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EXECUTIVE SUMMARY

The present public report from the GARPUR project synthesizes the main results of the work carried out in the context of work-package WP2 “Development of new reliability criteria for the pan-European electric power system”, 36 months after the start of the GARPUR project. The objective of WP2 was to develop a sound and general methodology to both assess and optimize power system reliability of the pan-European electric power system.

The mathematical/computational models were developed with the goal to predict the expected locations, amounts and durations of supply shortages implied by power system reliability management decisions. We also developed the optimization frameworks thanks to which reliability management decisions should be taken. The following list of requirements, ranked by increasing level of complexity have been taken into account while developing the new reliability management methodology:

- The reliability management methodology must be aware of the spatial-temporal variation of the probabilities of exogenous threats and take into account the socio-economic impact of its decisions.
- The reliability management methodology must explicitly take into account corrective control means and their probability of failure.
- The reliability management methodology must incorporate the possibility of using demand-side management to secure system operations.
- The reliability management methodology must cover both normal threats, as well as low-probability high-impact threats.
- The reliability management methodology must cover the multiple decision-making contexts and timescales, from long term planning to real-time operation, while enabling the evaluation of the effects of system expansion and asset management on the reliability management in operation, and vice-versa.
- The methodology must also take into account the multi-agent and multi-area nature of the organization of the pan-European electric power system.

WP2 thus essentially aimed at developing a conceptually sound reliability management methodology that is scalable to any control zone in Europe and robust by design to address the pan-European system at all time-scales. The results of the work are synthesized in the present report in the form of 5 chapters.

Chapter 1 provides a list of terms and definitions.

Chapter 2 starts with a discussion of the different practical reliability management contexts, followed by the definition of the notion of RMAC (Reliability Management Approach and Criterion) and by a generic functional analysis of reliability management decomposed into assessment and control tasks. It then discusses the need for coordination among different temporal decision-making horizons and introduces the notion of “proxy” to model shorter-term decision-making environments when considering longer-term reliability management problems. The chapter concludes by stating the main practical requirements for the RMACs that were developed in WP2.

Chapter 3 presents a general mathematical formalization of reliability management, in the form of a multi-stage stochastic programming problem explicitly stated by formulating a decision making horizon, a socio-economic objective function, and a reliability target in the form of a chance-constraint, and completed by a “discarding principle” prescribing a sought level of accuracy and a “relaxation principle” prescribing how to manage situations where the reliability target can not be reached. The last section of this chapter shows how this general mathematical framework can be used in the different practical contexts, from real-time operation and short-term operation planning, to mid-term outage scheduling and long-term system expansion and maintenance policy choices.

Chapter 4 describes the algorithmic implementations that have been developed both for real-time reliability management and outage scheduling, and discusses the main ideas proposed for operation planning and long-term decision-making. While in this chapter the focus is on the reliability control problems, which computational complexity is the most challenging, it also shows how the proposed algorithms can be used for the purpose of reliability assessment. This chapter concludes with a discussion of the main directions of further research in order to tackle the very high complexity of reliability management under uncertainties, especially by building on recent developments in the context of machine learning and optimization.

Chapter 5 discusses the coherency with the work carried out in the parallel work-packages of the GARPUR project, focusing respectively of the assessment of the socio-economic impact of reliability management, and on practical needs and goals relevant for reliability management in system development, asset management, and power system operation.

Chapter 6 summarizes the main finding of the work carried in WP2 and identifies the main steps needed for the practical implementation of its results, in the form of guidelines for further work during the last year of the GARPUR project, and beyond its termination.

1 TERMS AND DEFINITIONS

CAPEX: Capital Expenditures

Energy not supplied: Energy not supplied is the estimated energy which would have been supplied to end-users if no interruption had occurred [Nordel, 2009].

Monte-Carlo simulation: A family of simulation methods suited to problems where the input variables are largely random. From the distributions of the probabilistic input variables, many draws are sampled and then processed to compute the likely outcomes over a large space of possible situations.

N-1 criterion: The N-1 criterion is a principle according to which the system should be able to withstand at all times a credible contingency – i.e., unexpected failure or outage of a system component (such as a line, transformer, or generator) – in such a way that the system is capable of accommodating the new operational situation without violating operational security limits. (The definition is partly based on ENTSO-E documents [ENTSO-E, 2004a] and [ENTSO-E, 2013b].)

OPEX: Operational Expenditures

OPF: Optimal Power Flow

Proxy: In our framework, a proxy is a method that enables to quickly determine a realistic behaviour of the TSO for the shorter-term decision making stages. Normally such shorter-term decisions are made based on the low-level information that will be revealed in the future. However, from a longer-term perspective, dealing with such level of accuracy is not tractable and arguably realistic. Consequently, an approximated method is suitable.

Reliability criterion: A reliability criterion is a principle imposing a standard to determine whether or not the reliability level of a power system is acceptable.

RMAC: Reliability Management Approach and Criterion, namely the joint definition, for a certain reliability management context, of i) a reliability criterion and ii) a reliability constrained decision-making problem.

SCOPF: Security Constrained Optimal Power Flow

VOLL: Value of lost load (VOLL) is defined as a measure of the cost of energy not supplied to consumers (the energy that would have been supplied to consumers if there had been no outage). It is generally normalised in €/kWh [ENTSO-E, 2013b].

2 INTRODUCTION

The present public report documents the work within WP2 of the GARPUR[1] project titled *Development of new reliability criteria for the pan-European electric power system* (GARPUR Consortium 2013). The objective of WP2 was to develop a sound and general methodology to both assess and optimize power system reliability of the pan-European electric power system.

The report synthesizes the work carried out in WP2. Parts of the foundations of this work have also been published in [Karangelos, 2013], [Karangelos, 2016], [Dalal, 2016b], and [Dalal, 2016a].

The present report is organized as follows:

- The rest of Chapter 2 introduces the general reliability management framework and the main concepts and requirements that have been guiding the work of WP2.
- Chapter 3 explains the mathematical formulations developed.
- Chapter 4 focuses on the definition of scalable algorithmic approximations of the mathematical formulations.
- Chapter 5 focuses on the analysis of the developed principles and algorithms in terms of their coherency with the parallel work carried out in WP3, WP4, WP5 and WP6, further detailed in their corresponding deliverables D3.2 [GARPUR, 2016a], D4.2 [GARPUR, 2016e], D5.2 [GARPUR, 2016b] and D6.2 [GARPUR, 2016c]. These latter documents also discuss more in details the data and computational requirements within their focus.
- Chapter 6 concludes and provides guidelines for further work towards practical validations and real-life implementations.

2.1 Background information on WP2 within the GARPUR project

According to the *GARPUR Description of Work*, the GARPUR project designs, develops, and assesses new probabilistic reliability criteria and evaluates their practical use while maximizing social welfare. In response to the ENERGY call 2013.7.2.1: Advanced concepts for reliability assessment of the pan-European transmission network, GARPUR aims at:

- defining new classes of reliability criteria able to quantify the pan-European electric power system reliability in coherence with its evolution towards and beyond 2020;
- evaluating the relevance of the criteria and compare different reliability management strategies through impact comparison on the resulting global social welfare, thus pinpointing the most favourable evolutions away from the N − 1 criterion in the decades to come.

GARPUR also aims to ensure that the new reliability criteria can be progressively implemented by TSOs at the pan-European level to address new types of system threats while effectively mitigating their consequences on society as a whole. In this context, the work carried out in WP2 has been mainly focusing on the following two overall objectives of the GARPUR project:

- **O1:** To develop a consistent probabilistic framework for reliability management, covering the definition of reliability, the calculation of reliability criteria, and the formulation of optimization

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[1] http://www.garpur-project.eu/

problems expressing the economic costs and the desired target reliability levels at the pan-European level and within each individual control zone.

- **O4**: To ensure the compliance of the developed methodologies with the technical requirements of system development, asset management and power system operation, and to demonstrate the practical exploitability of the new concepts at the pan-European level and in all decision making contexts.

When starting the work in WP2, it became clear that the term “Reliability Criterion” was understood in different ways by different people, and hence needed clarification: the precise meaning of this term was thus first clarified within WP2. A “reliability criterion” is used for reliability assessment and control in order to ascertain whether a decision in a certain context would lead to an acceptable system response with a sufficiently high level of confidence. Beyond the precise definition of a family of such reliability criteria, suitable for the different decision-making contexts of TSOs, the work in WP2 also aimed at specifying in a formal way the decision-making problems that should be solved in order to choose decisions so as to meet a reliability criterion, and also how to relax the constraints of these problems when they are found to be unfeasible.

To avoid any confusion, we have therefore introduced the new acronym **RMAC** (standing for “Reliability Management Approach and Criterion”) to denote this notion of a joint definition, for a certain context, of i) a reliability criterion and ii) a reliability constrained decision-making problem.

2.2 The multiple facets of reliability management

In this section we synthesize the overall picture of the scope of the work carried out in WP2. We start by describing the various practical contexts of TSO’s reliability management, then we outline the general functional organization of reliability management combining reliability assessment and reliability control developed in WP2, and finally we discuss the various needs of coherency between reliability assessment and control activities carried out in the different TSO practical contexts.

2.2.1 The different practical reliability management contexts faced by TSOs

Figure 2.1 below shows the three main classes of TSO activities (System Development, Asset Management, System Operation) covered in GARPUR, within five different temporal horizons, namely long-term (several years to decades ahead in time), mid-term (several months to a few years), short-term (several hours to a few weeks), real-time (a few minutes to an hour), and finally ex-post.

This figure is the result of the analysis carried out jointly by WP4-5-6, and led to the definition of the precise scopes of the remaining tasks in these work-packages (see [GARPUR, 2015c][GARPUR, 2015d][GARPUR, 2015e]).

The intersections among lines and columns of Figure 2.1 define different reliability management contexts (i.e., classes of activities and corresponding temporal horizons) that need in principle to be addressed all by the methods developed within WP2. The objective of WP2 is thus to define a coherent set of Reliability Management Approaches and Criteria (RMACs) together with their algorithmic approximations so as to fit all these needs.

To this end, we first carried out a functional analysis of the actual reliability management processes, so as to isolate their main components, requirements, and variations. The resulting ideas are introduced in the next three subsections.

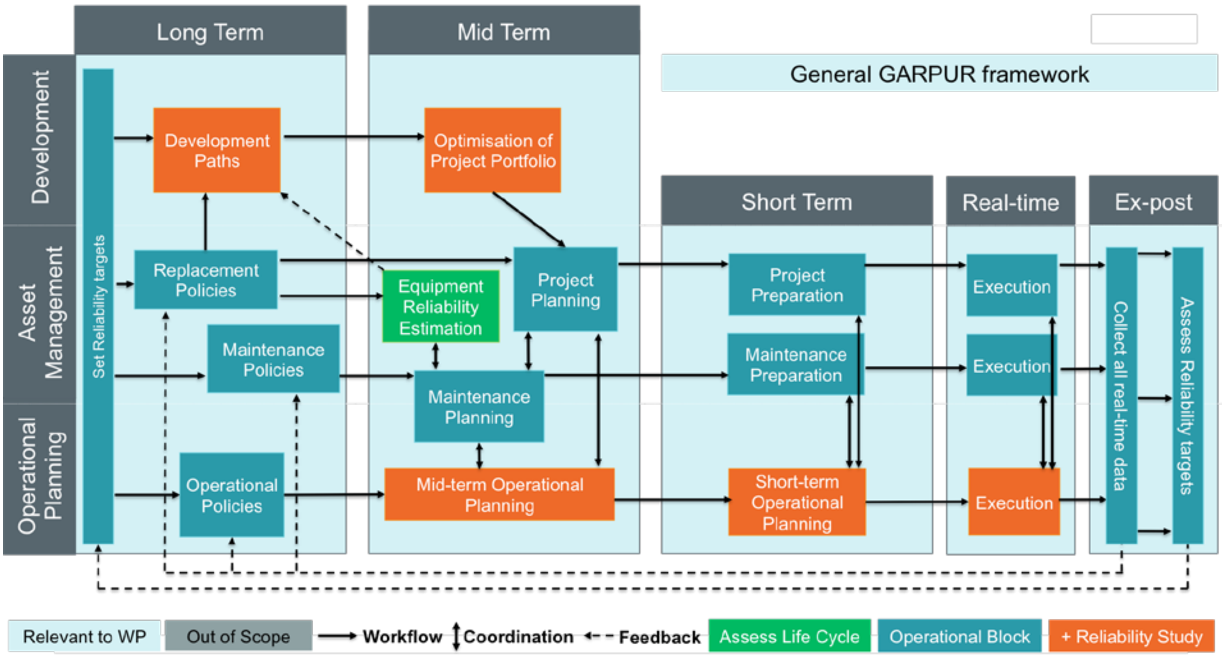


Figure 2.1: Reliability management contexts faced by TSOs.

2.2.2 A generic functional structure of reliability management activities

Figure 2.2 shows the generic functional structure of reliability management resulting from the work carried out in WP2.

From top to bottom, we find the three main functional blocks:

- **Modelling task**: aiming at defining the required models of the behaviour of the transmission system and its environment, while taking into account the possible internal and external threats.
- **Assessment task**: aiming at computing indicators and checking the criteria so as to evaluate reliability and socio-economic performance, for a given candidate decision.
- **Control task**: aiming at selecting among a set of candidate decisions one that is nearly optimal from the socio-economic point of view and that complies with the criteria, and, whenever this is not feasible, choosing how to relax the constraints of this optimization problem.

Notice that this organization is suitable for any practical reliability management context, from long-term system expansion to real-time operation, and that it covers as well current practice along the N-1 criterion, as any envisaged future practice along any suitable future probabilistic reliability criterion.

Figure 2.3 provides a more compact version of the same diagram, whose five components highlight the main ingredients of any reliability management approach and criterion, and need to be precisely defined for each particular context highlighted in Figure 2.1, in order to specify the methodology, as well as the models, data, and decision support tools required to fit the needs of that particular context. Notice that, while the diagram can obviously be instantiated in a different way for the different activities and temporal horizons of Figure 2.1, it is paramount to ensure coherency among these different instantiations. This is further discussed in the next section.

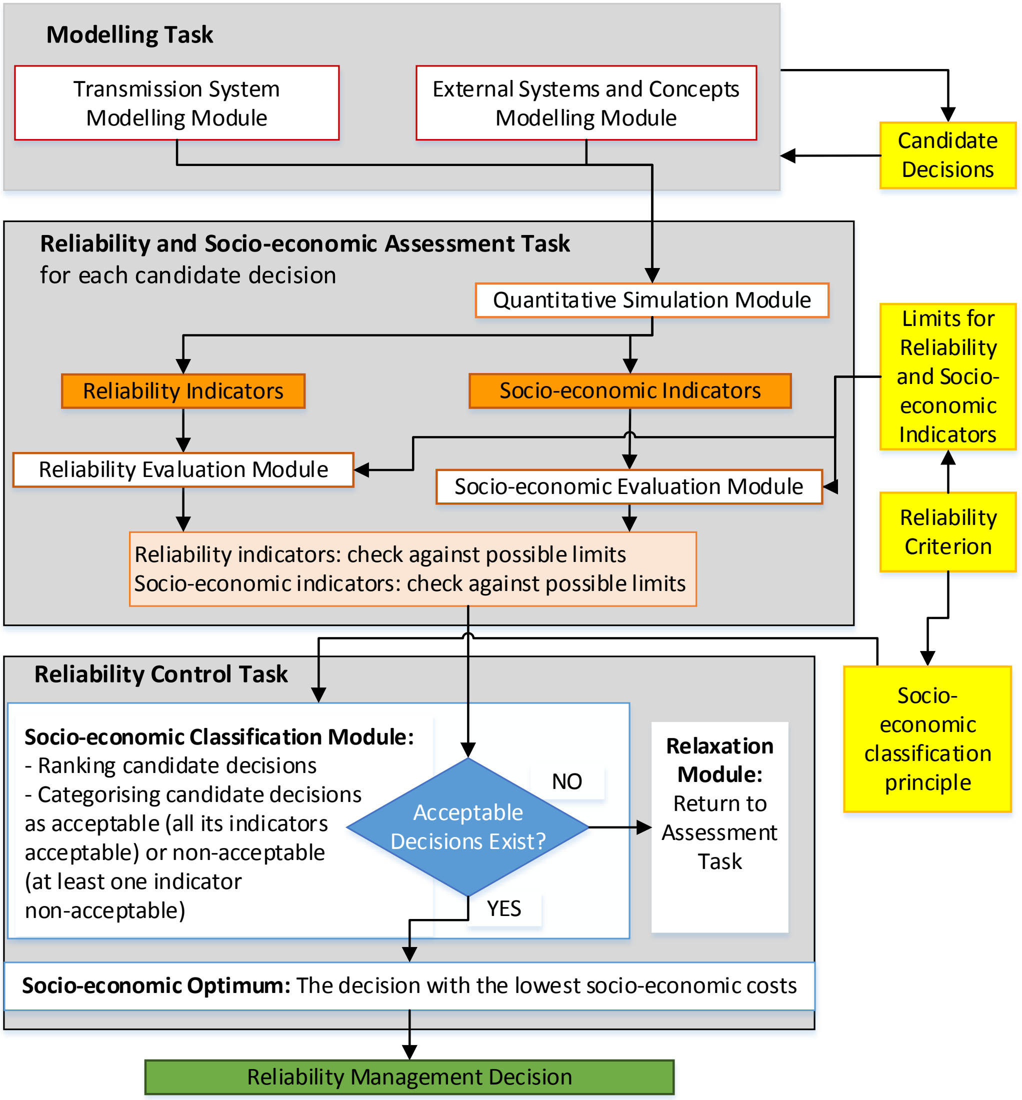


Figure 2.2: **Reliability management organization.**

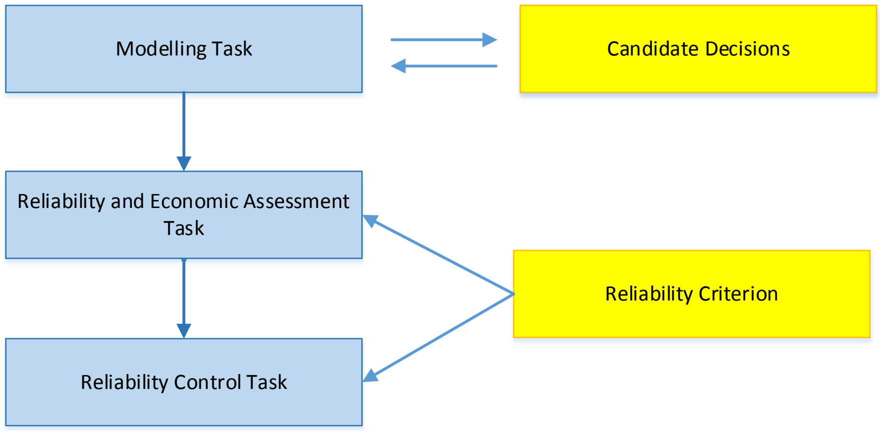


Figure 2.3: **Reliability management subtasks and their interaction with candidate decisions and reliability criterion in a generic context.**

2.2.3 Needs for coherency between the different reliability management tasks

The overall goal of WP2 is to develop well founded and practically usable RMACs that may be used in various tasks carried out in TSOs' reliability management contexts in order to take into account various kinds of uncertainties and stochastic factors that have an influence both on the reliability and on the socio-economic performances of the power system. The resulting methods would hence be used within the different contexts discussed in the previous two subsections. For this to make sense, it is most important to ensure that the different components of these methods (as those depicted in Figure 2.3) and their different declinations according to the various contexts (as those highlighted in Figure 2.1) are worked out in a coherent way.

In the next two subsections we explain what is actually implied by these needs for coherency.

2.2.3.1 Coherency between reliability assessment and reliability control in each context

In each context (as all those that are highlighted in Figure 2.1), reliability management is based on the use of two complementary methods as shown in Figure 2.4, namely:

1. an **assessment method**, whose aim is to help in deciding whether or not a given decision that could be taken in this context would meet the reliability criterion as well as to evaluate the implied socio-economic cost;
2. a **control method**, whose aim is to assist in the choice of the most appropriate decisions to take: starting from a set of candidate decisions, the goal is to automatically exclude those that do not meet the reliability criterion, and among the remaining ones select one with a (close to) optimal socio-economic impact. In addition, if none of the proposed candidate decisions meets the reliability criterion, the control method should also propose at least one way to relax the optimization problem in order to make it feasible.

In order to ensure coherency between assessment and control, within a specific practical context, both methods should be based on the same reliability criterion, and also use consistent representations of the system behaviour and the threats and uncertainties they take into account.

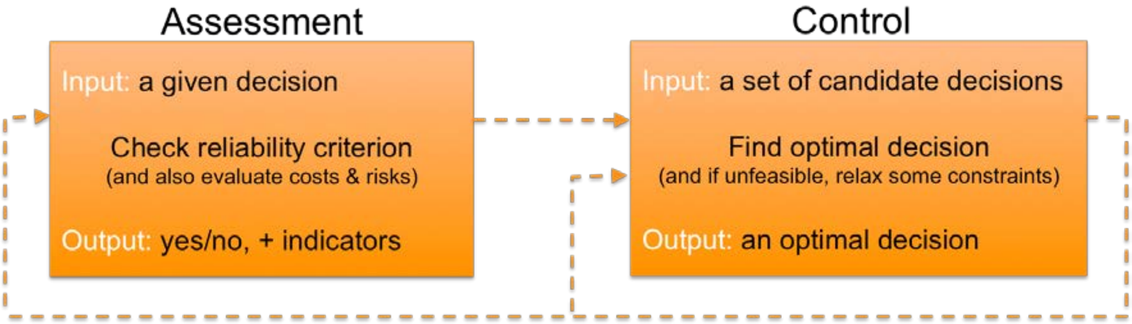


Figure 2.4: Interplay between assessment and control.

From an algorithmic point of view, the nature of the assessment and the control problems of a given context are however fundamentally different:

- **Assessment problem**: it is essentially a ***simulation problem*** aiming at verifying which (or which proportion) of a (potentially huge) number of constraints are satisfied, corresponding to a (typically very large) number of scenarios, each one of them being verifiable independently of the others. In this context massive parallel simulations can clearly be exploited together with a broad range of existing state-of-the-art scenario screening/sampling techniques.

- **Control problem**: it is essentially an ***optimization problem***, which aims at selecting among a given set of candidate decisions available in a particular context, one or several decisions that would lead to a successful outcome of the assessment problem. When the set of candidate decisions is finite and of small cardinality, this problem trivially reduces to a small set of assessment problems and can be solved by screening these candidate decisions with any suitable method for assessment, provided sufficient computing power is available (typically, at least one order of magnitude more than what would be needed for assessing a single candidate decision). However, in many practical contexts of reliability management, the space of candidate decisions is itself high-dimensional so that such a brute-force screening is not a tractable approach. Hence, the resolution of a reliability control problem will always be intrinsically much more complex than the resolution of the corresponding assessment problem. It will therefore require the development of smart optimization techniques, which will in the end also require simplifications in the physical models, as well as in the uncertainty models they explicitly take into account, so that they can fit the needs of real large-scale power systems such as those targeted by GARPUR.

One of the main goals of the work in WP2 is to define suitable approximations, trading-off in a proper way accuracy and computational tractability. From the above analysis of the natures of the assessment and control problems, we see that this compromise will have to be different for these two problems. This leads, for each one of the reliability management contexts, to the necessary use of more simplifications in the models used in its control method than in its assessment method. We can thus safely assume that within a given context, any near-optimal decision proposed by the control method should be passed back to the assessment method for a more precise 're-assessment'. This is suggested by the outer feedback loop from control to assessment shown in dashed lines in Figure 2.4. Similarly, the control method would be activated in practice only under the circumstance where the outcome of assessment requires the search for another decision, or under the circumstance that the previously considered control problem was found to be infeasible, as it is suggested in Figure 2.4 by the two other dashed arrows feeding the control method.

2.2.3.2 Coherency between RMACs used in different contexts via the notion of RMAC-PROXY

As we will explain in more details in Chapter 3, the GARUR notion of RMAC specifies in a mathematical way, and for a given practical context of reliability management, what it means for the power system to be considered as sufficiently reliable, and how decisions should be chosen in order to optimize the socio-economic performance of the system while assuring a target level of reliability. For instance, the "Real-Time RMAC" will specify in a mathematical way what we mean by managing reliability in the context of real-time operation, while a "Long-Term RMAC" would do this for system development and/or for maintenance policy choices.

In other words, our methodology in WP2 consists in decomposing the overall specification of how reliability should be managed, into a family of sub-specifications, each one focusing on a different subset of candidate decisions and on a different horizon for assessing the system performance for any of its considered candidate decisions, along the decomposition of current practice outlined in Figure 2.1. While we do not question this currently used decomposition into subsets of decisions and sub-horizons, we do explicitly address the coherency among the RMAC formulations considered for use in all these subtasks.

To explain the need of coherency between the RMACs used in different contexts, let us envisage the change of the RT-RMAC used in real-time, away from the current N-1 criterion towards a novel probabilistic approach, and let us analyse the impact of such a change on how reliability would have to be managed in other contexts considering longer time horizons. In other words, the question we want to address is the following one: “Assuming that the change of the RT-RMAC has been considered as a desirable one, how should then longer-term decision-making practice be adapted in order to support this desirable change away from the current N-1 based real-time reliability management approach?”

The answer to this question is as follows: “Longer-term RMACs need to model explicitly the way shorter-term reliability management is carried out, in order to assess and optimize their longer-term decisions, and they therefore should be able to model in a sufficiently flexible way the system behaviour implied by using any candidate RMAC considered for shorter term decision making.” Indeed, in order to enable change it is necessary to develop methods for longer-term reliability management that may take advantage and incorporate changes in shorter-term reliability management practice. We therefore developed the notion of RMAC-PROXY: an RMAC-PROXY is a (possibly very simplified) mathematical and computational specification of the reliability management process that is used by a TSO in a certain context, that is suitable for modelling this process in the context of other reliability management processes of the same TSO or of other TSOs.

The concept of RMAC-PROXY is very general, and it allows one to abstract away from the details of how reliability management is carried out by a certain TSO in a certain context, while taking into account the constraints resulting from this behaviour in another (broader) reliability management context of this TSO or of another TSO. A ‘proxy’ is thus a simplified model of a ‘source’ reliability management context, expressed in such a way that it may be effectively exploited in another ‘target’ reliability management context, while sufficiently well modelling the considered source-decision-making process for the purpose of the considered target-decision-making-process.

Figure 2.5: Russian dolls suggesting the entanglement of the different RMACs defined for different temporal horizons and decision-making stages.

The Russian dolls of Figure 2.5 suggest the entanglement of the different RMACs defined for different temporal horizons and decision-making stages of a single TSO: from long-term reliability management (on the left) to real-time operation (on the right). The bigger dolls correspond to higher uncertainties and more complex reliability management problems, relying more on human expertise. The smaller dolls correspond to fewer uncertainties but more stringent performance requirements. When considering a longer-term RMAC, one has in principle to model in a sufficiently accurate way all the shorter-term decision-making processes that are driven by their corresponding shorter-term RMACs. The specifications of the way these shorter-term processes are taken into account are therefore expressed in the form of proxies. In a similar way the behaviour of neighbour TSOs and DSOs may be formalized by describing the corresponding proxies.

In Chapters 3 and 4 of the present document we will use the concept of 'PROXY' to specify mathematical and algorithmic formulations of RMACS covering the broad scope of TSOs' reliability management.

2.3 Practical requirements for the proposed RMACs

In the following chapters we will present and discuss the various RMAC formulations and implementations proposed by WP2 for reliability management over the broad spectrum of practical TSO problems. These were designed by taking into account a certain number of requirements linked to practical applicability. We briefly discuss the dimensions of these requirements in the present section.

- **Relevant system behaviour and uncertainty models**: since the threats and uncertainties to be modelled are mostly defined by the time-horizon of decision-making, they can in principle be fully shared among contexts corresponding to a similar time horizon irrespectively of the particular set of candidate decisions considered. On the other hand, the models expressing the system behaviour and socio-economic cost functions over the considered evaluation horizon should possibly be adapted to the kind of decisions that would be evaluated, so as to correctly reflect the impact of the considered decisions on the relevant performance criteria.
- **Computational tractability**: the requirements, in terms of software response times and expected amount of data and computational resources that should be made available, may strongly depend on the reliability management context and be more or less easily covered by different TSOs. Our proposals aim therefore to be already compatible with current computational and data resources that could be deployed rather broadly in the existing decision-making contexts of several TSOs, and we will outline the approximations needed to make this possible.
- **Sustainability**: beyond the requirements that would enable the more or less immediate applicability of the proposed methods, we want also to ensure that these methods do not become obsolete as soon as more data or significantly more computational resources would become available, as we can forecast this to happen over the coming years.
- **Interpretability**: being conscious of the need to explain and convince when it comes to the evolution of power systems reliability management approaches, we also devoted part of our work in order to ensure that the proposed methods can be usefully compared with existing approaches, in particular those based on the N-1 criterion.

3 A GENERIC MATHEMATICAL MODEL OF RELIABILITY ASSESSMENT AND CONTROL PROBLEMS

In this chapter we present, in mathematical terms, the general probabilistic framework developed in WP2 in order to state in a precise way the family of proposed RMACs, for the different contexts and timeframes of TSO decision making, and we also explain how they translate into

- a family of 'simulation problems' corresponding to the use of these RMACs for the purpose of reliability assessment
- a family of 'optimization problems' corresponding to the use of these RMACs for the purpose of reliability control
- a family of 'proxy specifications', responding to the need for explicitly modelling shorter-term reliability management activities when assessing and/or optimizing decisions in the context of longer-term reliability management activities.

The present chapter is organized in the following way:

- In Section 3.1 we briefly discuss the two main uncertainty modelling frameworks developed in operations research, namely robust optimization and stochastic programming approaches. We argue that both frameworks are relevant in the context of power system reliability management, but that the latter (the stochastic programming approach) is more general and thus more suitable as a generic modelling approach, and has therefore been adopted as an overarching mathematical framework for the development of the theoretical formulations of the GARPUR RMACs.
- In Section 3.2, we describe and motivate the 4 mathematical ingredients of the proposed family of probabilistic RMACs and we explain how they can be used both for reliability assessment and reliability control. We also show how the currently used deterministic N-1 criteria can be seen as particular (but very much downgraded) versions of this family of probabilistic RMACs.
- Section 3.3 explains the main ideas that we propose for adapting the proposed mathematical formulations when going from real-time to long-term reliability management contexts. In this section we also highlight how proxies of shorter-term RMACs should be 'plugged' into the formulation of longer-term RMACs.

3.1 Choice of the overarching theoretical framework

In the theory and in the practice of decision-making under uncertainties there exist two main frameworks that have been successfully applied in many different fields, namely:

- **Robust optimization**: in this approach uncertainties are modelled by defining a set of possible values of some parameters of the problem (intervening in the constraints and/or in the objective function), and the 'robust' optimization problem is formulated as seeking for a decision that would satisfy all the constraints for any possibly combination of values of these uncertain parameters, and which would under these conditions maximize the objective function either under the 'worst' or under a 'nominal' condition within the uncertainty set.
- **Stochastic programming**: in this approach the set of possible uncertain parameters of the problem is loaded with a probability distribution, to express the fact that some parameter values

may be more likely than others, and the 'stochastic' optimization problem is formulated as seeking for a decision maximizing an objective function weighted by these probabilities, while ensuring that the constraints for all the values of the uncertain parameters are satisfied with high enough probability.

From a purely theoretical point of view, the stochastic programming framework is more general than the robust optimization approach [Powell, 2014]. This means, on the one hand, that it typically leads to more complex reliability assessment and control problems but, on the other hand, that it is able to exploit more information about the problem features, and most importantly more informative models of the uncertainties that the decision maker faces. At the same time, the 'stochastic programming' framework is general enough, from a theoretical point of view, to also allow the treatment of part (or even all) of the uncertainties according to the 'robust optimization' approach [Powell, 2014].

Therefore, we naturally chose to adopt the stochastic programming framework in order to formulate our RMACs. This choice allows for a broad panoply of practical declinations, ranging from a purely robust approach, the approach based on the current N-1 criterion, to a purely stochastic optimization approach.

Indeed, we will see that in some practical scenarios, envisaged for the future reliability management of power systems, parts of the uncertainties would still have to be handled in a robust way while others would be handled in a stochastic way. This means actually that migration away from a robust criterion, such as the N-1 criteria, towards a full probabilistic criterion such as the GARPUR RMACs, can be addressed by using the same (stochastic) modelling framework proposed in the present chapter.

3.2 The main ingredients of the generic GARPUR RMAC

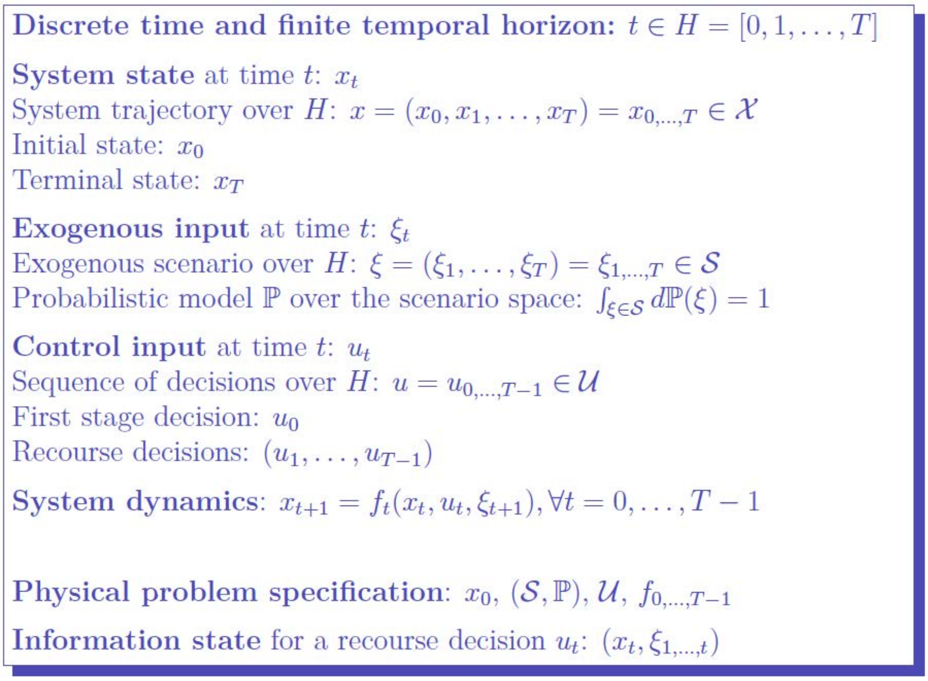
In the present section we introduce the mathematical formalization of an RMAC, as it was developed within WP2. We first introduce, in section 3.2.1 the notations related to the abstract modelling of the behaviour of a power system over a relevant horizon, driven by a combination of exogenous uncertainties and decisions taken by the TSO along the considered horizon. Next we formulate the objective function expressing the socio-economic performance and the constraints expressing the desired level of reliability, together with two 'principles' prescribing how the corresponding optimization problem may be simplified and/or relaxed in order to allow for the computation of 'near-optimal' decisions in a tractable way. In section 3.3, we will show how this very generic model has been adapted to the different time horizons and reliability management contexts as discussed in Chapter 2.

3.2.1 Model of multi-stage decision making under uncertainties: horizon, uncertainties, system states, decisions, system dynamics

Reliability management means to take 'first stage' decisions at a certain time-step, while planning for the possibility to use flexibility over the future time-steps (by taking appropriate 'recourse decisions') so as to react in a proper way to the realization of exogenous processes that are uncertain at the first time-step. This kind of problem is naturally casted as a 'multi-stage decision making problem under uncertainties' that we formalize with more precise mathematical notions and notations in this sub-section.

Figure 3.1 introduces in a compact and abstract way the different notions and their notations that we use in order to formalize in a mathematical way our generic multi-stage stochastic programming problem (see [Powell, 2014], for an in depth discussion of the full generality of this framework).

Below, we comment these notions by suggesting how they would translate in the particular context of day-ahead operation planning on the one hand, and in real-time operation on the other hand.



Discrete time and finite temporal horizon: $t \in H = [0, 1, \ldots, T]$

System state at time t: x_t
System trajectory over H: $x = (x_0, x_1, \ldots, x_T) = x_{0,\ldots,T} \in \mathcal{X}$
Initial state: x_0
Terminal state: x_T

Exogenous input at time t: ξ_t
Exogenous scenario over H: $\xi = (\xi_1, \ldots, \xi_T) = \xi_{1,\ldots,T} \in \mathcal{S}$
Probabilistic model $\mathbb{P}$ over the scenario space: $\int_{\xi \in \mathcal{S}} d\mathbb{P}(\xi) = 1$

Control input at time t: u_t
Sequence of decisions over H: $u = u_{0,\ldots,T-1} \in \mathcal{U}$
First stage decision: u_0
Recourse decisions: $(u_1, \ldots, u_{T-1})$

System dynamics: $x_{t+1} = f_t(x_t, u_t, \xi_{t+1}), \forall t = 0, \ldots, T-1$

Physical problem specification: x_0, $(\mathcal{S}, \mathbb{P})$, $\mathcal{U}$, $f_{0,\ldots,T-1}$

Information state for a recourse decision u_t: $(x_t, \xi_{1,\ldots,t})$

Figure 3.1: Basic ingredients and notations of a generic multi-stage stochastic programming problem used to model reliability management of a TSO in a certain context.

- Decision making horizon
    - In day-ahead operation planning, the temporal horizon would span the period starting with the moment where the day-ahead (i.e. first stage) decision needs to be taken (t=0), and the time steps corresponding to recourse decisions would correspond to the 24 hours of the next day, decomposed into (say) 24 hourly or 48 half-hourly steps.
    - In real-time operation, the horizon would span a period starting at a particular moment, and lasting for a few minutes to say one hour. Such a horizon would be decomposed into three steps, namely t=0 corresponding to the moment where a preventive control decision is applied, t=1 corresponding to the moment of a contingency occurrence (potentially leading to the application of corrective post-contingency control), and the final state T=2 would be the one expressing the combined effect of preventive control, contingency occurrence, post-contingency corrective control and automatic emergency control in terms of eventual service interruptions.
- Exogenous uncertainties
    - In the day-ahead context, the exogenous input modelled in a stochastic way would essentially be a complex, high-dimensional spatio-temporal stochastic process expressing the uncertainties about the next day weather conditions, demand and renewable generation, forced outages, component failure-rates, corrective control failure probabilities, etc.

  - In the real-time context, the space of exogenous inputs would essentially be discrete, describing the set of possible contingencies together with the possible failure modes of post-contingency corrective and emergency controls. The probabilistic model of these exogenous inputs would in principle depend on the actual real-time conditions (weather, system state, etc.).
- Initial state and first stage decision
  - In the day-ahead, the initial state is the state of the system at the moment where the operation planner must commit his day-ahead decision (must-runs, reserves, outage rescheduling, etc.).
  - In real-time, the initial state is the state of the system when the preventive control decision is applied.
- Recourse decisions and information states
  - In the day-ahead context, the recourse decisions correspond to the sequence of real-time decisions that could be taken the next day by the real-time operator; at a certain recourse step t, the corresponding information state corresponds to the combination of the real-time power system state at that moment, and the observed realization up to that moment of the exogenous process.
  - In the real-time context, the recourse decision is the post-contingency corrective control and the corresponding information state corresponds to the combination of the pre-contingency state and the particular contingency that has occurred.
- System dynamics
  - In the day-ahead context, it models how the power system steady state would evolve over the next-day given a sequence of exogenous inputs and real-time control decisions.
  - In the real-time context, it models the physical system dynamics, i.e. how it responds to combinations of contingencies and controls.
- Physical problem specification
  - It contains a complete probabilistic model of the exogenous input, expressing the set of uncertainties faced in the context considered, together with a description of the system dynamics, its initial state, and the range of possible control decisions.

Notice that the physical problem specification is agnostic about the notion of power system reliability and the notion socio-economic performance. On the other hand, the information state represents all the information that could in principle be used when choosing a decision at a certain time step.

In the next section we explain how these ingredients are exploited in order to specify an RMAC for a particular context.

3.2.2 RMAC specification: objective function, reliability target, discarding and relaxation principles

In order to specify a reliability management approach and criterion for a given context, we proceed in 4 successive steps: we start by explaining the specification of a risk-neutral socio-economic objective function, then introduce the way we propose to model risk-aversion in the form of a reliability target, and then proceed by explaining two additional ingredients required to enable the practical application of the proposed RMAC, namely the uncertainty discarding principle and the relaxation principle.

3.2.2.1 Specification of a risk-neutral socio-economic objective function

Suppose that we are in a reliability management context, where the physical model of Figure 3.1 has already been specified, and that we want to assess from the socio-economic point of view a particular sequence of decisions over the horizon. For each possible realization of the exogenous inputs over the horizon, the physical model together with the chosen sequence of decisions yield a particular system trajectory; hence the probabilistic uncertainty model induces a probability distribution over these trajectories which is dependent on the chosen sequence of controls. In order to compare different sequences of controls, we thus need to specify a mathematical model of what we deem is a good or a bad socio-economic performance over the considered horizon. While it is not in the scope of WP2 to specify this model (rather, it is the scope of WP3 of GARPUR), we do assume that it could be specified in the form of a sequence of 'cost' functions that decompose in an additive fashion the evaluation of the socio-economic performance along a sequence of controls, an exogenous scenario, and the induced system trajectory. Second, we assume that the socio-economic evaluation criterion is risk-neutral (see the next subsections concerning the discussion about risk-averse decision making strategies), meaning that faced with uncertainties, we would ideally try to do our best in order to minimize the **mathematical expectation** of this compound socio-economic performance criterion.

For example, in the real-time operation context, the socio-economic objective function would be the sum of the cost of preventive control, of the expected cost of corrective control, and of the expected cost-of service interruptions to end-users, that would depend on the initial state, on the (weather dependent) probabilities of contingencies and corrective control failures modes, and on the particular combination of preventive and corrective controls that is assessed.

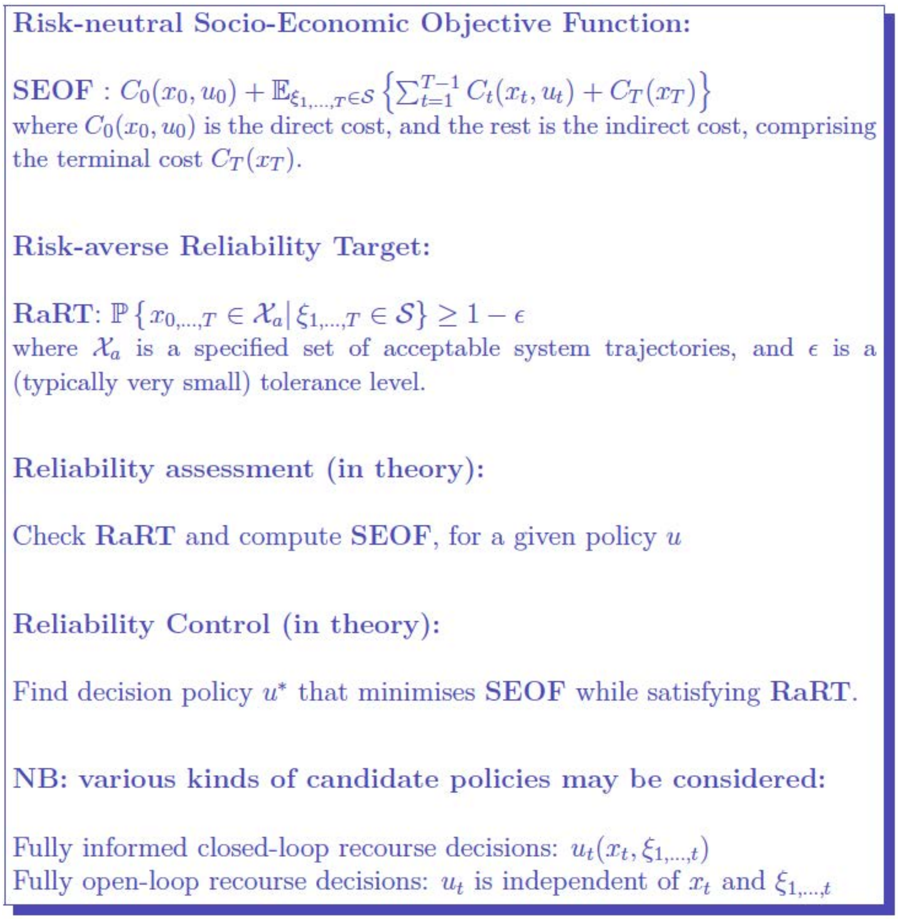
3.2.2.2 Specification of a reliability target

Choosing decisions so as to optimize a risk-neutral socio-economic performance criterion, as outlined in the previous section, may lead to situations that may be considered as not acceptable when analysing how the risk decomposes over time and space. For example, it might lead to operate the system occasionally with a too high risk of large service interruptions; it might also lead to choosing decisions that would lead to systematically concentrating the risk of service interruptions in relatively small but weak areas at the benefit of overall market surplus. Both situations could be considered as not being acceptable from the societal point of view.

Furthermore, we need to acknowledge that modelling in a sound and accurate way the behaviour of power systems is extremely difficult, and specially when considering low-probability high-impact events. This implies that the scope of validity of the 'physical model' (as depicted in Figure 3.1) that may practically be exploited in reliability management contexts will necessarily be limited to a range of "usual" operation conditions already experienced by TSOs in the past. Thus, the decision-making strategy should be sufficiently cautious so as to limit the likelihood of steering the system outside of this range of known conditions.

Introducing cautiousness in a stochastic programming problem may be carried out in various ways, more or less easy to handle from a mathematical and algorithmic point of view, and more or less faithful in terms of modelling the kind of situations that one really wants to avoid. Our proposal is to carry this out by defining a subset of so-called acceptable physical system trajectories and then to impose a confidence level for being in this subset, or equivalently to tolerate a small probability threshold of being outside that set. The joint specification of the set of acceptable system trajectories and this tolerance level yields a chance-constraint that is called the 'reliability target' in our terminology.

The joint definition of the socio-economic performance measure and the reliability target are formulated mathematically in Figure 3.2, which also suggests how these two ingredients could be used for reliability assessment and for reliability control, as well as the different kinds of control policies that may be considered in practice.



Risk-neutral Socio-Economic Objective Function:

SEOF : $C_0(x_0, u_0) + \mathbb{E}_{\xi_{1,\ldots,T} \in \mathcal{S}} \left\{ \sum_{t=1}^{T-1} C_t(x_t, u_t) + C_T(x_T) \right\}$
where $C_0(x_0, u_0)$ is the direct cost, and the rest is the indirect cost, comprising the terminal cost $C_T(x_T)$.

Risk-averse Reliability Target:

RaRT: $\mathbb{P}\left\{ x_{0,\ldots,T} \in \mathcal{X}_a \middle| \xi_{1,\ldots,T} \in \mathcal{S} \right\} \geq 1 - \epsilon$
where $\mathcal{X}_a$ is a specified set of acceptable system trajectories, and ϵ is a (typically very small) tolerance level.

Reliability assessment (in theory):

Check **RaRT** and compute **SEOF**, for a given policy u

Reliability Control (in theory):

Find decision policy u^* that minimises **SEOF** while satisfying **RaRT**.

NB: various kinds of candidate policies may be considered:

Fully informed closed-loop recourse decisions: $u_t(x_t, \xi_{1,\ldots,t})$
Fully open-loop recourse decisions: u_t is independent of x_t and $\xi_{1,\ldots,t}$

Figure 3.2: Socio-economic objective function and reliability target yielding a flexible family of theoretical RMACs.

For example, in the context of real-time operation, the direct cost would correspond to the cost associated to preventive control, while the indirect cost would be composed of the corrective control cost as well as the costs of service interruptions, both accounted via their expectation along the trajectories induced by contingencies and corrective control failure modes. In this particular context, the recourse decisions (corrective control) would typically be chosen according to a closed-loop policy, by selecting them based on the contingency that has occurred or as a function of the system response to that contingency. The precise range of recourse policies considered in a particular context is determined by the available infrastructure (measurement system, and control devices flexibility).

3.2.2.3 Conservative uncertainty discarding principle

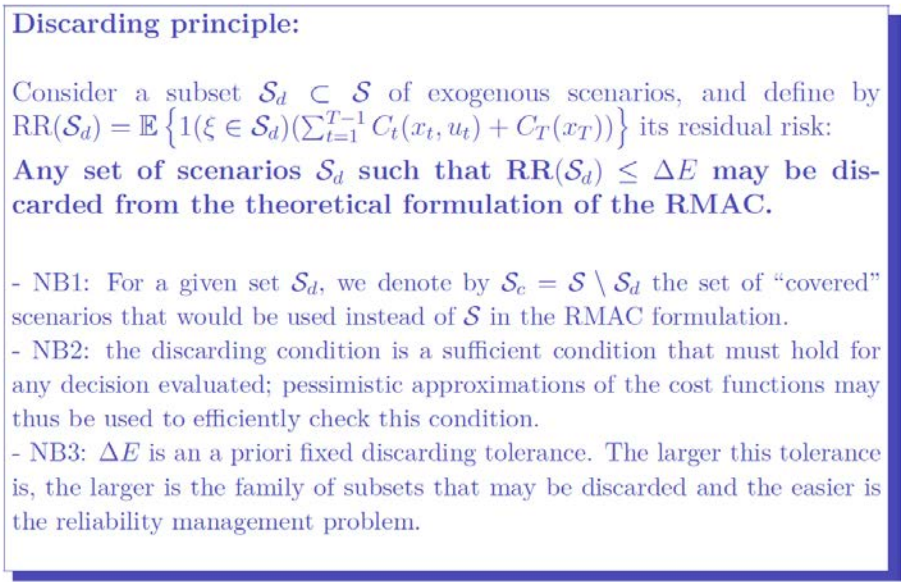
Given the complexity of the space of uncertainties and of the dynamics of power systems, the exact computation of the two ingredients of the theoretical RMAC introduced in the preceding section is in practice not reachable, even when considering huge computing resources and reasonable simplifications of the dynamic and uncertainty models. For example, in the context of real-time operation, the set of possible combinations of contingencies (N-1, N-2, … N-N) combined with the set of possible failure modes of corrective controls is already extremely large, and even in the simpler context of reliability assessment could not be covered exhaustively, let alone when searching for an optimal real-time control strategy.

Therefore, in order to allow for the practical use of this RMAC, we need to introduce a systematic approach that allows one to simplify its formulation, while keeping control on the level of approximations thus introduced. In order to do so, we propose to allow for a simplification of the uncertainty model, by replacing the set of possible exogenous scenarios by a typically much smaller subset, thus discarding a large part of the scenario space. The question then is to define what would be a sensible approximation of the uncertainty model in a certain context. In the literature of stochastic programming (and more generally decision making under uncertainty), this question has been studied along various directions (we refer the interested reader to [Powell, 2014], for an in depth discussion of these issues and an extensive bibliography). Our proposal is to specify formally what kind of 'simplifications' should be considered as useful in the context of power systems reliability management.

In the context of WP2, we have thus proposed to allow one to discard any subset of exogenous scenarios from the theoretical statement of the problem, if the result of discarding this subset would not lead to a too large over-estimation of system performance when optimizing over it. To this end, we propose a discarding principle based both on the probability of the exogenous scenarios and on (an upper bound of) the impact they could have on system performance.

For example, in real-time this principle would allow one to discard any (possibly very large) subset of contingencies over which one can ascertain that the joint service interruption cost expectation would be negligible. While the joint service interruption cost expectation over any contingency subset is indeed a function of real-time preventive control/corrective decisions, at the worst case, and using an upper bound of the service interruption impact, the discarding principle can be ensured to hold, whatever the chosen real-time control decision.

As for the other RMAC ingredients, the proposed discarding principle will have to be specified for each reliability management context. It is expressed in generic mathematical form in Figure 3.3.



Discarding principle:

Consider a subset $\mathcal{S}_d \subset \mathcal{S}$ of exogenous scenarios, and define by $\mathrm{RR}(\mathcal{S}_d) = \mathbb{E}\left\{1(\xi \in \mathcal{S}_d)(\sum_{t=1}^{T-1} C_t(x_t, u_t) + C_T(x_T))\right\}$ its residual risk:

Any set of scenarios $\mathcal{S}_d$ such that $\mathrm{RR}(\mathcal{S}_d) \leq \Delta E$ may be discarded from the theoretical formulation of the RMAC.

- NB1: For a given set $\mathcal{S}_d$, we denote by $\mathcal{S}_c = \mathcal{S} \setminus \mathcal{S}_d$ the set of "covered" scenarios that would be used instead of $\mathcal{S}$ in the RMAC formulation.
- NB2: the discarding condition is a sufficient condition that must hold for any decision evaluated; pessimistic approximations of the cost functions may thus be used to efficiently check this condition.
- NB3: ΔE is an a priori fixed discarding tolerance. The larger this tolerance is, the larger is the family of subsets that may be discarded and the easier is the reliability management problem.

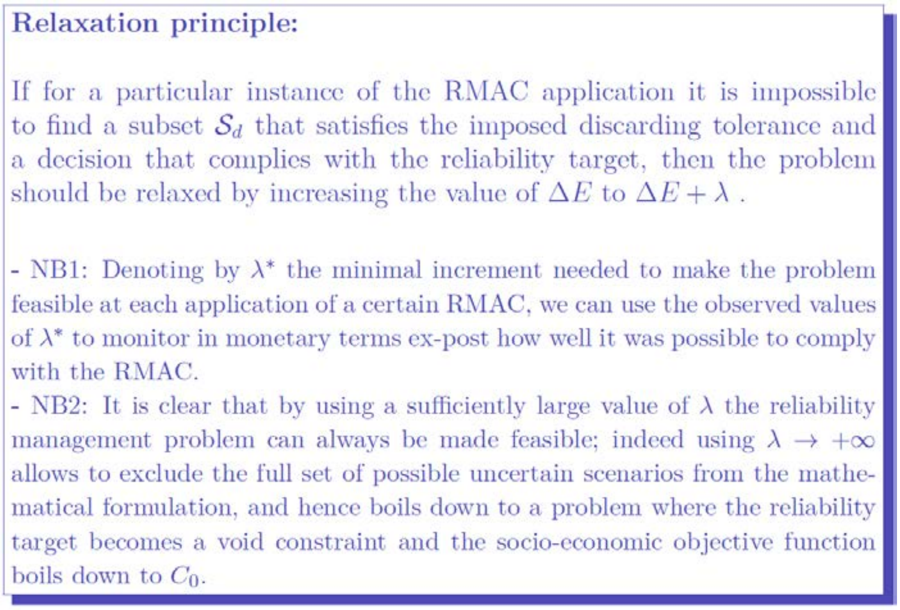
Figure 3.3: Discarding principle: how to exploit the family of theoretical RMACs while coping with practical scalability.

3.2.2.4 *Relaxation principle*

Even with the use of the discarding principle, the decision making problem of a specific instance of the reliability management problem of a given context may turn out to be infeasible, in the sense that either no decision policy actually exists that satisfies the (trimmed) reliability target, or that none can be computed in due time. When the decision-maker is faced with such a situation she will have to further simplify the specification of the reliability management problem so as to nevertheless find a good decision.

For example, in real-time operation it may turn out that the set of available decisions is not sufficiently large to allow for complying with the reliability target of real-time operation (this happens already from time to time in todays practice, when there is no way to comply with the N-1 criterion, or when the used SCOPF software tool simply is unable to converge towards a feasible solution).

In coherence with the discarding principle, which expresses the overall level of acceptable approximation of the uncertainty model used in a certain context, we propose to carry out this relaxation by minimally reducing the requirement normally used by the discarding principle. This relaxation principle is expressed in generic form in Figure 3.4.



Relaxation principle:

If for a particular instance of the RMAC application it is impossible to find a subset $\mathcal{S}_d$ that satisfies the imposed discarding tolerance and a decision that complies with the reliability target, then the problem should be relaxed by increasing the value of ΔE to $\Delta E + \lambda$.

- NB1: Denoting by λ^* the minimal increment needed to make the problem feasible at each application of a certain RMAC, we can use the observed values of λ^* to monitor in monetary terms ex-post how well it was possible to comply with the RMAC.

- NB2: It is clear that by using a sufficiently large value of λ the reliability management problem can always be made feasible; indeed using $\lambda \to +\infty$ allows to exclude the full set of possible uncertain scenarios from the mathematical formulation, and hence boils down to a problem where the reliability target becomes a void constraint and the socio-economic objective function boils down to C_0.

Figure 3.4: Relaxation principle: how to cope with feasibility problems.

3.2.2.5 *Summary and discussion*

The theoretical model for reliability management approaches and criteria (RMACs) proposed by the GARPUR project is composed of 4 main ingredients compiled in Figure 3.5:

1. A *Socio-Economic Objective Function* (SEOF) to be minimized (accounting for costs and benefits[2] resulting from TSO reliability management decisions).

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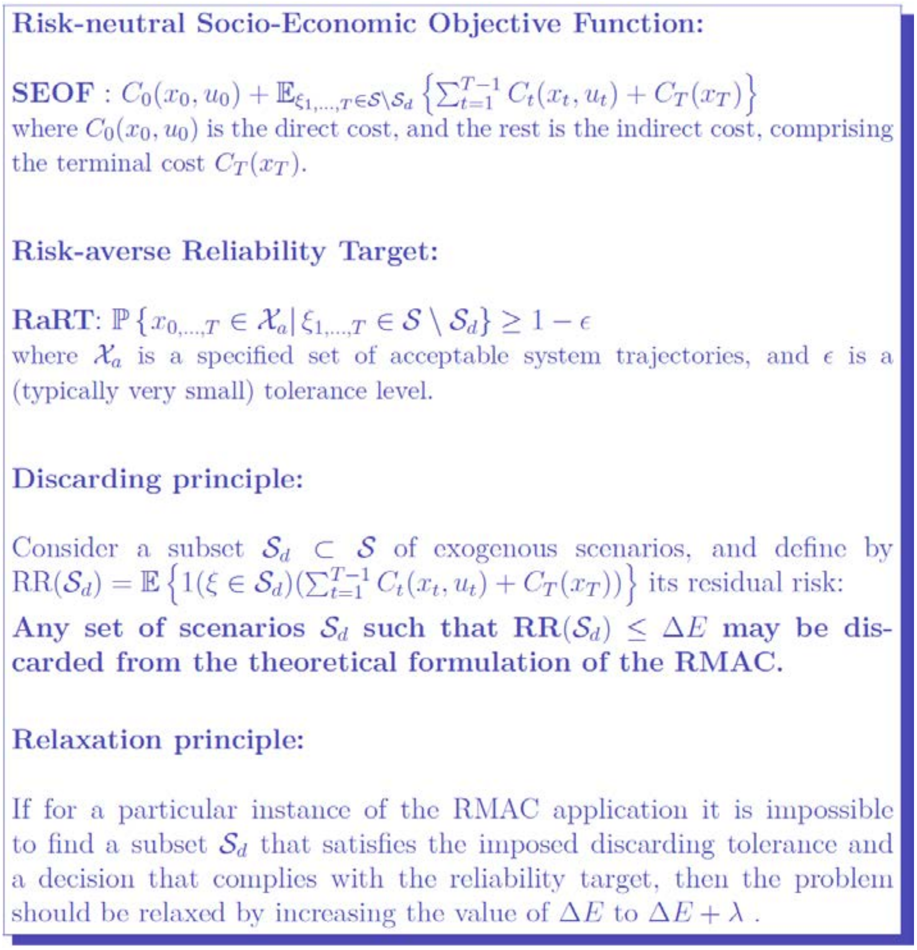
[2] Accounted as negative costs.

2. A *Risk-averse Reliability Target* (RaRT) aiming to ensure that the decisions considered as acceptable indeed lead with high enough probability to an acceptable system behaviour.
3. A *Discarding Principle* allowing one to avoid detailed computations over the generally intractable space of exogenous uncertainties, by specifying how to neglect large portions of this uncertainty space, both in the context of reliability assessment and reliability control.
4. A *Relaxation Principle* prescribing how the reliability management problem should be progressively relaxed, whenever no feasible decision can be found according to the previous three components. It basically indicates that the level of approximation tolerated by the discarding principle should be relaxed as little as possible in order to enable the determination of a decision compliant with the reliability target.



Risk-neutral Socio-Economic Objective Function:

SEOF : $C_0(x_0, u_0) + \mathbb{E}_{\xi_{1,\ldots,T} \in \mathcal{S} \setminus \mathcal{S}_d} \left\{ \sum_{t=1}^{T-1} C_t(x_t, u_t) + C_T(x_T) \right\}$
where $C_0(x_0, u_0)$ is the direct cost, and the rest is the indirect cost, comprising the terminal cost $C_T(x_T)$.

Risk-averse Reliability Target:

RaRT: $\mathbb{P}\{x_{0,\ldots,T} \in \mathcal{X}_a | \xi_{1,\ldots,T} \in \mathcal{S} \setminus \mathcal{S}_d\} \geq 1 - \epsilon$
where $\mathcal{X}_a$ is a specified set of acceptable system trajectories, and ϵ is a (typically very small) tolerance level.

Discarding principle:

Consider a subset $\mathcal{S}_d \subset \mathcal{S}$ of exogenous scenarios, and define by $\mathrm{RR}(\mathcal{S}_d) = \mathbb{E}\left\{ 1(\xi \in \mathcal{S}_d)(\sum_{t=1}^{T-1} C_t(x_t, u_t) + C_T(x_T)) \right\}$ its residual risk:
Any set of scenarios $\mathcal{S}_d$ such that $\mathrm{RR}(\mathcal{S}_d) \leq \Delta E$ may be discarded from the theoretical formulation of the RMAC.

Relaxation principle:

If for a particular instance of the RMAC application it is impossible to find a subset $\mathcal{S}_d$ that satisfies the imposed discarding tolerance and a decision that complies with the reliability target, then the problem should be relaxed by increasing the value of ΔE to $\Delta E + \lambda$.

Figure 3.5: Summary of the proposed Reliability Management Approaches and Criteria (RMACs).

Clearly the proposed family of RMACs is a broad family able to comply with a broad range of regulatory constraints, and suitable to cover the broad range of TSO reliability management contexts. This flexibility is already incorporated in the theoretical formulation of the RMACs (steps 1 and 2), and allows one in particular to cope with different sets of candidate decisions, temporal horizons, and levels of risk-averseness, as could be encountered in the practice of the broad set of European TSOs targeted by GARPUR.

The proposed family of RMACs also explicitly recognizes the fact that practical constraints may not allow, at a certain moment or in a certain context, to find a near-optimal and feasible solution of the resulting optimization problem or assess it exactly. It therefore incorporates in an explicit way how the RMAC should be approximated whenever its exact application is not feasible from a practical point of view. To this end, it first states a discarding principle expressing an acceptable level of approximation, and a relaxation principle that may be used in a last resort to choose decisions whenever even the approximate model turns out to not yield any solution to the reliability management problem.

For any given context, the RMAC is based on a physical model relevant for this context and a specific socio-economic objective function; it is also parameterized by the following three items:

- A set of acceptable system trajectories
- A confidence level on the probability of acceptable system response to controls
- A level of admissible under-estimation of the socio-economic objective function

These three parameters will need to be set in order to tune the compromises that will be suitable in practice.

3.2.3 Assessment versus control: different computational complexities and different approximations needed

In this section we very briefly analyse the computational nature of the reliability assessment and the reliability control problems, in order to highlight already at this stage that they will call for different levels of approximations in order to allow their tractable solution (further discussed in Chapter 4).

3.2.3.1 Reliability assessment problems: a family of simulation problems

In the context of reliability assessment, the TSO decision is already fixed, and the purpose is to check whether the reliability target is reached and to estimate the expected socio-economic performance. This is essentially a simulation problem, where one needs to screen a large enough set of exogenous scenarios, and plug them into the dynamic model together with the fixed decision so as to compute the resulting system trajectory and then compute the socio-economic costs of this scenario and check whether it is acceptable. While, in particular contexts and with certain assumptions about the uncertainty models, the reliability assessment problem can as well be addressed by so-called analytical methods (see, e.g. the bibliography on state-of-the-art methods provided in D.1.1 [GARPUR, 2014]), in WP2 of GARPUR we have focussed on its solution via standard Monte-Carlo simulations. This latter methods may indeed be very generically applied to solve this broad class of problems, while not relying on strong assumptions about the uncertainty models and performance indicators that are to be assessed, and provided that a sufficient number of computing nodes can be exploited in parallel. We call this ‘the (Monte-Carlo) simulation problem’, since it does not call for searching for a ‘good’ reliability management decision.

Whatever the particular TSO reliability management context, the resolution of this problem always boils down to the same kind of consideration: how to maximize the quality of the information obtained from a large set of simulations of the system behaviour over the considered horizon, under a certain computational budget that may be available in the practical TSO decision making context. Various well-known techniques for reducing the variance in the context of Monte-Carlo simulations may be exploited in this context. Work packages 4, 5 and 6, discuss such approaches in their deliverables D4-5-6.2, prepared in parallel with the present document [GARPUR, 2016e],[GARPUR, 2016b],[GARPUR, 2016c]. Indeed, from a practical point of view, disposing of a suitable implementation of reliability assessment in a certain context is a prerequisite when considering the use of the GARPUR RMAC in such a context. This, in particular, requires sensitivity studies in order to determine proper values of the 3 meta-parameters of the RMAC for that context, while taking into account the sought level of accuracy, computational efficiency, and the actual quality of input data.

3.2.3.2 Reliability control problems: a family of stochastic programming problems

In the context of reliability control, the objective is to find a near-optimal decision policy (or control strategy) that complies with the reliability target. As already suggested earlier, the exact resolution of these control problems is typically not feasible, given their large-scale and generally non-convex nature. Moreover, the exact nature of these optimization problems strongly depends on the kind of candidate decisions that are considered as well as on the nature of the set of uncertainties that need to be covered. We have therefore focused the research in task 2.3 on the design of a first set of reliability control algorithms, each one targeting a specific temporal horizon, from real-time to long-term.

3.2.4 Understanding the N-1 criterion as a particular case of the generic GARPUR RMAC

In this section we consider the real-time context, in order to draw a parallel between the N-1 criterion and the GARPUR RMAC:

- Uncertainty modelling and discarding principle:
  - N-1: an essentially fixed set of (mostly single) contingencies is used, without explicitly exploiting their probabilities; corrective and emergency control responses are considered as deterministic. All other scenarios are always discarded.
  - RMAC: all kind of contingencies may be used, and the discarding principle allows one to select dynamically (e.g. depending on the weather conditions and system state) subsets based on their probabilities and worst-case consequences in terms of service interruptions; corrective and emergency control failure modes may be taken into account if deemed necessary.
- Reliability target:
  - N-1: 100% continuity of service for all single contingencies; the sought level of risk-aversion is hard coded here[3].
  - RMAC: defined by the notion of 'acceptable system response' to contingencies and corrective controls actions, which may tolerate a small risk of 'failure'; the level of risk-aversion may be adjusted by a suitable choice of the reliability target.
- Socio-economic objective function:
  - N-1: only preventive control costs are explicitly taken into account
  - RMAC: preventive control costs are blended by the expected costs of corrective controls and the costs of the consequences of emergency controls (the latter being modelled by the cost of service interruptions to the end-users).

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[3] It must be noted that the uncertainty in the behaviour of post-contingency corrective controls is not explicitly acknowledged in the N-1 approach. It follows that the sought level of risk-aversion may not actually be achieved by the N-1 approach [Karangelos, 2013].

- Criterion relaxation:
    - N-1: when the N-1 criterion is unfeasible, it is left to the judgment of the human expert to decide how to relax it; TSO specific rules taking into account system and regulatory specifics may exist but are not documented in the literature.
    - RMAC: prescribes to progressively discard more contingencies, by increasing order of the product of their probability and an upper bound on the cost of the service interruptions they could induce.

Anticipating on the presentation, in Chapter 4, of the algorithm proposed for real-time reliability control along the GARPUR RMAC, let us already notice that it uses a modified version of the N-1 SCOPF.

3.3 Outline of the declination from real-time to long-term contexts

In the present section we briefly outline the modelling choices that we have made in order to adapt the generic RMAC principle to the different temporal horizons covered by the GARPUR project. It is important to notice that these versions of the RMAC have been defined by taking into account the current decomposition of TSO's reliability management, both in terms of the subsets of candidate decisions and the extension of the temporal horizons that are considered.

3.3.1 Real-time instance of the GARPUR RMAC

Within GARPUR, we have defined the real-time RMAC in the following way:

- **Horizon, uncertainties, and candidate decisions:** the real-time decisions of TSOs aim at facing the possible occurrence of contingencies over the next few minutes (up to one hour), while arbitrating among pre-contingency (preventive) controls and post-contingency (corrective) controls. To this end, both system topology, generation shifting (re-dispatch), and calls to demand flexibility may be used as preventive or corrective controls, and the risk of failure of corrective controls is taken into account to avoid being overoptimistic when arbitrating among preventive and corrective controls.
- **Information state:** to inform the 'real-time' decision maker, the current system state and topology, together with the current weather conditions are exploited to assess or optimize real-time decisions. In particular, the current weather conditions are used to express the probabilities of contingencies and of corrective control failures, and possibly also to adjust the evaluation of the economic impact of service interruptions to end-users.
- **Socio-economic objective function**: this function blends the cost of TSO preventive and (probability weighted) corrective controls, with the expected cost of service interruptions (VOLL weighted amounts of energy not supplied that could occur, depending on the choice of control variables and given the probabilities of contingencies and corrective control failures, and a suitable model of the emergency control layer allowing one to predict in a realistic way the extent and duration of the possible service interruptions).
- **Reliability target**: with high enough probability all covered combinations of contingencies and corrective control failures should lead to an acceptable system response over the next hour (meaning no system-wide instabilities and otherwise minor loss of load, as defined by TSO specific rules).

- **Discarding principle**: it allows one to neglect a subset of (uncovered) contingencies in the assessment and control procedures, as long as it can be ascertained that they would lead collectively to a negligible additional cost, notably of service interruptions.
- **Relaxation principle**: if, without relaxation, the reliability control problem is not feasible, the subset of 'uncovered contingencies' (already tolerated by the discarding principle) may be further expanded. This relaxation would be carried out in such a way that the expectation of the additional uncovered service interruption costs remains as small as possible, while assuming worst-case emergency control behaviour for each one of these additionally neglected contingencies.
- **Shorter-term behaviour**: the assessment and computation of real-time reliability management decisions have to take into account the automatic cyber-physical reaction of the power system to contingencies, planned and automatic corrective controls, and the intrinsic power system dynamics. In GARPUR we do not address the design of this part of the required system response models, and we use the term 'emergency control layer' to denote it. Depending on the system under concern, different modelling details will have to be synthesized in the form of a relevant 'emergency control layer proxy'. The precise design of such system specific models is beyond the scope of GARPUR; in Chapter 4 of the present document some standard ones will be discussed.

3.3.2 Short-term instances of the GARPUR RMAC

Short-term operation planning comprises several decision-making problems, from intra-day to several weeks ahead in time. From a mathematical point of view they essentially lead to similar decision-making problems, where uncertainties are mostly related to the future weather conditions, the future demand and renewable generation, the future market outcomes, as well as the forced network component outages that could occur over the considered horizon. In order to exemplify the nature of these problems, we will describe the particular version of this look-ahead mode operation planning problems corresponding to the decision making of a TSO in day-ahead (D-1), just after the market clearing outcome has been revealed to him.

We have defined the D-1 RMAC in the following way:

- **Horizon, uncertainties, and candidate decisions:** the D-1 decisions of TSOs aim at preparing real-time operation over the 24 hours of the next day, facing a range of scenarios that cover the uncertainties about load and renewable generation. The decisions mainly concern the availability and deliverability of active and reactive power reserves, possibly leading to an adjustment of the generation unit commitment resulting from the market clearing process and or the modification of planned outage schedules.
- **Information state:** to inform the 'D-1 operation planning' decision maker, the current system topology combined with the planned outages for the next day, together with the weather forecasts and market outcome, are used to model the set of possible next-day scenarios in terms of power injections at the nodal level and their impact on power flows.
- **Socio-economic objective function**: this function blends the cost of TSO D-1 decisions (e.g. the cost of deviating from the market outcome), with probability-weighted costs of operating the system over the next day and the set of possible scenarios. Notice that in our approach, these latter 'forecasted' real-time operating costs incorporate themselves the costs of real-time

preventive and corrective controls, as well as the expectation of the costs of service interruptions, in accordance with the modelling of the real-time RMAC specification.

- **Reliability target**: for D-1 operation planning, the reliability target states that throughout the 24 hours of the next day, real-time operation can be achieved while meeting its own reliability target over a range of scenarios.

  *N.B.: Stressing the strong coupling between operational planning and real-time operation, the purpose of such a reliability target is to establish that the degree of risk-aversion sought during real-time operation is indeed attainable (over all operational planning scenarios). That is***,** *no additional chance constraint is introduced here on top of the one prescribed in the real-time declination of the proposed RMAC.*

- **Discarding principle**: it allows to neglect in the assessment and control procedures a subset of (uncovered) scenarios for the next day, as long as it can be ascertained that, whatever the chosen D-1 decision, they would lead collectively to a negligible expected cost of real-time operation.
- **Relaxation principle**: the relaxation of the D-1 RMAC is carried out implicitly via the relaxation of the real-time RMAC; no additional relaxation is hence needed.
- **Shorter-term behaviour**: the assessment and computation of D-1 reliability management decisions have to take into account the way the system will be operated in real-time over the next day. This is modelled by using a proxy of the real-time 'operator' formulated as a simplified version of the optimization problem corresponding to the presupposed real-time RMAC.

In our work in WP2 on the look-ahead operation planning problems, we assumed that in real-time operation the proposed GARPUR RMAC would also be used. It is nevertheless possible to adapt the look-ahead mode RMACs to a situation where real-time operation would still follow the N-1 criterion. In that case, the main part that needs to be adapted is the proxy used for modelling the shorter-term behaviour of the real-time operator; notice that this N-1 real-time proxy would however need to be complemented by a computational model of the way the N-1 criterion would be relaxed in real-time, whenever it is found to be unfeasible for a particular simulated real-time state.

Compared to D-1 operation planning, the formalization of RMACs for the other operation planning problems would need some further adaptation:

- Intra-day operation planning: a shorter horizon of a few hours, to enable early enough revision of a subset of D-1 decisions (e.g. thermal generation start-up, coordination with neighbour TSOs) that need more time than what can be covered in real-time; otherwise no fundamental change with respect to D-1.
- Day-k and Week-k operation planning: more uncertainties given the longer horizon and the fact that market clearing is still unknown at these moments; possibility to carry out more computations and cover more complex sets of decisions given the additional time available; in particular a new kind of decision « variable » may be optimized: it concerns the information about network capacities provided as input to the market clearing mechanism.

The detailed derivation of these RMACs is left to further work outside of the scope of WP2.

3.3.3 Mid-term instances of the GARPUR RMAC

The canonical mid-term horizon considered within WP2 is of one year, and to design the corresponding RMAC we have focused on the outage-scheduling problem, briefly explained below. The proposed formalization may be adapted straightforwardly to cover slightly shorter or slightly longer horizons (from several months to a few years) and it may as well be adapted to the context of system development decisions taken over similar temporal horizons.

We have defined the mid-term outage scheduling RMAC in the following way:

- **Horizon, uncertainties, and candidate decisions:** the outage scheduling decisions of TSOs aim at complying with asset management logistic constraints while ensuring that system operation over the next year can be done while meeting its own reliability target over a range of scenarios that cover the uncertainties about load and renewable generation, weather conditions, and while also modelling the stochastic nature of corrective maintenance as well inspection driven maintenance activities, as seen one year ahead in time. Given a list of component outage requests for the next period (of say one year), the purpose is to determine the particular moments where each one of these outages should be scheduled. In a more sophisticated version of the problem, alternative ways of carrying out the outages (such as night-work, etc.) may also be considered as additional decision variables.
- **Information state:** to inform the 'outage scheduling' decision-maker, the schedules of generator outages and the available logistic resources for the next year are supposed to be already known, together with the list of components that need to be scheduled for outage, as well as the expected duration of each one of these outage requests. In the case of hydro-dominated systems, he also has information about the way hydro-reservoirs would preferably be exploited over the mid-term horizon, e.g. in the form of value-of-water scenarios.
- **Socio-economic objective function**: this function integrates over the mid-term horizon the impact of a particular outage schedule on the costs of system operation (short-term operation planning decisions and real-time decisions taken by the TSOs) and on the settling of electricity market prices and surplus (since in some cases, planned outages may lead to the reduction of transmission capacities made available to the market).
- **Reliability target**: with high enough probability the real-time reliability target can be met over the next year; the modelling of this condition exploits the real-time relaxation procedure to account for the importance of eventual real-time reliability target violations; it may be formulated in the form of more than one single chance constraint, e.g., to avoid concentrating the 'unreliability' at some particular moments of the year, or in some particular zones of the system.
- **Discarding principle**: it allows to neglect in the assessment and control procedures a subset of (uncovered) scenarios for the next year, as long as it can be ascertained that, whatever the chosen outage scheduling decision, they would lead collectively to a negligible expected residual cost of service interruptions, given the way system operation is carried out.
- **Relaxation principle**: if the expected amount of required relaxations of the system operation reliability targets is too high, an additional relaxation would consist in postponing the smallest number of requested outages to the subsequent years.
- **Shorter-term behaviour**: the assessment and computation of outage scheduling decisions have to take into account the way the system will be operated over the next year. This is modelled by

using a proxy of the short-term 'operation planner' and another proxy of the real-time 'operator' formulated as simplified versions of their own RMACs.

In our work in WP2 on the mid-term reliability management problems, we assumed that in shorter term contexts (operation planning and real-time operation) the proposed GARPUR RMAC would also be used. It is nevertheless possible to adapt the mid-term RMAC to a situation where system operation would still follow the N-1 criterion. In that case, the main parts that need to be adapted are the proxies used for modelling the shorter-term behaviour of the system operator, while augmenting them with a proper relaxation procedure to enable the treatment of simulations yielding infeasibilities of the N-1 criterion.

3.3.4 Long-term instances of the GARPUR RMAC

The canonical long-term horizon considered in GARPUR is of 20 years. Such a horizon is typically used in order to study the impact of major evolutions of the system structure (system development) and of the maintenance policies (asset management). The questions addressed concern the impact of changes in the system structure or in its maintenance policies on the operation of electricity markets and on its 'maintainability and operability' both in terms of costs and reliability levels that could be sustained.

The main additional ingredient that needs to be modelled for such long-term studies concerns the fact that a certain number of additional uncertainties need to be taken into account that can not be represented adequately as stochastic processes: they concern changes in the regulation, in technology, in the climate, in the macro-economic context, as well as investment decisions of market participants and end-users. In order to take them into account we introduce the notion of macro-scenario, which models at a yearly time step these assumptions over the long-term multi-year horizon; to carry out a long-term study, we assume that a set of relevant such macro-scenarios is postulated based on expert saying, and that they can be combined with stochastic models at the yearly time-scale, similar to those used for mid-term decision making, so as to express the overall uncertainty that needs to be covered in these long-term studies. Based on such models, the impact of long-term system development decisions (or asset management policies) may be evaluated by incorporating suitable proxies of mid-term and short-term reliability management processes, along the ideas already explained in the previous subsections.

Further details about the mathematical statements of the long-term RMACs developed in WP2 may be found in refs [Dalal, 2016a] and [Dalal, 2016b].

4 ALGORITHMIC FEASIBILITY AND SCALABILITY

In the present chapter, we summarize the results of the work carried out in WP2 concerning the algorithmic feasibility and scalability of the proposed methods. Parts of these results have already been published in [Karangelos, 2016] and [Dalal, 2016b].

The work in WP2 on algorithmic feasibility and scalability has first focused on the definition of guidelines for the approximation of the proposed theoretical versions of the RMACs and on a common choice of benchmark systems. The largest part of the work was then devoted to the design, implementation and testing of reliability control algorithms on the one hand for real-time reliability control, and on the other hand for mid-term reliability control. In addition, work has also been carried out for the short-term and long-term horizons, but this work is still on going at the moment of issuing the present report.

4.1 Real-time operation

We start by presenting the overall algorithmic principle for real-time reliability control, and then we briefly report the current implementation of this scheme and discuss how it could be expanded and upgraded in the future.

4.1.1 Overall algorithmic principle

In the real-time context, the reliability control problem essentially boils down into the simultaneous selection of a subset of contingencies that should be covered (according to the discarding principle) and the resolution of an optimization problem where a combination of preventive and contingency specific corrective controls are to be determined so as to optimize the socio-economic objective function while meeting the reliability target (chance constraint) given this subset of contingencies. The larger the set of discarded contingencies, the easier is the resolution of the optimization problem and the simpler is the resulting real-time control strategy. Therefore, the strategy is to discard a maximum number of contingencies while still meeting the threshold on the residual risk imposed by the discarding principle.

The proposed iterative approach for solving these two problems jointly is outlined in Figure 4.1, and briefly commented below.

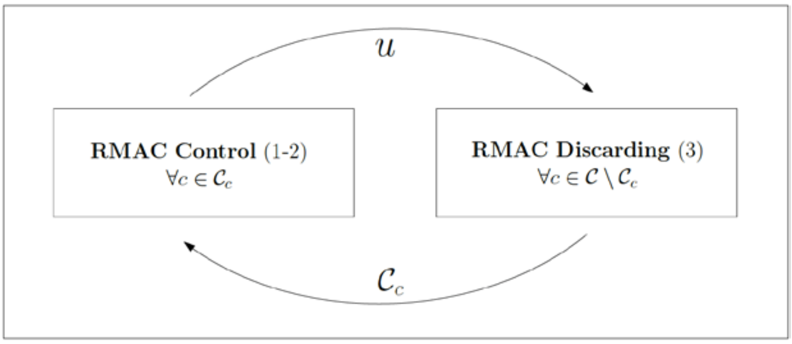

Figure 4.1: Overall principle of the real-time reliability control algorithm.

- Starting in the left part of the figure, and from an initially empty subset of covered contingencies, the optimization problem is solved: notice that this first problem boils down to a simple OPF problem, since no contingency at all is considered (the chance constraint on the reliability target vanishes), and only a preventive control decision minimizing its own cost has to be determined in order to yield a viable (i.e., 'N-0' secure) operating state.

- Next, the set of currently discarded contingencies (at the first iteration this set thus comprises all contingencies) is considered as input for the right part of the figure. These currently discarded contingencies are then screened in decreasing order of their probability, and for each one the system response is computed based on the real-time control computed at the previous step. From the system response, one determines the corresponding residual risk (i.e. the cost of service interruption multiplied by the contingency probability). Then a small subset of contingencies yielding the highest residual risk is selected, and these latter are added to the set of contingencies to cover at the subsequent iterations.
- The updated set of contingencies is fed back to the left part, in order to re-compute a suitable combination of preventive and corrective controls, optimizing the socio-economic objective and complying with the reliability target.
- The procedure continues, until either of the two following conditions holds:
    - The optimization problem becomes unfeasible; in that case the last feasible solution may be used, and the total residual risk for the set of contingencies that were discarded at that stage gives an indication of the degree of infeasibility of the real-time RMAC.
    - The total residual risk of the still discarded set of contingencies becomes smaller than the imposed threshold; in that case a feasible and near-optimal combination of preventive and corrective controls has been obtained.

Anticipating on the subsequent sections, let us first notice that the optimization problem corresponding the left part of Figure 4.1 will be stated in the form of a modified SCOPF problem, where the reliability target is formulated by using steady-state approximations of the response of the system to contingencies and corrective controls (while taking into account the possible failure modes of the latter).

Concerning the progressive contingency selection process in the right part of Figure 4.1, any preferred contingency evaluation software may be exploited, provided that it is able to determine the cost of service interruptions resulting from a scenario where some load would eventually be shed, i.e. the corresponding criticality expressed in monetary terms. Obviously, when assessing the response for a large set of contingencies, this process may take advantage of parallel computations. It is however important to notice that, even if the complete set of contingencies to consider may be huge, it is not necessary to evaluate all these cases explicitly at each iteration of the algorithm. In practice only a relatively small set of most probable contingencies will be evaluated at each iteration, and those that lead to the largest residual risk are sorted out and included for the next iteration; all the non-evaluated contingencies at a certain step (of lower probabilities) can be treated implicitly in a pessimistic way, by using an upper bound on the cost of service interruptions as a worst-case approximation of their potential consequences.

Finally, let us remark that while in the context of the reliability control approach of Figure 4.1 the contingency response evaluation is carried out only for yet uncovered contingencies (hence contingencies for which no corrective control action has yet been computed), the same software module may be used for real-time reliability assessment of any proposed combination of preventive and corrective controls, and while considering any desired set of combinations of contingencies and corrective control failure modes. In other words, in this context of real-time operation (as well as in other contexts), the algorithmic solution of the assessment problem is essentially a by-product of the algorithmic solution of the control problem. Notice that the pessimistic approximation of the system response in terms of costs of service interruptions may also be exploited in the context of reliability assessment so as provide a sensible stopping criterion for the process that screens the huge set of possible scenarios.

4.1.2 First implementations and testing

In order to test the proposed algorithms, we have considered the IEEE RTS96 benchmark [Grigg, 1999].

For the contingency response simulations, two software modules were considered. The first module is based on state-of-the-art algorithms published in the literature [Yan, 2015]. The second one is an adaptation of the SAMREL software, originally developed in house by SINTEF [Sperstad, 2015].

In the optimization problem, we modelled an "acceptable system trajectory", as the existence of a viable steady-state equilibrium throughout: (i) the pre-contingency operation (using permanent limits for currents and voltages), (ii) the short-term interval after the occurrence of any contingency and before the application of the respective corrective control actions (using short-term limits), and, (iii) the final state reached by following the application of corrective control actions while taking into account their possible failures (using permanent limits). Further, the reliability target was modelled by including binary variables to account for (a) the possibility of the lack of a viable steady-state equilibrium after the occurrence of any contingency and before the application of the respective corrective control actions, and (b) the possibility of failure of the chosen corrective controls per contingency. We underline here that many elementary control operations are by nature discrete hence the binary variables are also necessary to model them properly even in the classical problem statement.

We have first worked out the resolution of the full formulation based on a DC power flow model, allowing us to use state-of-the-art MILP solvers, which can handle very large-scale problems. Results gotten with this implementation, as well as the detailed mathematical formulation, have been published in [Karangelos, 2016].

This first implementation, while not suitable for most real power systems, because of the DC approximation, is suitable for carrying out further research. It has already been exploited in a parallel research project carried out at the University of Liège where several thousands of simulation scenarios were screened in order to compare the behaviour of the GARPUR RMAC and the N-1 criterion in reproducible conditions, and to apply machine learning methods in order to exploit the results of these simulations [Duchesne, 2016].

Next, we have extended the approach to an AC model of the power system. The proposed solution approach is based on the decomposition of the subset of covered contingencies into three contingency clusters, as highlighted in Figure 4.2.

In Figure 4.2, we show three clusters of contingencies: in green those that don't require corrective control, in yellow those that can be coped with sufficiently reliable corrective controls, and in red those that can't be secured at all. If the joint probability of the green contingencies and the yellow ones (assuming no failure of the respective corrective control) is sufficiently high, then the reliability target is met. Conversely, if the joint probability of the red contingencies and the yellow ones (assuming failure of the respective corrective control) is sufficiently high, then the reliability target is not met.

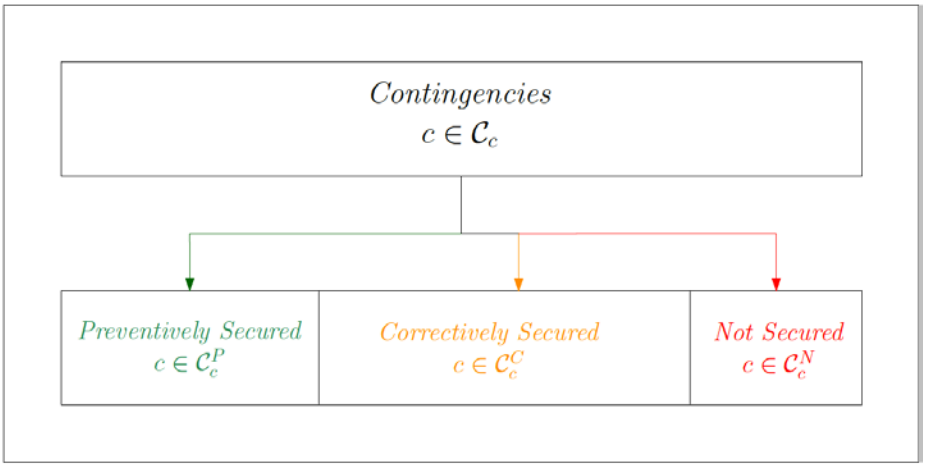

Figure 4.2: Three clusters of contingencies considered by the real-time reliability control algorithm.

4.1.3 Upgrading for practical use

Assuming that in the context of real-time operation of a certain TSO, we already dispose of a contingency evaluation software deemed sufficiently accurate and fast, as well as a SCOPF software well taking into account the kind of real-time controls and acceptability constraints that should be modelled, we believe that the GARPUR RMAC could be implemented relatively easily, by adapting these two software modules so as to take into account the additional features and data needed.

In particular, concerning contingency assessment, this means mainly to add a model of the socio-economic impact of service interruptions, so as to monetize MWs of load shedding, and to account for a relevant set of corrective control failure modes.

Concerning the optimization of real-time controls, this will imply the complete modelling of the socio-economic objective function, taking into account probabilities of contingencies, and both corrective control costs and costs of service interruptions. Also the software would have to be adapted so as to handle the integer variables needed to express the chance constraint of the reliability target, as well as suitable probabilistic models of corrective control failure modes.

Obviously, in order to make such a migration effort possible, additional data about the (weather dependent) values of contingency probabilities and corrective control failure modes would have to be provided by the information system used in the context of real-time operation.

4.2 Short-term operation planning

While the algorithmic implementation of the real-time RMAC has already been carried quite far, at the current stage of the research in GARPUR, work is still going on in order to address the much higher complexity of the look-ahead type of reliability management problems of short-term operation planning.

The main additional difficulty of this class of problems is that the set of uncertain scenarios to be covered is not any more a discrete set, that can be sorted according to scenario probability and then naturally exploited to build up an anytime algorithm for control.

In the next two sections, we discuss separately the current proposals concerning assessment and control in this context.

4.2.1 Reliability assessment in the look-ahead mode

Reliability assessment over the look ahead-horizon aims at the evaluation of:

(i) an indicator of the achievability of the real-time reliability target over the uncertainty space, and,

(ii) the compound expectation of the socio-economic function and (i.e., risk as perceived at the look-ahead decision stage).

Both these quantities depend not only on the realizations of exogenous parameters but also on the eventual response of the system operator in real-time, according to the respective real-time control strategy (e.g., as per the N-1 criterion, the GARPUR RMAC, etc.). Therefore, in order to perform reliability assessment in look ahead mode, it is necessary to simulate and evaluate the response of the real-time operator to a representative set of scenarios modelling the possible system conditions over the look-ahead horizon. An algorithmic solution to this problem therefore would be composed of three main ingredients (see Figure 4.3):

- A scenario generator.
- A computational model of the control strategy used during real-time operation.
- A computational model of the physical behaviour of the system.

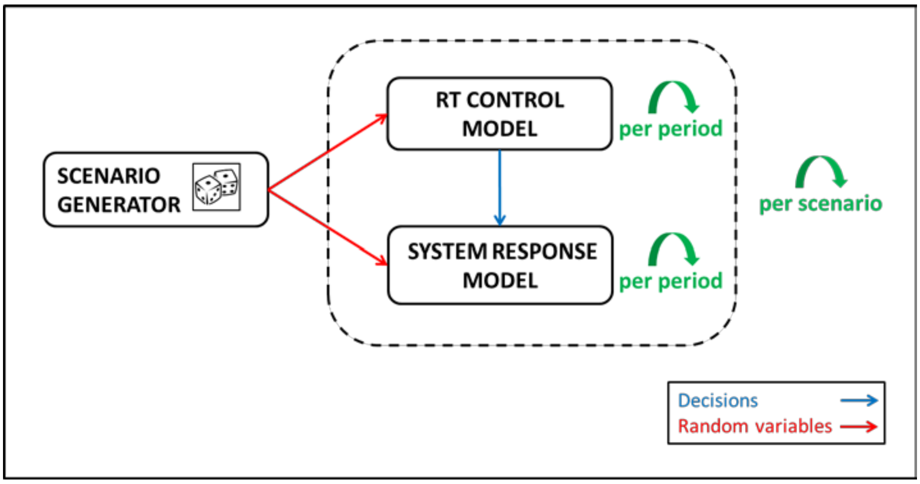

Figure 4.3: **Look-ahead mode reliability assessment components.**

Although not explicitly illustrated in Figure 4.3, we underline the sequentiality between realizations of uncertain parameters (i.e., temporal correlation) and between decision variables of successive real-time instances (e.g., generation ramping constraints).

The scenario generation tool serves to produce sequences of realizations of the uncertain exogenous parameters, taking into account their spatial and temporal correlation. The RT control model serves to simulate the reaction of the real-time operator to such input, producing anticipated real-time preventive/corrective decisions as per the applicable reliability criterion. Finally, the model of the system physical behaviour is used to evaluate such decisions, simulating the response of the system to uncertainty realizations and real-time operator decisions so as to quantify (i) the achievability of the real-time reliability target per period and scenario, and (ii) the corresponding socio-economic costs, including those implied by a potential interruption of service. Notice that, as discussed earlier in the document, this latter model would employ less restrictive assumptions and simplifications with respect to the representation of the system within the computational model of the real-time control strategy.

Also notice that, for sake of sustainability, the algorithmic approach for reliability assessment in look-ahead mode is agnostic on the precise approach influencing the real-time control strategy (i.e., be it the N-1, an instance of the RMAC proposed in GARPUR or any other approach, etc.) as well as on the degree of sophistication of the mathematical tools used to model such approach. Indeed, different models representing the relationship between uncertainty realizations and real-time preventive/corrective decisions are, in principle, interchangeable components of the look-ahead mode reliability assessment algorithm.

Current practice in look-ahead mode already uses SCOPF tools in order to model the control strategy during real-time operation, although this is normally done only along the most likely scenario (the forecast). Maintaining a similar style of approach, the replacement of the SCOPF tools currently modelling real-time operation as per the N-1 criterion with SCOPF tools modelling operation as per the GARPUR RMAC (presented in the previous section) is, at the algorithmic level, straightforward. However, the corresponding tools would need to be upgraded in order to enable such computations along a sufficiently large sample of scenarios. To break the increase in computational complexity, massive parallel computations and importance sampling may be suitable approaches. We refer the reader to the deliverable D6.2 [GARPUR, 2016c], which has worked on this look-ahead mode reliability assessment problem, from the viewpoint of practical needs. Finally, let us also suggest the development of a machine-learnt ‘proxy’ of the control strategy during real-time operation as a promising alternative. Early work on the development of such a proxy predicting several outputs of real-time SCOPF tools (as per the proposed GARPUR RMAC) is reported in [Duchesne, 2016].

4.2.2 Reliability control in the look-ahead mode

Solving the reliability control for the look-ahead problem means solving a very high-dimensional stochastic programming problem, where the output is the decision to commit in advance, and the objective function and constraints express the reaction of the real-time decision-making process.

This problem is currently open (both in the literature and within GARPUR).

On-going work on algorithmic approximations within the GARPUR project is focusing on the day-ahead, post-market variant of the problem. First stage decisions relate to reserve availability (e.g., requesting modifications on the unit commitment schedule of the following day resulting from the market clearing process) and deliverability (e.g., rejecting outage requests for the planned maintenance of transmission components).

In addition to such first-stage decisions (common for all scenarios describing uncertainty) the problem entails scenario dependent preventive and corrective decisions for each time period within the planning horizon. Considering the continuous set of uncertainty realizations per time period implies an infinite set of real-time RMAC problem instances, which is evidently not tractable. In our algorithmic approach (under development), we adapt ideas originally introduced in [Capitanescu, 2012] to overcome such barrier by approximating the continuous set as a finite set of “problematic” (worst-case) real-time RMAC instances that need to be covered by the common day-ahead operational planning decisions.

On top of the aforementioned issue, an additional challenge for the efficient resolution of the problem under consideration arises from the (in practice) gradual revelation of a realized scenario across the sequence of recourse time steps (t=1, … , T). Such property of the exogenous parameters calls for nonanticipative recourse decisions. To tackle the complexity of this, we attempt to further decompose the approximated problem (over a finite set of "problematic" real-time instances) by means of the progressive hedging algorithm. We refer to the work of [Li, 2014] for a state-of-the art implementation of the progressive hedging algorithm on the day-ahead, N-1 reliability constrained, unit commitment problem.

4.3 Mid-term outage scheduling

The work concerning algorithmic approximations for mid-term reliability management has focused on the outage-scheduling problem (with a standard horizon of one year). The corresponding reliability management problem is modelled in the following way:

- For a given target year, a list of component outages to schedule is given as input; the corresponding outage durations are given a priori, but the moments where they should be carried out are decision variables to be determined, in order to reach an acceptable result in terms of system reliability management in operation.
- A generative model of the uncertainties that are seen from the viewpoint of the outage-scheduling decision-maker and that could be encountered in operation over the outage scheduling horizon is given as input to the study: this model allows one to draw upon request a sample of possible operation conditions at an hourly time-step, as well as the uncertainties faced in D-1 operation planning.
- Two proxies are given as input in order to represent the way the system would be operated: a D-1 operation planning proxy and a real-time operation proxy.
- Cost functions are provided in order to allow the evaluation of operating and maintenance costs incurred by a particular outage schedule and for a particular scenario of exogenous conditions expressed at an hourly time step over the mid-term horizon.
- A criterion expressing the requirements for an acceptable outage schedule is formulated in the form of chance constraints incorporating the 'system operability under the short-term and real-time RMACs'.

NB: Mathematical formulations are given [Dalal, 2016a] and [Dalal, 2016b], where also a first set of simulations results obtained on academic test systems is presented). Further details about the practical nature of the outage-scheduling problem addressed within GARPUR are provided in deliverable D5.2 [GARPUR, 2016b], issued in parallel with the present document.

4.3.1 Overall algorithmic scheme

The algorithmic scheme proposed in WP2 for optimizing outage schedules is based on a distributed implementation of the cross-entropy optimization method [Dalal, 2016b]. In essence, this method combines a random search over the space of optimization variables (here the vector of moments where the considered outages are to be scheduled), with a noisy evaluation of the objective function and constraints (here, based on Monte-Carlo simulations combining the generative model of exogenous scenarios and the proxies used for evaluating the objective functions and constraints).

The developed approach exploits massive parallelism and high-performance computing infrastructures. One main advantage of this algorithmic scheme is that it is agnostic with respect to the details of the system response models (shorter-term proxies) and with respect to the particular nature of the uncertainty models (e.g. spatiotemporal correlations).

4.3.2 First implementation and testing

The approach has been implemented for a small test-system while assuming that shorter-term operation is carried out according to the N-1 criterion. The results are reported in **Error! Reference source not found.** and [Dalal, 2016b]. More recent work has been carried out in order to scale this up towards the IEEE RTS96 system, and exploit machine learning to speed up computations (see Annex A.2 of D5.2 [GARPUR, 2016b], for some preliminary results).

4.3.3 Upgrading for practical use

The overall approach is clearly open to incorporate enhancements in the way shorter-term processes are simulated, as well as in the way the uncertainties seen in mid-term decision-making are modelled.

4.4 Long-term system expansion and maintenance policy choices

The development of scalable algorithms for the *automatic* optimization of system expansion plans and of maintenance policies (i.e. the corresponding long-term reliability control problems) has been considered as being out of scope of the GARPUR project.

Rather, in this long-term context, the efforts in GARPUR have been focused on the design of reliability assessment methods, useful to help domain experts in their work. The corresponding work has been carried out within WPs 4 and 5, and is documented in the deliverables D4.2 [GARPUR, 2016e] and D5.2 [GARPUR, 2016b] prepared in parallel with the present document.

These works can obviously take advantage of the implementations of the short-term and mid-term RMACs documented in the present document, since these long-term reliability management problems should take into account how the system reliability is actually managed over the mid-term and short-term horizons.

4.5 Summary and further work directions

In this chapter we have presented synthetically the algorithms developed within GARPUR for solving the optimization problems posed by the GARPUR RMACs adapted to the different time-scales of TSO's reliability management. For the real-time context, these algorithms essentially are proposing adaptions of the currently used contingency simulation techniques and the currently used SCOPF formulations in this context. For the longer-term horizons (short-term and mid-term operation planning and long-term system expansion and maintenance policy choices), they have to address a much larger complexity because on the one hand they need to take into account a more complex set of uncertainties and on the other hand they need to sufficiently well model the shorter-term processes of TSO's reliability management over many future time-steps. Still, they may benefit in these contexts from more extensive human expertise and investments into high-performance computation infrastructures. Thus the challenges for deploying algorithmic schemes for these longer-term reliability management problems is to combine massive Monte-Carlo simulations with a well designed search over the space of candidate decisions (that itself is of high complexity), while keeping the human expert in the loop.

The complex dependence between short-term and mid-/long-term planning and the high uncertainty in the latter makes longer-term reliability management very challenging. For a concrete example, consider the mid-term task of outage scheduling, which necessitates coordination with the short-term market clearing process and the TSO's available actions in that scope, simulated using the unit commitment (UC) problem. As found out in the context of WP5 (see D5.2 [GARPUR, 2016b]), solving an extensive amount of

UC problems to mimic short-term decision-making in a varying, stochastic environment does not computationally scale well to realistic grids, with thousands of nodes, generators and loads.

To tackle this intractability issue, additional research is being conducted at present time. Its goal is to utilize machine-learning methods for designing proxies that predict short-term decisions-making outcomes without actual exact simulation of the short-term decision process.

Let us consider again the mid-term outage-scheduling example. In the context of parallel work in GARPUR (see D5.2 [GARPUR, 2016b]), a proxy is designed for this problem using on a well-known machine learning algorithm, 'nearest-neighbour classification'; this algorithm is adapted and extended to the particular task of predicting UC decisions under the possible conditions the system may be under during the year-long period of the planning problem. The methodology relies on a simple concept - creating a large and diverse dataset that contains samples of the environment and grid conditions along with their respective UC solution. Consequently, during assessment of an outage schedule, instead of solving the multiple UC problem instances required to simulate decisions taken, one can simply choose among the already pre-computed UC solutions. The UC solution chosen is the one with the closest conditions to the environment and grid conditions of the current UC problem that needs to be solved.

Promising initial results in this current research suggest that usage of the aforementioned proxy in particular, and other machine-learnt proxies in general can turn highly beneficial in the context of planning for longer time horizons. This is thus a main direction of further research.

5 COHERENCY WITH RESPECT TO THE SOCIO-ECONOMIC ANALYSIS AND THE PRACTICAL NEEDS EXPRESSED IN OTHER WORK PACKAGES OF GARPUR

In this chapter we discuss the coherency between the RMACs proposed in the context of WP2 of GARPUR and explained in the present document, with respect to

1. the socio-economic analysis of WP3, documented in D3.2 [GARPUR, 2016a], as well as the issues of fairness (see D3.1 [GARPUR, 2016f]) and the development of reliability markets;
2. the needs and pathways for implementation expressed by TSOs in the various practical reliability management contexts, documented in the deliverables D4-5-6.1 [GARPUR, 2015c][GARPUR, 2015d][GARPUR, 2015e] and D4-5-6.2 [GARPUR, 2016b][GARPUR, 2016c][GARPUR, 2016e].

5.1 Coherency with respect to socio-economic considerations

5.1.1 Social surplus optimization

The GARPUR RMAC explicitly takes into account in its objective function the expected system costs including costs of service interruptions, which is a monetized measure of the social value of continuity of supply. This term is combined with the system costs borne by the TSO when he takes his decisions, and in case where these decisions have an impact on the outcome of the electricity markets, it should also be combined with the associated change in system costs and benefits that arise with other stakeholders in the system (e.g. generators and flexible consumers) (cf. Figure 3.1 in D3.1 [GARPUR, 2016f])). For example, when the RMAC is used to guide decision-making in the D-2 context, where the first stage decision comprises the transmission capacities provided by the TSOs to the market operators, a term should be included in the socio-economic objective function so as to take into account the expected system costs of D-1 and real-time recourse decisions and expected costs of service interruptions.[4] This would allow one to rationally set the transmission capacities provided as input to the market-operator in such a way that the overall system cost is indeed minimized, respectively as stated in D3.1 and D3.2 that social surplus (also taking into account environmental costs) is maximized.[5]

Similarly, when long-term system expansion decisions are assessed, not only the impact on reliability over the target horizon but also the impact on the overall system cost, should obviously be modelled in the socio-economic objective function used to carry out such studies – taking notably into account reduced investment costs for generation capacities when transmission capacities are expanded (cf. e.g. [Spiecker, 2013]).

The precise definition of these various terms that should be included in the socio-economic objective function depends on the horizon chosen for the decision making problem, which itself depends on the time needed to implement the concerned decisions, and the expected length of the future time-period during which this decision will have a significant impact on the socio-economic performance of the system. We refer the reader to D3.2 [GARPUR, 2016a] for an in depth discussion of these temporal accounting and discounting questions.

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[4] Under the assumption that costs can be additively decomposed and assigned to different time horizons.

[5] The assessment framework developed in D3.1 [GARPUR, 2016f] and D3.2 [GARPUR, 2016a] is developed under the premise of maximizing social surplus whereas the term socio-economic optimization means cost minimization in this document. One problem formulation can be transformed into the other, as long as all benefits are redefined as negative costs and vice versa.

Let us further notice that the discarding principle allows one to simplify the uncertainty space explicitly taken into account when evaluating the expectation of the socio-economic objective function under uncertainties. It explicitly sets an accuracy level for this evaluation, and thus enables a simplification of the problem, under the condition that the resulting loss in accuracy remains under control. Further work needs to be carried out, in order to define a sensible value for the corresponding tolerance, in the different contexts of reliability management. Given the fact that data quality and the level of detail of the physical models that are used in practice are necessarily limited, most cost-terms can in practice not be assessed with perfect accuracy. For example, whatever the framework used for the estimation of value of lost load, it will in practice lead to only a rather noisy estimation of the actual cost of service interruptions; also, when setting network capacities, the true impact on market performance can in practice only be predicted by making some partly idealizing assumptions about the functioning of markets and the behaviour of market participants. We believe that these intrinsic limitations in the evaluation of the different cost terms should be carefully assessed and taken into account when the accuracy tolerance used in the discarding principle is to be defined.

Beyond the socio-economic objective function, the family of RMACs defined in this document also incorporates a set of constraints: while we have left implicit those constraints that are anyhow imposed by the physics of the power system (e.g. power flow equations, ranges of admissible values of controls), or by the practical context of TSOs reliability management, we have explicitly stated an additional constraint in the form of a so-called ‘reliability target’, so as to allow the explicit modelling of conditions that should be avoided, even if this comes at the price of reduction in the overall socio-economic surplus achievable in a certain context. The reliability target was expressed in a generic way, so as to allow its adaptation to system specifics and regulatory choices. It allows for example to exclude decisions that would lead the power system towards extreme operating modes, for example conditions where the technical and/or socio-economic consequences would be very harmful (such as loss of system stability and/or cascades of outages, that would lead to the propagation of service-interruptions over large areas and long durations). Acknowledging the fact that in practice a full guarantee for avoiding such situations cannot be attained, this reliability target has been formulated in the form of a chance constraint imposing a desired confidence level with which one wants to avoid such unacceptable system behaviours.

5.1.2 Multi-TSO considerations and distributional fairness

The proposed family of RMACs has been formulated in the context of a single TSO. In practice, to manage the reliability of an interconnected system, several TSOs and regional reliability coordinators will work in parallel, each one focusing on a particular subset of problems and decisions, and each one possibly having its own technical, organizational and regulatory constraints. Depending on the particular area-wise RMACs used by these different TSOs, the resulting global social-surplus will not necessarily be optimized or, conversely, it may be distributed among the different areas in a way that is considered as unfair by some of the concerned actors.

In a similar fashion, within a particular control-area under the responsibility of a particular TSO, the use of a particular version of the RMAC (i.e. with a particular choice of the reliability target and socio-economic objective function) may lead to suboptimal area-wise social surplus or, conversely, it may lead to an unfair distribution of the surplus among the different geographical zones and/or end-users of this control-area.

The fundamental question of how to properly arbitrate between the objective of maximal global social surplus and a fair distribution of this surplus among the different actors is clearly unavoidable, but also beyond the scope of the GARPUR project, which focuses on the development of methods and algorithms for reliability management under uncertainties suitable for practical use in a broad range of contexts. The socio-economic-impact assessment framework proposed in WP3 is however aware of these distributional aspects, and it is designed in order to allow one to compare different combinations of RMACs in simulation, so as to study the impact of them on this “global vs local” compromise. On the other hand, fairness objectives may be included in the RMAC formulation by adapting its reliability target and/or its socio-economic objective function in a suitable fashion. The GARPUR framework therefore provides the ground for agreeing in the future on the appropriate reliability targets and socio-economic objectives imposed by the different RMACs used for system expansion, asset management and system operation, in the context of the multi-TSO European electric power system. This question is one of those that are to be studied in the last year of the GARPUR project.

5.1.3 New technological opportunities and the development of reliability markets

Exploiting the flexibility of demand and investing in electricity storage systems are important technological opportunities for the reliability management of the future power systems. These possibilities are in principle covered by the proposed reliability management framework, since they can be modelled as additional control resources having their own physical constraints and economic cost functions (both CAPEX and OPEX).

Reliability markets could be viewed as a tool in order to provide appropriate price signals so as to encourage the deployment of these resources in the most appropriate way from the socio-economic point of view. The socio-economic impact assessment framework of WP3, as well as the RMACs proposed in WP2, both may be extended in order to integrate the existence of such markets into the reliability management process and its evaluation. They might thus as well be used in order to help in the design of such reliability markets. This latter topic is however beyond the scope of the GARPUR project, and hence is left for further research.

5.2 Coherency with respect to the pathways for system development

5.2.1 Needs expressed in D4.1

For system development reliability management studies, the following two types of needs have been expressed in D4.1 [GARPUR, 2015c]:

- ability to identify system weaknesses that would show up in a target year and that should guide the planner in the search for sensible candidate system expansion decisions ;
- ability to assess the impact of a candidate system expansion decision both on the reliability level and on the market performance in a given target year (and to rank a number of alternatives in terms of these two aspects)

The proposed RMAC for long-term horizons may be used in both contexts, while modelling the reliability management over the mid-term and short-term horizons according to the corresponding RMAC versions that one wants to consider.

5.2.2 First implementations proposed in D4.2

This implementation proposes to perform the long-term reliability assessment (i.e. predicting reliability and economic performance expected to occur in the planned power system, for some given expansion plan) by stressing the expected RT operating states using a set of contingencies that can either be fixed (e.g. according to the N-1 criterion) or a function of the expected RT operating state (e.g. according to the GARPUR RT-RMAC).

The modelling of the envisaged short-term and real-time situations is based on the generation of credible operating states using a market model, while the model of reliability management over the short-term and RT horizons is based on a SCOPF that will trigger pre-contingency and post-contingency control actions, the later of which being currently restricted to load shedding. Clustering techniques are also proposed in order to reduce the computational burden of the implied simulations, by reducing a larger sample of potential operation conditions to a manageable number of cluster prototypes that would be simulated in details.

The proxy used to take into account the mid-term outage scheduling process aims at assessing the maintainability of the planned power system by evaluating the width of the time windows in which outages can be planned prior to real-time operation. A this stage several alternatives are envisaged, one of them being to perform a simple but realistic maintenance scheduling over the long-term scenarios modelled in the context of the long-term planning study.

In essence, this means that the framework for system expansion studies developed in GARPUR WP4 is formulated in such a way that it could adapt itself ‘automatically’ to any change in the RMACs plugged-in for taking into account the short-term & real-time reliability management processes, as well as the mid-term outage scheduling process. We refer the interested reader to D4.2 [GARPUR, 2016e] for a more in depth presentation of the kind of market, mid-term and shorter-term proxies that are currently envisaged by WP4 in the system expansion context.

5.3 Coherency with respect to the pathways for asset management

5.3.1 Needs expressed in D5.1

In the context of asset management, the following needs have been expressed in D5.1 [GARPUR, 2015d]:

- ability to (re)schedule over a mid-term horizon a set of outages needed for the maintenance and/or replacement of components, in such a way that they comply with the available logistics resources (e.g. crews) while minimizing the negative impact of these outages on system performance in operation;
- ability to define maintenance policies over a long-term horizon, in such a way that they are feasible in terms of outage scheduling and system operation, and at the same time lead to sufficient fitness of the components at the end of the evaluation horizon ;
- ability to carry out cost-benefit analyses for the investment into more effective component condition monitoring systems, so as to improve the understanding of ageing and facilitate the anticipation of needs for maintenance activities.

The proposed RMAC for the long-term horizon may be used to cover the second need, while modelling the reliability management over the mid-term and short-term horizons according to the corresponding RMAC versions that one wants to consider. The RMAC proposed for the mid-term horizon may be used for covering the first need. For the long-term asset management policy choice, in addition to what was already stated in the context of system development problem in the previous section, there are however important requirements on the resources management (budgets, workforce) that need also to be modelled and taken into account.

On the other hand, the nature of the third problem has been discussed in more details in the context of WP2, where it was found out that the mathematical nature of this problem is much different from the other problems addressed in WP2. The needed research to address this problem has been identified as an important direction of work beyond the GARPUR project.

5.3.2 First implementations proposed in D5.2

These implementations propose to use proxies for mid-term and short-term reliability management based on the currently used N-1 criterion. This is compatible with the overall framework, where the longer-term decision-making processes, rather than 'deciding themselves on the shorter-term recourse strategies', consider that these shorter-term strategies are part of the shorter term 'physical system response' to the choices of the longer-term decision-maker.

We refer the interested reader to D5.2 [GARPUR, 2016b] for a more detailed presentation of the proposed implementations aiming at providing tools for reliability assessment over the mid-term and long-term asset management activities, while proposing a set of proxies for the shorter-term horizons, as well as a set of reliability targets allowing one to model preferences in terms of fairness to the end-users. This deliverable also discusses the important question of how to present the information computed by an assessment tool in a useful way to the experts responsible for asset management.

5.4 Coherency with respect to the pathways for system operation

5.4.1 Needs expressed in D6.1

In the context of system operation, the following two types of needs have been expressed in D6.1 [GARPUR, 2015e]:

- ability to support decision-making in the context of real-time operation, and in particular the arbitration between preventive and corrective control while taking into account the spatio-temporal variation of threats perceived by the real-time operators;
- ability to support decision-making in the context of short-term operation planning, and in particular to take into account the uncertainties about future weather conditions, load and renewable generation in-feeds.

The proposed RMACs for short-term and real-time horizons have been designed so that they may be used in these two contexts, while modelling the physical response of the system to contingencies with suitable proxies. In these shorter-term contexts, the time available to take a decision is strongly constrained (a few minutes in real-time operation, and a few hours in operation planning), and the tools need to be robust and present their recommendations in a way suitable for fast decision-making by the operators.

5.4.2 Implementations proposed in D6.2

In D6.2 [GARPUR, 2016c] the real-time RMAC proposed by WP2 has been used as the starting point so as to address both reliability assessment and reliability control in operations. The resulting analysis aims at building on top of the tools and the data currently available within TSO organizations, and suggests two possible extensions, namely

1. Expanding the uncertainty model, so as to enable also the treatment of very-short-term uncertainties in the power injections (mainly renewable in-feeds, that may be uncertain even when considering a short horizon of say one hour).
2. Proposing alternative ways for the relaxation of the reliability target, whenever the control problem appears as infeasible. In particular D6.2 advocates to relax the control problem by enlarging the definition of the set of ‘acceptable’ trajectories, rather than by increasing the tolerance level of discarding principle.

These two extensions of the RMAC proposal of WP2 should be assessed in the context of pilot tests, and compared with the real-time RMAC developed in the present document, so as to eventually figure out what is the most appropriate choice. We however notice that the first one implies possibly a significant extension of the algorithmic (SCOPF based) solution proposed in the present document, while the second one would have no major impact on the algorithms (in terms of tools, and computational complexity).

On the other hand, the short-term operation-planning context has been considered in WP6, so as to propose practical implementations of the look-ahead mode RMAC developed in WP2. In this context, the proposal is to first focus on the reliability assessment counter part, since at the current stage of research the reliability control framework for look-ahead mode operation planning is not yet mature in terms of algorithmic implementations.

6 SUMMARY AND GUIDELINES FOR PROGRESSIVE IMPLEMENTATION

We start this chapter by summarizing the results presented in this report. The last part of this chapter then proposes a number of guidelines for progressive implementation of these novel ideas in the practice of electric power system reliability management. These guidelines should be considered as our input to the subsequent work to be carried out during the last year of the GARPUR project (Pilot testing in WP8, and Recommendations and roadmap for migration in WP9).

6.1 Summary

In this report we have synthesized the work carried out in the context of WP2 of the GARPUR project so as to define a new probabilistic framework for the reliability management of the European interconnected power system. The proposed framework explicitly takes into account uncertainties (e.g., meteorological conditions, renewable generation, etc.) and enables the exploitation of several opportunities (e.g., post-contingency corrective controls, demand-side response, etc.) with the objective of optimizing socio-economic welfare by means of the various TSO activities.

In this endeavour, this research work in WP2 has been decomposed in three progressive steps, namely

1. **T2.1**: the definition of vocabulary, concepts and a functional model of reliability management, decomposing it into reliability assessment and reliability control. This model is sufficiently general to cope with the needs of different TSOs and in their various decision-making contexts, from long-term system expansion studies to real-time operation.
2. **T2.2**: the definition of mathematical models expressing the reliability management (assessment and control) problems in a formal way, as an objective function and a set of constraints of a multi-stage stochastic program. These models establish also the coordination of reliability management over the different temporal horizons. Moreover they allow one to explicitly state what kind of approximations are deemed acceptable when targeting algorithmic implementations, as well as how the reliability control problems should be relaxed whenever they turn out to be unfeasible.
3. **T2.3**: the development of reliability control algorithms by building on state-of-the-art optimization and simulation techniques so as to ensure tractability, scalability, and sustainability. In this context we have also proposed the main ingredients of algorithms for reliability assessment that have been further developed in other work packages of the GARPUR project. For the sake of empirical experiments on academic test systems, we have actually implemented such reliability control algorithms both for real-time operation and mid-term outage scheduling, in the form of research grade software. On the other hand, the basic ideas for suitable algorithms for short-term operation planning and for long-term reliability management studies have been outlined but not yet implemented and tested.

In parallel with these three tasks, the role of **T2.4** has been to ensure coherency with the initial goals of the GARPUR project and the findings of work packages WP3-4-5-6 carried out in parallel while focusing on specific sub-problems. In particular, the mathematical framework and the proposed algorithms are stated in such a way that they can incorporate the findings of WP3 in terms of the quantification of socio-economic impact, and that they can cope with the practical requirements of TSO activities in system development, asset management, and system operation, as worked out in WP4, WP5 and WP6.

The novel ideas developed in WP2 have also been presented, challenged and published at several occasions during the last three years, so as to incorporate feedback from a broader community, comprising scientists working the field, as well as other TSOs not part of the GARPUR project, and other stake-holders (regulators, producers, distribution system operators, etc.). In particular, we refer the reader to the following presentations:

- First GARPUR Workshop towards TSOs (April 2014) – Functional Analysis of Reliability Management
  http://www.garpur-project.eu/system/resources/W1siZiIsIjIwMTQvMDYvMjMvMTBfMDZfMjJfOTQ1XzIwMTQwNDA3X0dBUlBVUl9Xb3Jrc2hvcF90b3dhcmRzX1RTT3NfM19GdW5jdGlvbmFsX0FuYWx5c2lzX1VMRy5wZGYiXV0/20140407_GARPUR_Workshop_towards_TSOs_3_Functional_Analysis_ULG.pdf
- First GARPUR Workshop towards external stakeholders (October 1014) – Probabilistic Reliability Management
  http://www.garpur-project.eu/system/resources/W1siZiIsIjIwMTQvMTAvMDgvMTRfMDBfMzZfMzMyXzIwMTQxMDA3X0dBUlBVUl93b3Jrc2hvcF8yX1Byb2JhYmlsaXN0aWNfcmVsaWFiaWxpdHlfbWFuYWdlbWVudC5wZGYiXV0/20141007-GARPUR_workshop-2-Probabilistic_reliability_management.pdf
- Second GARPUR Workshop towards TSOs (June 2015) – Development of New Reliability Criteria
  http://www.garpur-project.eu/system/resources/W1siZiIsIjIwMTUvMDYvMDUvMTBfNDhfNDJfNTE0XzJfR0FSUFVSX1RTT18yX0p1bmVfMjAxNV9FZnRoeW1pb3NfS2FyYW5nZWxvcy5wZGYiXV0/2_GARPUR_TSO_2_June_2015_Efthymios%20Karangelos.pdf
- Second GARPUR Workshop towards TSOs (June 2015) – Alternative Reliability Criteria to be Developed
  http://www.garpur-project.eu/system/resources/W1siZiIsIjIwMTUvMDYvMDUvMTBfNTVfMDRfODU5XzlfR0FSUFVSX1RTT18yX0p1bmVfMjAxNV9Mb3Vpc19XZWhlbmtlbC5wZGYiXV0/9_GARPUR_TSO_2_June_2015_Louis_Wehenkel.pdf
- Third GARPUR Workshop towards TSOs (June 2016) – GARPUR RMACs. Main stakes for probabilistic approaches vsN-1 in reliability assessment and control
  http://www.garpur-project.eu/system/resources/W1siZiIsIjIwMTYvMDYvMDkvMDlfMTlfMDhfODc0XzA2Tl9FdXRoeW1pb3NfR0FSUFVSX1dQMl8zcmRfVFNPX3dvcmtzaG9wX3dlYl92ZXJzaW9uLnBkZiJdXQ/06N_Euthymios%20GARPUR%20WP2%203rd%20TSO%20workshop%20--%20web%20version.pdf
- Third GARPUR Workshop towards TSOs (June 2016) – The overall mathematical and algorithmic challenges for the new RMAC
  http://www.garpur-project.eu/system/resources/W1siZiIsIjIwMTYvMDYvMDMvMjBfNDRfMDlfMTAzXzAyX0xvdWlzX0dBUlBVUl9STUFDX3ZzX05fMS5wZGYiXV0/02_Louis%20-%20GARPUR%20RMAC%20vs%20N-1.pdf

While the work is certainly not yet finished, we believe that the principles, methods and algorithms developed in WP2 already provide a solid ground for evolving away from the N-1 criterion.

6.2 Progressive implementation in practice

For the progressive pan-European implementation of the methods developed in GARPUR we propose to work in six stages. These stages are motivated and discussed in the following subsections.

6.2.1 Stage 1: prototype tools for probabilistic reliability assessment

As a first step towards a progressive implementation of the methods developed in WP2 of the GARPUR project, we recommend to start with reliability **assessment** according to RMAC variants, for each one of the different TSO reliability management contexts considered in GARPUR. Here the goal is to develop prototype reliability assessment software that is able to run in reasonable time on representative power system models of the different European TSOs and/or regional reliability coordination centres.

These prototype implementations should, to the extent possible, rely on existing simulation tools used currently by TSOs, but must be complemented by the appropriate models of uncertainties (sampling of scenarios, modelling of weather dependent probabilities of failure rates, contingencies and corrective control failure modes) and the required socio-economic performance metrics (costs born by TSOs, market surplus, costs of service interruptions to end-users, etc.). In order to be useful, they will also require the provision of suitable high-performance computing resources. Furthermore, in order to make tractable the longer-term reliability assessment problems, further work needs to be carried along the construction of suitable proxies to model within them the shorter-term decision making processes. This could be done by leveraging machine learning approaches and by defining suitable trade-offs between accuracy and computational efficiency.

Notice that this strategy to first focus on reliability assessment has already been adopted in the context of the work packages WP4, WP5 and WP6, as a first step towards practical implementation.

6.2.2 Stage 2: prototype tools for probabilistic reliability control

The end-goal is would be to use the proposed RMACs for choosing near-optimal decisions in the different reliability management contexts. As explained in the earlier chapter of this report, this will be possible only if robust enough optimization tools are made available in the different contexts.

Also, to justify the switch from N-1 based decision making towards probabilistic reliability control, it is necessary to enable the systematic comparison of the impact of moving away from the current N-1 driven decision-making policies on socio-economic performance criteria. It is the role of the GARPUR quantification platform to enable such comparisons, based on suitable implementations of the new reliability control approaches.

The implementation of reliability **control** prototype software should logically follow the following sequence, and build on the algorithms described in Chapter 4:

1. Real-time reliability control ;
2. Short-term operation planning reliability control (e.g. for Day-1 and then Day-2) ;
3. Mid-term outage scheduling ;
4. Long-term system expansion and maintenance policies.

Indeed, the shorter-term reliability control algorithms are in principle needed to formulate the longer-term reliability assessment and control problems, be it by replacing the full-fledged versions of the former by suitable proxies.

In order to reach these goals, it will be necessary to carry out further research work on some of the optimization algorithms and, for some of the problems, improve the quality of proxies used for the representation of the shorter-term decision-making stages. Further research on the use of machine learning approaches for the design of such proxies is a very promising research direction.

6.2.3 Stage 3: gather experience and tune parameters with the help of experts

Once the new probabilistic reliability assessment and/or control prototype tools are ready to be used in the different contexts, they should be extensively tested and compared with the currently used methods. Also, the impact of the quality of the additional data needed should be studied in depth, by carrying out sensitivity studies with respect to the additional parameters introduced in the probabilistic approach (probabilities of contingencies, value of lost load, corrective control failure modes, spatio-temporal models of uncertainties of demand and renewable generation, etc.).

In order to carry out such studies, a quantification platform will be a very useful tool, by allowing several TSOs to study what would be the impact of using these new techniques as a replacement of their current N-1 based decision-making approaches.

By carrying out such comparisons and sensitivity studies, it should indeed be possible to gain understanding and also to determine the correct settings of the meta-parameters (tolerance level of the discarding principle, acceptability constraints and tolerance of the reliability target) while taking advantage of human expertise.

6.2.4 Stage 4: industrial use of probabilistic reliability assessment

Once the methods are well understood and their added value with respect to current practice is recognized by the field experts, the ‘industrial grade’ software tools needed for practical use of these new reliability assessment methods should be developed and progressively enhanced, so as to reach a suitable compromise between computational efficiency, robustness and accuracy.

They should then be integrated in the information systems available at the TSO sites, and complemented with industrial grade man-machine interfaces comprising appropriate summarization and visualization tools to present their results in a way convenient for human interpretation and exploitation.

In addition to the reliability assessment software that would be implemented in the different decision-making processes of the TSOs, it will as well be necessary to adapt the current ‘ex-post’ performance monitoring methods used in practice (the right-most stage represented in Figure 2.1), in order to take into account the ingredients of the probabilistic approach.

In terms of software developments, we believe that the implementation of the reliability assessment tools, in the context of system operation (real-time and look-ahead) could greatly benefit from first prototypes developed in the context of the FP7 project iTESLA[6].

6.2.5 Stage 5: improve data quality

While the new probabilistic approaches to reliability management developed in GARPUR might in principle be implemented on the basis of the data and models that are currently available to the TSOs, they are essentially intended to exploit additional data. Thus, the full benefit of these methods will require further work in order to gather more and more accurate data (e.g. about weather-dependent failure rates and contingency probabilities, corrective control failure modes, and value of lost load, as well as better uncertainty models reflecting the spatio-temporal correlations of demand and renewable generation).

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[6] http://www.itesla-project.eu

We believe that such work should be carried as soon as possible, driven by the willingness of different 'champion TSOs' to implement the methods.

At this stage, the need for additional data and model refinements should be justified, so as to identify the priorities in terms of modelling and data collection efforts.

Let us also notice that the use of the probabilistic approaches at the pan-European level will also induce novel needs in terms of data exchanges between TSOs.

6.2.6 Stage 6: industrial use of probabilistic reliability control

Adopting new planning, maintenance and operation policies for TSOs' reliability management according to the probabilistic approach proposed in GARPUR will lead to several further challenges:

1. **Regulatory challenge**: national and European regulatory choices will have to be adapted, so as to enable a progressive migration towards probabilistic reliability management policies.
2. **Human challenge**: even if more sophisticated decision support tools can be developed, it will always be of paramount importance to keep the human expert in the loop; with the paradigm change, this implies to train the staff of TSOs and regulators on the theory behind the new methods and on the practical use and maintenance of the new software tools and their data requirements.
3. **Technical challenge**: robust and sufficiently efficient computational implementations of the proposed multi-stage stochastic programming paradigm need to be developed; they should cover the practical needs of TSOs (by incorporating their technical constraints and degrees of freedom to act on the system), and yield recommendations which degree of sub-optimality can be quantified and which are interpretable by the experts. Recent progress in the field of convex relaxations of the OPF problem and in the filed of chance-constrained optimization could be leveraged (see e.g. [Panciatici, 2014] and [Capitanescu, 2016] for an overview).

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