can be enhanced by adding redundancy either on connections or components. Different options are investigated to quantify their impact of the architecture reliability:

- Option A : reference case, no redundancy requirement ($n_R = 1$ in [\(4\)](#))
- Option B : The number of paths to the functions (propulsion, hotel load or heating) should be superior or equal to 2. It is enforced by a number of connections involving functions superior or equal to 2 ($n_R = 2$ in [\(4\)](#) for selected connections).
- Option C : all connections represented in the elementary chains are doubled ($n_R = 2$ in [\(4\)](#) for all connections).

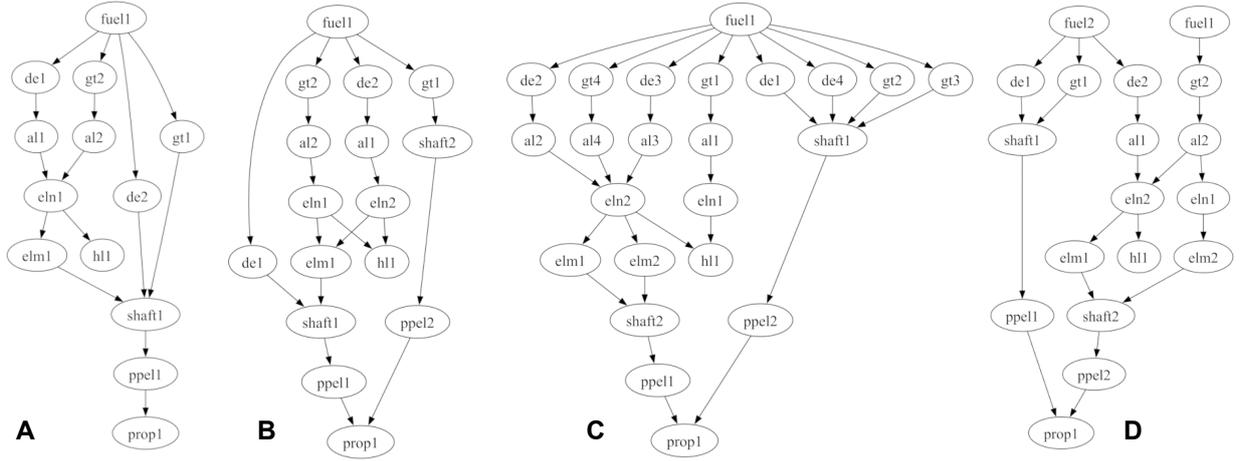


Figure 2: Case 1 : Ship architectures

- Option D : all components except functions are doubled (modification of min and max values for each component, see (2))

Based on the solutions of the systems of equations presented in Section 2, the ship architectures obtained for Case 1 and Case 2 and the different options are gathered in Figures 2 and 3. The reliability results for each function, along with the number of components and connections, are presented in Tables 2 and 3, for Case 1 and Case 2, respectively.

Option	Nb Components	Nb Connections	Rel. Prop	Rel. Hl
A	13	15	0.956294	0.926871
B	16	19	0.983325	0.932839
C	23	30	0.998129	0.992158
D	18	20	0.993757	0.926871

Table 2: Case 1 : Reliability results

Option	Nb Components	Nb Connections	Rel. Prop	Rel. Hl	Rel. Heat
A	20	31	0.960110	0.977633	0.984649
B	23	35	0.994916	0.992255	0.984649
C	35	58	0.998223	0.998656	0.999756
D	28	42	0.994141	0.978397	0.999478

Table 3: Case 2 : Reliability results

As expected, there is an increase in reliability between option A and other options including redundancy requirements. While the difference in reliability may appear small (0.006 difference for the hotel load function between option A and B for Case 1), the redundancy can be helpful if one component is lost during the mission. For example, the complete failure of the first electrical network in the architecture A in Case 1 results in the hotel load function no longer being achievable. In the architecture B, the reliability of the hotel load function remains at 0.80 with the same damage. The highest reliability levels for both cases are obtained by the option C, which also corresponds to the maximal number of components and connections in the ship architectures. However, a good compromise is obtained by the option B, which offers lower complexity and relatively similar reliability compared to option C. Regarding option D, the ship architecture gives similar results than option B, with a higher reliability for propulsion but a lower one for the hotel load function. On the ship architecture C for Case 2, it is clearly visible that the number of connections for similar components can be very different. For example, the first heat recovery system is only connected to one diesel engine while the

second heat recovery system is connected to three diesel engines and four gas turbines. The balance of the number of connections for similar component type is not taken into account at the moment in the algorithm. The implementation of this constraint will be realized in future work for higher quality solutions.

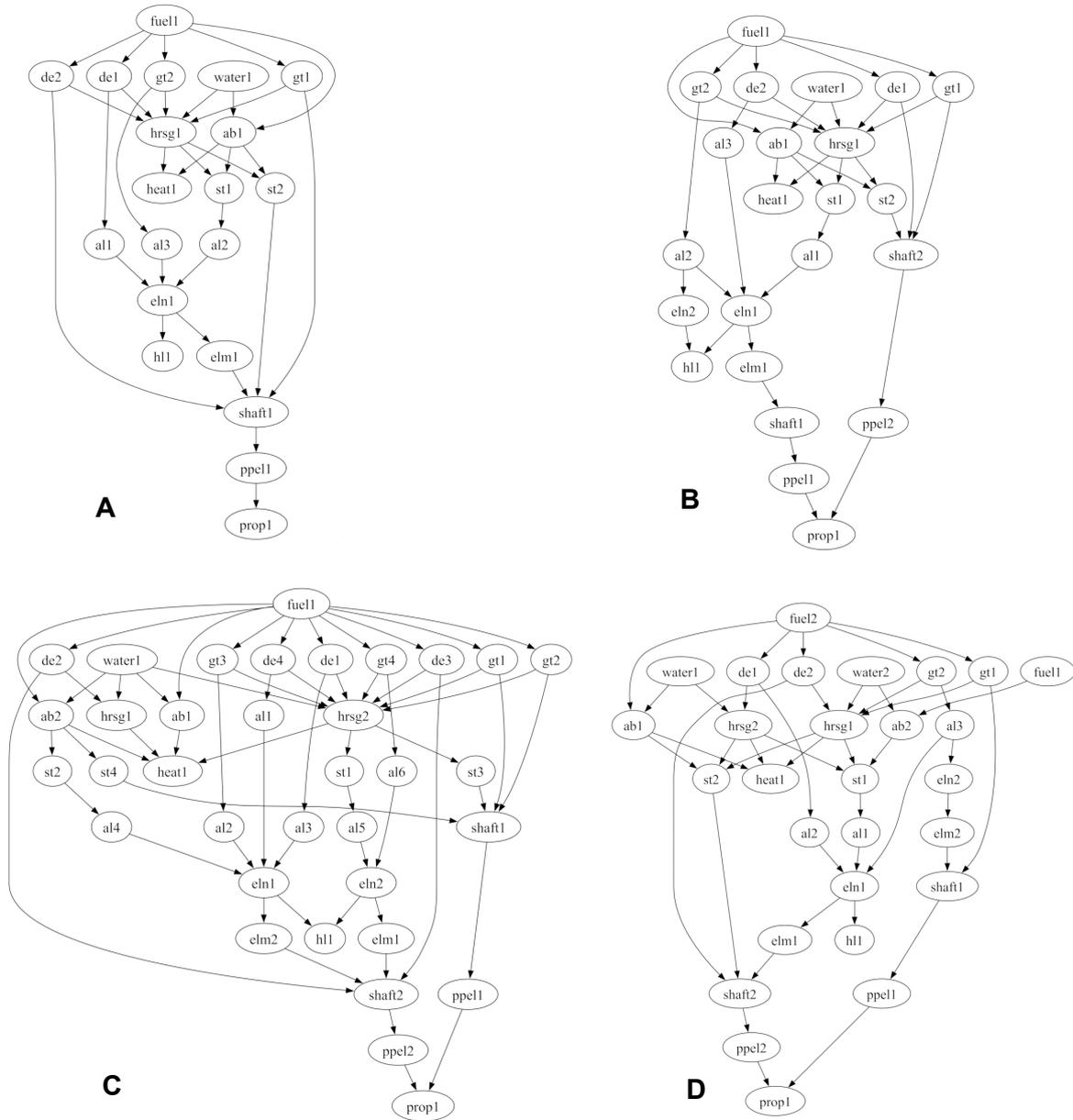


Figure 3: Case 2 : Ship architectures

4 Conclusions

A topology generation algorithm including reliability constraints has been developed in this work for the architecture of a ship energy system. The constraint-programming approach is generic, allowing different options to be easily applied depending on the desired global reliability. Two numerical cases have been investigated illustrating the capabilities of the proposed method. One can conclude that the option B is a good compromise between architecture complexity and reliability. A future direction for this work is to incorporate a reliability target in the equations to achieve the desired reliability with a finer tuning on the number of components and connections.

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