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Is Shipboard Power Reconfiguration a Self-Adaptive Problem? A Systematic Literature Review

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Abstract: The Shipboard Power System (SPS) supplies power to navigation, communication, operation and critical systems. This paper focuses on the reconfiguration of the shipboard electrical layer, i.e. the capability of facing unexpected events such as faults, variable environment conditions, and so on. Reconfiguration procedure should be timely in restoring power in faulted areas of the ship, also to avoid subsequent cascade failures.

A previous study highlighted that SPSs have some common characteristics with self-adaptive systems, such as the perception of the environment (electrical network features, faults, changed conditions, etc.) and the implementation of a feedback loop.

This paper reports a novel systematic classification on SPS reconfiguration methods, regarding Self-Adaptation attributes. The purpose of this survey is to investigate to which extent engineering an SPS may be considered as a sub-problem of building self-adaptive system. Answering this question may provide an interesting synergy between these two research areas. From the one side, SPS may represent an interesting benchmark for comparing self-adaptive approaches; on the other side, the state-of-the-art in self-adaptive systems may provide new ideas for improving SPS approaches.

I. INTRODUCTION

The Shipboard Power System (SPS) is the component responsible for granting energy to navigation, communication, and operational systems. It consists of various electric and electronic equipment, such as generators, cables, switchboards, circuit breakers, fuses, buses, and many kinds of loads.

Shipboard equipment increasingly demands higher performance from the electric sources in a vessel. Moreover, after the occurrence of faults and their subsequent isolation, there could be perfectly working sections that remain without supply. A reliable SPS must be able to supply power even when in the case of loads demand power variations or critical events such as faults occur. The problem of fast and efficient restoration of the SPS service has been a topic of research for around three decades. Nowadays, the real-time data acquisition, classification, assimilation, and correlation can be almost entirely automated at a reasonable cost, with modern computer technologies. Software-based reconfiguration systems consist of two different layers: the software layer encapsulates the logic for the monitor and the control of the underlying electrical layer. In practice, the software system manages on-board switchboards and circuit-breakers, to direct the power flow where it is needed for restoring a fault situation.

The problematic of fault detection, isolation, and reconfiguration (FDIR) has been investigated in many others research fields. In [1] authors make a survey on FDIR methodologies, focusing the attention on reconfiguration techniques related to flight control systems. In particular, they classify the reconfiguration methodologies into two categories: multiple-model approach, and adaptive-control approach.

In literature, several authors investigate many approaches to monitor, control, and reconfiguring the electrical layer topology to survive when facing several kinds of scenarios. In [2], authors compare reconfiguration techniques applied to the terrestrial and maritime domains. They include an analysis of the SPS characteristics, highlighting the need for an integrated protection and power distribution. In [3], authors surveyed different formulations of the reconfiguration problem and the different techniques used for the solution. They compare the problem of SPS

reconfiguration to that of large-scale systems, exploring the issue of optimal reconfiguration from a variety of perspectives. In [4], some of the most recent software-based reconfiguration methodologies have been analysed and classified by comparing the correlation between hardware and software properties. Moreover, in [4], the SPS reconfiguration was analysed using a description of the problem from the point of view of electrical characteristics. The interesting finding is that a series of common characteristics exist between the software layer of an SPS and smart IT systems.

This paper analyses the literature on SPS exclusively from a software point of view, and it proposes a systematic classification of reconfiguration methodologies through the characteristics of self-adaptive systems (software based systems able of changing their functioning to continue addressing goals and users' preferences [5], [6]). The objective of the work is to demonstrate that an SPS can be benchmark-platforms for self-adaptive approaches, and, on the other side, that state of the art in self-adaptive systems may be employed for solving some of the SPS open issues.

This paper is organized as follows: Section II introduces the SPS problem and it presents a couple of possible reconfiguration scenarios; Section III reports the methodology we adopted for conducting the review; Section 4 reports the results that are discussed in Section 5 where the emerging deductions of this study are presented; finally, some conclusions are drawn in Section 6.

II. SHIPBOARD POWER SYSTEMS

The SPS is the electrical and electronic hearth of a ship, composed of a series of equipment such as power generators, buses, circuit breakers, different kind of loads, and other electric sub-systems such as navigation, communication, and others. Loads often are distributed in zones and fed power from the main electric buses. Since the last decades, ships are equipped using DC-equipment mostly because they show several advantages if compared to the AC counterpart:

- smaller components and compact power converters
- easier connections
- no reactive power and harmonic issues
- faults reduction and easier reconfiguration procedures

On the contrary, the main disadvantage of DC systems is that voltage shifts are more difficult to be realised than in AC systems where transformers do that with minimal losses.

A. SPS Reconfiguration

Reconfiguration in an electrical SPS is a critical operation requested in unexpected situations such as in the case of severe or major faults. The reconfiguration procedure is driven by the ship power and energy management control that communicates with all the generators and loads to keep the continuity of service during reconfiguration operations. In this way, the reconfiguration of the electrical layer can isolate faults, restore/transfer power to vital loads, but also more generally to optimise the management of electrical and electronic equipment to improve energy efficiency.

During normal navigation or after a specific event such as a weapon effect or a collision, there can be a series of multiple equipment damages. These can affect electrical layer and/or other systems such as control one.

The strategy that enables restoration of the electrical power system is called *reconfiguration*. The number of steps and the adopted strategies that can also involve human intervention may vary. In particular, from a recent work [4] it is possible to depict that in literature exists several software-based reconfiguration techniques that enable smart and almost-immediately reconfiguration of the electrical layer after the appearance of a fault (or a series of faults). These systems got a specific environment perception that enacts reconfiguration strategies basing on several different levels of “smartness”, allowing a sophisticated real-time perception and a ready management in case of emergencies.

Smart reconfiguration methodologies are a challenging task that needs complex coordination between electrical power and protective functions, and they are applicable to several different electrical architectures, such as radial, ring, zonal, and others. Especially in zonal architectures, the zones are interconnected among them, and a single minor fault may spread in a systemic failure; on the contrary, they seem to be the most reliable in order to isolate and repair electric failures.

A simplified example of high-performance medium-voltage DC-current (MVDC) ship power system design [7] is shown in Figure 1.

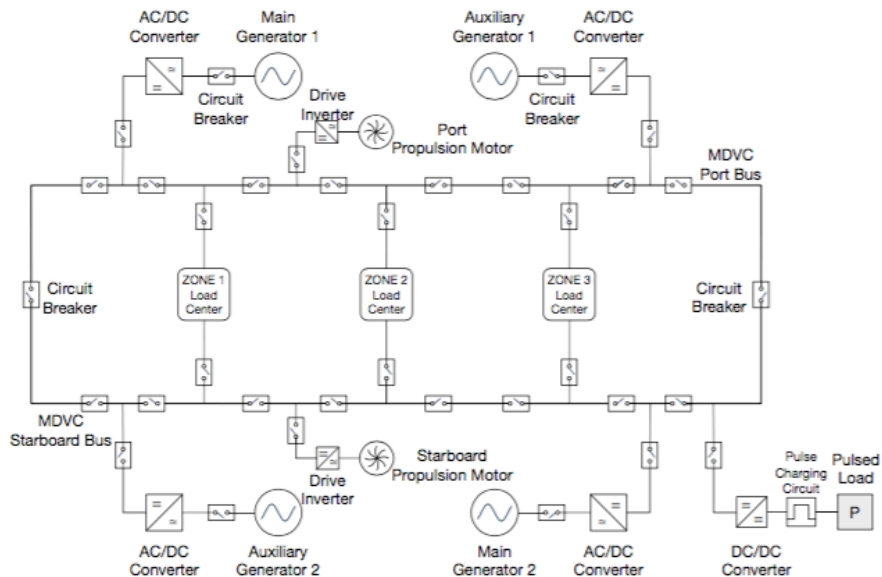


Figure 1: A typical SPS MV-DC topology.

It is composed of two main and two auxiliary power generators; a port and a starboard electrical bus; three zones with a series of loads; other electrical equipment such as AC/DC converters, circuit breakers, pulsed loads and others.

The electrical layer is ideally divided into zones corresponding to the feeds, i.e. Zone 1, 2, and 3. The two main buses connect loads and generators, and they can be supplied from any of the main AC generators through a power supply, while breakers are used to connect and disconnect equipment from power supplies.

It is usual to classify loads according to their importance into vital and non-vital categories, where vital loads are non-sheddable loads that directly affect the survivability of the ship, while the non-vital ones may be shed in order to prevent a total loss of ship’s electrical power, or for protection purposes. Moreover, the loads can be categorised regarding QoS as uninterruptible, short-term interrupt, and long-term interrupt [8].

- Un-interruptible load: loads that can not tolerate power interruptions on the order of two seconds;

- Short-term interrupt load: loads that can tolerate power interruption in the order of maximum one-five minutes;
- Long-term interrupt load: load that can tolerate service interruption longer than five minutes.

Here, a brief example wants to clarify when the reconfiguration procedure is activated, and what its capabilities are. Let us assume that loads of zone #3 are the less vital for the ship. Suddenly, during a battle scenario, let's suppose that the vessel is hit on the port side, and at time $t=0$, a series of contemporary faults happens, i.e. a fault on the bus near the generator #1, a fault between zones 2 and 3, and a fault on the auxiliary generator #1, as schematically depicted in Figure 2. The sensors of the power control system detect failures and immediately starts the reconfiguration procedure (time $t=1$), opening circuit breakers for isolating faults, and shutting down both the main generator #1 and the auxiliary generator #2, as can be depicted in Figure 3.

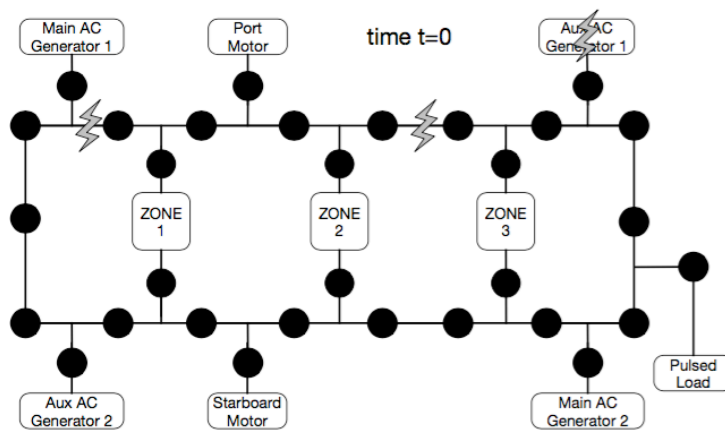


Figure 2: Several multiple and contemporary faults of the on-board SPS after a weapon hit.

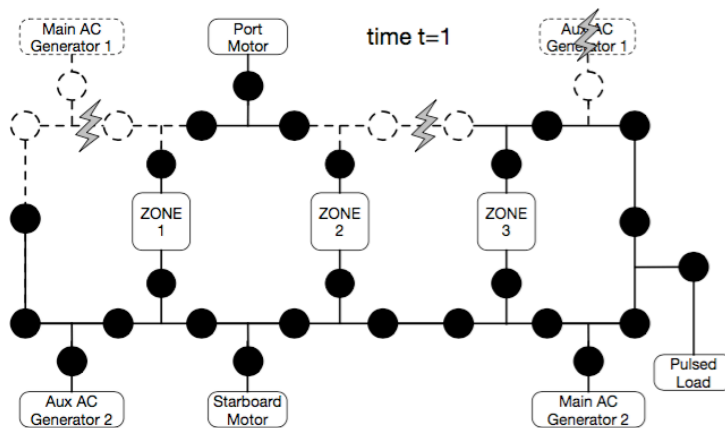


Figure 3: The reconfiguration procedure isolates the faults opening the appropriate circuit breakers (white circles).

After the reconfiguration of the electrical layer, the power system control detects that the overall generated power from main generator #2 and auxiliary generator #2 is not sufficient to satisfy all the demanded power of the loads. Most of the reconfiguration algorithms are able to perform load-shedding, that shed non-necessary loads; in this case, a priority list depicts that loads of zone #3 are the less important for the ship survivability, so the algorithm opens the circuit breakers near the zone #3 shedding

the loads in order to not compromise the survivability of the ship, as can be depicted in Figure 4 (time $t=2$).

In [4], reconfiguration algorithm' sub-problems are classified according to the capability of facing single or multiple failures, considering also load priorities and shedding capabilities:

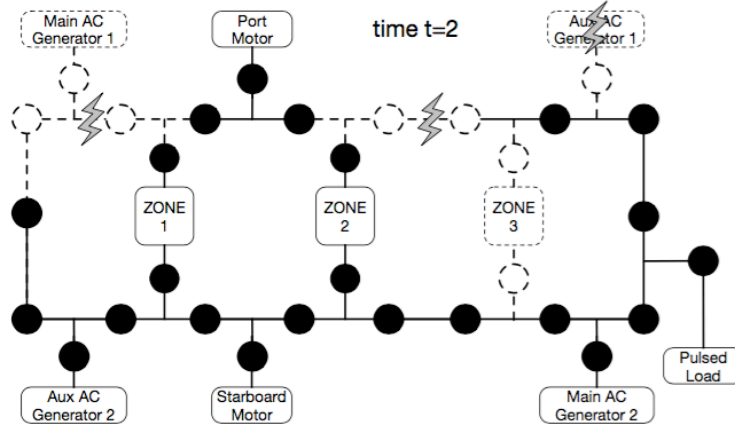


Figure 4: The reconfiguration procedure sheds the non-vital loads of zone #3 due to insufficient generated power.

- **Faults:** they can be single failures, multiple and contemporary failures, cascade failures, or predicted failures;
- **Load Priority Capability:** if the reconfiguration algorithm considers loads according to priority levels, such as vital loads, semi-vital loads, and non-vital loads;
- **Load Shedding Capability:** if the reconfiguration algorithm is able to shed loads for protection purposes, or for insufficient generated power (i.e. a generator is not able to supply all its power to loads, and some non-vital load may be shed).

A correspondence between load's vitality and interruptibility is depicted in Table I.

Table I: Load's vitality and interruptibility features.

	Non-Vital Loads	Vital Loads
Un-interruptible load	-	✓
Short-term interrupt load	✓	✓
Long-term interrupt load	✓	-

These reconfiguration sub-problems may be managed using smart and proactive methodologies, which at run-time can detect, isolate, and restore the system (or part of it) after failures. The reconfiguration strategy will attempt to recover the fault after a precise series of step, that can be decided at design-time, or elaborated at run-time.

In the next section, the proposed comparison approach will discuss these reconfiguration procedures from a self-adaptation point of view.

III. THE REVIEW METHODOLOGY

Systematic literature reviews are conducted to “identify, analyse and interpret all available evidence related to a specific research question” [10]. To achieve this goal, this review follows the guidelines set in [9]: (i) planning, (ii) conducting and (iii) reporting. Four researchers were involved in the review, and it took around three months.

In the planning phase of the review, the main aspects are: identifying the need for the review (i.e. the specification of research questions), and the definition of a review protocol. The protocol includes a search and evaluation strategy, some inclusion/exclusion criteria, data extraction forms and synthesis methods. Figure 5 depicts the proposed comparison approach.

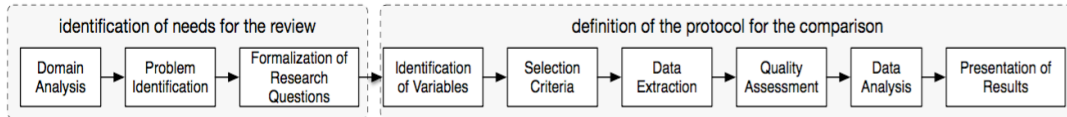


Figure 5: The proposed comparison approach based on Brereton et al.'s guidelines [9].

A. Identification of the Needs for the Study

The SPS reconfiguration can be achieved with several techniques, having their roots in research fields like artificial intelligence, operations research, and knowledge engineering.

A previous study [4] highlighted that SPSs have many similarities with self-adaptive systems. The first relevant attribute is that the control system monitors the electrical layer, mainly for identifying network features and faults. The second –even more interesting– feature is the implementation of various types of feedback loops [11]. This point is interesting because SPSs and self-adaptive systems have different roots and a direct association has never been done. Indeed the terminology is sometimes difficult to conciliate. However, despite a different vocabulary, probably SPS and self-adaptation share more than what is immediately visible.

The purpose of this survey is to investigate to which extent engineering an SPS may be considered as a sub-problem of building self-adaptive systems [5], [11]. Answering this question may provide an interesting synergy between these two research areas. From the one side, SPS may represent an interesting benchmark for comparing self-adaptive approaches; on the other hand, the state-of-the-art in self-adaptive systems may provide new ideas for improving existing reconfiguration techniques.

Research Question. This paper formulates the following research question:

RQ 1: *Are self-adaptive software systems suitable for the solution of SPS reconfiguration problems?*

The research question is formulated as a comparison of two research lines: shipboard power reconfiguration and self-adaptive systems. Hence, the objective is to conduct a systematic review of the state-of-the-art to provide empirical evidence for a possible synergy. The baseline for self-adaptive systems is constituted by two research agenda [6], [5], some position papers about relevant features of self-adaptive systems [11], [12], [13] and a paper proposing a taxonomy of types of adaptation [14].

In order to simplify answering the *RQ 1*, it has been decomposed in a couple of sub-questions.

RQ 1.1: *Does the state-of-the-art highlight common characteristics between self-adaptation systems and software-based strategies for the reconfiguration of the SPS?*

In particular, the following features have been identified as relevant for implementing a self-adaptive system [6], [5]: i) specification of goals and quality assets, ii) run-time decision-making, iii) anticipation of changes, iv) techniques for reaction, v) feedback loop, vi) human in the loop, vii) duration of the adaptation. The specification of goals and quality assets indicates the flexibility of the system to deal with high-level and dynamic requirements [6]. The degree of autonomy in the decision process often measures the ability of the system to take decisions about its behaviour: the level of abstraction used in the decision process has a great impact on the mechanisms for the adaptation [5]. Assuring the continuity of service is often related to the ability to anticipate failures and changes [6]. The techniques for reaction capture how the system deals with unanticipated changes [6], [5]. The feedback loop is a fundamental part of the architecture of a self-adaptive system, and many reference models are available in the literature [6], [11], often including the human in taking some role in it. Finally, the time aspect is central for a self-adaptive system, because it strongly contributes to reliability and robustness [6], [5].

Moreover, a second sub-question can be formulated as:

RQ 1.2: *Which kind of adaptation is more suitable for a software controlling reconfiguration of the SPS?*

The definition of self-adapting system is quite fuzzy thus to gather many sub-fields under a common umbrella. In the last years, Qureshi et al. [15] have provided a classification with four categories of adaptation: *Type I* consists in systems in which the reaction to changes is anticipated at design-time: the system owns a single operating plan. This plan may contain decisions points that are influenced by the results of perceptions about the environment. In the SPS domain, the plan aims at generating a reconfiguration schema as a consequence of the perceived fault. *Type II* consists of systems that own many strategies for reacting to changes: the selection of the right one is done at run-time. The run-time decision manages a trade-off between goals and quality aspects, and it is influenced by monitoring the environment. *Type III* consists in systems able to operate with uncertain knowledge about the environment; they do not own pre-defined strategies but it rather assembles ad-hoc functionalities, according to dynamic goals and quality aspects and the execution context. *Type IV* is inspired by biological systems that are able of self-inspecting and self-modifying their own specification when no other possible additions or simple refinements are possible.

To answer *RQ 1.2*, we exploit the meta-model drawn in [16] that reveals the increasing complexity of the four types, from the type I (the less complex) to the Type IV (the most complex). In particular, Type II is characterised by an ‘Awareness Engine’ and therefore on the possibility to reason on runtime models. Type III introduces a ‘Solution Builder’ that generates new strategies on the fly, by exploiting a repository of core functionalities. Finally, Type IV is characterised by an ‘Evolution Engine’ that is able of changing the run-time model for enacting new functionalities that are not available.

B. Establishing the Protocol for the Comparison

The characteristics of the problem generally lead to the identification of a protocol that establishes the procedure for conducting the review [10].

Identification of Variables. From the research questions, three qualitative variables are set for the following analysis:

- 1) algorithms used for the reconfiguration (independent): the algorithms are extracted mainly by looking at the sections of the papers where the approach is described;
- 2) reconfiguration sub-problems (independent): the reconfiguration sub-problems, as loads priority, loads shedding and the number of failures the system can handle.
- 3) self-adaptive characteristics of the approach (dependent): the characteristics are extracted by looking at goals/quality aspects, algorithm to derive reconfiguration schemas, decision-making process and feedback loop architecture;

Selection Criteria. To answer the research questions, an extensive search for research papers was conducted. The search strategy contained the following decisions. Firstly relevant databases have been identified: IEEE Xplore, Springer Link, ISI Web of Knowledge, ScienceDirect, Wiley Inter Science Journal Finder, ACM Digital Library. Then, a large collection of papers is selected from the following journals (IET Journals & Magazines, IEEE Transactions on SMC, PS, IAS, II) and conference proceedings (IEEE ESTS, ITEC, ICIST, ISAP, NAPS, PESGM, ACC). The search is done by accessing digital libraries, using a set of keywords (as ‘shipboard reconfiguration’, ‘shipboard power fault’, ‘shipboard power restoration’).

The search strategy (inclusion criteria) regards: i) written in English; ii) only published works; iii) date of publication: 2000–present; iv) no duplicates; and v) focus on software SPS reconfiguration techniques. It is worth noting that, according to this selection criteria, the strategy is to discard every approach based on a hardware solution or an *embedded* solution.

Data Extraction. Once the papers are selected, a data extraction form is provided to facilitate collecting the required information for the review. The form is reported in Table II.

Table II: The data-extraction form used by the authors.

Paper info	Authors, year of publication, conference/journal, number of citations
Short summary	brief description of the paper
SPS Technique	main algorithm used for the reconfiguration
SPS Reconfiguration sub-problems	failures, load priority, load shedding
Goals	hard-coded (H-C), multi hard-coded (M-HC), run-time model(R-T)
Decision Making	hard-coded rules, goal-based, QoS-based, learning, utility function
Trigger for reconfiguration	monitoring, prediction
Feedback Loop	centralised, decentralised, multi-level
SAS Adaptation Type	I, II, III, IV
Case Study Size	small (1-20), medium (20-50), large (50-100), very large (+100)
Repeatability	experiment/simulation data
Prototype	hw prototype, sw prototype

Researchers of the group split the work of reviewing and analysis of the articles. Some are occupied to extract the technical data relating to the sub-problems, the goals and the algorithms used. Others have dealt with the classification of items. To classify the type of adaptation, the reviewer focuses on the run-time decision-making process.

If the decision-making is a hard-coded strategy (like *if..then..else* statements or a set of rules), then the type is I. This kind of system must be able of monitoring the environment to enact the strategy.

If the system is instrumented with more alternative strategies to adopt, and the strategy is selected at run-time, then the type is (at least) II. This kind of system must be able of monitoring non-functional aspects that allow making a decision about the optimal strategy to be used.

If the system is able of assembling new strategies according to the contextual needs, then the type is (at least) III. This kind of system must be able of monitoring the state satisfaction of the objectives to be addressed thus to evaluate possible deviations and to decide to generate new ad-hoc functionalities.

Table III: Run-Time decision making activities and decisions

Adaptation	Monitoring	Execution
type I	environment	reconfiguration strategy
type II	quality aspects	strategy selection
type III	goal satisfaction	ad-hoc assembled strategy
type IV	self-inspection	evolution

Finally, if the system is able of generating, at run-time, new basic functions then the system is IV. This kind of system must be able of inspecting its own source code for evaluating which kind of changes to execute.

It is interesting to highlight that approaches of Type II and Type III are very similar to multiple-model approach and adaptive control approach depicted in [1], respectively, where the multiple-model is a bank of parallel models that describes the system under normal and faulty conditions (coded strategy selected at run-time), while the adaptive-control approaches estimate system parameters on-line (assembling new strategies according to the contextual needs).

It is worth noting that this kind of system does not necessarily correspond to a genetic algorithm approach. Along with this review, we faced some SPS approaches based on genetic algorithms. However, on a deeper analysis, these approaches have been employed for building a reconfiguration plan, i.e. a solution strategy rather than a new system functionality.

During the analysis, the reviewers will be supported with the guidelines in Table III. To avoid biases in classifying the type of adaptation, for this task, reviewers are divided into two groups (each composed of two persons). Each group is asked to provide a decision about the type of adaptation. Where the classification is different, an expert moderator is asked to solve the conflict and take the final decision. In the case the moderator is still undecided then the type attribute is flagged as 'not available' (n/a).

Analysis. The aim of this work is to provide an answer to the research questions that have been identified. Due to the qualitative nature of data, statistical analysis was infeasible. The analysis is mainly based on clustering data in categories, to identify possible trends and answering to research questions. However, a statistical analysis may also be conducted to check evidence of a direct correlation between *reconfiguration techniques* and the *reconfiguration sub-problems*.

The selected papers are thirty-five and they are listed in Table IV, which summarises our results.

In this table we report the data extracted from papers (see Table II), using the selection criteria described before. Table IV synthesizes the conducted survey, reporting the reconfiguration techniques of the papers, and categorising them into

three main categories: SPS Reconfiguration Sub-Problems, Self-Adaptation Attributes, and Quality Assessment.

The SPS sub-problems depict the kind of failures, in terms of single, multiple, and cascade failures; both load priority and load shedding attributes are pointed out. The Self-Adaptation Attributes are related to the used technique in a self-adaptation fashion. In particular, the goal may be coded into the solution or calculated at run-time; the decision-making process can rely on a utility function, on a rule-based reasoning, or on quality metrics. The Quality Assessment columns are related to the case study, where the SPS electrical layer can be small, medium, large or very large depending on the number of equipment. Repeatability is pointed out when it is possible to repeat the experiment using the provided data; the prototype can be a hardware implementation or a software simulation.

Table IV: Data extracted from the review.

Legend: Technique column (PSO=Particle-swarm optimization, MAS=Multi-agents system, GA=Genetic algorithm, MDP=Markov decision-process); Failures column (SF=single-failure, CF=cascade-failure, MCF=multi-contemporary failures, FP=failure-prediction); Goal column (M-HC=multi-hard coded, HC=hard-coded, RT=run-time); Decision-making column (U=utility-function, R-B=rule-based, L=learning, Q-B=QoS-based, G-B=goal-based); Triggering column (M=monitoring, P=prediction); Loop column (M-L=multi-level, D=decentralised, C=centralised); Case Study Size column (S=small, M=medium, L=large, VL=very large).

Technique	SPS Reconfiguration Sub-Problems			Self-Adaptation Attributes					Quality Assessment		
	Failures	Load Priority	Load Shedding	Goal	Decision Making	Triggering	Loop	SAS Type	Case Study Size	Repeatability	Prototype
[17] Metaheuristic	SF	✓	✓	M-HC	U	-	-	I	L	✓	SW
[18] MAS	SF	✓	✓	M-HC	R-B	M	M-L	I	S	-	SW
[19] MAS	SF	-	-	HC	R-B	M	D	I	L	✓	SW
[20] MAS	SF	✓	✓	M-HC	R-B+L	M	D	II	S	-	HW+SW
[21] Optimization	MCF	✓	✓	RT	U	M	C	III	M	✓	SW
[22] Linear Programming	MCF	✓	-	RT	U	M	-	III	M	✓	SW
[23] Metaheuristic	MCF	✓	-	HC	U	M	-	I	M	✓	SW
[24] MAS	FP	✓	✓	M-HC	R-B	P	C	III	-	-	SW
[25] Metaheuristic	MCF	✓	✓	M-HC	Q-B	M	C	II	M	✓	HW+SW
[26] Metaheuristic	MCF	✓	✓	M-HC	Q-B	M	C	III	S	✓	SW
[27] Optimization	SF	✓	✓	M-HC	U	M	-	I	S	-	SW
[28] Probabilistic	CF+FP	✓	✓	M-HC	U	P	-	II	VL	-	SW
[29] Machine Learning	MCF	✓	-	HC	Q-B+L	M	C	III	S	partial	SW
[30] Machine Learning	MCF	✓	-	HC	Q-B+L	M	-	III	S	partial	SW
[31] Deductive System	MCF	✓	✓	HC	R-B	M	-	II	VL	✓	SW
[32] MAS	SF	✓	-	HC	R-B	M	D	I	M	partial	SW
[33] Metaheuristic	MCF	✓	✓	HC	U	M	-	I	L	✓	SW
[34] Optimization	CF	-	-	M-HC	R-B	M	C	III	S	-	SW
[35] MAS	SF	✓	✓	M-HC	R-B	M	M-L	I	VL	partial	SW
[36] Metaheuristic	SF	✓	-	HC	U	M	C	I	M	-	SW
[37] Metaheuristic	SF	✓	✓	M-HC	U	M	-	III	L	✓	SW
[38] Deductive System	SF	✓	✓	RT	R-B	M	C	III	S	-	HW+SW
[39] MAS	-	✓	✓	HC	R-B	M	D	III	S	-	SW
[40] Metaheuristic	-	✓	-	HC	R-B	M	C	III	L	✓	SW
[41] Linear Programming	SF	-	-	HC	R-B	M	C	II	L	✓	SW
[42] Deductive System	MCF	✓	✓	HC	R-B	M	-	II	VL	-	SW
[43] Deductive System	MCF	✓	✓	HC	R-B	M	-	II	VL	-	SW
[44] MAS	SF	✓	✓	HC	R-B	M	-	I	M	-	SW
[45] MAS	-	-	-	HC	R-B	M	D	I	S	-	SW
[46] Metaheuristic+MAS	MCF	✓	✓	RT	Q-B	M+P	D	III	L	-	SW
[47] Metaheuristic+MAS	SF	✓	✓	RT	Q-B	M	D	III	S	-	HW+SW
[48] Metaheuristic	SF	✓	-	M-HC	R-B	M	C	II	M	✓	SW
[49] MAS	-	✓	✓	HC	G-B	M	D	II	M	-	SW
[50] Metaheuristic	SF	✓	-	M-HC	R-B	M	C	II	M	-	SW
[51] Metaheuristic	SF	-	-	HC	R-B	M	C	I	M	-	SW

The next section reports the results and a detailed discussion of them.

IV. RESULTS

The analysis of the papers reveals a great variety of approaches for SPS reconfiguration. The most used approaches are multi-agent systems (MAS) and metaheuristic methods. Others, less used, are based on optimisation, machine learning, and deductive reasoning.

Figure 6 reports a series of pie-chart diagrams that highlight the relationships between one of the SPS sub-problems (multi-failures, reconfiguration priority, and loads shedding) with each of the selected characteristics of a self-adaptive system: goal definition, decision making, and feedback loop. Below, some interesting findings are commented.

Goals/QoS definition (see Figure 6.a/b/c). Multi failures management is mainly realised by *hard-coded* goals. Conversely, it seems that *hard-coded* and *multi hard-coded* are equally used to address the reconfiguration with priority, while *multi hard-coded* are more predominant if in the case of load shedding. The use of dynamic goals, specified at run-time, is quite constant (20-25%) in the three cases. We discovered that dynamic goals are often correlated to a meta-heuristic approach. Indeed, goals are used in meta-heuristic approaches in order to specify quality of service rather than functional objectives to be fulfilled. Summarising, some of the analysed approaches adopts high-level specification of goals, while the remaining approaches hard-code them into the code, or use some utility functions for selecting the desired result.

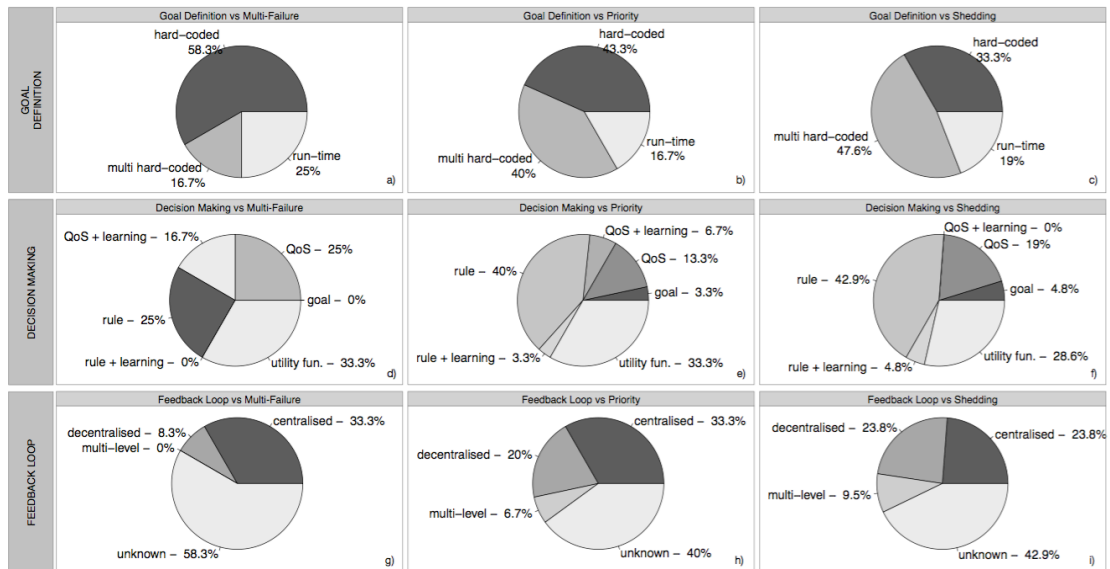


Figure 6: Pie-Chart diagrams that show the relationship between Adaptation and SPS reconfiguration.

The data analysis shows that static goals have been implemented into SPS control systems until 2006; after, smarter goal implementations (multi hard-coded and run-time) have been used. Furthermore, run-time goals are implemented by type III adaptive systems as can be depicted from IV.

Decision Making (see Figure 6.d/e/f). The management of multi failures seems strictly related to a specific type of decision-making based on either an *utility-function* or a *rule-based* system. The first category is mainly adopted in meta-heuristic approaches, whereas the latter is employed in deductive and multi-agent systems. The choice of the decision-making approach appears to be relevant for handling reconfiguration priority and load shedding.

Feedback loop (see Figure 6.g/h/i). Although some papers do not provide this information (unknown labelled results in Figure 6.g/h/i), the remaining ones are mainly either centralised or decentralised. Despite the capability to scale, the multi-level architecture is scarcely adopted and mainly it is used in type I adaptive systems. It is worth noting that decentralised control always corresponds to multi-agent

systems. It is worth noting that decentralised control always corresponds to multi-agent systems.

Triggering. Pie-charts for the triggering attribute have been not shown, because, in almost all the studied papers, the cause of adaptation is due to a monitoring of actual energy in circuits (see Table IV). So the emerging data is not relevant for this analysis.

Type of Adaptation. Figure 7 shows a histogram for the adaptation type used for implementing the various SPS sub-problem (multi-failures, priority and load shedding). This

diagram highlights that approaches with adaptivity classified as type III are the most used for each of the three categories: multi-failures management, adaptation with priority, and load shedding. Conversely, Type IV (a form of adaptation very complex to achieve) is never adopted for SPS reconfiguration. Other considerations may be done by analysing separately the three categories. Whereas for load shedding and priority the difference among the type of adaptation is moderate, in the management of multi-failure, type III appears very often, and it is definitively the most adopted one.

The data analysis highlights that the classes of *meta-heuristic* and *multi-agent* algorithms are used for all three types of adaptive systems. *Machine learning* is only used for type III adaptive systems, while *probabilistic* algorithms are employed in type II adaptive systems.

Concluding the analysis, Table V reports the results of the *Polychoric Correlation* [52], a test frequently used for studying the dependency between two ordinal variables. In this case, this test for checking the correlation between the self-adaptation domain and the SPS domain has been used.

The first evidence is that the kind of goal specification is weakly related to the loads shedding functionality. This emerges because the use of goals as run-time entity has never been adopted in the analysed works [6]. The most frequent solution is to hard-code goals into the code, making them disappearing at run-time. Some solutions try to provide a mathematical formulation of goals, thus to be included (in alternative or in conjunction) for calculating the utility function. Indeed, a dependency appears between goals and shedding. This may be justified by looking at the shedding columns of Table IV. Evidently, when the SPS system implements the load shedding, it also implements the reconfiguration with priority.

In other words, the load shedding is always a ‘second’ option for the reconfiguration, i.e. the system must choose which kind of reconfiguration to operate. For supporting this run-time decision, it is necessary to implement goals and QoS in specific ways.

Additionally, there is no (or little) dependency between the type of decision making and the SPS sub-problems (multi-failure, load priority and shedding). All kind of approaches (utility-functions, rule-based systems, and QoS based) have been used, across the various papers, to solve the three sub-problems.

Conversely, the kind of event that triggers the adaptation is strongly related to the kind of failures. It strongly depends on the specific reconfiguration technique.

Also, the kind of implemented feedback loop is strongly related to the reconfiguration technique and the domain. For instance, a decentralised feedback-loop solution is often realised through a multi-agent system.

For example in [46] an agent will not have complete control over its environment; it is limited to a domain of reasonable complexity, where it has only a partial control and knowledge of the surrounding system. Moreover, agents have the capability to

influence a part of the whole environment, giving rise to dependence relationships between the agents.

Finally, the kind of adaptation is a relevant data, because it is strongly related to the characteristics of the fault to be repaired. For instance, as seen in figure 7, an adaptation of type III is evidently associated with the most complicated multi-failures scenarios, while type II adaptation seems to be rather equivalent to type III for load shedding purposes and type I is used the same number of times of type II for load's priority scheduling.

Table V: Results of the polychoric analysis of factors. The result is interpretable as the Pearson correlation: a value $r = 0$ indicates no correlation, $0.1 < |r| < 0.3$ indicates a small correlation, $0.3 < |r| < 0.5$ indicates a medium correlation and $|r| > 0.5$ indicates a strong correlation.

	Goal/QoS	Decision Making	Triggering	Feedback Loop	Type
Technique	0.23	0.14	0.51	-0.07	-0.18
Failure(s)	-0.03	0.12	-0.55	-0.07	-0.54
Priority	0.53	0.13	0.95	0.52	0.36
Shedding	0.50	-0.15	0.98	0.46	0.14

V. DISCUSSION

This survey has provided evidence that system has many characteristics in common with self-adaptive systems. This section draws the conclusion that it is possible to positively answer to the RQs raised in Section III-A.

A. SPS as a Self-Adaptive System

The analysis shows there is a correlation between SPS sub-problems (failure, priority, and shedding) and the characteristics of a self-adaptive system (goal/QoS definition, decision making and feedback loop).

Indeed, the SPS reconfiguration problem embraces a series of possible scenarios, goals, and decisions based on functional and non-functional requirements. Goals are often global, i.e. the goal of restoring the SPS electrical layer after the occurrence of fault(s). However, the operating scenario may change, and a series of reconfiguration goals are requested to comply with specific requirements of the SPS electrical layer, concerning some specific constraint. This can go, obviously, through a series of sub-goals, i.e. protecting healthy loads (load shedding), re-routing energy to loads without power, and so on.

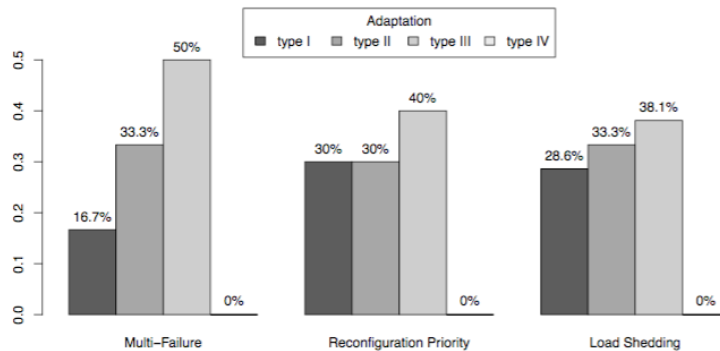


Figure 7: Histogram showing the relationship between SPS reconfiguration sub-problem and the four types of adaptation.

Moreover, the management of multi failures seems strictly related to the kind of decision-making approach. The choice of which kind of events to be handled (the triggering property) seems to be relevant for the reconfiguration with priority and load shedding.

Therefore, we can conclude that RQ 1.1 has been positively addressed.

B. Best adaptation for controlling reconfiguration procedure

To answer the second research sub-question (RQ 1.2, section III), it is possible to classify different approaches according to guidelines established in [14]. This is enforced by Figure 7 where the relationship between SPS and adaptation type is highlighted. It is a matter of facts that it is not possible to depict an overall winner methodology. Conversely, it is possible to highlight a series of characteristics that may be suitable for the reconfiguration problem in terms of adaptation type.

As shown in Table IV, the literature suggests that goals are mostly hard-coded or multi-hard coded in Type I and II, while run-time goals are mainly used in Type III.

Regarding the feedback loop, a centralised architecture is mostly used in Type III, while a multi-level architecture is exclusively used in SPS control systems of Type I.

Finally, looking at the technique used for reconfiguration problems, Type I is often implemented by using either multi-agent systems or optimisation algorithms. Type II is associated with probabilistic, deductive, and linear programming algorithms. Finally, Type III often adopts machine-learning, meta-heuristic, and optimisation algorithms.

As a summary, Table VI suggests the type of adaptation that from the analysis of literature seems to be the most suitable for solving SPS fault scenarios and goals. Operating conditions that are depicted in [8] may be suitable for any type of reconfiguration.

Table VI: Relation between SPS and self-adaptation types.

Fault Scenarios	Suggested Type
Single failures	Type I
Multiple Failures	Type II and III
Incoming weapon-hit	Type III
Goals	Suggested Type
Full service restoration	Type II and III
Maximization of an objective function	Type II and III
Prediction of damages	Type III
Re-routing the power according to priorities	Type I, II and III
Run-time load priority and magnitude	Type III
Load shedding	Type I, II and III
Operating conditions	Suggested Type
Cruise	Independent
Onload/Offload	Independent
Battle	Independent
Restricted manoeuvrability	Independent

It is clear that simple fault scenarios, such as single failures can be managed by systems of Type I, while advanced features such as multi-failures or faults prediction are managed using Type II and III adaptivity systems; in terms of goals, objectives such as power re-routing and shed of loads are achieved using Type I, while complex objectives request smarter Types (II and III). If the goal is damage prediction or run-time reconfiguration, we need to use Type III SPS control systems.

C. Limitations of this Study

In a systematic review, the external validity¹ and the construct validity² are ensured by capturing as much as possible of the available literature to avoid all sorts of bias. Consequently, the validity of this study considers three factors: i) the *search strategy*; ii) the *selection criteria* and iii) the *data extraction* as suggested in [53].

Search Strategy. In this work, the search was organised through a specific set of journals and conference proceedings. We selected some of major journals and conferences in the area, and then we used the snowballing technique as the complementary search technique. Indeed, by looking at the reference section of the selected papers, we have extended the search scope. However, some study may have missed due to the multidisciplinary theme of the SPS reconfiguration. In particular, we may have missed papers published in national journals and conferences. The search was conducted as a manual search process, not an automated search process. A couple of young researchers selected the candidate studies, although the final selection of studies to be included and excluded were checked by two senior researchers.

Selection Criteria. The duplication of papers is a potential threat to frequency counts and the statistics. During the review, several authors that recur in many papers have been

discovered. These papers can not be considered as duplicates, so they are not discarded, according to the selection criteria. However, reviewers had to consider possible bias due to approaches that were very similar. In these cases, we tried to judge the real improvement of the paper in the state-of-the-art and used a double check procedure to decide whether to discard it or not. This happened in only two cases. However, this decision may have introduced a threat to the internal validity of the study.

Data Extraction. To obtain consistent extraction of relevant information, we defined a data extraction form. A couple of young researchers conducted the data extraction and checked whether the data to be extracted would address the research questions. During this phase, the extraction of data about goals and decision-making proved to be the most difficult to extract because it required a high level of understanding of the studied approach. For dealing with erroneous data, and reducing the degree of subjective interpretation, data has been checked by an expert in multi-agent systems and an expert in self-adaptive systems.

Thus, in general, we believe that the validity of the study is high, given the use of a very systematic procedure and the involvement and discussion among four researchers.

VI. CONCLUSIONS

This paper reports a systematic review of SPS reconfiguration methods, to classify them regarding self-adaptation attributes. The survey has investigated to which extent engineering an SPS may be considered as a sub-problem of building self-adaptive system. The answer has been that the state-of-the-art highlights many common characteristics between self-adaptation and shipboard power reconfiguration. Moreover, it is possible to classify SPS reconfiguration strategies according to types of adaptive systems. This result highlights a potential synergy between two research areas that are quite independent so far. From the one side, SPS may represent an

¹ The external validity represents the possibility to generalise the results of the study.

² The construct validity concerns the reliability of measures

interesting benchmark for comparing self-adaptive approaches; on the other side, the state-of-the-art in self-adaptive systems may provide new ideas for improving SPS approaches.

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