

Advanced Architectures and Control Concepts for More Microgrids

Specific Targeted Project

Contract No: SES6-019864

**WPG. Evaluation of the system performance on power
system operation**

Deliverable DG2: Demo GIS platform as a policy making-aid

December 2009

Final Version

Coordinator: George Kariniotakis
Company: ARMINES
Address: BP 207 F-06904 Sophia Antipolis Cedex France
Telephone: +33.4.93.95.75.01
Fax: +33.4.93.95.75.35
Email: georges.kariniotakis@mines-paristech.fr

Document Information

Deliverable: DG2: Demo GIS platform as a policy making aid

Title: Agent-Based Modelling & Simulation applied to the Planning of Distribution Systems

Date: December, 2009

Coordination: George Kariniotakis Georges.kariniotakis@mines-paristech.fr

Authors: Christophe Chevallier ARMINES (France)
George Kariniotakis ARMINES (France)

Access: Project Consortium
European Commission
X PUBLIC

Status: _____ For Information
_____ Draft Version
_____ Final Version (Internal document)
_____ Submission for Approval (deliverable)
__X Final Version (deliverable, approved on)

Contents

Specific Targeted Project	1
Contract No: SES6-019864	1
WPG. Evaluation of the system performance on power system operation	1
Version 2.0	Error! Bookmark not defined.
Abbreviations	6
Chapter I. Introduction.....	7
1 General context: reorganisation of the electricity sector and integration of Distributed Generation.....	7
2 Power system planning for large-scale integration of DG, From DG-aware to DG-oriented – Problem formulation.....	8
2.1 Position of system planning in the general efforts.....	8
2.2 Need for more adapted planning methods and tools	8
2.3 Brief review and classification of first answers in the literature	10
3 Proposal: Agent-Based Modelling & Simulation of a MAS as a framework for studying distribution system planning.....	11
3.1 Why is ABM&S relevant for the study of DS-Planning.....	11
3.2 Why is ABM&S <i>a priori</i> interesting for the study of DS-Planning: value of the M&S /ABM&S approach.....	13
4 Outline.....	19
4.1 Objectives of this work	19
4.2 Identification of work-packages and outline of the document	19
Chapter II. Analysis of the DS-Ecosystem.....	21
1 Overview of the DS-MAS.....	21
2 Description of the environment.....	22
2.1 Perspectives on the environment.....	22
2.2 Illustration of a typical environment	23
2.3 The land: relief and land cover	23
2.4 Local energy resources.....	24
2.5 Land use, type of zones regarding rules	25
2.6 Power system.....	25
2.7 Miscellaneous	25
2.8 Environment’s dynamics.....	25

3	Description of Distribution system actors.....	26
3.1	Roundtable of distribution system stakeholders.....	26
3.2	Focus on the problem of planning of DG installation	28
3.3	Considerations on society’s organisation and regulations – Focus on coordination between DG-Installers and the DSO	29
Chapter III.	Application of ABM&S to a basic DS-society	32
1	System and objectives definition	32
1.1	Objectives of the simulator.....	32
1.2	DS-Society’s organisation, rules, and coordination procedure	32
2	Assumptions /simplifications related to modelling	35
2.1	Assumptions on the DS-Environment.....	35
2.2	Assumptions on DS-Actors.....	35
2.3	Miscellaneous assumptions	37
3	Environmental model.....	37
4	DG-Installers.....	38
4.1	Planning process overview.....	38
4.2	Stage 1: Identification of the domain of feasibility of project alternatives	39
4.3	Stage 2: Construction of a feasible project alternative for evaluation	40
4.4	Stage 3: Evaluation of alternative	41
4.5	Stage 4: Filtering out of unacceptable and Pareto-dominated alternatives.....	47
4.6	Stage 5: Selection of “best” alternative	48
5	The DSO	49
5.1	Project approval process.....	49
Chapter IV.	Implementation and simulation.....	51
1	Implementation.....	51
1.1	Choice of a multi-agent modelling and simulation platform.....	51
1.2	Block-diagram of the DS-Eco-Sim	51
1.3	Data models	52
2	Demonstration of modules	53
2.1	Use of GIS for modelling environment	53
2.2	Use of multi-objective optimisation module (QMOO) in pair with Retscreen®	54
3	Envisaged case studies	56
Chapter V.	Conclusions.....	57
1	Contributions.....	57

- 1.1 Introduction of the agent-based modelling and simulation framework for the problem of distribution system planning..... 57
- 1.2 Analysis of typical distribution system society organisations and actors..... 57
- 1.3 Proposition of a simple automated DG planning method, i.e. of a simple model of DG installers 57
- 1.4 Implementation 58
- 2 Value of the approach and of the work 58
 - 2.1 Overall advantages..... 58
 - 2.2 Different uses for different stakeholders 58
 - 2.3 Scope, limitations and difficulties of the approach 59
- 3 Perspectives 59
- References..... 61

ABBREVIATIONS

ABM&S: Agent-Based Modelling and Simulation
ABM: Agent-Based Modelling /Agent Based Model
B/C ratio: Benefit /Cost ratio
DG: Distributed Generation
DG-Installers: Installers of Distributed Generation units
DN: Distribution Network
DS: Distribution System, considered to be composed of the DN + generation units connected to it.
DS-Actors: Actors of the Distribution System
DS-Eco-Sim: name of the simulator of the DS-Ecosystem
DS-Ecosystem: Distribution System Ecosystem
DS-Envt: Distribution System Environment
DS-MAS: Distribution System Multi-Agent System
DSO: Distribution System Operator
DS-Planning: Distribution System Planning
DS-Society: Distribution System Society
EBM&S: Equation-Based Modelling and Simulation
EBM: Equation-Based Modelling /Equation Based Model
ERDF: Acronym for ‘Electricité Réseau Distribution France’, the French DSO in most regions
GIS: Geographical Information System
HV: High Voltage
LV: Low Voltage
M&S: Modelling and Simulation
MAS: Multi-Agent System
MO: Multi-Objective
MOO: Multi-Objective Optimisation
MV: Medium Voltage
NPV: Net Present Value
PDE: Partial Differential Equations
PV: Photovoltaic
RES: Renewable Energy Sources
T&D: Transmission and Distribution

Chapter I. **INTRODUCTION**

1 GENERAL CONTEXT: REORGANISATION OF THE ELECTRICITY SECTOR AND INTEGRATION OF DISTRIBUTED GENERATION

With the reorganisation of the electricity sector, the European Union created the conditions for the installation and connection of small and medium power Distributed Generation (DG) units to Distribution Systems (DS)¹.

However, in the traditional, centralised, technical paradigm of power systems, DS are initially not meant for the connection of DG. Systems margins currently allow us to temporarily endure DG, but massive, disorganised, penetration of DG will eventually jeopardise the reliable operation of the system (McDermott and Dugan 2003): DG may negatively impact system stability, power quality (harmonics, voltage flicker, voltage regulation...), and network protection. Moreover DG will most probably rely on non-dispatchable and possibly hard-to-predict generation, either because it uses renewable energy sources (RES) such as wind or solar energy, or because, according to enforced rules, there may be no obligation for the owner to communicate the programmed (or predicted) power output.

At the opposite, DG installation can be advantageous if installed and coordinated smartly, potentially providing (Pepermans, et al. 2005):

- Standby capacity or peak-use capacity;
- Better reliability and power quality;
- Grid support and ancillary services (such as responding to a sudden under- or overcapacity, or reducing power losses);
- Expansion or use of the local network;
- Answers to environmental concerns (better energy efficiency thanks to the updated technology, use for cogeneration and proximity to the load, wider and easier exploitation of diverse and intrinsically dispersed renewable energy sources);
- And ease of acquisition and installation compared to larger units.

¹ In this text, we use the term 'distribution network' to refer more precisely to substations, lines, transformers, etc. and the term 'distribution system' to refer to the system composed of the distribution network (substations, lines, transformers...), AND all generation units and loads connected to it. The distribution system encompasses the distribution network.

2 POWER SYSTEM PLANNING FOR LARGE-SCALE INTEGRATION OF DG, FROM DG-AWARE TO DG-ORIENTED – PROBLEM FORMULATION.

2.1 POSITION OF SYSTEM PLANNING IN THE GENERAL EFFORTS

Much work is being undertaken in the frame of European projects, aiming both at the large-scale integration of DG in existing European power systems and at the electrification of non-electrified rural areas using DG, trying to magnify its advantages and overcome the difficulties it opposes us. Technical research is coherently carried out in parallel on four key (interdependent) subjects:

- *Architectures of networks*: search for new active, intelligent architectural models of networks. One of the candidates is the MicroGrids model;
- *Equipment and technology*: search for new standards, optimisation of performance, research on storage means;
- *System operation*: research on short-term production forecasting, and on advanced system management methods;
- *System planning for large-scale integration of DG*, to evolve existing power systems or develop new ones, depending on what case is considered.

The work presented in this document concerns System Planning, limited to the integration in existing European DS.

While solutions to power system planning in the old context were quite well established they are for example thoroughly detailed in (Willis, Power distribution planning reference book 2004)), the new context has largely complicated the problem of power system planning, and Distribution System Planning (DS-Planning) in particular, and completely questions the old approach and practice, for the reasons given in the next section.

2.2 NEED FOR MORE ADAPTED PLANNING METHODS AND TOOLS

2.2.1 *A deficiencies analysis*

The new context not only fosters but binds research for new planning methods and tools

It is useful to review black marks and deficiencies of traditional T&D planning methods and tools, whether implied by the recent evolution of the context or not, so as to bring out needs for a new planning approach. An interesting critical point of view on distribution system planning methods is expressed in (Ault, Foote and McDonald 2002), providing inspiration for the following list of serious deficiencies of traditional approaches:

- **Inability to deal with a highly uncertain future, leading to poor decisions and sub-optimal developments**: uncertainty on load evolution, uncertainty about future general demands (ancillary services...), uncertainty about future technological, political, social, economical and regulatory environment, including electricity prices, fuel costs, technological improvement or breakthroughs;

- ❑ **Inability to deal with the change in the technical paradigm (large-scale integration of DG in distribution networks):** traditional planning methods and tools implicitly assume a centralised and hierarchical network paradigm (no injection of power at distribution level), and cannot consider non-dispatchable /hardly predictable generation such as wind generation;
- ❑ **Too few interests considered in the overall process, too few consideration given to externalities:** such as consumer and environmental issues. Other actors' interests, such as consumers' interest, will need to be taken into account;
- ❑ **Inability to deal with the restructuring of the electricity sector (notably unbundling):** all activities of power system planning presented above are dependent upon one another and a coordination between them is thus required. Such a coordination was eased by the vertical integration of utilities, and traditional methods and tools were implicitly meant for this.

Highlighting those deficiencies, there is a clear necessity for new planning methods and tools.

2.2.2 *Analysis of main issues and research needs in the new context*

Problem formulation: Different problems to solve for different actors with different roles

Among all the deficiencies listed above, we believe unbundling of utilities is the one that is the most defeating traditional planning methods and tools. It is calling for a completely different approach. When in the old context, decisions regarding the distribution system were made by a single decision-making entity, these decisions are now in the new context distributed among different classes of actors with different problems to solve – at least two classes of actors, defining research needs:

- ❑ **DG installers, for generation planning:** what production units should be installed, and where, considering costs, natural resources, and desired services? There is a research need on DG installation planning methods for DG installers;
- ❑ **the DSO, for network planning:** how should the network be developed not only to meet future demand as traditional system planning, **but now also to accept future DG-generation**, while providing good quality and cheap service? There is a research need on network evolution planning methods in the new context;
- ❑ and possibly even more, such as **consumers, environmentalists, residents, municipalities...**

These actors have different, sometimes even conflicting, objectives: most of the time, optimal placement of a DG facility from the perspective of DG installers will not be that of the DSO. This is why, in the middle of these actors comes the **legislator**, whose problem is to determine what energy policies, what rules should be defined to ensure that distribution systems evolve in accordance with global objectives (such as average cost of energy, reliability of power supply, environmental impact, etc.)? In particular, what coordination mechanisms between the DSO and DG installers should be implemented? To what value should green tariffs be set to foster development of DG from RES?

2.3 BRIEF REVIEW AND CLASSIFICATION OF FIRST ANSWERS IN THE LITERATURE

These different individual problems, assumed by different actors, are the subject of a growing number of publications in the recent years. An interesting focus on DG planning is made in the book (Willis and Scott, Distributed power generation - Planning and evaluation 2000); it identifies basic issues that the generation-planner will need to consider from an individual perspective, notably power reliability, maintenance, modularity, storage, economics and uncertainty about/sensitivity to the hypotheses, and addresses them to a certain extent. An interesting detailed example of planning comparisons between alternative DG options and service from the utility grid is presented. However, it still does not address the large-scale integration of DG in a larger grid; there is little consideration of possible interactions with the utility grid, either technically or economically (such as ancillary services, DG impacts, import/export of power...). Once again, it essentially considers only the two traditional criteria: cost and reliability, and relies on the planner's 'manual' work, limiting the scope of the study to specific individual cases.

Among papers of interest, we would like to mention work presented in (Monteiro, et al. 2005) (Ramirez-Rosado, Fernandez-Jimenez, et al. 2005) (Ramirez-Rosado, Monteiro, et al. 2005), describing GIS-based (Geographical Information System) DG planning tools, and introducing a transition from decision-aid to negotiation aid-systems, giving weight to multiple (possibly conflicting) interests (similar to multi-criteria decision making). However, the scope of the work presented in these papers seems to be mainly limited to facilities siting, and does not address the issue of coordination between DG installers and DSOs.

Among the problems the literature deals with, the subject of coordination between the DSO and DG installers has also not yet, to our knowledge, been addressed fully. Two extreme approaches for coordination can be opposed, where either:

- **DG installers adapt to the network.** The DSO could refuse any DG project whose assessed impact on the DS is judged unacceptable; or it could send cost-reflective 'Use of System' price-signals to DG installers, so that the network be developed with economic efficiency, as detailed in (Strbac, Mutale and Pudjianto 2005) (De Oliveira De Jesus and Ponce de Leao 2005) or in (Ponce de Leao et Saraiva 2003); or
- **the DSO adapts the network to DG.** DG installers install DG completely freely and the DSO evolves the distribution system accordingly. This approach may imply 'spatial DG installation forecasting', as opposed to 'spatial load forecasting'. This approach can be eased by the development of flexible, plug-&-play style networks.

We believe that future efficient practices of coordination will combine both approaches (maybe the first one for short-range planning and the second for long-range planning) dividing the efforts among DG installers and DSOs, allowing a progressive transition from actual to future power systems.

But, with more hindsight, the strongest critique we can make is that these subjects are studied singly. We acknowledge that, in spite of the distribution of responsibilities, the problems the different actors are faced with generally stay very interdependent. We thus believe that all these problems should be studied together, with a holistic view.

3 PROPOSAL: AGENT-BASED MODELLING & SIMULATION OF A MAS AS A FRAMEWORK FOR STUDYING DISTRIBUTION SYSTEM PLANNING

Considering those elements, we have chosen not to deeply focus on one particular issue, but to define a framework in which the issues presented above could be holistically studied and addressed. We propose ‘Agent-Based Modelling & Simulation’ (ABM&S) as the framework for this. The following describes ABM&S and justifies this proposal, by developing *why ABM&S is relevant for the study of DS-Planning*, and *why it is interesting*.

3.1 WHY IS ABM&S RELEVANT FOR THE STUDY OF DS-PLANNING

3.1.1 *A Multi-Agent System is a natural representation of the distribution system society and its environment*

There are multiple classes of actors or groups thereof² concerned with DS-Planning (in this instance DG installers, the DSO, consumers, residents, environmentalists, municipalities...).

These actors can be abstracted to the concept of ‘**Agents**’, defined in (Ferber, Multi-agent concepts and methodologies 2007), adapted from (Ferber, Les systèmes multi-agents - Vers une intelligence collective 1995)³: they are capable of acting in an environment⁴; they are driven by a set of tendencies (individual objectives, goals, drives, satisfaction /survival function)⁵; they possess resources of their own⁶; they have only a partial representation of this environment⁸; they can directly or indirectly communicate with other agents⁹; (they may be able to reproduce themselves, which is not relevant here); and their autonomous behaviour is the consequence of their perceptions, representations and interactions with the world and other agents.

More than being just a set of multiple agents, these actors /agents form a **society**, that organises (constrains) their actions and interactions. Such organisation (including rules /norms) determines the emergent behaviour of the whole and is a means of control to pursue objectives defined at the society level when they are set.

This society ‘operates’ in an environment, that sets and maintains the ‘reality’. The interaction of the society and its environment is essential: the environment constrains the actions and interactions of the actors /agents, and in turn the actors /agents act on (and modify) the environment.

² Groups of actors can be seen as actors themselves.

³ We will use the term ‘actor’ to refer to the real entity, and ‘agent’ to refer to the abstract entity.

⁴ The term ‘environment’ here is not to be understood in its ecological sense, but in its wider sense ‘everything external to a system that interacts with the system’ - the system considered here being an actor concerned with the distribution system.

⁵ e.g. DG installers can connect production units to the network, and the DSO can manipulate the network.

⁶ e.g. DG installers try to maximise their revenues, or respond to an electricity service need.

⁷ e.g. DG installers have a budget to invest in DG installations.

⁸ e.g. DG installers may not be able to access detailed network data.

⁹ e.g. the DSO can send cost signals to DG installers so that they install effectively on the network, or disapprove a DG installation project.

The set composed of the society of actors /agents and its environment forms a type of **ecosystem**¹⁰, that finds a relevant abstraction under the concept of **Multi-Agent System** (MAS), i.e. a complex system composed of multiple agents interacting in and with an enclosing environment.

From now on, we will refer to the actors concerned by DS-Planning as the ‘DS Actors’ (DS-Actors), to the society of DS-Actors as the ‘DS Society’ (DS-Society), to their environment as the ‘DS Environment’ (DS-Envt), to the ecosystem composed of the DS-Society and the DS-Envt as the ‘DS Ecosystem’ (DS-Ecosystem), and to the DS-Ecosystem model counterpart as the ‘DS Multi-Agent System’ (DS-MAS).

3.1.2 Approaches for studying the DS-MAS

We investigate here various approaches that can be adopted to study MAS in general.

(a) *Simulation over analytical approach*

MAS are complex systems whose study commonly calls for simulation. A pure analytical approach (analytical modelling and solving) may prove technically difficult or even impossible, and anyhow very restricted in applicability because of the strong dependency the formulation would have towards the given problem.

(b) *Extreme alternative approaches in Modelling & Simulation: ABM vs. EBM*

The MAS modeller /designer is then compelled into the choice between Agent-Based Modelling and Simulation (ABM&S) and Equation-Based Modelling & Simulation (EBM) approaches. Roughly speaking, ABM(&S) focuses on deriving emergent behaviour of the system arising from individual actions and interactions of system’s elements. EBM focuses on finding relationships between observables of the system¹¹, without referring to interactions between elements of the system, even if recognising that these relationships result from such interactions. As (Parunak, Savit and Riolo 1998) notes, Partial Differential Equations (PDE) are computationally complete, so that a set of PDE can in principle be constructed to completely mimic the behaviour of any MAS and produce the same results as an ABM.

Each approach has its own advantages and limits, and applicability. The choice for one or the other approach is crucial and has strong implications that must be understood.

An EBM approach can be eased in the case where the objective is to model an existing MAS, by an analysis of real outputs, and by confrontation of the model to its real counterpart for validation, if practicable. Conversely, an EBM approach may prove very difficult for some other systems. In the words of (Parunak, Savit and Riolo 1998, 13): “the PDE model may be much too complex for reasonable manipulation and comprehension”, and “EBM’s (like system dynamics) based on simpler formalisms than PDE’s may yield less realistic results regardless of the level of detail in the representation.” An EBM approach can be made even more difficult when there is no real counterpart on which the modelling can base itself, like is the case when the objective is to design an original MAS, or when data is not available. Not to say efforts involved in an EBM can prove inadaptable for problems even slightly different

¹⁰ An ecosystem is ‘A system formed by the interaction of a community of organisms with their physical environment.’ [<http://wordnetweb.princeton.edu/perl/webwn?s=ecosystem>]

¹¹ That is “measurable characteristics of interest [that] may be associated with separate individuals (e.g. the velocity of gas particles in a box) or with the collection of individuals as a whole (the pressure in the box).” (Parunak, Savit and Riolo 1998),p10

than the original one: it focuses indeed partly on macro-level properties, whose emergence may not be noticed under even slightly different conditions.

The choice for one or the other approach must finally be made case by case (Parunak, Savit and Riolo 1998). (Parunak, Savit and Riolo 1998) present practical considerations for guiding such a choice and summarise in this way (p. 12): “*More generally, ABM’s are better suited to domains where the natural unit of decomposition is the individual rather than the observable or the equation[...]. EBM’s may be better suited to domains where the natural unit of decomposition is the observable or equation rather than the individual.*”

3.2 WHY IS ABM&S A *PRIORI* INTERESTING FOR THE STUDY OF DS-PLANNING: VALUE OF THE M&S /ABM&S APPROACH

As a MAS, evolution of the DS-MAS, that is evolution of the state and behaviour of agents, and of the environment (by natural evolution or influence of the agents), including the DS and natural resources, emerge from the individual actions and interactions of the actors of the DS-Society in the Distribution System Environment (DS-Envt) according to the ‘laws of the World’.

Modelling and simulating the DS-Actors’ actions and interactions in the DS-Envt would thus, ideally, allow to replicate the evolution of a real or imaginary or designed DS-MAS, offering a possibly prolific framework regarding the numerous issues pertaining to DS-Planning. Indeed, as presented in Table 1, M&S can be put to a number of alternative purposes, and (AB)M&S has interesting advantages (cf. 3.2.2), and as presented in (3.2.3), the problems of DS-Planning can logically be identified to the generic problems of MAS.

3.2.1 Summary of purposes served by M&S (including ABM&S) approaches

In its domain of applicability, a model stands for a dual system of the (real or imaginary) modelled system or process. This, with the extended control on experimental conditions and perception of the evolution of the model the experimenter has, gives the M&S approach the power to be put to a number of alternative purposes, according to the way the model is built and the simulator used. (Axelrod 1997, 3-4), (Balci 1998, 344), (Banks 1998, 10-13), (Hartmann 1996) and (Pritsker 1998)) identify general alternative purposes served by a M&S approach. The following summarising table (cf. Table 1) is inspired from their different lists:

Table 1 – Summary of purposes served by a M&S approach. Inspired from (Axelrod 1997, 3-4), (Balci 1998, 344), (Banks 1998, 10-13), (Hartmann 1996) and (Pritsker 1998).

Purposes of M&S
Analysis /investigation
<ul style="list-style-type: none"> <input type="checkbox"/> Qualitative behaviour analysis. <input type="checkbox"/> Investigation of detailed dynamics of the system by decomposing and zooming in or out through time and space. <input type="checkbox"/> Proof. <input type="checkbox"/> Discovery or determination of relationships. Determination or discovery of emergent phenomena (when modelled and simulated from the bottom-up – ABM&S). <input type="checkbox"/> Diagnose problems, identify constraints.
Design of system
<ul style="list-style-type: none"> <input type="checkbox"/> Assessment of design. <input type="checkbox"/> Find suitable specifications, parameters... <input type="checkbox"/> Sensitivity analysis (e.g. for checking of robustness), stability analysis. <input type="checkbox"/> Optimisation.
Control of system
<ul style="list-style-type: none"> <input type="checkbox"/> Comparison of operating policies.
Evaluation of system's evolution (predictive models)
<ul style="list-style-type: none"> <input type="checkbox"/> Forecasting /prediction, including of emergent phenomena (when modelled and simulated from the bottom-up – ABM&S). <input type="checkbox"/> Evaluation of performance. <input type="checkbox"/> Evaluation of real system state without sensors.
Heuristic purpose
<ul style="list-style-type: none"> <input type="checkbox"/> Develop and test hypotheses, models, theories.
Pedagogical purpose
<ul style="list-style-type: none"> <input type="checkbox"/> Training (developing understanding and skills). <input type="checkbox"/> Education (developing understanding and intuition). <input type="checkbox"/> Reflection /communication support.
(Performance of tasks)
<ul style="list-style-type: none"> <input type="checkbox"/> (Performance of automated tasks, by simulating the entity that is supposed to perform them, like in the field of artificial intelligence (e.g. speech recognition).

3.2.2 *Advantages and limitations, issues and challenges of M&S /ABM&S*

Advantages of M&S in general

In addition to all the possible purposes cited above, from which some can be seen as advantages in their own right in comparison to other approaches, the M&S approach features numerous other strengths, detailed in various references, but summarised rather completely in (Robinson 2004)p8-10. He identifies the following advantages, some of which may seem obvious, but still beneficial to explicit, under different perspectives:

Table 2 – Advantages of M&S in general. Adapted from (Robinson 2004).

Advantages of simulation
Versus experimentation with the real system
<ul style="list-style-type: none"> ❑ Cost. Changes made to the real system are likely to be costly, and may require interruption of operation of the real system. This is not the case for M&S. ❑ Time. Experimenting with the real system is time consuming (weeks or months) (time to commit changes and time for the system to reach full performance). According to model complexity and computing power, a simulation can run up to much faster as real time, allowing results for an extended period [and many times]. ❑ Control of the experimental conditions. ❑ Non-existence of the real system. The system to study may simply not exist because it is imaginary or not yet built.
Versus other modelling approaches
<ul style="list-style-type: none"> ❑ Modelling of variability. M&S allows to account for variability and its effects easily, when other approaches cannot or at the expense of more complex adaptation. ❑ Restrictive assumptions. “Simulation requires few, if any, assumptions, although the desire to simplify models and a shortage of data mean that some appropriate assumptions are normally made. Many other modelling approaches require certain assumptions.” ❑ Transparency. M&S, especially when backed by an animation, is more intuitive, “giving a non-expert greater understanding of, and confidence in, the model.”
Management perspective
<ul style="list-style-type: none"> ❑ Fostering creativity. “Ideas can be tried in an environment that is free of risk,” encouraging creativity. ❑ Knowledge and understanding from a clear statement of problem. The development of the model forces one to clearly state assumptions, seek information, give values to parameters, envisage issues that otherwise may not have been considered, possibly creating alone sufficient understanding to address the problem. ❑ Visualisation, communication and strength of conviction. ❑ Consensus building. A simulation can serve as a frame for reaching a consensus by sharing ideas and their consequences and/or for negotiating conflicting interests.

Advantages of ABM&S in particular

Specific advantages of ABM&S are mainly given in comparison to mathematical approaches, including EBM&S. They have been described in (Bonabeau 2002), (Gilbert and Troitzch 2005), and (Parunak, Savit and Riolo 1998).

We review these advantages under the perspectives of some of the steps that mark out the M&S process: model formulation, programming, design of experiments and experimentation, and validity of results and real-world implementation.

Table 3 – Advantages of ABM&S, i.e. modelling and simulating from the bottom-up, over mathematical approaches. Inspired from (Bonabeau 2002), (Gilbert and Troitzch 2005), and (Parunak, Savit and Riolo 1998)

Advantages of ABM&S in particular	
Model formulation	
<ul style="list-style-type: none"> ❑ Natural description of the system (for systems for which the natural unit of decomposition is the individual): <ul style="list-style-type: none"> ○ Agents, the environment, and their interactions have different characteristics and can be distinguished more easily and modelled independently. ○ Natural consideration of the spatial dimension if important. ❑ Modularity (decomposition of the system into subsystems) <ul style="list-style-type: none"> ○ Easier to construct (generally). ○ Easier to change and evolve the model. ○ More robust to changes in the problem specification. ○ Possible distribution of modelling efforts to different groups (expertise and confidentiality). ○ Consideration of parallel processes and processes without a well-defined order. ❑ Different levels of focus <ul style="list-style-type: none"> ○ ABM&S allows a local, non-average, perspective. Modelling of heterogeneous agents possible. ○ ABM&S allows changing levels of description and aggregation, and making different levels coexist in a given model. ○ ABM&S allows capturing emergent phenomena. 	
Programming	
<ul style="list-style-type: none"> ❑ Programming languages are generally more expressive and less abstract than equations. ❑ Simulation can be distributed across multiple processors. ❑ ‘More straightforward’ translation of the model formulation. ❑ Modularity, allowing, as for the model formulation: <ul style="list-style-type: none"> ○ Easier changes in the program. ○ Better robustness to changes in the problem specification. 	
Design of experiments and experimentation	
<ul style="list-style-type: none"> ❑ Flexibility: possible to easily change the conditions of the experiment, e.g. add more agents, tune abilities of the agents. ❑ ABMs support more direct experimentation: changing conditions are expressed more easily in terms of processes rather than equations relating observables. 	
Validity of results /real-world implementation	
<ul style="list-style-type: none"> ❑ ABMs give for some problems more realistic results. ❑ ABM&S offers an additional level of validation. The model, like equations, can be validated at the system level by comparing model outputs to real system behaviour but also at the individual level. ❑ ABMs are easier to translate back into practice. 	

3.2.3 Identification of the problems of DS-Planning to the generic problems of modelling or designing a MAS

The various problems of DS-Planning can logically be identified to the generic, **interdependent**, problems of modelling (problems of ‘type M’) or designing (problems of ‘type D’) a MAS.

Regarding problems of type D, for which the objective is to design the MAS to perform as desired, the following questions need to be answered: what should each agent do considering his own objectives, how should the agents interact /coordinate, how should they organise or be organised, including what norms should be defined to ensure good performance of the

system. Applied to DS-Planning, these generic problems of type D can be transposed in the following way (cf. Table 4):

Table 4 – Issues for designing a MAS and corresponding issues in DS-Planning – issues of ‘type D’

Generic issue (‘type D’)	Examples of corresponding issues in DS-Planning
What should each agent do considering the environment, his own objectives and constraints?	<ul style="list-style-type: none"> ❑ Planning methods for DG installation – required by DG installers. Being given an environment, what are the optimal or good decisions for installing DG? Where should DG installers install their generation units? What type, what capacity, how many generation units should be installed, where in the network should they be connected? ❑ Planning methods for Distribution Network (DN) evolution – required by the DSO.
How should agents coordinate to ensure good performance of the system and to ensure meeting system-level objectives?	<ul style="list-style-type: none"> ❑ Coordination methods between DG installers and the DSO so that DG installation and network evolution are coherent: <ul style="list-style-type: none"> ○ DG installation should not threaten the proper functioning of the distribution system, and should even be advantageous; ○ the Distribution Network evolves according to actual, future, or desired development of DG. ❑ Coordination methods between environmentalists, side-residents, DG installers and the DSO.
What organisation, including what norms constraining the actions of the agents should be enforced to ensure good performance of the system and to ensure meeting system-level objectives?	<ul style="list-style-type: none"> ❑ What general organisation should be put in place for the electricity sector, what roles and associated responsibilities should be created? The outline of the general organisation are already well defined in the European directives relating to the energy sector. ❑ What rules should the energy regulator implement to ensure or favour the attainment of general objectives, such as economical criteria (competitiveness), electrical /technical criteria (reliability and quality of electrical supply...), environmental criteria (GHG emissions, visual impact, consumption of non-renewable resources...). These rules can range from interdictions and obligations, to taxes to different cost allocation schemes...
How is the environment a support for the operation of the MAS?: What influence should the agents have on the environment? Conversely, how should the environment constrain the agents? Are the laws of the universe fixed or are they part of the design?	<ul style="list-style-type: none"> ❑ How should natural local resources be exploited? ❑ How should proximity to the network be considered in the planning process so as to avoid excessive installation of electric lines? ❑ How should impact on the network be considered in the planning process? ❑ How should environmental impact (GHG emissions, visual impact, noise...) be considered in the planning process?

With respect to problems of ‘type M’, modelling a MAS needs modelling the various agents’ actions and interactions, and thus their decision-making, the coordination procedures, the organisation and norms constraining them, as well as modelling the environment and ‘laws of the universe’. Applied to DS-Planning, these generic problems of type M can be transposed in the following way (cf. Table 5):

Table 5 – Issues for modelling a MAS and corresponding issues in DS-Planning – issues of ‘type M’

Generic issue (‘type M’)	Examples of corresponding issues in DS-Planning
How to reproduce agents’ decision-making? What are the mechanisms behind their decision-making? How to consider individual /local specificities, such as personal constraints, objectives, preferences, reasoning, perception, etc.? At what level of aggregation should the agents be modelled? Is it at all possible or relevant to model agents’ decisions?	<ul style="list-style-type: none"> ❑ Where will DG installers (want to) install their generation units? What type of units? What capacity? Where in the network will they (want to) connect? ❑ How will the DSO evolve the DS-network to integrate installation of new DG units? ❑ Can the decision-making /planning process of the DS-Actors (e.g. DG installers or the DSO) be modelled? ❑ What level of aggregation is the most appropriate for modelling the decisions of the various DS-Actors? ❑ According to the various levels of aggregation envisaged, how to model the decisions of these DS-Actors? ❑ If modelling is envisaged at an individual level, how to model the planning process of the DS-Actors, notably of DG installers and the DSO? What are the various steps of the planning process? What is taken into account?
Being given a real system to model, how to model agents’ interactions according to coordination procedures?	<ul style="list-style-type: none"> ❑ How to model interactions between DS-Actors?
Being given a real system to model, how to model the organisation of agents, including the norms constraining agents’ actions and interactions?	<ul style="list-style-type: none"> ❑ How to model the organisation of the actors of the DS-Society? How to model laws, procedures, obligations, prohibitions?
Being given a real system to model, how to model the environment? How to model the ‘laws of the universe’?	<ul style="list-style-type: none"> ❑ Being specified an environment in which the study takes place, what are the relevant aspects of the environment for modelling? Which ‘laws of the universe’, are relevant to model and how to model them?

3.2.4 Conclusion: We defend ABM&S over EBM&S for the study of the DS-Ecosystem /DS-MAS

Considering the nature of the DS-Ecosystem, and the advantages of ABM&S and EBM&S, we choose to adopt and defend an ABM&S approach for our problem of DS-Planning, and in further sections we will particularly concentrate on this approach.

4 OUTLINE

4.1 OBJECTIVES OF THIS WORK

Agent-Based Modelling & Simulation as a framework for studying distribution system planning

In light of the analysis above, we believe that ABM&S is a very interesting methodology for the study of the DS-Ecosystem, and that it gives a very interesting framework in which various issues of DS-Planning can be studied, holistically.

We thus set our frame-objective to be the “**Agent-Based Modelling & Simulation of the of the DS-Society actors’ actions and interactions in their environment for DS-Planning**”, or more simply the “**ABM&S of the DS-Ecosystem for DS-Planning.**” This will be concretised by the realisation of a prototype simulator, called the ‘DS-Eco-Sim’.

Our purpose is to demonstrate how the ABM&S approach applied to the DS-Ecosystem is an interesting framework for studying various issues of DS-Planning, to identify its advantages and limitations, as well as to draw main difficulties or identify specific issues, as well as perspectives for future work. Our work does not aim at providing a valid model of an existing DS-Ecosystem.

4.2 IDENTIFICATION OF WORK-PACKAGES AND OUTLINE OF THE DOCUMENT

Concerning the proper ABM&S of the DS-Ecosystem, we have more precisely identified the following major ‘work-packages’:

Social and Environmental Analysis: (cf. Chapter II)

- (1) General description of the problem: description of the environment, identification of the actors, their individual problems and motives; (cf. Chapter II.1, Chapter II.2, Chapter II.3.1, Chapter II.3.2)
- (2) Research into, and description of, society’s main common or plausible organisations and rules: interaction mechanisms, especially DSO–DG installers coordination; (cf. Chapter II.3.3)

Modelling: (cf. Chapter III)

- (3) Choice of a typical society for demonstration purposes: definition of the organisation of the society, including determinant rules: restriction to three types of actors: the DG installers, the DSO and consumers, choice of a DSO-DG installers coordination procedure (cf. Chapter III.1)
- (4) Modelling of the environment (element given in Chapter III.3)
- (5) Modelling of the individual decision-making of a DG installer in a given context and environment; (elements given in Chapter III.4)
- (6) Modelling of the individual decision-making of the DSO for the evolution of the network – will not be treated;
- (7) Modelling of the DSO-DG installers coordination; (cf. Chapter III.5)

Computer implementation and Experimentation: (cf. Chapter IV)

(8) Development of a prototype tool for demonstration purposes; (cf. Chapter IV.1, Chapter IV.2.)

(9) Presentation of case-studies; (cf. Chapter IV.3);

Conclusions: (cf. Chapter V)

(10) Comments on the general methodology/approach;

Chapter II. **ANALYSIS OF THE DS-ECOSYSTEM**

Analysis is the stage where a thorough understanding of the system situation must be gained, where elements of the system must be identified and described, as well as the variables of influence, where input data must be collected and analysed, and finally where simulation objectives must be settled. (Ricordel et Demazeau 2000) describe the analysis stage as “the process of discovering, separating and describing the type of problem and the surrounding domain.” This is the aim of this Chapter, with no ambition to be complete.

We try to analyse the DS-Ecosystem generically, without focusing on a particular DS-Society in general. We then define a DS-Society for the proper M&S process.

1 OVERVIEW OF THE DS-MAS

The ‘World’ of the DS-MAS is composed of:

- The DS-Environment:
 - Defined over a certain area
 - Composed of various elements:
 - The land itself
 - Local energy resources
 - Infrastructures, including:
 - The power system, including power plants, and DN
 - Roads...
 - Whose evolution (dynamics) is characterised by
 - Its natural evolution: evolution of local RES, average temperatures, etc.
 - The influence of the DS-Actors (agents)
 - Setting environmental constraints
- The DS-Society:
 - Composed of DS-Actors:
 - Taking one or several roles, such as consumer, producer, DG installer, DSO...
 - Having their personal profile: objectives, wealth, estate...

- Having an individual behaviour that is the result of a decision-making process, according to their role(s) and personal profile, and to their perception of the world
- Interacting with other actors, according to their role(s), personal profile, interaction situation (competition, cooperation, coordination...)
- Subject to constraints:
 - Of their own
 - Defined by the society, limiting the range of permitted actions
 - Imposed by the DS-Envt.
- Responding to a given organisation
 - Setting roles
 - Setting rules
 - Constraining and governing individual actions: prohibitions, obligations...
 - Managing relations between actors:
 - By setting interaction /coordination procedures
 - By giving veto power to some actors, relative weights in decisions
 - ...

2 DESCRIPTION OF THE ENVIRONMENT

First of all, we describe the DS-Envt in which the DS-Actors operate. The environment defines and maintains the ‘Reality’, and is a support for the agents’ perceptions, actions and interactions (the environment ‘executes’ the influences of the agents and objects). The environment can be characterised by its state and dynamics. In the following we analyse the DS-Envt, as a primary step towards reaching a model, by giving a description of its state component, but for this report, we will leave the description of its dynamics.

2.1 PERSPECTIVES ON THE ENVIRONMENT

According to the different perspectives on the World, there are different environments in our problem: the DS-Envt and actors /agents representations of it. Thus the environment may be described and modelled differently according to the perspective taken: that of an external observer of the (real or imagined) reference world, the various descriptions of the various actors of the reference world, the perspective of the modeller of the environment of the MAS, and that of the modeller of each agent. Describing the environment thus normally requires considering the various perspectives.

Each model and underlying description of the environment must be adapted to its use. The model of the environment kept by the agents must be designed so as to allow the agents to process their own decision-making, while the model of the actual environment must be

designed so as to be able to represent important state features of the environment and reproduce those real processes at work in the real world that are of interest for our problem.

Agents have different roles, objectives, decision-making processes, etc., and thus have different subjective models of the world they live in. Those individual representations of the environment require being fed by different environmental information.

Besides this, a model must be simple enough to be manageable and computable, however keeping the right level of detail and complexity to be representative of the reference world we aim to model. The simplification also concerns the description. As well as the environment may be described and modelled differently according to the perspective taken, it can be described to varying levels of detail and completeness, according to the purpose of the M&S study, to the required accuracy of the model, and to the processes we aim to model.

In spite of the variety of models and underlying descriptions of environment there may exist in the MAS, we give in the following a generic description that stands as a common basis for the different models of the DS-Envt. We describe hereunder the environment as it can be perceived by the various DS-Actors, that is, we have decomposed the environment into its plausible important features according to the main DS-Actors.

2.2 ILLUSTRATION OF A TYPICAL ENVIRONMENT

The following figure (cf. Figure 1) is a good illustration of the DS-Envt and the typical important features that describe it in our problem from the various perspectives: the land itself and land use, local energy resources, infrastructures, and the power system.

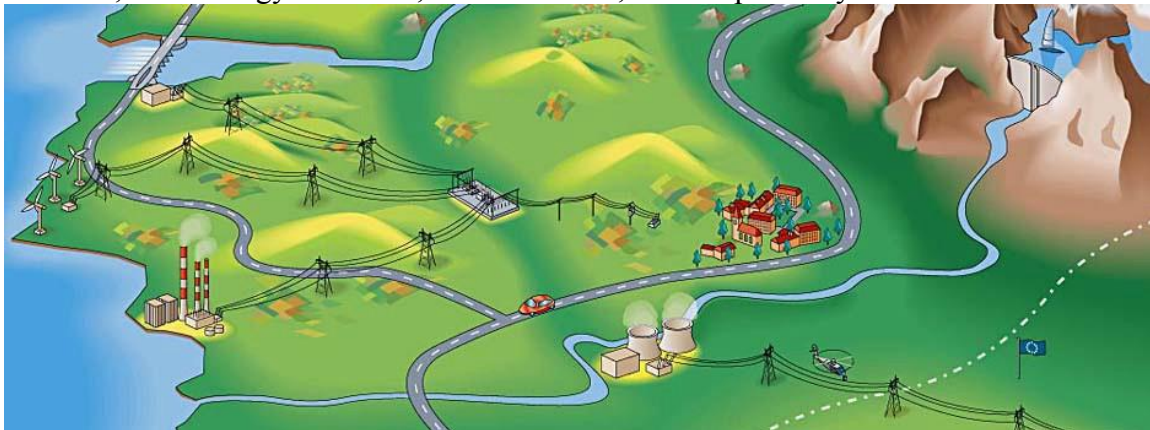


Figure 1 – Illustration of the DS-Environment, with its interesting features: the land itself (relief, soil, etc.) and land use (urban, agricultural uses...), energy resources, particularly renewable resources (wind, solar, hydro at different scales, marine, etc.), infrastructures (roads, rail, etc.), the power system (power plants, transmission and distribution networks, and load) – Copyright EDF.

We focus on the distribution level of the power system. Typically, the environment considered will extend to the region served by one feeder of a substation or a smaller region. The order of magnitude of length of feeders is ~10km.

2.3 THE LAND: RELIEF AND LAND COVER

The land is the skeleton of the environment. The land is defined by the relief (elevation of all coordinates of the land surface) and land cover. “Land cover is the physical material at the surface of the earth. Land covers include grass, asphalt, trees, bare ground, water, etc. Land cover is distinct from land use despite the two terms often being used interchangeably.”¹²

¹² <http://www.answers.com/topic/land-cover>

The illustration above shows different reliefs: mountains, hills, valleys, plains, and various land covers: rock, water (artificial lake, river, river mouth, sea).

Relief and land cover are essential descriptors of the environment for the DS-Actors: different reliefs encourage different DG installation and evolution of DN. When interested in network evolution planning (mission of the DSO), land relief and land cover are important data to locate substations and to route lines, for they impact largely both technical and economical perspectives. Ditto when interested in DG installation. For example a DG project is more easily installed and less costly in an easy-to-reach area. Land relief and land cover also give information on the exploitability of local energy resources, mainly renewable energy sources (RES). For example, in the northern hemisphere, solar energy is more easily exploited on the south-facing slope of a mountain, etc.

2.4 LOCAL ENERGY RESOURCES

We call local energy resources those resources whose sources are in the delimited environment considered. We have seen DG allowed a wider and easier exploitation of local energy resources, most of which are RES (wind, solar, hydro at different scales, marine, geothermal, biomass, etc.), although one may find fossil fuels locally.

Projects of DG installation involve a screening phase where the environment is scanned for interesting locations of the installation, according, among others, to the characteristics of local energy resources, assessing the availability and characteristics of the energy at a particular site, according to the type of energy source considered (characterisation takes different forms according to the type of energy source considered).

Location (/siting) of a DG installation is more or less critical according to the type of energy source considered:

- On one hand, energy sources are more or less easily transportable in ‘reasonable’ technical and economical terms. Biomass and fossil fuels are for example ‘easily’ transportable, and it is not technically or economically required that the DG installation be located where the energy source is located or even in the vicinity (even if this may lower the cost of transportation and thus the cost of energy in the end). This is not the case of wind or solar energy that must be exploited where the resource is present.
- On the other hand, energy sources’ availability and characteristics may be more or less constant over the environment, more or less discriminating interesting alternative locations (regarding generation potential). Solar energy availability and characteristics being rather constant over a given (reasonably small) environment, shade apart, it may offer more numerous equally interesting locations (once again regarding generation potential) than may wind or hydro energy, whose availability and characteristics are very dependent on the location considered.

Therefore, for our problem, characterisation of local energy resources is an essential descriptor of the environment. However, if modelling a real environment, there is an issue on obtaining data: obtaining such data is a difficult task, and there is a compromise to be made between the surface covered (quantity of data), thoroughness of data (accuracy, completeness, etc.), and cost. Most of the time, it is impossible to have complete and accurate data over a large surface.

2.5 LAND USE, TYPE OF ZONES REGARDING RULES

“Land use is a description of how people utilize the land and socio-economic activity.”
“Usual uses of land include agricultural, industrial, residential, recreational...”¹³ Land use is also an important descriptor of the environment. Land use is actually a descriptor of the environment in the DS-Society’s model of the DS-Envnt: it has no physical existence outside the society. This description may be useful for interpreting constraints set by rules that are expressed according to land uses.

2.6 POWER SYSTEM

The power system could be categorised within infrastructures, but as we give special focus to it, we detail it apart.

Of course, the power system is an essential descriptor of the environment for a number of DS-Actors, starting obviously with the DSO. The DSO keeps its own detailed information on the power system for its operation and for the planning of its maintenance and evolution.

In the general case, installation of DG requires consideration of the power system at some point in the process:

- First because, as we have seen, DG has non negligible impacts (negative or positive) on the power system it is connected to. Not all DG installations can be connected at any point in the network without threatening its normal operation. According to the organisation of the society and the rules, the responsibility of the impact of DG installations will be assigned to the DSO or to the DG installers themselves, and description of the network will be required by one or the other DS-Actor to assess such impact.
- Then, because connection of the DG installation to the network can represent a non negligible cost compared to that of the installation, and depends among others on the distance from the DG installation to the network (Willis and Scott, Distributed power generation - Planning and evaluation 2000) and other network data such as the voltage of the connection point, etc.

Thus information on the power system is required for DG installation. We will however see that, according to the rules of the society, information on the power system may not be mandatory when installing DG (it is the case if the DSO is completely responsible for connecting DG installation to the network).

2.7 MISCELLANEOUS

According to the needs, the descriptors of the environment can be extended to include air, water, flora and fauna, ambient noise, etc.

2.8 ENVIRONMENT’S DYNAMICS

A full analysis of the environment should include the analysis of the environment’s dynamics. However we do not consider it here, for we do not use it in the rest of this document.

¹³ <http://www.answers.com/topic/land-use>

3 DESCRIPTION OF DISTRIBUTION SYSTEM ACTORS

3.1 ROUNDTABLE OF DISTRIBUTION SYSTEM STAKEHOLDERS

We describe the various problems, motives, influence-power and profiles the various actors have.

DG-Installers. Their role is the installation of DG units. Their interests may be diverse, according to their type, and be related to their own needs or to the reward they get for answering someone else's needs, including the DSO (for auxiliary services) and consumers (for energy generation). We can distinguish between three types of DG installers: individuals, industrialists, and investors. DG installers of different types typically have different objectives and constraints, and can be subject to different society rules:

- **Pure investors:** they typically have purely financial objectives, and initially own no land so that they will have to buy it (adding to the initial costs), and have quite large investment capabilities;
- **Industrialists:** they will be sensitive to financial incentives, but may also be desiring special service from their generation units, such as emergency capacity. Industrialists will typically own land and will want to install generation units on site to get proximity services and have medium investment capabilities;
- **Individuals:** they will likely own their land and have low investment capabilities. They may be subject to preferential guaranteed tariffs, though not mandatorily.

The DSO. The DSO is solely responsible for maintaining, evolving and operating the DS. The DSO is a public service. In principle, the DSO does not aim at making profits, and costs-of-service are to be recovered so that the DSO has a balanced financial account. The DSO is normally "altruistic": its goals are related to itself but to the environment or the society only (minimisation of the environment impact, minimisation of the overall cost of electricity distribution, improvement of reliability of supply...). Planning of the evolution of the DN takes into account a Spatial-Load-Forecast, and would maybe even have to take into account a Spatial-DG-forecast in the new context.

Consumers. Consumers are the third essential party of the power system. They can be categorised in different sectors of electricity demand, ranging from residential to industrial through commercial:

- *Residential customers.*
 - Motives: We analyse them as being typically mainly interested in getting a low price for electricity, while having low demands relatively to other types of consumers for quality and reliability of supply.
 - Load characterisation: They have rather low power draw and low energy consumption. Their demand curves are irregular and not predictable. However, thanks to their low consumption, it is possible to aggregate numerous residential customers' demand curves into more regular and predictable load profiles.

- Tariff regimes: They don't participate in the electricity market, and generally have constant electricity rates (with sometimes day /night rates), unless a Demand-Side Management program is being conducted.
- Behaviour:
 - Control of consumption: Considering tariff regimes, consumers will not put much efforts into optimising (in time) their consumption in function of electricity rates if these are constant.
 - "Installation of load": Residential customers will not consider any aspects of electrical service when deciding to settle down in some place of the environment.
- Impact on and connexion to the power system: Residential customers have a small impact on the network, so that a new customer can usually easily and rapidly be connected to the network, without any important changes to the network.
- *Commercial customers.*
- *Industrial customers.*
 - Motives. While still having high expectations on electricity price, industrial customers will typically have higher expectations concerning quality or reliability of supply, due to the strong dependency of their activity on electrical energy. They may be ready to pay for improvements of these factors.
 - Load characterisation. Industrial customers consume energy in large quantities. Their load profile is more regular. However it is difficult to foresee the installation of an industrial customer, and thus to anticipate needs in terms of evolution of network
 - Behaviour.
 - Control of consumption. According to their activity, industrial customers will be encline to optimise their consumption in function of electricity rates to reduce their electricity charges.
 - "Installation of load". Industrial customers may be sensitive to aspects of electrical service when deciding where to install. This may be relevant under a network pricing policy (cf. later in 3.3.2).
 - Impact on and connexion to the power system. Connexion of industrial customers to the network can involve larger changes to the network, requiring larger delays before the load can be connected. Moreover it is difficult to foresee the implantation of a large customer, and thus to anticipate the needs in terms of evolution of network.

Characterisation of consumption can be done using typical load profiles specific to each class (and other subclasses) of customers. We refer the reader to the subject of 'Spatial Load Forecasting' for more details on the techniques to model evolution of the load.

Environmentalists. They defend the environment in terms of relatively global impacts, and potentially not *directly* related to human comfort, such as emissions of GHG, defence of protected areas, etc. This is the role borne by environmentalists in (Ramirez-Rosado, Monteiro, et al. 2005) and (Ramirez-Rosado, Fernandez-Jimenez, et al. 2005). Like side residents, they may interact with relevant actors to influence them in their decision-making.

Side residents (that live next to DG plant). Installation of DG or evolution of the DN (installation of new lines) may disturb side residents. Side residents would then be interested in minimising the impacts of this plant, in terms of any local environmental impact that would directly disturb them: noise, electromagnetic fields, aesthetics, etc. They may interact with relevant actors to influence them in their decision-making.

Municipalities. They can intervene in the decision-making so as to influence the pattern in development of the DS, for the sake of the harmonious development of infrastructures and living on their territory.

Regulator. The regulator is in charge of setting the social rules and social organisation that will guide the DS-Ecosystem to develop DS that “perform well” (the measure of this has to be defined).

3.2 FOCUS ON THE PROBLEM OF PLANNING OF DG INSTALLATION

3.2.1 *Problems to solve*

DG installation planning must solve a number of problems. Problems to answer will vary according to the profile of the actor. Generally, these problems to solve will be a subset of the following ones:

- **What for:** What service should be provided?
- **Where** to install?
- **What** to install:
 - What technology?
 - How much to install?
 - What design?
 - Where to connect?
- **When** to install?

The aim is to find the best possible project in the delimited environment, according to the DG-Installer’s own objectives, preferences, and constraints.

3.2.2 *Characterisation of DG installation planning problem*

The problem of DG installation planning can be characterised as follows:

- There are multiple decision-variables because many design elements influence the evaluation (performance of the project with respect to particular criteria), including when to install.
- There is uncertainty in certain variables: this is the case of fuel price, future sell price, etc.
- There are various constraints that must be complied with, for example:
 - Personal constraints and preferences, e.g. on investment capabilities
 - Social constraints imposed by rules of the society
- Performance of the project with respect to chosen criteria cannot be expressed as a linear function of characteristics of the project.
- There are multiple objectives for DG projects:
 - To be optimised against: how to optimise according to multiple objectives?

- To be decided upon (e.g. investment required and benefit-cost ratio): How to decide when there are multiple objectives?

Planning of DG installation is thus a non-linear, mixed integer multi-variable, multi-objective constrained optimisation problem.

3.2.3 *Characterisation of a DG project*

A particular DG project may be characterised using a number of variables:

- Technology used;
- Location of the installation;
- Connexion to the DN;
- Equipment reference;
- Power ratings;
- Technology-specific variables;
- Design-related variables;
- ...

3.2.4 *Summary of key factors for DG installation*

Benefits of a DG project depend on a number of key factors, including:

- Elements of the environment. The environment sets constraints on the installation of DG. These constraints are from different types:
 - Geographical constraints, such as relief, land cover and land use, proximity to roads or to the distribution network, etc.
 - Local energy resources: according to the energy source and technology envisaged, generation potential of the installation may be more or less dependent on the availability and exploitability of local energy resources, such as wind, solar, hydro energy, etc. Location (/siting /placement) of DG in this regard is thus more or less critical.
 - Distribution network. The distribution network is not capable of accepting any DG unit anywhere. Acceptability of the DG installation by the network may be encompassed in the decision-making process, according to available information, and to the enforced coordination mechanism.
- Organisation of the society, including society's rules. The benefits of a DG project are by and large determined by the society's rules that may alternately fix a guaranteed 'green' price for the selling of renewable energy generation, or fix various taxes, or allocate the costs implied by the connexion of the DG unit to the network in different proportions to the DSO (i.e. to the community) and to the DG unit's installer, etc.
- Technological context (available technologies and equipment);
- Future scenarios, on e.g. load evolution, fuel price, etc.

3.3 CONSIDERATIONS ON SOCIETY'S ORGANISATION AND REGULATIONS – FOCUS ON COORDINATION BETWEEN DG-INSTALLERS AND THE DSO

Regulations are made to govern actions of and interactions between the DS-Actors. There are different imaginable organisations or rules that can be enforced to "guide" the DS-Ecosystem to "perform well". Among those, it is notably required a coordination mechanism

between DG-Installers and the DSO to guarantee that the decisions they make are coherent from the point of view of the DS development. Concretely, the DSO should not develop the DN so as to accept DG where DG-Installers generally will most probably have no intention of installing DG capacity (because they have no interest in doing so – e.g. because local resources are non exploitable at these places, or because there is no close load to feed, etc.). And DG-Installers should not install their DG units where they will threaten the DS good operation.

We have already roughly opposed two extreme approaches for coordination (cf. Chapter I.2.3), where at the extremes either DG-Installers adapt to the DS, or the DSO adapts the network to DG. Enforced coordination procedure may combine both approaches.

We expose hereunder principles of some imaginable coordination mechanisms, without detailing underlying methodologies.

3.3.1 *‘Constant-network’ coordination mechanism*

The principle is that no evolution of the DN is made to accept any DG installation and DG must be installed where it is acceptable in terms of impacts on the DS or otherwise is forced to adapt its generation output on the order of the DSO.

3.3.2 *Network pricing /Network cost allocation*

One possible coordination mechanism, detailed in various references such as (Strbac, Mutale and Pudjianto 2005) or (De Oliveira De Jesus and Ponce de Leao 2005), is ‘network pricing’ or ‘network cost allocation’. One of the principal objective of network pricing is to influence users of the network (namely DG-Installers and consumers) by sending economic signals to users of the network in regard of the impacts and associated costs (e.g. for neutralising unacceptable negative impacts) they imply on network operation and /or development (Strbac, Mutale and Pudjianto 2005).

Thus network pricing is a combination of both approaches of coordination presented above: as DG installations are connected to the DN, the DSO evolves the network to guarantee that operation of the network stays within standards, but at the same time, DG-Installers have an economic incentive to adapt to the DS needs or weaknesses.

The challenge of network pricing is to determine the pricing policy. How to determine the costs /benefits provided by a DG installation? How should costs /benefits of DG be allocated between the DSO and DG-Installers, and between DG-Installers?

Various network cost allocation methodologies exist in the literature, and we refer the reader to literature for details.

3.3.3 *Partial recentralisation of DG installation planning*

Another imaginable coordination mechanism is to partly recentralise the planning of DG installation. While DG-Installers would still be in charge of installing DG, the DSO would partly be in charge of the planning of those installations on the basis of the network’s needs. The DSO could build a map of needs of the DN according to its weaknesses, and issue a call-for-proposal of DG installations that are able to satisfy those needs. DG-Installers would propose alternative DG projects to meet the needs, and the DSO would select the “best” (to be defined, e.g. the least expensive) set of projects among those.

Under this coordination mechanism, it is DG-Installers that adapt to the DS.

The DSO may more or less precisely characterise the DG projects it requests, from generally defining needs in terms of performance at specific locations to precisely defining design characteristics of the project.

While the efforts to be made are mostly concentrated on the DSO, it may be that the complexity of doing so be reduced in comparison to more independent DN evolution planning and DG installation planning, for decisions are taken coherently by a single actor.

3.3.4 *Real coordination procedure between the DSO and producers*

We refer the reader to (ERDF, Procédure de traitement des demandes de raccordement des installations de production d'électricité aux réseaux publics de distribution 2008) for details on the coordination procedure followed by ERDF, the DSO in most French regions.

Chapter III. **APPLICATION OF ABM&S TO A BASIC DS-SOCIETY**

1 SYSTEM AND OBJECTIVES DEFINITION

1.1 OBJECTIVES OF THE SIMULATOR

Definition of the objectives in a M&S study require defining the purpose of the study, the scope of the model, and for whom the model is designed.

The general objective of our work is to study the application of ABM&S to the problem of DS-Planning, i.e. to discuss its advantages and limitations, the potential scope of this methodology, and identify specific issues.

Thus we propose, for demonstration purposes and as a basis to discussion, to apply an ABM&S study to a basic, imaginary DS-Ecosystem, that we define hereafter by specifying the organisation and rules of the associated DS-Society. This will be concretised in the implementation of a simulator, the DS-Eco-Sim.

Scope of the simulator is related to the definition of the system and assumptions we make later (cf. 2). While the assumptions or simplifications made may seem simplistic and restricted in regard of the complexity of the original problem and the original claims, it is sufficient to serve our purpose of demonstration and to thrive the discussion on ABM&S methodology applied to DS-Planning.

We are aware however that over-simplistic models may not efficiently nourish the discussion on the ABM&S methodology as it will not allow to identify critical issues or difficulties, and thus propose a non trivial model for the DG-Installers' planning.

Although reasoning on a defined DS-Society, we try to stay generic so as to be able to extend our work to consider more complexity, or to apply it to other DS-Societies.

1.2 DS-SOCIETY'S ORGANISATION, RULES, AND COORDINATION PROCEDURE

1.2.1 Restriction of the DS-Ecosystem to main actors

Among all the different actors possibly concerned with the problem of DS-Planning, we restrict the problem to the main actors having a physical influence on the distribution system: the DG installers (generation) and the DSO (distribution) and consumers (the load). The

influence that Municipalities or Environmentalists or other DS-Actors may or could have in reality is not considered.

1.2.2 Definition of a simple DG-Installers – DSO coordination mechanism

As we have seen, a multitude of coordination mechanisms are imaginable, each **a priori** implying different patterns in the development (evolution) of the DS. For our purpose of demonstration, we have chosen a coordination mechanism where it is DG-Installers that adapt to the DS, according to the following principle: no evolution of the network is done by the DSO to make a DG project acceptable ('constant-network' coordination mechanism), and only DG projects acceptable for the DN's good operation are accepted.

The coordination mechanism adopted is represented on the diagram in the following figure (cf. Figure 2).

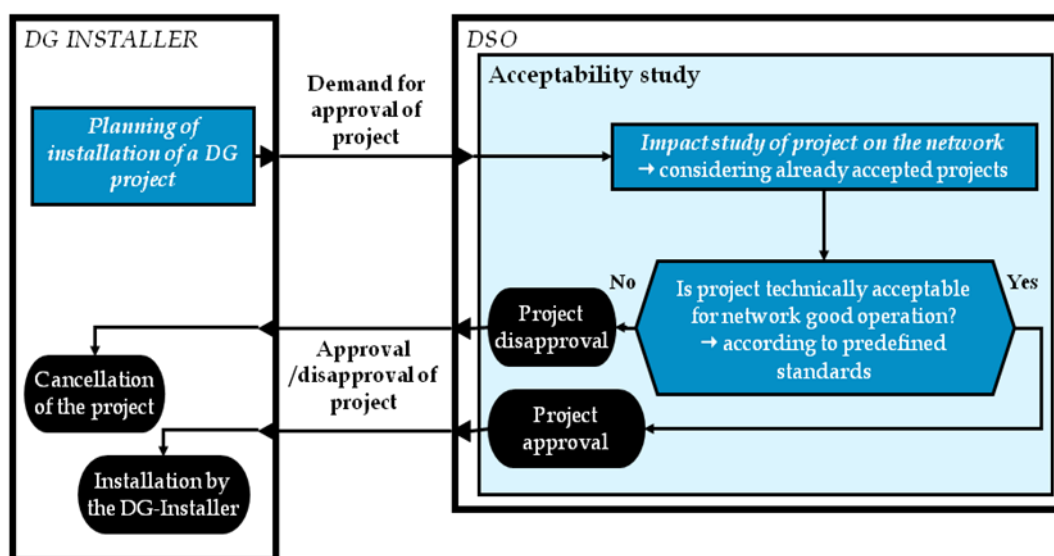


Figure 2 – Model of the coordination procedure between DG-Installers and the DSO.

The procedure is simple: after having gone through his planning process, the DG-Installer issues his intention of realising a DG project and communicates a description of this project to the DSO for approval.

The DSO approves or disapproves this project on the basis of an assessment of the impact this project would have on the DN if installed, considering the projects already accepted even if not yet installed. If the assessment of the DG-project's impact on the DN complies to predefined standards, the DSO must approve it. The impact may be characterised in regard of different criteria and assessed in many different ways, but we will not discuss this.

If the project is approved, the DG-Installer simply installs it, otherwise renounces it. The DSO does not give any other information than an approval or disapproval for a project. He does not give information such as where the network may easily accept connection of DG, nor information on how much DG capacity the network could accept at a particular point, etc.

The DSO may not respond to the DG-Installer straight away, and in the mean time, may receive other demands for approval of DG-projects. Priority rule between demands is "first come, first served."

This coordination procedure simplifies greatly the problems of the DSO. The DSO is limited to impact assessment, and has no evolution of DS to plan.

1.2.3 *Allocation of costs*

We assume that all the costs of installing a DG project are imputed to the DG-Installer, including the costs of connexion to the network, whatever the amount. This is an indirect incentive to install close enough to the DN to cut down connexion costs. There is otherwise no direct incentive for the DG-Installer to install at particular points of the DN, as could be the case with a network pricing policy.

As the DSO does not evolve the DN to accept DG, there are no costs associated to the evolution of the DN to be allocated.

1.2.4 *Remuneration of the services provided by DG installations*

There are different schemes under which a DG-Installer could be remunerated for the services he provides.

We assume in a primary step that the only service that they will get remunerated for is energy generation. DG-Installers do not get remunerated for ancillary services, such as reduction of losses, or correction of the voltage profile, etc. their installation would provide, and they do not get penalised either for any negative impact (negative but acceptable, as the project was accepted in the first place).

We assume the price at which the DG-Installer gets remunerated for his energy generation is fixed according to the energy source (DG from RES may be remunerated generously so as to foster its development), constant and guaranteed over the project's lifetime. There is thus no mechanism such as a market to match energy generation and consumption and to determine a 'market price'.

We make the assumption that the DSO must accept and buy all energy generation proposed by DG-Installers. We make the assumption that penetration of DG is sufficiently limited so that all energy produced by DG-Installers may not exceed consumption, and thus that all energy generated can and will be accepted (and bought). This assumption is backed by the assumption that, if ever the penetration of DG is such that, at times of low consumption and high generation potential (e.g. because of favourable RES potential), generation exceeds consumption, then the surplus energy will be dropped down but payed however to the DG-Installer. That way the DG-Installer does not have to consider in his planning process that the energy generated by a candidate project may not be bought.

1.2.5 *Maximum power capacity connected to the DN*

The French law (Ministère de l'écologie 2008) sets the maximum admissible power of a DG installation according to the voltage level of the network it is connected at, as follows:

- 18 kVA for single-phase LV-DN;
- 250 kVA for three-phase LV-DN;
- 12MW for MV-DN.

We adopt the same rules. Moreover, an index of the maximum theoretical admissible DG capacity is defined for each substation (HV /MV-DN interface)¹⁴. We adopt the same rule, for, defining such an index for each transformer (HV /MV-DN or MV /LV-DN transformer).

1.2.6 *Perception and knowledge of the DS-Actors*

In this system, DG-Installers:

¹⁴ See http://clients.rte-france.com/htm/fr/offre/carte_poste/offre_raccord_prod_carte.jsp#app

- Do not have access to the electrical model of the DS.
- Do not have access to other DG installers' projects.

The DSO has a perfect knowledge of the DN it is responsible for. DS-Actors have access to data defining the environment, according to their type. DG-Installer have access to resource information average over time and space. DS-Actors have knowledge of the constraints and rules.

2 ASSUMPTIONS /SIMPLIFICATIONS RELATED TO MODELLING

The defined society is organised in a way that already simplifies the problem. This section details assumptions and simplifications we make on the DS-Environment and on the DS-Actors to further characterise and simplify the modelling.

2.1 ASSUMPTIONS ON THE DS-ENVIRONMENT

The model of the DS-Envt may gather a lot of elements, as it models the real world! In a primary step we do not aim at providing a thorough simulation model of the environment, such as could be made by simulating hour by hour the evolution of the environment, including simulation of evolution of natural resources, hourly power system simulation, etc. We keep this as a perspective of our work though.

We thus limit the model of the DS-Envt to its bare minimum, and assume the DS-Envt does not change over time, other than by the actions of DG-Installers, which, according to our system definition and assumptions, is finally the sole type of actors to have an influence on the DS-Envt. There is thus no dynamic component to model: no modelling of natural evolution of the DS (that would represent ageing of the infrastructures...), no consideration of natural evolution of resources, no consideration of DS operation: no hourly modelling & simulation of load evolution, of generation, power flows in the model of the DS-Envt¹⁵.

2.2 ASSUMPTIONS ON DS-ACTORS

2.2.1 *Common assumptions*

DS-Actors have their perception of the World, and maintain their own model of it. We make the following common assumption for all DS-Actors: they have a partial representation of the world, but do not have a distorted perception of it. In other words, it means the information an actor has on the world are true but not complete.

2.2.2 *Assumptions /simplifications on DG-Installers*

We make the following hypotheses concerning DG-Installers:

- DG-Installers are “selfish”: their goals are expressed only according to their own interests, not those of the distribution system or of the environment.
- DG-Installers do not have a complex, strategic behaviour:
 - They respond “mechanically” to the economic signals;

¹⁵ Such a simulation model is needed for the DSO's impact assessment and could be later included in the dynamic model of the DS-Environment with relative ease.

- Their decisions do not consider aspects of competition with other DG-Installers.
- DG-Installers do not anticipate approval of their project by the DSO. This assumption is justified by the following (realistic) elements of the system definition (cf. 1.2.6):
 - They do not have access to the electrical model of the distribution system;
 - They do not have access to other DG installers projects.
- As a simplification, DG-Installers will only consider DG projects from RES, and we further restrict DG installations to be using photovoltaic (PV) arrays or wind turbines (WT). DG installations will be connected to the grid, without storage capacity.
- DG-Installers do not consider the temporal dimension of the planning problem: they do not reason about the best time to install their project.
- DG-Installers' decision-making is based on bounded-rationality:
 - **Rationality:** their decisions are made in view of their goals according to an understandable, consistent, reproducible reasoning, with transitive and fully defined preferences (that is the order of preference between alternatives can be given).
 - **Bounded:** information and computing /cognitive abilities are limited, as well as there are uncertainties that cannot be resolved.
- All energy generated by a DG installation will be bought (cf. 1.2.4).
- We assume DG-Installers evaluate the value of a DG project according to values that are computed with a yearly resolution over the project's lifetime.
- DG-Installers information on resources is partial: they are averaged over time and space, as would generally be the case in the real world.

2.2.3 Assumptions on the DSO

The choice of the DSO-DG Installers coordination procedure, where all projects are accepted in the order of request if their impact conforms to specified standards yields a good simplification on the DSO behaviour and model. The “first come, first serve” policy simplifies for the DSO the problem of deciding between multiple DG proposed projects. This principle is however realistic: the French DSO in most regions, ERDF, implements such a queue in its project approval procedure (ERDF, Procédure de traitement des demandes de raccordement des installations de production d'électricité aux réseaux publics de distribution 2008).

The impact assessment made by ERDF for example concerns a multitude of criteria. The impact on the distribution system can indeed be expressed against multiple criteria, such as voltage profile, losses reduction or increase, harmonics, stability, reliability, quality of supply, mean cost of distribution, impact on operation, etc. and all should be considered for a thorough evaluation of a project's impact and acceptability with respect to standards.

For our demonstration purpose however, we restrict the impact assessment on the distribution system performed by the DSO to the impacts on voltage profile, and maximal current or power flowing in already installed lines.

We assume these impacts must conform to following standards:

- Standard on maximal current /power flows in already installed lines. The value is defined for each line of the DN;

- Standard for voltage in all nodes of the DN. We choose the same standard as the one adopted by ERDF: $U_n \pm 5\%$, for MV-DN, and $U_n + 6\% \text{ } \begin{matrix} \square \\ -10\% \end{matrix}$, with U_n being the nominal voltage at the node (ERDF, Description physique du réseau public 2008).

We assume these electrical quantities will be checked in normal steady-state operation, but against worst conditions. As a preliminary step we will assume that worst conditions are defined by one of the two cases:

- Minimal load and maximum generation on the feeder (this case is the one retained by ERDF in its impact assessment methodology). Minimal load is either a measured one, or considered to be a fraction R of the maximal power capacity of the feeder, by default $R = 0.2$; or
- Maximal load, and minimum DG generation on the feeder.

We will also assume load-flow is balanced. And we will assume load are load buses, defined by their active power P and reactive power Q with $\tan\phi = 0.4$ by default.

The work can be later extended to provide more thorough assessment of the impact, e.g. include short-circuit or stability (steady-state or transient) analyses, and more criteria.

2.2.4 Assumptions on consumers

We make the following simplifying assumptions for consumers: **their consumption is predefined, spatially and temporarily**, and is not influenced by DG-Installers' or DSO's actions on the environment, nor is it elastic to electricity price, which, generally speaking, may change according to the evolution of the DS. Their model is thus very simple and takes the form of a spatio-temporal load scenario.

2.3 MISCELLANEOUS ASSUMPTIONS

We do not aim at reproducing a realistic timing in investments, i.e. realistic timing in the evolution of the DS-Envt (including the DS). Assumptions on the DG-Installer takes this into account. Steps in the simulation will not correspond to time increments, but a succession of planning cycles, where a DG-Installer is randomly chosen among all DG-Installers to perform its planning cycle and decide for a DG-project (or no project).

3 ENVIRONMENTAL MODEL

The static component describes essential descriptors of the DS-Envt as detailed in the Analysis section (Chapter II.2). This mainly includes the information our DG-Installers will require for their planning process:

- Geographical representation of land over the study area: boundaries, land relief, land cover;
- Geographical representation of the DN (for evaluation of the connexion costs): routing of lines, (position of substations), etc.;
- Representation of land parcels: boundaries, land use, ownership, availability, price of this land parcel if for sale;
- Averaged information on resource;

Note that including all these information in the model of the DS-Envt is a simplification. Part of the information presented here mainly pertains to a ‘social perception’ of the environment: land parcels (be it their boundaries, or the land-use, ownership, availability, or price of the land) and averaged information on resource have no physical existence outside the society¹⁶.

We have opted for a Geographical Information System (GIS) to manage models of the DS-Envt. GIS allow to store, visualise, edit, manipulate (process) and query geographical information easily.

4 DG-INSTALLERS

4.1 PLANNING PROCESS OVERVIEW

We have seen there are different types of DG-Installers, with different types of constraints and objectives: pure investors, industrialists, individuals. We however propose the same planning algorithm for all three classes of DG-Installers and consider their differences as parameters of the algorithm. The following diagram gives an overview of the algorithm (cf. Figure 3):

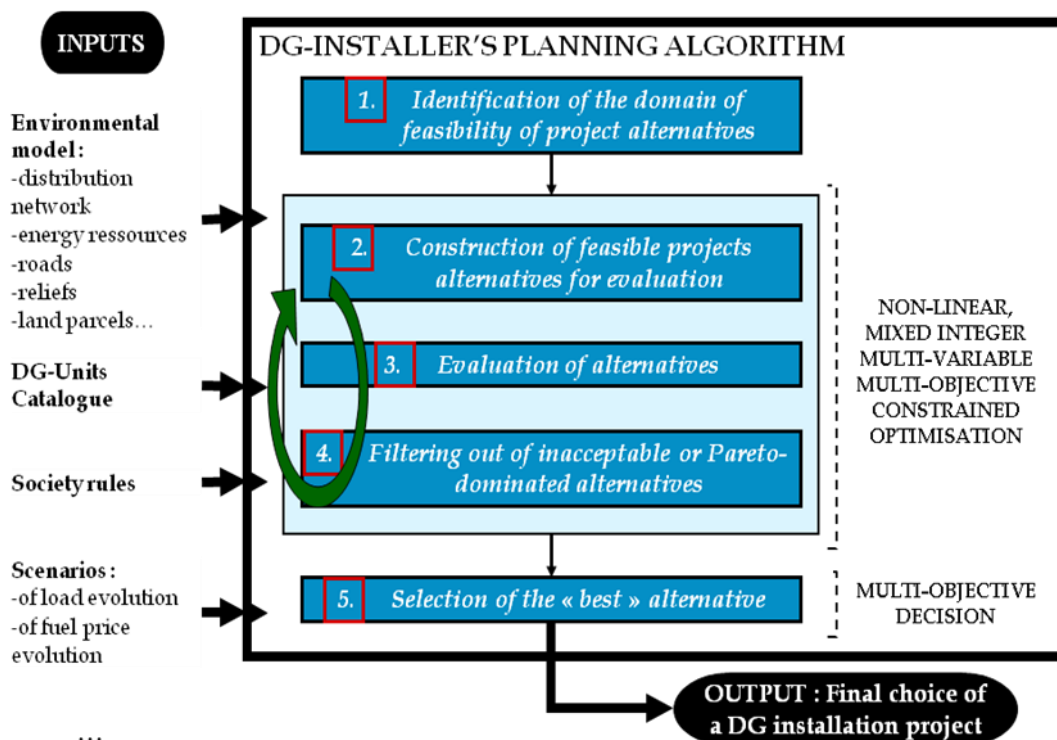


Figure 3 – DG-Installer's planning algorithm.

The algorithm is divided into five stages. The aim of this planning process is to plan the installation of DG. The project must be defined according to the model of the environment, of

¹⁶ Averaged information on resource is information that is maintained either collectively by the society or individually by the actors, unlike a dynamic model of evolution of resource in the DS-Envt that would represent reality.

DG-units catalogue in which to choose DG equipment, of society rules, and various scenarios. A DG installation is characterised by a set of variables, which must be decided upon in the planning process. We call this set of variables, the ‘decision vector’.

Stage 1 is the identification of the domain of feasibility of alternatives. This stage is the stage where constraints on decision variables are formulated. We call these ‘pre-constraints’.

Stages 2 to 4 are those of a non-linear, mixed integer multi-variable, multi-objective constrained optimisation process of the objective function giving a set of Pareto-optimal¹⁷ solutions. We have conceptually split this optimisation process into the different stages usually followed in optimisation algorithms in order to give a comprehensive view. These stages are processed in a loop a number of times until a termination criterion is reached.

Stage 2 is the stage where a feasible project, that is a project respecting the constraints aforementioned is selected, ready for evaluation. This consists in picking a set of values in the domain of feasibility for the components of the vector characterising the project, i.e. the decision vector. There may exist different algorithms for choosing among alternative vectors. We refer to the project characterised by a particular vector as a ‘project alternative’. We will refer to the algorithm used for the selection of values as the ‘search algorithm’. And we will call the domain in which the algorithm picks up the vectors the ‘search space’.

Stage 3 is the stage where the project alternative, characterised by the decision vector, is evaluated against a set of specified objectives. This set of objectives is chosen by the DG-Installer according to its goals and preferences. We call the mathematical function that gives the evaluation of objectives in function of the design variables the ‘objective function’. Calculation characterising the objective function is implemented in an ‘evaluation module’.

Stage 4 is the stage where unacceptable and dominated (in the sense of Pareto) projects are discarded from the final choice. Unacceptable projects are those that do not satisfy constraints expressed as a function of the evaluation results. We call these latter constraints ‘post-constraints’. We give details on Pareto-domination later (cf. 4.5).

Stage 5 is the final stage where it is decided what project alternative to choose among remaining acceptable and Pareto-optimal projects. This decision is taken according to the DG-Installer’s personal preferences and goals. In the general case, the decision is taken regarding multiple objectives at the time.

4.2 STAGE 1: IDENTIFICATION OF THE DOMAIN OF FEASIBILITY OF PROJECT ALTERNATIVES

Domain of feasibility of project alternatives is described by pre-constraints, i.e. constraints that are expressed on decision variables, possibly relating them to environmental information. The aim of this stage is listing and formulating all such constraints. They may be of different types (cf. Table 6):

Table 6 – Type of pre-constraints and corresponding examples

<i>Type of pre-constraints</i>	<i>(Virtual) Examples</i>
Personal constraints of DG-Installer	<ul style="list-style-type: none"> □ Constraints on investment. □ Technological preferences.
Equipment related constraints	<ul style="list-style-type: none"> □ Power rating of wind turbines is in a discrete set given by a catalogue of DG-units.
Geographical constraints	<ul style="list-style-type: none"> □ A wind-powered DG project should not be considered in

¹⁷ Actually these solutions are not optimal ones but best ones.

	<ul style="list-style-type: none"> urban environment. ❑ Maximum possible power rating cannot exceed a certain value, according to the available space
Regulatory constraints	<ul style="list-style-type: none"> ❑ A diesel-powered generator may not be installed closer than 50m of a school.
Network constraints	<ul style="list-style-type: none"> ❑ Power rating of the DG installation should not exceed 36 kVA if connected to LV-DN.

Note that in our case, network constraints do not include a complex assessment of the impact, which is done by the DSO. Network constraints in our case only apply on design of the project.

Formulating those pre-constraints is relatively simple. It consists first in defining a domain of definition for each design variable (continuous or discrete domain, and range bounds). It then implies the construction of a `isFeasible(project)` function that evaluates the feasibility of a project by checking Boolean expressions, as illustrated below.

```
isFeasible(project) {
  if (project.techno == wind) & (project.location in urban environment)
    return false
  if ...
}
```

4.3 STAGE 2: CONSTRUCTION OF A FEASIBLE PROJECT ALTERNATIVE FOR EVALUATION

The search algorithm can be as simple as exhaustive enumeration. This is a brute-force, deterministic technique that consists in going through all possible decision vectors. Of course this requires that the search space be discrete and thus the continuous dimensions of the search space to be discretised. While there is a guarantee to find the global optimum over a discrete search space, it can be very computationally intensive due to combinatorial explosion when dimensionality of the search space increases and proves impractical for even relatively small problems or when the evaluation of the alternative through the objective function is computationally intensive itself. However, if the number of feasible alternative projects is small due to severe constraints, this technique can be useful while simple to implement. We set this technique as a reference.

Convergence of this optimisation can be speeded up if the selection of a design vector at stage 2 is made relevantly, avoiding uninteresting subsets of the search space so as to avoid unnecessary evaluations, without omitting domains that may be of interest. Heuristics and metaheuristics try to do so by guiding the selection of the next candidates for evaluation to plausibly good solutions, according to previous results of evaluated vectors. While these techniques are not guaranteed to find optimal solutions, they are expected to produce ‘good’ solutions in a timely fashion¹⁸. Metaheuristics include genetic algorithms. We use both exhaustive enumeration and genetic algorithms for our DG-Installer model.

¹⁸ *Heuristic methods such as genetic algorithm do not claim to provide optimal solutions but good ones, ideally close to optimal ones, in a limited computing time. We are aware of the distinction that must be made. Though, for the sake of brevity, we will call the solutions found by the genetic algorithm ‘optimal solutions’, not in the sense that no better solution exists, but that no better solution was found.*

In all cases, the ‘search algorithm’ must of course select decision vectors that are compliant with the constraints identified, i.e. that are feasible.

4.4 STAGE 3: EVALUATION OF ALTERNATIVE

The evaluation module is the implementation of the objective function. It assesses the values of some chosen objectives according to the description of the alternative project and additional data required for evaluation. We detail hereunder the outputs usually desired from the evaluation module by typical DG-Installers, then give the corresponding necessary inputs, and give an overview of the algorithm we use for evaluation.

The evaluation module presented here is subject to assumptions made, namely that DG project alternatives are from RES (solar or wind), are connected to the network, and electrical energy generated is mandatorily bought by the DSO and paid the green tariff, which is constant, guaranteed and known.

4.4.1 *Outputs of the evaluation module*

Note that we assumed in 2.2.2 that the objectives of interest for DG-Installers (corresponding to the outputs of the evaluation module) would be computed with a yearly resolution over the project’s lifetime.

DG-Installers will typically desire the following outputs for their decision-making:

- Summary of costs and benefits /saving year, by year
- Financial objectives: Net present value, initial investment, year to positive cash flow, Benefit /Cost ratio, etc.;
- Technical objectives
 - Details on expected energy generation, such as number of kWh produced per year or over the life-time of the project;
 - Measures of satisfaction of special needs, such as reliability of supply, etc.;
 - ...
- (Sensitivity /risk analyses on some of the outputs considering uncertainties on some of the inputs.)
- ...

While a much more complete list of classic outputs may be listed, the ones described here are a relevant simplification. According to his own goals and preferences, the DG-Installer will concentrate on a particular set of these outputs to choose upon all alternative projects. This characterisation of outputs is relatively open, as the choice for one or the other set is specific to the actors considered and may be changed easily.

4.4.2 *Inputs of the evaluation module*

The evaluation module may require various sets of inputs, according to how the algorithm and related simplifications, and according to the objectives that are to be assessed. However, it will generally be provided inputs such as:

- The description of the project to be evaluated (and in the end optimised), that is the decision vector. Once again, the decision vector can take many various forms, according to the technology envisaged in the first place, and to the evaluation module itself. As an example, it may include:
 - Location of the project;
 - Nominal power of the installation;

- Reference of the generation equipment selected;
- If PV technology is considered: inverter capacity and efficiency, sun tracking system: fixed, one-axis, two-axes, or azimuth tracking, slope and azimuth of PV array when not tracking, etc.
- Etc.
- Equipment technical characteristics:
 - If wind turbines are considered: hub height, rotor diameter, wind turbine rated power, power curve, etc.
 - If PV technology is considered: PV module type, nominal PV module efficiency, PV temperature coefficient, etc.
- Information on various costs: related to equipment, to operation and maintenance, to connexion to the network (not to be considered in our case, for these are charged to the DSO), etc.
- Environmental information:
 - Energy resource information if not included in the evaluation module;
 - Proximity of electricity network and proximity of roads;
 - Etc.
- Information on society rules, including e.g. the green tariff, etc.
- Financial parameters: detail on debt (amount, ratio, term), discount rate, inflation, etc.

4.4.3 *Overview of algorithm*

An infinity of algorithms are imaginable for the evaluation module, depending on the assumptions made, the desired outputs, the available data for inputs, and levels of precision and detail. We have chosen to use RETScreen® as a support for this evaluation module. RETScreen® is a recognised tool for performing pre-feasibility and feasibility analyses of clean energy projects, i.e. for estimating (more or less precisely) the value of a project according to its description against the objectives mentioned in 4.4.1. The tool is organised in a set of spreadsheets, one per clean technology (Natural Resources Canada n.d.): wind, photovoltaic, biomass, hydro, etc.

While our evaluation module does not use all functionalities of RETScreen®, nor limit itself to these functionalities, the core of the evaluation is performed by RETScreen®. We roughly explain hereafter the main steps of the algorithm, somewhat describing the process followed in RETScreen®, but we refer the reader to (Minister of Natural Resources Canada 2005) for details on calculations performed.

The following figure illustrates the generic principle of the algorithm used for the evaluation of wind or PV project alternatives (cf. Figure 4).

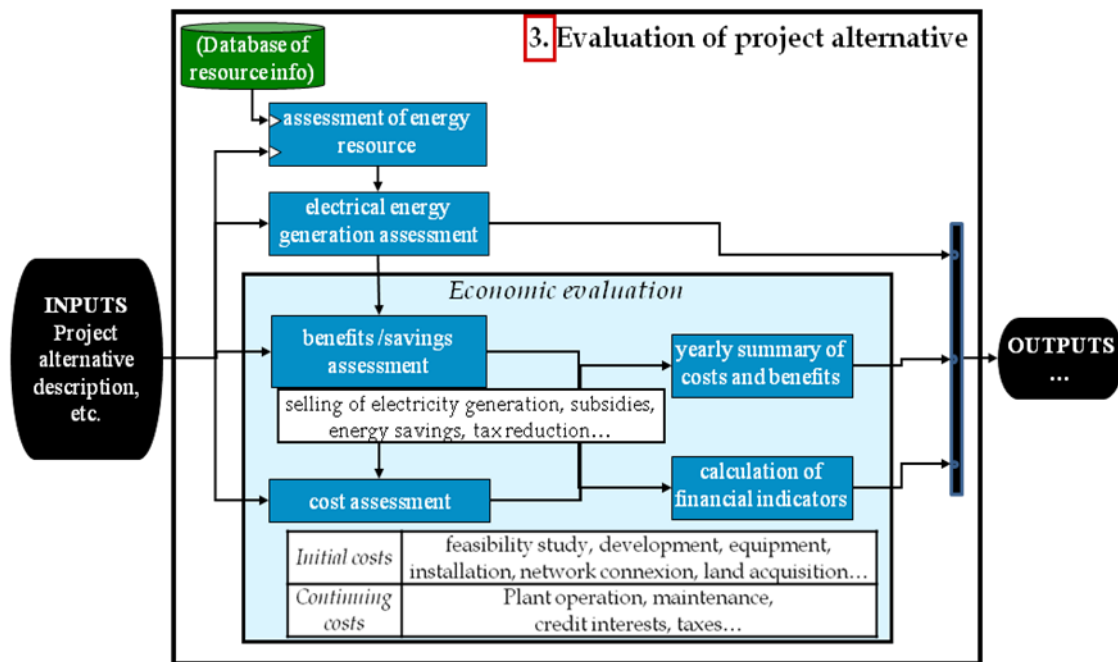


Figure 4 – Generic overview of the algorithms we use for evaluation of wind or photovoltaic project alternatives. This algorithm is subject to certain hypotheses.

(a) *Resource assessment*

Energy resource may be expressed in various forms, according to the technology considered and to the formula linking the resource assessment to energy generation assessment: for PV, solar resource may be expressed as (monthly averaged) daily irradiance on horizontal surface (in kWh/m²/day) and transformed to be expressed in the plane of the PV array. For wind turbines, wind resource may be expressed using wind speed probability distributions, transformed to be expressed at the hub's height. Weibull's distribution, characterised by its shape and scale parameters, is relatively popular for characterising wind resource.

At this stage, brute information on energy resource, provided by the database or directly by the inputs, is transformed into the desired form, possibly using the project's characteristics.

(b) *Electrical energy generation assessment*

Assessment of electricity generation is done by calculating how much of the available energy resource the DG plant may convert into electricity, considering project alternative's characteristics. This is done using more or less complex and accurate formulae, according to hypotheses and simplifications made.

PV energy projects

For example, RETScreen® calculates the electrical energy produced by the PV array and available to the load E_A in the following way: (Minister of Natural Resources Canada 2005)

$$E_A = S \cdot \eta_p \cdot (1 - \lambda_p) \cdot (1 - \lambda_c) \cdot \bar{H}_t$$

Where:

- S is the area of the array,
- η_p the average efficiency of the PV array (function of the reference PV module efficiency at reference temperature, corrected to take influence of variations of temperature around its reference),

- λ_p miscellaneous PV array losses ratio, taking into account e.g. dirt or snow, etc.,
- λ_c other power conditioning losses ratio, and
- \bar{H}_t the daily irradiance in the plane of the PV array (which takes slope and azimuth angles of the array into account).

Wind energy projects

For wind energy projects, RETScreen® evaluates the produced electrical energy from wind distributions and turbines' power curve, taking into account adjustments to be made due to deviation average temperature and atmospheric pressure at the site from the standard values, as well as various losses occurring throughout the energy conversion process.

(c) *Economic evaluation: assessment of costs and benefits and calculation of financial indicators*

Calculation of financial indicators is based on the assessment /calculation of the different costs and benefits /saving generated by the project (how much will be spent/earned), as well as the timing of the associated cash flows (when will it be spent/earned). The reference period for assessing costs and benefits here is the year.

Generalities on costs and benefits

Types of costs

Costs (and benefits) may be characterised in two ways (Willis and Scott, Distributed power generation - Planning and evaluation 2000, 316-318)¹⁹:

- According to the timing of expense. They may be *initial*, or *continuing* costs
 - Initial costs are those associated to the installation of the DG plant. They apply at year 0 of the project (year of installation).
 - “Continuing costs are those associated with keeping the unit available and in service.” They usually are periodic, and continue as long as the unit is left in service.
- According to the variability of expense with usage. They may be *fixed* or *variable* costs.
 - Fixed costs are costs that do not vary as a function of the amount or patterns of usage. This is the case of DG equipment: its cost does not depend on the usage made of it, but is a fixed value (though it may vary in time).
 - Variable costs are costs that do vary as a function of the amount or type of usage. This is the case for example of fuel: the more power produced, the more fuel paid.

Time value of money

Timing of expense is important in evaluating a project alternative. The reason is the time value of money: in the words of Willis, (Willis and Scott, Distributed power generation - Planning and evaluation 2000, 129), “future money is not worth as much as present money”, meaning 1000€ in one year will not be worth 1000€ today. This is can be attributed to different reasons: the risk, the interest rate, planning errors, etc.

¹⁹ *The characterisation is applied to costs but can apply to benefits as well.*

“Present Worth analysis is a method of measuring and comparing costs and [benefits/] savings that occur at different times on a consistent and equitable basis for decision-making. It is based on the present worth factor, P, which represents the value of money a year from now in today’s terms. The value of money at any time in the future can be converted to its equivalent present worth as:

$$\text{Value today of X dollars t years ahead} = X \cdot P^t$$

where P is the *present worth factor* ” (Willis and Scott, Distributed power generation - Planning and evaluation 2000, 129)

The value of P is empirical and peculiar to the decision-maker.

Discount rate, that is the perceived rate of reduction in value of money from year to year can be related to P as $P(t) = \frac{1}{(1+d)^t}$, where d is the discount rate and t the future year.

Assessment of costs and benefits

One of the main difficulties in a economic evaluation resides in identifying all costs and benefits /savings. In its cost analysis, RETScreen® proposes a relatively thorough list of typical costs, according to the technology considered. We refer the reader to RETScreen® for details but summarise in the following table some of the typical costs related to a DG project as identified in RETScreen® and (Willis and Scott, Distributed power generation - Planning and evaluation 2000, 318), and classified across the initial /continuing categories:

□ **Initial costs:**

- Feasibility study: site investigation, precise resource assessment, etc.
- Development: permits and approval (other than from the DSO), land rights, project financing, legal and accounting, project management...
- Engineering: mechanical design, electrical design, civil design, construction supervision...
- Energy equipment: DG units (PV modules /wind turbines), spare parts, transportation...
- Balance of plant: cost of site, site preparation (foundations, noise abatement, aesthetic conditions, even road construction), electric system interfaces, controls and protection system, connexion line to the network, system installation labour, transportation...
- Miscellaneous costs.

□ **Continuing costs:**

- Annual costs for operation and maintenance: land lease, site maintenance, parts and labour for scheduled general maintenance, property taxes, income tax, insurance, general and administrative, debt cost...
- Periodic costs for parts replacement: blades and drive train for wind turbines, and inverter for PV project.

Some of these costs are fixed, some other are expressed as functions of other variables describing the project.

Generally, benefits /savings originate from selling of the energy generated. According to the definition of our system, and the statement of constant guaranteed green tariff, the formula for calculating incomes from selling of energy is simple:

energy selling income(€) = energy generated (kWh) * guaranteed green price (€/kWh)

There may be other sources of incomes, according to the rules of the society, such as:

- Incentive for construction of the project: this includes any third-party contributions paid to compensate part of the initial cost of the project. Such contribution may be a subsidy from the society to encourage DG from RES.
- Other services than energy supply:
 - Capacity credit (€/kW): amount given by the DSO to pay the avoided cost of installing generation or distribution capacity itself.
 - Credit for generating electricity from RES (€/kWh). We have already included this component in the guaranteed green tariff.

From the assessment of the amount and time of all benefits and costs, a summary of yearly cash flows and cumulative cash flows can be issued.

Calculation of financial indicators

Financial indicators can be assessed from the assessment of the amount and time of all benefits and costs. There exists various financial indicators used to evaluate a project. Classic ones are (Minister of Natural Resources Canada 2005):

- Net Present Value (NPV): value of all future cash flows, discounted at the discount rate, in today's currency;
- Initial investment required;
- Internal Rate of Return: value of the “discount rate that causes the Net Present Value of the project to be zero.”;
- Year-to-positive cash flow: “first year that the cumulative cash flows for the project are positive.”;
- Benefit-cost ratio: relative profitability of the project.

We refer the reader to (Minister of Natural Resources Canada 2005) or (Willis and Scott, Distributed power generation - Planning and evaluation 2000, 129) for details on the calculation of financial indicators.

4.4.4 Considerations on precision, and time and space resolutions

Note the algorithm presented gives an assessment of a project alternative against various objectives. This assessment may be more or less precise with respect to reality due to a number of reasons:

- Because of time and space resolutions of energy resource information. Average (over time and space) values of past observations are used. Averages are typically given with a monthly or yearly resolution to obtain statistical comparability between different years. ;
- Because of variability of resource around the average that creates a difference between resource assessment and real resource;
- Because of simplifications made, e.g. on formulae used for the calculation, and namely because of averaging of values;

Considering our hypothesis of constant selling tariff over time, time resolution of the resource information is not penalising for the precision of the assessment of the revenue. The space resolution however is more important.

As mentioned by (Willis, Power distribution planning reference book 2004, 169-170), talking of network planning: “The evaluation process must provide accurate evaluation, sufficient for the decision-making process. All analytical methods have limits. If the analysis method used to estimate lifetime cost of different options for a new substation is accurate to only 5%, then that method is not really contributing to good decision-making among alternatives that are evaluated as costing with only 3% of one another.”

Accuracy of RETScreen is discussed in (Minister of Natural Resources Canada 2005).

4.5 STAGE 4: FILTERING OUT OF INACCEPTABLE AND PARETO-DOMINATED ALTERNATIVES

As we have seen, part of the constraints are expressed on the variables of decisions, some other are expressed on the results of project evaluation. These constraints may come from society’s rules or be personal constraints of the DG-Installer (e.g. “a project that does not have a Benefit/Cost ratio greater than 2 is not acceptable”). Stage 4 is the stage where projects are checked against those constraints, and eliminated if not compliant.

Our general process is a multi-objective optimisation process. When an alternative is deemed worse than another optimal it should not be considered as a potential candidate and should be eliminated from the final set of alternatives retained. Stage 4 is also the stage where “non optimal” alternatives are discarded. Though, when multiple conflicting objectives are being optimised, ranking of evaluated alternatives becomes non trivial: there is not one ‘best solution’, but many ‘best solutions’.

For example, a DG-Installer could want to optimise both initial investment (minimise) and net present value (maximise). In the general case, these objectives tend to be in conflict because, broadly speaking, bigger projects (higher investments) yield increased energy generation thus higher incomes thus higher NPV. Which is best then: a project with medium investment and medium NPV or larger NPV but larger investment? This is not decidable unless by the decision-maker (at next stage) and none of these alternatives should be discarded until the final decision-making.

The notion of ‘domination in the sense of Pareto’ or ‘Pareto-optimality’ accounts for this. Informally speaking, a project alternative p is said to be dominated by another project alternative p' in the sense of Pareto if the evaluation of p is worse than that of p' in ALL objectives. The set of Pareto-dominant (or Pareto-optimal) solutions define the ‘Pareto front’ or ‘Pareto surface’. This is illustrated in Figure 5. Project alternative p can then be eliminated from the final set of interesting alternatives because there exists at least one alternative that performs better with respect to all objectives.

Note that even if discarded from the final set of interesting alternatives, Pareto-dominated alternatives may be used to help the search algorithm find dominant solutions (genetic algorithm).

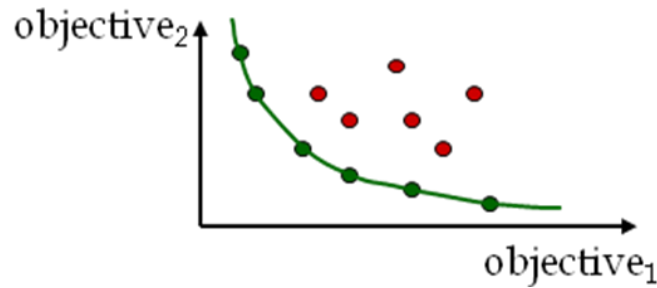


Figure 5 – Illustration of domination in the sense of Pareto. Here, the goal is to minimise both objectives 1 and 2. Evaluation of each decision is plotted on this chart against objective₁ and objective₂. The Pareto-dominant solutions are those whose evaluation is plotted in green. The set of these define the ‘Pareto front’ or ‘Pareto surface’. Same is applicable for a higher number of objectives – for three objectives, the Pareto frontier will be a surface. Solutions whose evaluation are plotted in red should be eliminated.

Once this filtering is done, we have a set of project alternatives such as there does not exist any project better than another with respect to one objective without being worse in at least one other objective. The final decision is to be made between those optimal alternative projects, according to the DG-Installer’s preference, as no one alternative is better than another.

4.6 STAGE 5: SELECTION OF “BEST” ALTERNATIVE

Deciding between multiple Pareto-dominant alternatives is difficult, all the more when no human expertise is to be involved in the process. Selection of the best solution among dominant alternatives depends on the decision-maker’s goals and preferences. The problem is the subject of intensive research under the keyword of ‘Multi-Objective /Attribute /Criteria Decision-Making’, and the domain proposes numerous methodologies for solving this class of problem.

Among these methodologies a simple one is based on Multi-Attribute Utility Theory (MAUT), which is an extension of Utility Theory to multiple objectives. The principle is to assign a score to each alternative using its evaluation against each objective. The multi dimensional evaluation then transforms to a one-dimensional evaluation using which the best solution can simply be identified. The score is given by:

- ‘Scoring’ the alternative for its performance against each objective individually, using a utility function, and
- Assigning weights to each objective to reflect relative importance;
- Finally aggregating the multiple scores into a single one using a relation such as:

$$s(x) = \sum_{i=1}^n w_i * s_i(f_i(x))$$

, where:

- x is the decision vector characterising the project alternative;
- $s(x)$ is the final score associated to project alternative characterised by the decision vector x ;
- $f_i(x)$ is the evaluation of x against the i^{th} objective;
- $s_i(f_i(x))$ is the score attributed to the evaluation of x against the i^{th} objective using the function s_i , which is specific to this i^{th} objective;
- w_i is the weight coefficient given to the i^{th} objective; and
- n the number of objectives

This technique requires relative importance of objectives, as well as the scoring functions to be fully defined, which introduces additional difficulties. Then this work should be included in the ‘profile’ of the DG-Installer.

Note that if such a method is applied at the decision-making stage, then it could be applied in the optimisation process to change the multi-objective optimisation process directly into a (single-objective) optimisation process of the score function. We have however decided to detail and execute all stages as independently as possible to keep a generic and modular approach.

Besides these methodologies, another strategy, as done in power system planning in cases where multiple objective are concerned (Willis, Power distribution planning reference book 2004, 175), could be to get round the problem “by converting all but one of the attributes to criteria.” Attributes in Willis’ terminology is equivalent to our objectives, and criteria to post-constraints setting a standard (minimum requirement) . Then note that, using this strategy, the multi-objective optimisation is changed to a single-objective optimisation.

Or yet another “easy” strategy, more or less relevant according to the profile of the DG-Installer, could be to deem all alternatives as equal to the DG-Installer and to choose according to another objective not yet considered, such as environmental impact.

We have not put too much efforts in this stage, and have chosen to implement the MAUT approach, simplistically and naively choosing relative weights and score functions for our demonstration purpose. This stage of multi-objective decision-making should however be more investigated, either to reflect best actual decision-making of real DG-Installers, provided it does not have too strong human components, or to provide them with the most valuable planning tool, according to the objective. The literature on the subject is prolific.

5 THE DSO

5.1 PROJECT APPROVAL PROCESS

We present hereunder the DSO’s project process (cf. Figure 6). Given the assumptions made, the model is relatively simple, and mainly features power flow simulation as the method used for assessing the impact. We however give some more details hereafter.

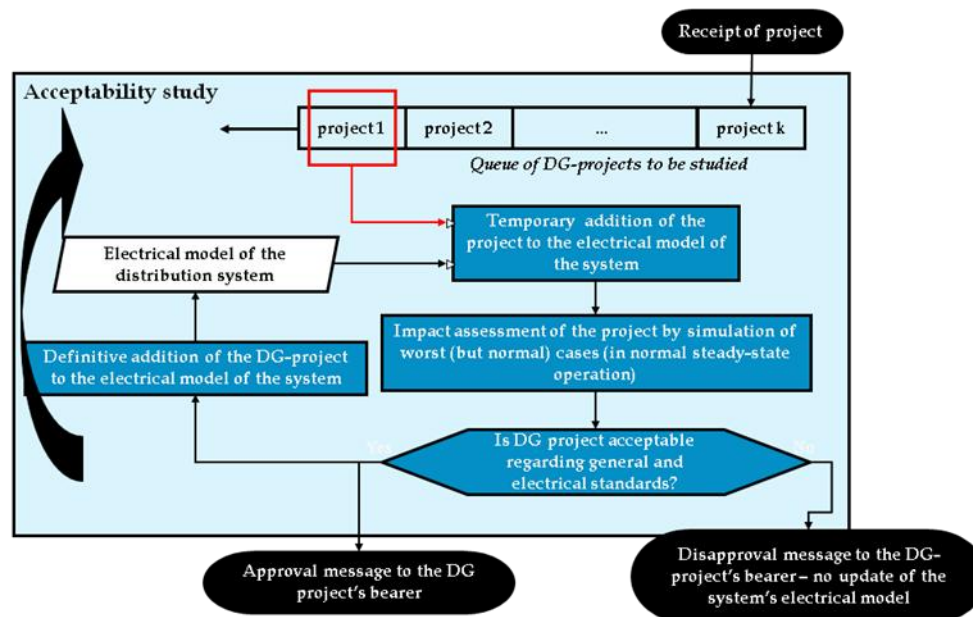


Figure 6 – Representation of DSO's project approval process.

Reception of project

Assessment of the project requires that some specific characteristics of the project be communicated. Financial indicators are of no interest for the DSO, but some of the technical characteristics such as installed capacity, technology, etc. are. Considering our assumptions on the assessment of the impact, only installed capacity and location of the project (to determine connexion point on the network) are necessary.

The queue

The order of reception of projects is managed with a queue (First-In-First-Out) of DG-projects to be studied. Projects are simply queued in order of reception and considered later one by one in the same order. We assume it is impossible that projects be received at the same time.

Assessment of the impacts on the DS

Assessment of the impacts on the DS are made using power-flow simulation in normal steady-state operation in the worst conditions as defined in the assumptions (cf.). The assumption of balanced load-flow, allows to use a one-phase model of the DN.

The DSO maintains multiple models of the DS.

- One corresponding to reality;
- Another corresponding to forthcoming reality, including already accepted projects as if installed.

Yet another temporary model, issued from the second model, is used to temporarily add the project to be assessed. If the project is approved, the temporary model replaces the DS model of forthcoming reality, otherwise if the project is disapproved, the model of forthcoming reality is left untouched.

Chapter IV. IMPLEMENTATION AND SIMULATION

1 IMPLEMENTATION

1.1 CHOICE OF A MULTI-AGENT MODELLING AND SIMULATION PLATFORM

There exists multi-agent modelling and simulation platforms as a software frame for developing and simulating multi-agent models, providing many tools and libraries useful for ABM&S. (Castle and Crooks 2006) give guidelines for choosing Agent-Based M&S platforms and compare a set of platforms.

We have selected Repast Symphony, a free and open-source ABM&S toolkit, from which a description of features is given in (Repast Agent Simulation Toolkit 2008). Among those features, central ones are the **scheduler**, that manages time and launches agent processes at certain time-steps, a **graphical user interface** providing control on the simulation run and on parameters and allowing visualisation, and an integrated **Geographical Information System** (GIS) tool for easy manipulation of geographical information, including storage, queries, manipulation /processing, basic edition, visualisation, etc.

1.2 BLOCK-DIAGRAM OF THE DS-ECO-SIM

The following figure (cf. Figure 7) is a block diagram of the implemented DS-Eco-Sim.

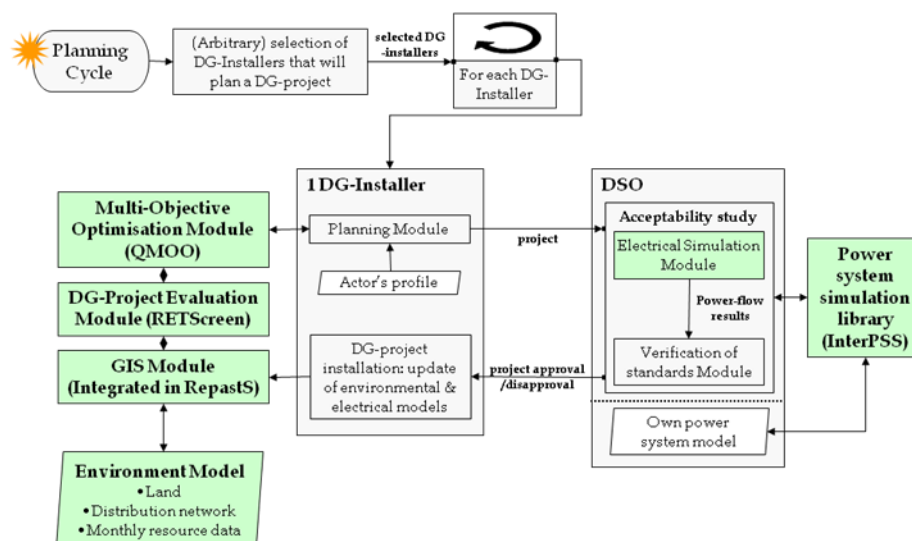


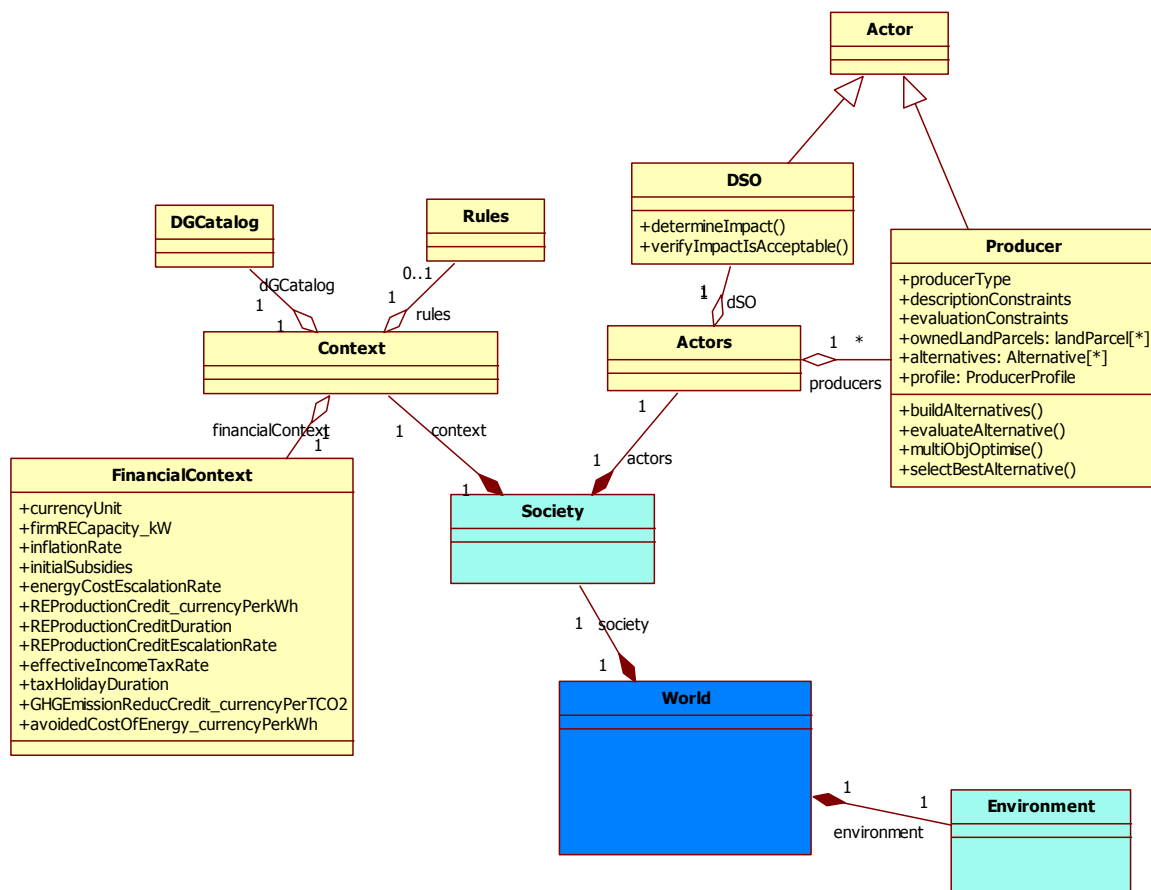
Figure 7 – Block-diagram of the DS-Eco-Sim.

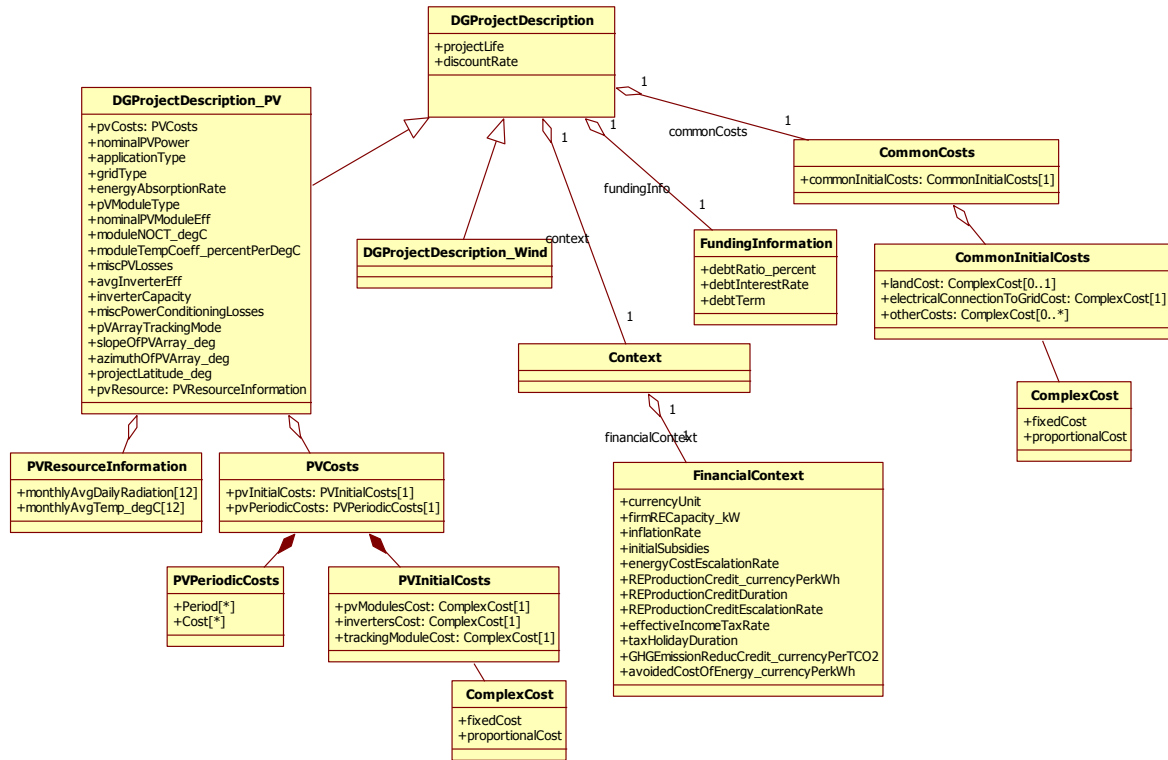
We use the scheduler to launch the planning cycle, in which one or more DG-Installer will be selected to go through their planning process. The planning module takes into account the actor’s profile, and uses a clustering multi-objective optimisation (MOO) module, QMOO (Queuing Multi-Objective Optimiser), developed by EPFL for optimisation of energy systems (Leyland 2002). This optimisation module in turn uses RETScreen® as the core of the evaluation module to evaluate alternative DG-projects. The GIS module integrated in Repast Symphony, which operates on the model of the environment, is used by the evaluation module to access or assess some environment-related quantity, such as distance to the closest connexion point on the network, available land parcels, resource data, etc.

When the demand of approval of DG-project is sent by the DG-Installer to the DSO, and the DSO runs his approval process, which makes use of a power system simulation library, InterPSS (InterPSS - An internet technology-based open power system simulation system n.d.) to calculate power flows. The power system simulation library uses the electrical model, maintained by the DSO, of the DS considering already accepted DG-projects.

1.3 DATA MODELS

We give here examples of some of the implemented data models:





2 DEMONSTRATION OF MODULES

2.1 USE OF GIS FOR MODELLING ENVIRONMENT

The following figure (cf. Figure 8) is an example of an environmental model used for virtual case-studies. It describes over a delimited area of approximately 5*5km the land parcels, the DN routing, the availability of land, and resource information, as an attribute of each land parcel.

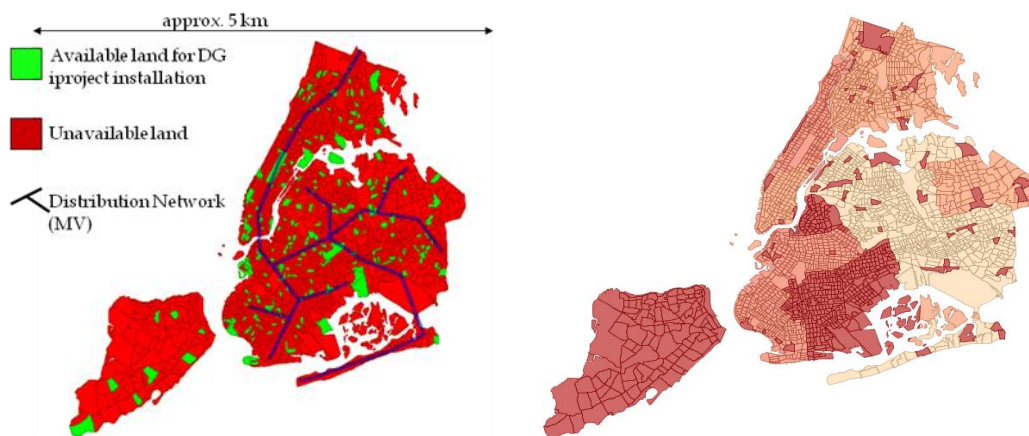


Figure 8 – Modelling of the environment in a virtual case-study. Map used is initially a map of New York City down-scaled to approx. 5x5km. Left: Land parcels, of homogenous attributes, are delimited by thin black lines. Available lands for DG installation are coloured in green, as opposed to unavailable lands coloured in red. The thick blue lines represent the MV distribution network. Right: solar resource in (kWh/yr) is represented here for each parcel on a red colour scale.

2.2 USE OF MULTI-OBJECTIVE OPTIMISATION MODULE (QMOO) IN PAIR WITH RETSCREEN®

The following figure shows the results of the optimisation of a photovoltaic project using the QMOO clustering genetic algorithm. The decision-space in this case has four dimensions, i.e. there are four input variables for the project evaluation:

- **Nominal power of the project:** continuous variable within [0; 250kW];
- **Array tracking mode:** integer variable between 0 and 3:
 - 0 for a photovoltaic array mounted on a fixed structure (slope and azimuth to specify);
 - 1 for azimuth tracking (fixed slope to specify, rotation around a vertical axis);
 - 2 for one-axis tracking (the axis is in the plane of the PV array, slope and azimuth of tracking axis to specify);
 - 3 for two-axis tracking (positions the PV surface normal to the beams of the sun, no angle to specify). Choosing one or the other array tracking mode impacts the initial costs;
- **Azimuth and slope angles:** continuous variables within [0; 90°] (depending on the array tracking mode, specifying them may have no sense: in this case, they are not considered).

Other parameters required by the project evaluation module have been set to predetermined values: the site considered is near Stuttgart, the resource information, is the one provided by RETScreen® for this location, and cost and financial parameters have been set to arbitrary (more or less realistic) values. Note the resource information is given as (monthly) spatial averages, so it would more or less differ from values that could be measured on a particular site, impacting at the same time the evaluation precision.

The evaluation considers two, a priori conflicting, objectives:

- **The Net Present Value of the project:** to be maximised (the opposite is to be minimised);
- **Initial costs of the project:** to be minimised;

Clustering of the decision space is set to discriminate on the array tracking mode.

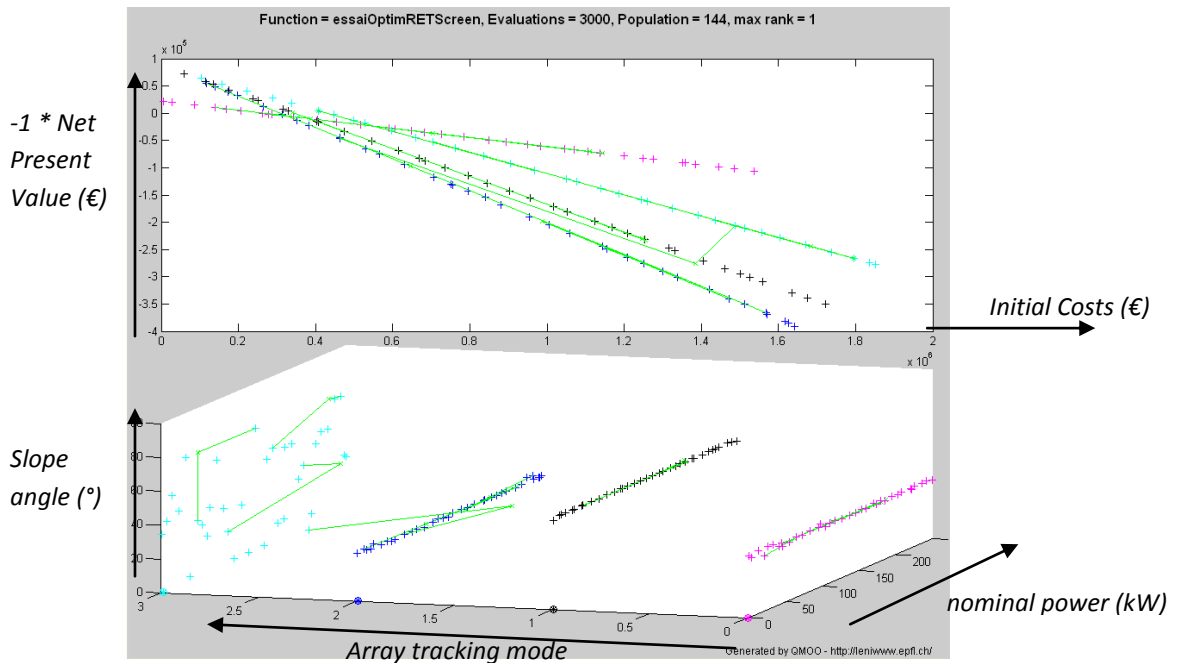


Figure 9: Results for the optimisation of a photovoltaic project on a given site using a state-of-the-art genetic algorithm. Decision-space is represented at the bottom. Plotted variables are the project nominal power, the array tracking mode, and the slope angle (azimuth angle is not represented). Clustering of the decision-space is set to discriminate on the array tracking mode (clusters are represented as different colours). Objective-space is represented at the top. Plotted objectives are the opposite of the Net Present Value and initial costs. One Pareto-frontier is found and displayed for each cluster.

The algorithm displays a Pareto frontier for each cluster. The Pareto frontier defines the Pareto-optimal²⁰ projects (no project, in a cluster, can be better, regarding an objective, than another project of the same cluster, unless degrading the evaluation regarding another objective). We can see that:

- The algorithm has converged to an optimal slope angle for each array tracking mode except two-axis, for the slope angle is irrelevant in this mode. Optimal angles are independent of nominal power;
- No project is profitable unless at least approx. 260k€ is invested;
- One-axis tracking is always preferable (here) to azimuth tracking and two-axis tracking (energy production surplus of two-axis tracking never compensates its higher costs);
- ...

Note that the algorithm can be ran, in principle, with any number of decision-space variables and of objectives.

The same algorithm can be run with location as a decision variable (integer variable), or other variables.

²⁰ Because the genetic algorithm is a heuristic method, it does not claim to provide optimal solutions but good ones, ideally close to optimal ones, in a limited computing time. We are aware of the distinction that must be made. Though, for the sake of brevity, we will call the solutions found by the genetic algorithm 'optimal solutions', not in the sense that no better solution exists, but that no better solution was found.

3 ENVISAGED CASE STUDIES

At the time of this writing, the DS-Eco-Sim was almost but not achieved, so that we do not present simulation studies. Instead we present the case-studies we intend to perform in a very near future.

A virtual environment has been modelled for the definition of a base case-study. We envisage to present 4 virtual case-studies derived from this base case-study, on which the approach and the prototype tool will be demonstrated:

- **Case study n°1: “Influence of the green guaranteed tariff on DG installation”**. This case-study will study the impact of different green tariffs on DG installation;
- **Case study n°2: “Necessity of a coordination mechanism between DG installers and the DSO”**. In this case-study, DG installers will install their units completely freely (no DSO approval required). The objective is to show how unconstrained DG integration eventually threatens the network good operation and concludes on the necessity of a coordination mechanism between DG installers and the DSO. The simple coordination mechanism exposed before (DSO approval required) will be introduced to show how it protects the network good operation, even though it limits DG penetration;
- **Case study n°3: “Creating incentive rules to encourage network-efficient DG installation: an incentive rule for loss reduction”**. In this case-study, DSO approval will be required, but a simple rule will be introduced to financially reward DG installers if their installation helps reducing losses on the network. The influence of this rule on DG installation and on the overall network losses will be studied;
- **Case study n°4: “Limiting DG installation to maximum nominal power of 36kVA”**. In this case-study, the maximum nominal power of DG units is limited to 36kVA. It will be shown how this simple rule implies a more distributed pattern in DG installation and implies different impacts on the network.

Our model of the virtual DS-Society is tuned to adapt to these case-studies, but the modifications to bring are minor, provided we already have all the “bricks”.

Chapter V. **CONCLUSIONS**

1 CONTRIBUTIONS

1.1 INTRODUCTION OF THE AGENT-BASED MODELLING AND SIMULATION FRAMEWORK FOR THE PROBLEM OF DISTRIBUTION SYSTEM PLANNING

The bottom-up approach we propose in our work is an innovative approach, not brought up yet in the literature of the distribution system planning domain, to our knowledge, giving a holistic framework for:

- the development, test and validation of automated planning methods for DG installation;
- the development, test and validation of automated planning methods for the evolution of the distribution network;
- studying different organisations and rules, especially coordination mechanisms, cost allocations, and tariffs determination;
- studying natural trends in the evolution of distribution systems depending on the conditions, regarding many different criteria/interests, such as network performance, environmental impact...;
- and more completely, for the development and test of interaction mechanisms with and between all the other actors concerned by the distribution system, such as consumers, environmentalists, side residents...

1.2 ANALYSIS OF TYPICAL DISTRIBUTION SYSTEM SOCIETY ORGANISATIONS AND ACTORS

The models developed depend on the specific cases to study, on the available data, on the modelling scale (LV or MV)... As an infinite number of society organisations and legislation sets may be imagined, we do not aim at generically describing and modelling all possible ones. Instead, we describe the characteristics of main plausible societies and choose a sample society organisation to demonstrate the general principle of the approach and its interests.

1.3 PROPOSITION OF A SIMPLE AUTOMATED DG PLANNING METHOD, I.E. OF A SIMPLE MODEL OF DG INSTALLERS

According to the society structure defined, a simple prototype model of DG installers, i.e. an automated DG planning method, is proposed. This method makes use of state-of-the-art

modules to optimise the multiple variables characterising a DG-project against multiple objectives.

1.4 IMPLEMENTATION

Implementation is a major difficulty of the exercise: the ABM&S approach completely relies on computer simulation. We have identified interesting APIs and toolkits and software for our problem, and have briefly described how they were integrated. We also have developed data models of the society, of the environment, of the actors, of the distribution network (using an external electrical network API) and of DG projects.

2 VALUE OF THE APPROACH AND OF THE WORK

Our work surely ignores (in conscience) a lot of complexities. This work however is an exploratory work only aiming at highlighting potential interests and difficulties of the ABM&S approach applied to DS-Planning, as well as setting the bases for more advanced work. Efforts are to be continued...

2.1 OVERALL ADVANTAGES

When mature, we attend that this type of simulation tool, based on a bottom-up approach it would:

- allow at least to avoid evident bad solutions for planning methods and interaction mechanisms;
- allow to study the robustness of the planning methods depending on the scenarios, and stimulate development of robust methods;
- allow to determine conditions (notably rules & regulations) favourable for reaching society's key-objectives such as renewable energy penetration...;

Moreover, this type of modelling from the bottom-up is modular and evolutive, and as such, adaptable to future unknown conditions. For a given DS-Society, one may examine a number of different case-studies without bringing major modifications to the base model of the DS-Society.

2.2 DIFFERENT USES FOR DIFFERENT STAKEHOLDERS

When mature, the approach presented here and the work realised can be interesting for real actors of the distribution system society:

- the DSO can use the DG installers model to predict future DG installation in order to optimise the planning for the evolution of the network;
- DG installers will find a basis for the development and evaluation of robust planning methods;
- the DSO will find a basis for the development and evaluation of robust planning methods, and will be reassured that they will be able to face their responsibilities;
- the legislator will be able to perform policy analysis so as to set intelligent rules & regulations for meeting society's key objectives.

2.3 SCOPE, LIMITATIONS AND DIFFICULTIES OF THE APPROACH

We believe the ABM&S approach we propose for the problem of DS-Planning in the new context can have important advantages, but we are also aware of its limitations and difficulties:

- **Availability and accessibility of data:** we assumed the important input data was available and accessible, but it might not be the case in reality. Cases where data may be hard to obtain include getting a full description of the electrical network for simulation (down to LV if that is the scale considered), and precise local resource estimation. Building models with grounding to reality will have to consider this issue;
- **Computationally intensive.** Running simulations may require large computational resources (power and storage), and thus be time consuming. The M&S approach calls for multiple runs but computation time practically limits the parameter space that can be explored or the number of alternative scenarios that can be tested. Although computing power grows constantly, making M&S more and more efficient, the number of alternative scenarios to simulate and parameter space can virtually be infinite, and computation time remains a limitation when modelling large systems (Castle and Crooks 2006), especially from the bottom up (ABM&S) (and despite the possible distribution of simulation across multiple processors).
- **Difficulties for the evaluation of a project:** thoroughly evaluating a project may be much more difficult than what is presented here using RETScreen. Some society rules may completely defeat the RETScreen evaluation: indeed RETScreen is based on simple assumptions made on the basis of the present context and general rules, such as the selling of DG production being guaranteed, and the tariff for DG production being fixed and guaranteed. These simplifications, based on computations of average values, may not be adapted at all to some other context. In general, a project's 'fitness' depends on the rules of operation of the production units, thus linking planning to operation. RETScreen is limited in the contexts it can face, and a more advanced evaluation method should be developed to consider this issue. One of the proposed approach for solving this is to come down to hourly resolution for the evaluation;
- **Modelling DG installers:** the predictability of DG installers' decision-making is to be answered, and it may be hindered by the availability of data and non rational decision-making. We believe the answer to this question will depend on the scale that is considered. It is to note that DG implies more numerous and small projects, giving preference to automatic, less "human" decisions, and so certainly allows easier and more reliable modelling.

Whatever the answer to this last question, the modelling and simulation of virtual, designed, DG installers can still give interesting insights on "mechanical" trends of evolution of the system.

3 PERSPECTIVES

We think the problem of availability and accessibility of data should be faced from now on, to improve the realistic dimension of the work.

If the interest in the ABM&S approach is confirmed, more advanced models (planning methods) of DSOs and DG installers could be further-developed in collaboration with the real actors concerned, so as to fit better with their real planning process, vision and needs. We expect that the most difficult task following this work will be the development of advanced planning methods for the DSOs.

In our work, consumers are modelled as predetermined load scenarios. The development of demand-side management will require that models of consumers be also developed: their global consumption will evolve in unknown ways, and they will be respondent to electricity prices.

References

- Ault, G.W., C.E.T. Foote, and J.R. McDonald. "Distribution system planning in focus." *IEEE Power Engineering Review* 22, no. 1 (2002): 60-62.
- Axelrod, Robert. "Advancing the art of simulation in the social sciences." In *Simulating social phenomena*, edited by Rosario Conte, Rainer Hegselmann and Pietro Terna, 21-40. 1997.
- Balci, Osman. "Verification, Validation, and Testing." Chap. 10 in *Handbook of simulation - Principles, methodology, advances, applications, and practice*, edited by Jerry Banks. 1998.
- Banks, Jerry. "Principles of simulation." Chap. 1 in *Handbook of simulation - Principles, methodology, advances, application and practice*, edited by Jerry Banks. 1998.
- Bonabeau, Eric. "Agent-based modeling: methods and techniques for simulating human systems." *PNAS*. 2002. 7280-7287.
- Castle, Christian J.E., and Andrew T. Crooks. "Principles and concepts of agent-based modelling for developing geospatial simulations." 2006.
- De Oliveira De Jesus, P. M., and M.T. Ponce de Leao. "Long term cost allocation methodology for distribution networks with distributed generation." *15th PSCC*. Liege, 2005.
- ERDF. "Description physique du réseau public." *Documentation Technique de Référence*. 2008.
- . "Procédure de traitement des demandes de raccordement des installations de production d'électricité aux réseaux publics de distribution." *Documentation Technique de Référence ERDF*. 3 2008.
- Ferber, Jacques. *Les systèmes multi-agents - Vers une intelligence collective*. InterEditions, 1995.
- Ferber, Jacques. "Multi-agent concepts and methodologies." In *Agent-based modelling and simulation in the social and human sciences*. 2007.
- Gilbert, N., and K. G. Troitzch. *Simulation for the social scientist*. Open University Press, 2005.
- Hartmann, Stephan. "The world as a process: simulations in the natural and social sciences." 1996.
- InterPSS - An internet technology-based open power system simulation system*.
<http://www.interpss.org/> (accessed 12 2009).
- Leyland, Geoffrey Basil. "Multi-objective optimisation applied to industrial energy problems." PhD thesis, Faculté STI Section de Génie Mécanique, EPFL - Ecole Polytechnique Fédérale de Lausanne, 2002.
- McDermott, T.E., and R.C. Dugan. "PQ, reliability and DG." *IEEE Industry Applications Magazine* 9, no. 5 (2003): 17-23.

Minister of Natural Resources Canada. "Clean energy project analysis: RETScreen engineering & cases textbook." 9 2005.

Ministère de l'écologie, de l'énergie, du développement durable et de l'aménagement du territoire. «Arrêté du 23 avril 2008 relatif aux prescriptions techniques de conception et de fonctionnement pour le raccordement à un réseau public de distribution d'électricité en basse tension ou en moyenne tension d'une installation de production d'énergie élec.» 25 Avril 2008.

Monteiro, C., V. Miranda, I. Ramirez-Rosado, P. Zorzano-Santamaria, E. Garcia-Garrido, and L. Fernandez-Jimenez. "Compromise seeking for power line path selection based on economic and environmental corridors." *IEEE Transactions on Power Systems* 20, no. 3 (2005): 1422-1430.

Natural Resources Canada. *RETScreen International Home*. <http://www.etscreen.net/ang/home.php> (accessed 12 2009).

Parunak, H. Van Dyke, Robert Savit, and Rick L. Riolo. "Agent-based modeling vs. equation-based modeling: a case study and user's guide." *Workshop on Modeling Agent Based Systems*. Paris, 1998.

Pepermans, G., J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'Haeseleer. "Distributed generation: definition, benefits and issues." *Energy Policy* 33, no. 6 (2005): 787-798.

Ponce de Leao, M., and J. Saraiva. "Solving the revenue reconciliation problem of distribution network providers using long-term marginal prices." *IEEE Transactions on Power Systems* 18, no. 1 (2003): 339-345.

Pritsker, A. Alan B. "Principles of simulation modeling." In *Handbook of simulation, principles, methodology, advances, applications, and practice*, edited by Jerry Banks. 1998.

Ramirez-Rosado, I., C. Monteiro, E. Garcia-Garrido, V. Miranda, L. Fernandez-Jimenez, and P. Zorzano-Santamaria. "Negotiation aid system to define priority maps for wind farm development." *IEEE Transactions on Power Systems* 20, no. 2 (2005): 618-626.

Ramirez-Rosado, I., L. Fernandez-Jimenez, C. Monteiro, V. Miranda, E. Garcia-Garrido, and P. Zorzano-Santamaria. "Powerful planning tools." *IEEE Power and Energy Magazine* 3, no. 2 (2005): 56-63.

Repast Agent Simulation Toolkit. 2008. <http://repast.sourceforge.net/> (accessed 12 2009).

Ricordel, Pierre-Michel, and Yves Demazeau. "From analysis to deployment; a multi-agent platform survey." 2000.

Robinson, Stewart. *Simulation - The practice of model development and use*. John Wiley & Sons, 2004.

Strbac, G., J. Mutale, and D. Pudjianto. "Pricing of distribution networks with distributed generation." *International Conference on Future Power Systems*. Amsterdam, Holland, 2005.

Willis, H. Lee. *Power distribution planning reference book*. 2nd edition, revised and expanded. 2004.

Willis, H. Lee, and Walter G. Scott. *Distributed power generation - Planning and evaluation*. 2000.

