Improving the Robustness of Urban Electricity Networks
IRENE

D5.1 – State-of-the art in gaming simulations and stakeholder workshops for method evaluation

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1 EXECUTIVE SUMMARY

This document constitutes deliverable D5.1 within work package WP5 of the IRENE project. It reports outcomes of research on state-of-the-art of infrastructure evaluation literature. We cover the diversity of evolution methods, functionality of existing grid modelling tools, and how infrastructures models can be assessed. The purpose of this document is to sketch out best practices related to evaluating systems and tools. As a result, it forms the basis for designing and studying outcomes of gaming simulations and stakeholder workshops that aim to improve infrastructures.

First, the deliverable outlines resilience characteristics important to consider during grid modelling exercises. Consequently, it introduces approaches relevant for evaluating infrastructure-related decisions making processes. For this, we build on advances in resilience management of socio-ecological systems. Relevant approaches include methods that concentrate on collaboration frameworks, collaborative planning, tool-supported collaborative planning, and how tools can help in making specific decisions. The latter task concerns evaluating decision support systems. By taking these aspects as complementary, this document sketches out an 'Evaluation Continuum' that embraces relevant processes. This allows us to link constructs that commonly belong to different approaches. By elaborating on these links, the evaluation continuum can be used for planning gaming simulations and stakeholder workshops, as well as devising questionnaires for such sessions and positioning the sessions within overall tool development efforts.

Next, this document surveys microgrid modelling tools and cross-relates their functionality. We account for tools and services available, including DNV GL's Microgrid Optimization tool, MIT's laboratory-scale microgrid, and solutions by Masdar Institute, Siemens, Etap Grid, and Argonne National Laboratory. After summarizing functionalities of these solutions, we briefly review challenges relevant to modelling microgrids. This overview of state-of-the-art methods is closely linked to the work to be published in deliverables D4.1 (Toolsets of supply demand prediction and threat identification and security classifications) and D5.2 (Evaluation method design, evaluation of IRENE methods, collaboration framework and modelling tool). It forms a reference baseline for evaluating novel solutions.

Finally, we review the state-of-the-art of model-based assessment techniques that can be used for evaluating outcomes of gaming simulations and stakeholder workshops. For this, we enumerate modelling formalisms and modelling methodologies. We then describe a model-based approach to support Smart-grid evolution and populate it with examples. This technique will be used to assess outcome of the evaluation sessions. D5.2 will include the description of this assessment.

Thus, the major aspects of the document are:

- Review of evaluation methods concerning tools to support collaborative infrastructure-related decision making;
- An outlined 'evaluation continuum' as a structure to assist in the designing of gaming sessions and stakeholder workshops;
- Review of existing microgrid modelling solutions and challenges related to modeling microgrids;
- Review of state-of-the-art in dependability analysis;
- Introduction to how the dependability analysis can be applied for analyzing models of microgrids constructed during collaborative modeling exercises.

By sketching out an 'evaluation continuum' of state-of-the-art evaluation methods, this deliverable allows linking tools for collaborative decision making to different contexts. We see the proposed evaluation continuum as one of unique contributions of this deliverable. It unites methods dealing with the tool functionality and outputs to several contexts of possible use cases.

Given the extensive nature of this document, we can anticipate that readers might prefer to focus on particular sections of this deliverable. Readers interested in the evaluation continuum are referred to subsection 3.6. The continuum elements are described in more detail in subsections 3.1-3.5. Readers interested in functionalities of existing grid modelling tools can refer to section 4. A state-of-the-art process for considering grid-related investments using a tool is described in subsection 2.3. Readers with interest in model-based assessment can focus on the review of assessment techniques (section 5).

The constructs described in this document will underpin the study of IRENE solutions during upcoming stakeholder workshops and gaming sessions. The outcomes will be reported in D5.2 – the next deliverable within work package WP5, which will investigate the practicability and efficiency of IRENE solutions. D5.2 will study feedbacks from students, assess scalability of the methods and tools to real-life situations, and report on quantitative assessment of the dependability of microgrids schemes improved during modelling sessions.

2 INTRODUCTION

Accounting for resilience and robustness of a system is a complex task relating to its management. Therefore, before outlining the state-of-the-art in in evaluation, we introduce the background of such management-related processes to position this task within relevant activities.

This section begins with an overview of resilience management from the socio-ecological systems (SES) perspective, which can be directly projected to grid resilience management. We build on advances in resilience analysis from the water management domain. This domain is not only well-developed, but it is similar to grid resilience management. It has been chosen because it is particularly relevant to managing electricity distribution in urban networks during blackouts, when only limited amount of electricity generation is available.

Next, we highlight the role of collaboration and the need of different experts to make decisions on how to update the grid. We conclude this section with a state-of-the-art example of the process for considering investments for grid resilience.

2.1 BRIEF ON MANAGEMENT

With the introduction of renewables and decentralization of the grid structure more and more actors will be involved in grid management. They together need to handle a number of questions related to robustness and resilience management. It is a complex undertaking that requires consistent and comprehensive procedures. Due to the novel nature of this task for the electricity domain and the need to involve actors not previously considered, the topic is still under development. Consequently, it can benefit from advances in other domains having similar interests and properties, such as water management. This subsection begins with the justification of why water management seen from the socio-ecological systems point of view can be related to grid resilience management. Subsequently, it outlines major dimensions of resilience management.

2.1.1 Characteristics of Resilience and Robustness

The task of robustness and resilience of the grid can be formulated as a one aiming to find how to share a limited resource between multiple stakeholders. The increased interconnectivity of ever smarter grids and direct interdependencies of critical infrastructures, whose services are consumed by citizens, make energy such a limited resource. A well-researched natural resource management domain can provide some insights into how this task can be performed.

Important management and process evaluation aspects from the water resource management can be projected to managing electricity resources in times of need. This is possible because of similar goals and characteristics when one sees energy as a scarce resource available during blackouts. Specifically, it was suggested [25] that water resource management particularly concerns the following features:

- Water resources are typically state managed. Agencies involved in participation programs may therefore be particularly concerned about the cost-effectiveness of tax payers' resources, and the publics' perception of the legitimacy of the process (for example, through access and representation);
- Water resource management frequently involves multiple interest groups and sponsoring agencies who may be interested in factors such as facilitation and dialogue that focus on integrating multiple perspectives;
- Water management decisions might be improved by basing them on the maximum

information available. Knowledge inclusion might therefore be considered an important characteristic of a good participation process.

These features can be projected to managing electricity. In particular, the two latter features highlight the importance of knowledge inclusion and involvement of multiple actors. The first one emphasizes the need to account for fair resource distribution, public perception, and the need to consider governmental organizations (such as city planner in case of urban grids). Therefore, based on the similarities with corresponding needs of grid management, collaborative grid management can be seen as being related to water management.

In addition, grid management can be seen as being similar to water resource management if seen from the perspective of resilience. According to [26], resilience management has two aims:

- To prevent the system from moving to undesired system configurations in the face of external stresses;
- To nurture and preserve the elements that enable the system to renew and reorganize itself following a massive change.

Another similar feature between the mentioned domains is the need for finding trade-offs. Unavoidably, the governance of common-pool resources invariably involves trade-offs [27]. These trade-offs exist between different stakeholder objectives, risk and productivity, and between short-term and long-term goals. One of the examples in water resource management [27] illustrates trade-offs in balancing salt, water and agricultural productivity. Grid balancing in turn implies finding agreements between different electricity consumers.

To find suitable arrangements, stakeholders need to build a shared understanding of their systems of interest. In particular, for robustness and resilience management it is important to agree on possible undesirable events. Because the robustness can hardly be defined in absolute terms, the decision to invest in robustness should specifically concentrate on which threats to address and what vulnerabilities can be accepted.

Having elaborated definitions is highly relevant for these tasks. There are several resilience concepts that focus on different aspects of resilience, as shown in Table 1 adapted from [28].

If the outlined differentiation is commonly accepted, it allows stakeholders to focus on specific resilience and relevant evaluation factors. For instance, the evaluation might consider resilience with respect to Engineering, Ecological/ecosystem, or Socio-ecological resilience.

With a number of systemic feedbacks, cross-scale dynamic interactions, and institutional learning aspects, the task of resilience management call for the need to structure it. According to [26], resilience management of a system might include four steps that are conducted sequentially. During these steps stakeholders focus on resilience 'of what', resilience 'to what', resilience analysis (processes and thresholds; processes leading to actions with respect to resilience, which in turn result in resilience management and policy), and stakeholder evaluation of all the process. The first of these steps can be seen as related to Table 1, while others further elaborate on the task. Together, these four steps are interconnected as follows:

- Step 1: Description of system (key processes, ecosystems, structures and actors);
- Step 2: Exploring external shocks, plausible policies, and exploring vision;

- Step 3: Resilience analysis of 3-5 scenarios obtained after Step 2. This step can result in a return to either Step 1 or Step 2. It can also result in better integrated theories outside of the framework.
- Step 4: Stakeholder evaluation (processes and products). This step can lead to return to step 1 or provide outputs to policy and management actions.

Table 1. Characteristics of resilience concepts

Resilience Concept	Characteristics	Focus on
Engineering resilience	Maintaining efficiency and constancy	Deviation from actual performance (often also understood as robustness), recovery effort
Ecological/ecosystem resilience and social resilience	Buffering capacity, withstanding shock, maintaining function	Persistence, absorbability
Socio-ecological resilience	reorganization, sustaining and developing	Adaptive capacity, transformability, learning, innovation

This process should build on shared understanding of specific resilience aspects under consideration and relevant tradeoffs. As these meta-steps are generic, they can be applied to structure IRENE activities on grid management. Once again, they illustrate that such a process can be related to the water management domain. Therefore, we can conclude that reviewing the state-of-the-art of evaluation approaches can be built on advances of the water management domain.

Before elaborating on the evaluation methods in section 3, we briefly introduce the needs for collaboration and complementary expertise, including domain-specific knowledge.

2.2 ROLE OF COLLABORATION IN IMPROVING URBAN GRIDS

The collaboration of stakeholders is vital for improving the resilience of a complex system, such as an urban grid. This was suggested, among others, by the German Federal Office of Civil Protection and Disaster Assistance that analyzed impacts of power outages that lasted for more than 24 hours. The corresponding report [29] provides stakeholders with the expected timeline about failure of critical infrastructure elements. It also emphasizes the importance of involvement of infrastructure operators, civil protection authorities, and media, in disaster response. The multi-faceted and multi-layered nature of planning and modeling infrastructures call for Private Public Partnership collaboration schemes. The US Federal Emergency Management Agency (FEMA) [13] points out to the need to involve the whole community in enhancing the resilience and security. This aims at bringing together people for collaborative emergency planning. It assists in evaluating their needs, find the stakeholders, get them engaged, and raise awareness.

Different stakeholders should be particularly involved in the modeling task for planning critical infrastructure protection [5], as highlighted by government agencies, e.g., [22]. To reach a good understanding of the infrastructure, its vulnerability and relevant interdependencies, stakeholders' expertise might be complementary, as shown next.

2.2.1 Examples of Stakeholders' Expertise Needed to Account for Changes in the Grid

To ensure the continuity of electricity supply to critical city consuming nodes during power outages, employing the complementary expertise of different city-level stakeholders might be beneficial [12]. This subsection outlines complementary expertise on a large scale and then points out at expertise needed when a decision concerns introducing a new component into the grid architecture. This task needs be tailored to the social, economic and technical context, as well as relations to grid-specific features [3]. Deliverable 1.1 of the IRENE project described how these settings can be considered. Noteworthy, the approach described in D1.1 is closely related to the idea of communicating scenarios as strategic tools, as shown in Appendix C.

As mentioned, the multi-stakeholder approach might account for input from different actors. These actors include might include city planners, Distribution Network Operators (DNOs), and Critical Infrastructure (CI) operators [16]. Their expertise is complementary. City managers might have significant expertise in daily administrative operations, but not necessarily in the topic of CI planning. Meanwhile, grid operators, who are responsible for day-to-day functioning of the infrastructure, may overlook the importance of particular customers for the proper functioning of the city as a whole. Emergency agencies, in turn, might have expertise in contingency planning, but lack an overall picture of city development strategies and contexts. All these stakeholders might account for multiple factors and consider how the introduction of new components can improve the grid functioning in times of outages. According to their specific technical knowledge, the stakeholders of the city under analysis may relate the continuity of electricity supply to other city-level tasks (e.g., risk assessment and socio-technical aspects). In addition, some stakeholders have a local knowledge while others have regional knowledge. Therefore, the multi-stakeholder approach is valuable not only from a thematic point of view.

Integration of a novel element in the grid demands that grid-related features are considered by an adequate professional. These features might include the renewable energy-related landscape [2] and the overall aim to reduce greenhouse gas emission [9]. For instance, to find a suitable location for a biogas plant, one should account for distances from the site to the biomass sources is needed [4]. In case of solar urban planning, the interplay between the urban form and solar energy inputs is another concern [1]. For these tasks a relevant expert, such as a city planner, should be involved in grid resilience planning.

Another aspect to address is securing proper functioning of the system (see e.g. [11]). Because of the variability in generation, it is essential that IT elements of the grid will be able to act efficiently to manage fluctuations in energy generation. Adversarial attacks and software or hardware failures can cripple the power grid. Moreover, list of threats to consider can significantly change with introduction of new grid components [15]. Therefore, Risk Assessment [14][18] (RA) and devising mitigation strategies [17] should be part of the planning activities. RA should include cyber-security of grid elements and pay particular attention to changes in the grid, the introduction, updates, or removal of new components. This calls for the need to involve experts familiar with grid security, including physical and IT security.

Security experts might also account for compliance to infrastructure protection plans adopted by a specific country. As [30] points out, both the United States and the European Union instituted committees and working groups on prevention, preparedness, response to terrorist attacks, and solidarity programs on the consequences of terrorist threats. As a result, the EU adopted in 2005 a green paper on European programme for critical infrastructure protection and adopted the Directive 11/08 in 2008. In 2009, the US adopted its National Infrastructure Protection Plan (NIIP). In NIIP the risk management approach is composed of six steps: establishment of security objectives; identification of assets, systems, networks and functions; risk assessment; prioritization of actions; implementation of protection programs and measuring effectiveness. The continuous improvement is ensured by providing feedback from the last step to previous ones.

In addition to the mentioned professionals, final users can also be involved. These users might represent businesses and citizens. This is in line with the paradigm that requirements engineering starts with problem identification and requires input from stakeholders. As collaborative modelling was demonstrated to be useful (see, e.g., [6][7]), such representative can provide a complementary view on threats to the grid. By identifying possible misuse cases of a system, it might be possible to progress towards formulating security requirements [32]. This will allow to focus on security and encourages stakeholders' creativity, as well as invites end users into the discussion, even if they lack significant technical expertise.

It is worth to note that business and citizen representatives might need additional support to participate in grid planning. Specifically, the stakeholders might not possess significant expertise in modeling (e.g., DFD) or using security-related approaches (e.g., UMLsec). Thus, tools should be tailored to the task, as noted in [8]. Importantly, the modeling notation used "should be palatable to the users" [31]. For instance, making elements iconic may be helpful [10][19]. Also, employing tangible elements can assist modeling tasks [23]. The modeling language outlined in D2.1 of the IRENE project is expected to support non-expert users in threat identification. This aspect is under evaluation in WP5 of the IRENE project. We use appropriate scales, e.g. described in [20], to assist users. Deliverable 5.2 will report on these activities.

Altogether, the complementary experience of the city planners, security experts, and business representatives might ensure that a number the tasks related to improving the urban grid are properly addressed. Still, a number of aspects need to be elaborated in detail. The next subsection illustrates what steps a state-of-the-art grid planning process can take in particular.

2.3 State-of-the-art process to Consider Grid-related Investments

A tool to support decisions how to improve the grid infrastructure might be positioning in a context who and what tasks considers. This section illustrates an example how a number of actions can be organized around a tool and points out that even larger contexts might be accounted for.

Probably, the most noteworthy example of how grid improvements can be considered is described in in the report by the New York State Energy Research and Development Authority (NYSERDA) [59]. The report focused on how microgrids can support critical facilities, which might already have backup generation capabilities. It looked at real sub-grids in the New York State that have been analysed by network planners with the support of the grid planning tool HOMER. Each of the five feasibility studies in both urban and sub-urban grids followed the same procedure to upgrade a vulnerable grid to a more resilient microgrid infrastructure.

As the NYSERDA process concerns collaborative planning activities and decisions of users, it illustrates important aspects to take into account for grid planning. Noticeably, they might include different expertise of stakeholders who are familiar with the site, grid, its users, and costs associated. By concentrating on investments into the grid, the NYSERDA feasibility study (see Appendix B in [59]) starts with an overview of the considered site, including:

- Main buildings and their types which have to be supported;
- Existing emergency generators (mainly diesel generators) and UPS
- A map of the site;
- Report of the site visit and key findings such as:
    - Place for additional backup generation;
    - Other energy supply such as natural gas;
    - Historical events such as flooding, storms, etc. in the past.

The next step is the data collection. It accounts for:

- Hourly load data for each facility (buildings);
- If the above is not available, monthly data and example hourly load profiles;
- Detailed diagrams of buildings specifying the surface of buildings;
- On-site generation information;
- Utility information: substation, transformers feeders and feeder connections to the buildings.

Subsequently, a demand supply model (the HOMER tool in the NYSERDA process) is used. It concerned several aspects:

- projected load data of the microgrid;
- existing and proposed local generation sets;
- generation cost parameters: capital costs, operation and maintenance costs;
- fuel costs.

The next step is devoted to setting the electrical infrastructure design. It leads to the diagrams:

- a layout of electrical infrastructure with existing and new lines;
- electrical interconnection diagram;
- communication and control overlay: showing the building, campus and microgrid controllers and their communication.

Afterwards, cost calculations are made, including infrastructure costs (breakers, switches, transformer, cables, etc.), communication, and control costs. Finally, a cost-benefit assessment follows. The costs incurred in the existing grid due to a major outage have to be estimated: for example schools, hospitals have to be evacuated and the inhabitants relocated. Defect equipment has to be replaced.

It is also expected that the upgrade to a microgrid might allow the site to participate in a demand response program. The demand from the macrogrid would be reduced offsetting the increased operational costs of the microgrid. The conclusions from the cost-benefits can then show that the investment for an upgrade to a microgrid and to better resilience are justified only if the duration of the outages exceeds a threshold of *x* days per year (which correlates with high probability of natural disasters or attacks).

From the design point of view, NYSERDA adopted a systems-level and top-down methodology to improve microgrid architecture and components. First, the site requirements and operational objectives are assessed at the enterprise-level. Requirements and system functions are correlated and understood at the enterprise scale as well as the site-level. This allows to account for grid-level macro operational objectives and inherent grid infrastructure constraints and effects. Also, site's critical performance, sustainability, infrastructure and cost constituents are addressed. Next, the site-level functional and performance requirements, together with physical infrastructure constraints are organized as a system-level microgrid platform. Functional and performance requirements are allocated to the component level constructs defined in the Microgrid Reference Architecture. The requirements are assigned to an optimized set of components and configured for an individual site. Individual microgrid components and their function/performance/benefit/cost aspects are identified. This is closely related to a number of assumptions around the tool.

This high-level description highlights that a number of stakeholders should respect their (possibly conflicting) interests, pay attention to the manner in which they collaborate, and contemplate the decisions to be made. Starting from the larger context of devising the new grid, which is a collaborative task, the process more and more focus on individual features, tasks, and tools that can support the larger process. At the same time, the context can be further enlarged, similar to the IRENE approach, it would go in more detail on threats to the system. An even larger context might include collaboration dynamics and evaluation of collaboration schemes. Therefore, the described approach might be carefully positioning within a larger fabric of possible interactions that concentrate around the tool. Up to date, such view is not sufficiently elaborated due to the novelty of the task to manage grid by means of collaborative experts. This hampers the task of evaluating specific approaches.

In the next section we outline a number of state-of-the-art evaluation techniques that step-by-step slice the context of using tools that can support collaborative grid planning. These methods can be further considered in designing scenarios (and especially devising questionnaires) for validating frameworks, methods, tools, and processes.

3 OUTLINING STATE-OF-THE-ART IN EVALUATION: 'EVALUATION CONTINUUM'

This section outlines an 'evaluation continuum' that sketches high level interrelations between different evaluating methods, which cover overlapping aspects of the collaborative infrastructure planning using software tools. These existing evaluation methods are well-suited to study collaborative frameworks, collaborative planning processes, collaboration technologies, and tools that can support planning, namely decision support systems (DSS). This review draws on advances in evaluation in water management domain, given that the domain of collaborative grid resilience management is comparatively less established. We review how evaluation approaches can be linked to each other within the view that the context can be continuously enlarged.

The initial view on how a specific system evaluation can be located within its expanding contexts is shown in Figure 1. This figure illustrates that evaluation can focus on different aspects: collaborations, collaborative planning as a process, planning with tools as a part of it, and tool evaluation as the next step. Herewith tool evaluation is seen as DSS evaluation, as the software might support specific decision-making processes. DSS evaluation is related to: 1. decision value and 2. decision maker(s). The latter concerns the perception of decision makers, while the formed is about a more objectively quantifiable characteristic of the result and the process. Noteworthy, this research considers DSS as being dissimilar to a serious game, which are used for education purposes as specialized objects (see Appendix D for a more elaborates remark on this).

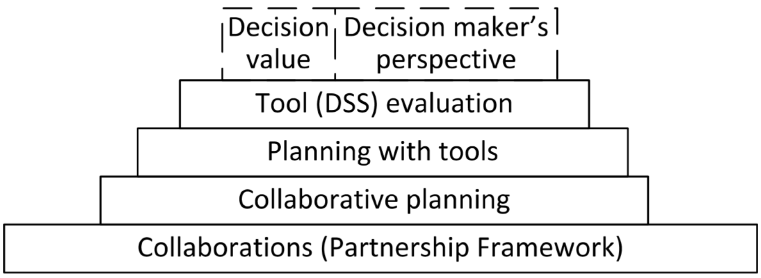


Figure 1. Outline of the evaluation continuum

This section describes how the elements shown in Figure 1 can be evaluated. This provides a mechanism for 'zooming in' on grid planning aspects that can be evaluated. In what follows, we classify frameworks that deal with evaluations and highlight which aspects are relevant for them. We slice the context of applying a tool into several (continuously enlarging) contexts, connected to each other. By doing so, we provide a structure that can be used to construct questionnaires for stakeholder sessions. These questionnaires can be oriented to specify how the artifact acts with respect to a particular context. These questionnaires aim to approach evaluation-specific aspects about using a tool in a particular context. Ultimately, these structure is oriented to develop sessions to consider how collaborative planning and corresponding collaborations can be performed.

3.1 EVALUATING COLLABORATIONS

Community collaboration can be evaluated with respect to interactions between participants. This collaboration stays mostly in the interaction domain and is less concerned with specifics of technological solutions. A Partnership Framework developed in Ireland [33] is an example of how one can evaluate this level of interaction (as shown in Figure 2).

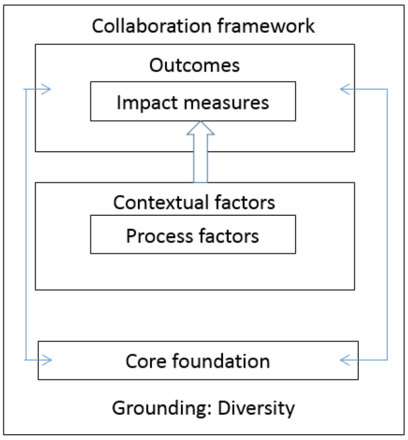


Figure 2. Partnership framework

This framework aims at helping individuals and practitioners who are either starting collaboration or need help in strengthening an existing collaboration. The goal of community collaboration is to bring individuals and members of communities, agencies, and organizations together to systematically solve problems that could not be solved by one group alone. Several *Contextual factors* influence and are influenced by the process factors. These factors include connectivity, history of working together, political climate, policies/laws/regulations, resources, and catalysts. *Process factors* include communication, community development, understanding community, research and evaluation. *The core foundation* is formed by the interrelated Vision, Mission, and Values/Principles.

According to its large scope, this framework can be useful for considering interactions between citizens, businesses, and governmental organizations. At the same time, it is less suitable for evaluating specific processes, compared to other methods described next.

3.2 EVALUATING COLLABORATIVE PLANNING

A *collaborative planning process*, such as a collaborative planning of land use and natural areas, can be evaluated as presented in [34]. In this work the framework with four key evaluation/design perspectives and their success criteria was developed with the help of literature and data from interviews and focus groups in two case areas in the Helsinki metropolitan area, Finland. It provides the structure of evaluation/design perspectives and corresponding success criteria to evaluate the collaborative planning process, as shown in Table 2.

Such design perspectives indicate several aspects of concern that might be studied with the aim of improvement. Most of these design perspectives are directly relevant to collaborative planning of urban grids, while the last one can be operationalized with other criteria. These criteria can be borrowed from the water management domain.

Table 2. An exemplary structure to evaluate a collaborative planning process[1]

Evaluation/design perspectives	Knowledge integration	Meaningful involvement	Functioning governance	Sustainable use of the area (outcomes)
Comment	Collaboration improves the knowledge and value base of planning	Collaboration is meaningful for stakeholders	Collaboration is operational in the governance system	Collaboration helps guide the area development into a sustainable direction
Success criteria	*Adequacy of high-quality information*+; *Improvement of the knowledge and value base because of the use of experiential information*+	*Participatory process worth the effort*; Accessibility of Information+; Adequacy of opportunities to participate+; learning in the community	Good-working cross-border collaboration+; Cost-effectiveness of collaboration; Organizational learning	Better plan; Better quality of environment; Enhanced collaboration and decision-making capacity; Follow-up

3.2.1 Exemplary Evaluations of Participation in Water Management

As collaborating planning concerns a number of aspects, it can be studied with respect to a number of parameters. Some examples of dimensions that can be evaluated and features relevant to the process are presented in this subsection. Specifically, constructs from participatory modeling can be used for this purpose. Such an approach combining collaborative participation with modeling is increasingly recognized as an effective way to assist collective decision-making processes in the domain of natural resource management [35].

A sophisticated example how to evaluate projects that have adopted a participatory modeling approach is Protocol of Canberra [35]. This framework consists of two main components: the Designers Questionnaire and the Participant Evaluation guide. It captures the project team's experiences, including the logic of their research design. It studies *context* (including socio-political setting, physical setting, and objectives) and the *process* (including why particular methods and tools used). The participants Evaluation Guide mirrors the Designers Questionnaire allowing participants' responses to be compared and contrasted with those of the project team. It guides the task of gaining an understanding of the participant's experiences of the project. This differentiation allows to study how the design a specific approach is related to perception of participants.

[1] Key criteria are in italic. Criteria applicable in formative evaluation are marked with '+'

Another work [25] employs an alternative differentiation of methods for evaluating participatory programs and projects. In particularly, methods can be classified into three groups:

1. *Process evaluation* methods assess the quality of the participation process, for example, whether it is legitimate and promotes equal power between participants. Process evaluation concerns accountability, cost-effectiveness, deadlines and milestones, facilitation, knowledge inclusion, legitimacy, and power. Two essential characteristics of good participation process (an 'ideal speech') can be elaborated: fairness (equal opportunities to participate in the process) and competence (enabling participants to protect their interest and take part in the process). Qualitative data, such as participation rates, can serve as proxy indicators for participant satisfaction and attitudes toward the process. Desirable characteristics of good participation process can be measured by means of the following groups of evaluation criteria: accountability, cost-effectiveness and resources; deadlines and milestones; facilitation; knowledge inclusion, legitimacy, and promoting equal power.
2. *Intermediary outcome evaluation* methods assess the achievement of mainly nontangible outcomes, such as trust and communication, as well as short- to medium-term tangible outcomes, such as agreements and institutional change. Intermediary Outcome Evaluation can be seen as related to the development of social capital (interaction and network development and trust) and products from the process: agreements, end to a stalemate, innovation, institutional change, shared knowledge and information. Social capital refers to the capacity and willingness of participants to invest in collective activities to achieve shared objectives. Products of the process are relevant to consider, as reaching agreements and achieving support for action plans can be seen as a positive intermediary outcome from participation.
3. *Resource management outcome* evaluation methods assess the achievement of changes in resource management, such as water quality improvements." This evaluation is related to direct goals that collaborators aim to achieve. In case of resource management it is related to: ecological improvement, economical improvement, human health and wellbeing improvement, implementation of an accepted plan, reduction in conflict/increased harmony. Clearly, some of these outcomes (e.g., implementation of an accepted plan and reduction in conflict) can be used for electric grids. Other outcomes, such as ecological improvement, might be additionally elaborated.

Existing studies in participatory modeling in the domain of natural resource management also highlight a number of aspects relevant to designing resilient solutions for smart cities. In general, participatory methods aim at structuring group processes in which stakeholders play a central role and articulate their knowledge, values, and preferences for different goals. Two studies mentioned below illustrate what aspects can be relevant to consider in grid participatory modeling.

To investigate and illustrate how potential participatory methods can be practicably applied in practice, [36] presented an overview of four natural resource management projects. Participatory goals mentioned in the paper are complicated and can even be contradictory. Such goals can include: to increase the project effectiveness, to include local knowledge in decision making, to manipulate public opinion, or to encourage social learning. In [36] four different process structures (two bottom-up and two top-down) were used to achieve two basic project goals (management solution generation and DSS design). Six aspects influenced the process structures: project goals; democratic participatory goas; researchers' normative beliefs; existing management power structures;

stakeholder numbers and the scale at which final decisions need to be supported. All of them appear relevant to community-centric development of urban grids.

Another paper [37] reports on research into how a computer-based simulation model can be valuable for the implementation of participatory water allocation policy in Sri Lanka. This also shows a complex nexus between water and electricity networks, and illustrates how continuous involvement of multiple stakeholders can be organized. In Sri Lanka water resources development mostly focused on irrigation, drinking water or hydropower. They are subject to Flood, droughts, and landslides, which are the most common natural disasters in Sri Lanka. During droughts, the country faces power cuts, sometimes extending to eight hours per day. Water and electricity networks have to be managed in such a manner that water is used for irrigation in the current season without jeopardizing water supply for the next season, while the maximum possible electric energy is produced. Three agencies are directly involved in managing the bulk of the water in nine river basins and their interests are in conflict if the available water in insufficient.

The process adopted in Sri Lanka involves multiple stakeholders at different stages. For this, modelling and stakeholder consultation processes are established and a continuous stakeholder involvement in the process is assured. Four meetings are related to the modeling: 1. at the stage of planning for the season; 2. approving the ‘best’ seasonal water allocation plan; 3. implementing the accepted water allocation plan (weekly meeting); and 4. review of the performance at the end of season. The first two meetings are related to how the model is used. First, input data for the model are collected. Then, during the second meeting the stakeholders make a decision based on the outcome of the model simulation. The meetings has different focus. The first and the last meetings held in the districts and concentrate on details. The second and fourth meetings are related to discussions at the system level. This continuous involvement is needed to ensure that all needs of the stakeholders are addressed and the implementation is adequate. A similar process might be relevant if one considers an electric power as a common and scarce resource if the system is under pressure (e.g. lack of hydropower during droughts). This implies analyzing resilience of the system. All these steps, as well as the degree of involvement of stakeholders and the level of details considered, cover a number of perspectives of evaluations.

The evaluation dimensions mentioned in this subsection cover a range of possibilities that can be investigated. It includes relations between the ideas that are behind the design of collaborative planning, how steps of planning are linked, as well as how meetings contribute to the overall goal. The corresponding constructs and their interrelations can be used for devising questionnaires with optional connection to specifics of the tool used. Other questionnaires can focus more on studying how the tool contributes to the planning process or how the tool can be used as a part of a system itself.

3.3 EVALUATING TOOL-SUPPORTED COLLABORATIVE WORK

The next relevant evaluation approach considers how a system can support various kinds of collaborative work. To evaluate specifics of such a system, the *Collaboration systems* framework [38] can be employed. This framework, shown in Figure 3, can be used in either a top-down (requirement level to technology level) or bottom-up fashion.

Layers that can be portioned as several planes located above each other: Requirement, Capability, Service, and Technology levels. The Technology level is the lowest, while the Requirement level is at the top. The Technology level is linked with the Service level. The Service level is directed towards the Capability level and the Capability level is linked to the Requirement level.

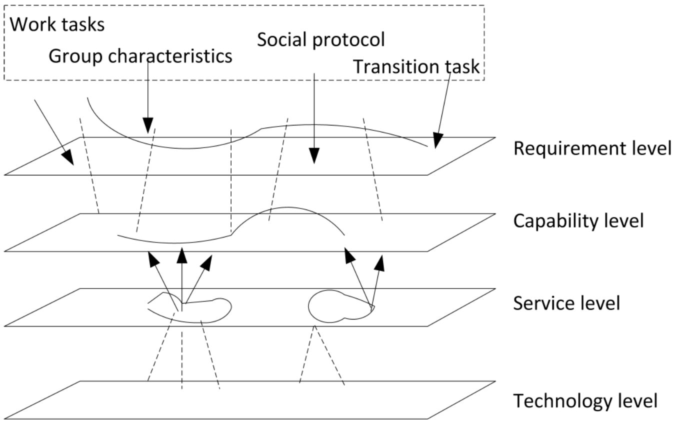


Figure 3. The collaborative framework

The requirement level is related to work tasks, social protocol, group characteristics, transition task, etc. Examples of work tasks include: generate tasks, choose tasks, negotiate tasks, and execute task. The social protocol can consist of formal or informal sessions to support communication between group members, awareness of group members, etc. Transition tasks concerns the following needs: to move between tasks, taking role, requesting changes to an agenda, locating missing meeting participants; group characteristics: number of participants, homogeneity, training and others.

For evaluation one can use scenarios (what the users should try to do at the requirements level) and scripts (how the users will carry out their tasks on the three lower three levels of the framework). With this framework oriented towards evaluation of particular systems, the way how to reach measures from specific goals is less elaborated. A way to do so can complement the framework. Such a possible way is shown next.

3.3.1 Towards Metrics to Evaluating a Collaboration Systems

A coherent way of mapping measures and system goals can clearly assist evaluating tool-supported collaboration work. In particular, using such a structured collaboration systems can be evaluated and compared to each other in a strict manner.

A suitable approach to structure evaluations by mapping system goals to evaluation objectives, metrics, and measures is presented in [39]. Table 3 indicated how ‘levels’ of the framework can be arranged. These layers guide the steps from system goals to implementation-specific measures. The authors suggest that this top-down approach is particularly useful for comparing evaluation results where a number of conditions have changed and for performing assessments of effectiveness with respect to process and product in operational environment.

As an example, the framework can be operationalized as follows:

- System goal: if a system provides capabilities to meet the identified functional requirements;
- Evaluation objective: assess specific synchronous communication capabilities of the tool;
- Metric: *efficiency*;
- Conceptual measure: composition time;

- Implementation-specific measures: for instance, start of typing until "send" function activated.

Table 3. Evaluation process of a collaborative technology

	Examples of Collaborative technology aspects				
Levels	System Goals	Evaluation Objectives	Metrics (conceptual)	Measures (conceptual)	Measures (implementation specific)
Examples	Technical performance, process, and product goals	Partitioned evaluation concerns	Attribute assessment	Performance indicators	Measured values

This structured way of relating goals, metrics, and measures can be used to clearly specify how the evaluation of a tool-supported collaborative work can be linked to the overall goal(s). The next element of the continuum concentrates on the tool itself.

3.4 Evaluation of a Tool: DSS perspective

The previous evolution approaches concentrated on formalizing collaboration dynamics as ways they can be performed, including perspectives of using tools to support collaborative planning. More specific methods can hone in even more on how to evaluate different aspects of systems that can support relevant decisions. For this, important constructs can be borrowed from the perspective of evaluating Decision Support Systems (DSS) – computer-based information systems to support business or organizational decision-making activities.

It is worth noting that DSS evaluation differs from the evaluation of tool-supported collaborative work. As shown in the previous subsection, collaborative planning processes might require using software solutions to model and simulate specific processes and their outcomes. It is not necessary that the tool is employed to encourage collaborative work. Possibly, the tool might assist in solving a specific question, which is important for one of the professionals involved in collaborative planning. Although indirectly, this tool still heavily impacts the overall process. Therefore, a tool can be evaluated in its smaller context – specifically, how it can support specific decisions.

Three evaluation approaches (the general approach to DSS evaluation, three-faceted approach, and the sequential approach) are discussed in [40]. These approaches aim to provide practitioners with support for choosing appropriate evaluating methods for their own purposes and circumstances. In this way, they are useful elements of the evaluation continuum.

A general model of DSS evaluation constructed according to [40] is shown in Figure 4. In this model evaluation criteria influence measurement variables directly. Also, measurement variables related to the decision value and to a decision maker's satisfaction. This classification implies a taxonomy of evaluation, which includes metrics related to decision values and decision makers.

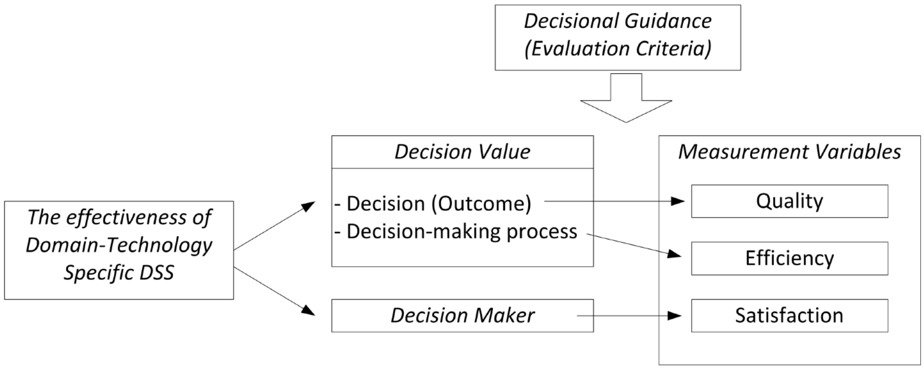


Figure 4. The general model of DSS evaluation

The three-faceted view sees evaluation criteria as a continuum from objective to subjective. Each aspect contains relevant evaluation objects (technical aspects, empirical aspects, and subjective aspects). Objective criteria are related to evaluating technical aspects (e.g., data flow and application control) and empirical aspects (such as cost benefit analysis). Less objective empirical aspects include decision makers' confidence and time taken. Finally, subjective aspects includes ease of use, user interface, and understanding.

The sequential approach to DSS evaluation integrates the idea of continuous evaluation, as shown in Table 4. In this way, evaluation process of a DSS includes several steps aligned with the sequence of human decision-making process.

Table 4. Evaluation process of a DSS

Processes	**Sequence (from left to right) of DSS Evaluation**						
Human Decision-Making Process	Intelligence		Design	-	Choice	Implementation	
DSS Development Life Cycle	Project Assessment	Problem Analysis	Design	Development Testing	-	Implementation	Maintenance
Relevant Steps in System-Reengineering & Prototyping-Design	Requirement Analysis, Model Analysis		Method Selection, Software Selection & Design, Hardware Selection & Design, Transformation		-	System Evaluation, Feedback	
DSS Evaluation Process	**Identification of Criteria**		**Formative Evaluation**		**Evaluation of Outcome (not of the system)**	**Summative Evaluation**	

Together, DSS evaluation methods move the evaluation focus from collaboration processes to systems that support specific decisions. Additionally, as such systems are developed according to some requirements, the latter evaluation process includes Identification of Criteria as a part of DSS Evaluation process. Considering such integration is important, as it relates the evaluation criteria to the needs of the system. This perspective can be further elaborated by considering design science methodologies, as shown next.

3.5 Evaluation in Design Science Research Methodologies

This subsection introduces how design science methodologies position validation and evaluation efforts. With the direction of the question outlined in the previous subsections, this subsection positions when such questions can be asked and how they are related to the overall tool development process. Thus, it locates stakeholder workshops and gaming sessions to the tool development steps.

In design science, evaluation concerns the investigation of a treatment as applied by stakeholders in the field [41]. Validation, in contrast, deals with justifying if the treatment would contribute to stakeholder goals if implemented. The relation between validation and evaluation enables to project some evaluation aspects to a setting suitable for validating the artifact. In other words, asking relevant validation questions we can consider possible answers to evaluation questions for artifact in specific contexts. Thus, relating testing artifacts in controlled settings (such as gaming sessions and, to an extent, stakeholder workshops) to their application in the field can be linked to evaluation methods outlined earlier.

Design science research methodologies account for several actions. Specifically, they clarify connections between the identification of the problem (point of departure) and the evaluation of an artifact. Two methodologies are particularly relevant in this case, namely those outlined by Peffers et al. [42] and by Wieringa [41].

Peffers et al. [42] pictures the design science research methodology as several steps that form a ‘nominal process sequence’. These steps include:

1. Identify problem and motive (Define problem, Show importance);
2. Define objectives of a solution (What would a better artifact accomplish);
3. Design & Development (Artifact)
4. Demonstration (Find suitable context, Use artifact to solve problem);
5. Evaluation (Observe how effective, efficient; Iterate back to design);
6. Communication (Scholarly publications; Professional publications).

Input to the first step can be different because of four possible research entry points, caused by their connection to the steps of the nominal process sequence:

1. Problem-Centered initiation;
2. Objective-Centered solution;
3. Design and Development centered initiation;
4. Client or Context initiation.

This methodology can be particularly useful if metrics for evaluation are related to a departure point and the corresponding sessions should be held accordingly. Also, direct feedbacks are outlined that can help to structure interactions between specific steps. Both Evaluation and Communications have a feedback connection to 'Define objectives of a solution' and 'Design & Development'. Steps 'Define objectives', 'Design', 'Demonstrate', and 'Evaluate' form the design research loop.

From the perspective of behavior of an artifact in context, Wieringa [41] outlines the design cycle that includes tasks of Problem Investigation, Treatment Design, and Treatment Validation. This cycle differs from the cycle of the Engineering science, as it does not include the Treatment Implementation step. Also, it depict a possible distance between the use of artifact in artificial and real contexts.

An instantiation of the design cycle can be elaborated as follows. First, the design problem can be formulated as**:** Improve *a problem context* by (re)designing an *artifact* that satisfies some *requirements* in order to help *stakeholders* to achieve some *goals*. Here, a problem context, requirements, stakeholders, and goals are formulated for their later use for validation. The design cycle can be shortly characterized as (question marks indicate questions to be answered, exclamation marks indicate actions):

- **Problem investigation:** Clarification of Stakeholders? Goals? Conceptual framework? Phenomena Theory of the phenomena? (statistical, causal, architectural); Contribution to goals?
- **Treatment design:** Requirements! Contribution to goals? Available treatments? New treatment design!
- **Treatment validation:** Effects? Requirements satisficing? Trade-offs? Sensitivity?

The treatment validation is the element of the design cycle most relevant to this deliverable. The validation questions about how the interaction of instances of 'artifact' × 'context' can be elaborated as follows:

- Effect questions: what effects are produced by the interaction? Why?
- Requirements satisfaction questions: do the effects of the simulation satisfy requirements? Why (not)?
- Trade-off questions: what happens if the artifact architecture is changed? Why?
- Sensitivity questions: What happens if the context is changed? Why?

These questions (and answers to them) can be used to consider limits of the artifact, as well as a structure to communicate them with stakeholders. Similar to the design science research methodology mentioned above, it acknowledges that the process is iterative. The first of the mentioned methodologies can provide input for questionnaires that investigate the origin of the research and development efforts. The second one can be useful to study limits of applicability of an artifact, as well as explicate assumptions behind the design and challenge them.

Design science methodologies also point out that mechanism should be specified as to how outputs of workshops and gaming sessions should be projected to a larger scope. In general, Design Research methods differentiate single-case studies into those conducted in the lab or field settings. Evolution methods include: single-case mechanism experiments, technical action research, or observational case studies [41]. The lab setting can be used in connection to single-case mechanisms, while all three methods can be related to the field research. In both cases, single-case mechanism experiments might employ analogic inference – generalization by similarity, as statistical inferences will not be valid. This similarity between workshops settings and real evaluations should be carefully considered. These methodologies suggest how stakeholder workshops and gaming sessions, which aim at studying artifact's behavior in context, can be positioned in connection to a larger tool development efforts.

Design science methodologies depict that outputs of design steps are inputs for the consequent iterative steps. As iterations continue, an architecture of a solution is a subject to continuous change. Changes in architecture can be another subject to study, which can help to structure workshops and gaming sessions. An approach to describe architecture in connection to the need of stakeholders is shown next.

3.5.1 Designing Subsystems and Their Tests

To structurally develop realistic systems according to the demands of stakeholders one can benefit from the systems engineering approach. This subsection briefly overviews how an evaluation of subsystems (within a system architecture) can be organized and what tests correspond to it. It is closely related to design methodologies that concern the tool development. From the point of view of the outlined 'evaluation continuum', this subsection looks into verification aspects. This 'inwards' view of the system is complementary to the 'outwards'-oriented efforts of other methods that look at the dynamics around using the tool.

A systems engineering process is a comprehensive, iterative, and recursive problem solving process, applied sequentially top-down [43]. In this process, design and requirements tasks are intertwined. Requirements analysis and Functional analysis tasks form a Requirements loop, while Functional analysis and Synthesis steps form a Design Loop. Both the requirements and the design loop concern verifying that the design synthesized can perform the required functions at required levels of performance. In principle, the system architecture can be useful to design, debug, and experiment with components.

To confirm that design synthesis has resulted in a physical architecture that satisfies the system requirements, one might apply the verification process. The verification process can be seen as related to validation (and later, evaluation) as it represents the intersection of requirements engineering and tests. A well-known V-model (Figure 5, a) is an example of such interrelation linking requirements (the left part of Figure 5, a) and tests (the right part of Figure 5, a). For instance, stakeholder requirements are linked to acceptance tests, where stakeholders validate the product. Analyzing components and subsystem requirements might be performed with respect to component and integration tests correspondingly. This way of disassembling requirements and assembling a system, which complies with it, provides an opportunity to structurally approach system development. Well-defined use cases can be seen as being central for this process, as they might form a bridge between validation and evaluation efforts. Use cases might be closely linked to stakeholder requirements. Using these settings, the stakeholder can examine the relevant processes and consider whether the method or tool is usable for their needs.

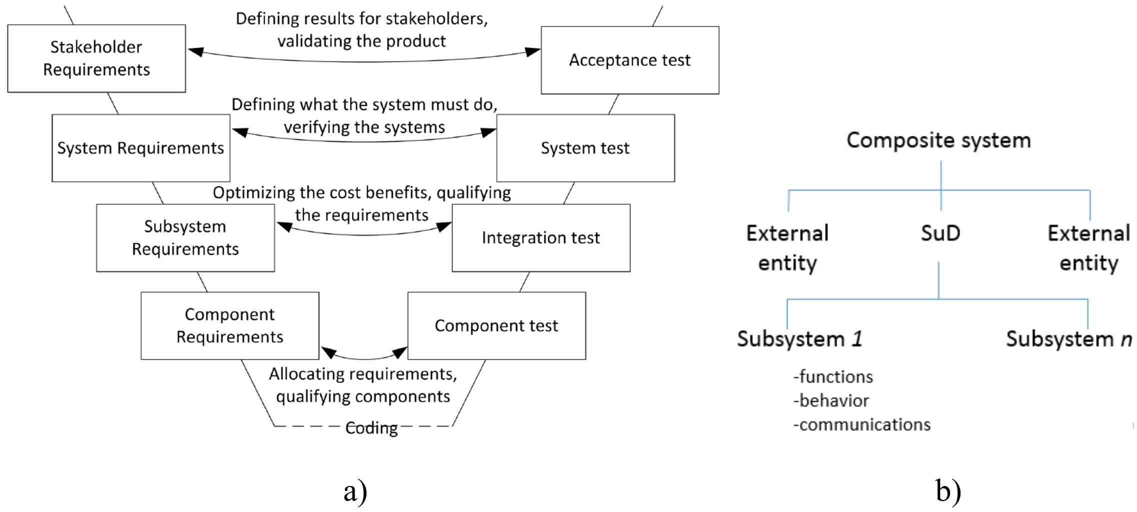


Figure 5. Considering system architecture: a) V-model; b) subsystem properties

A possible way to outline features a subsystem of a System under Development (SuD) can be described by its functions, behavior, and communications (as shown in Figure 5, b) [44]. These features can be related subsystem requirements and be considered for integration tests.

In short, the design science and systems engineering perspectives complement the evaluation continuum, as they deal with development of a particular tool. By arranging these and other above mentioned approaches we can outline the overall structure of considering evaluations as described next.

3.6 Summary on the Evaluation Continuum

Together, the factors relevant to evolutions can be mapped to an 'Evaluation continuum' as shown in Figure 6. This figure reflects real-world factors in which the evaluation of a tool for collaborative grid modeling might take place. These factors can be related to technology space (T-space) and Interaction space (I-Space).

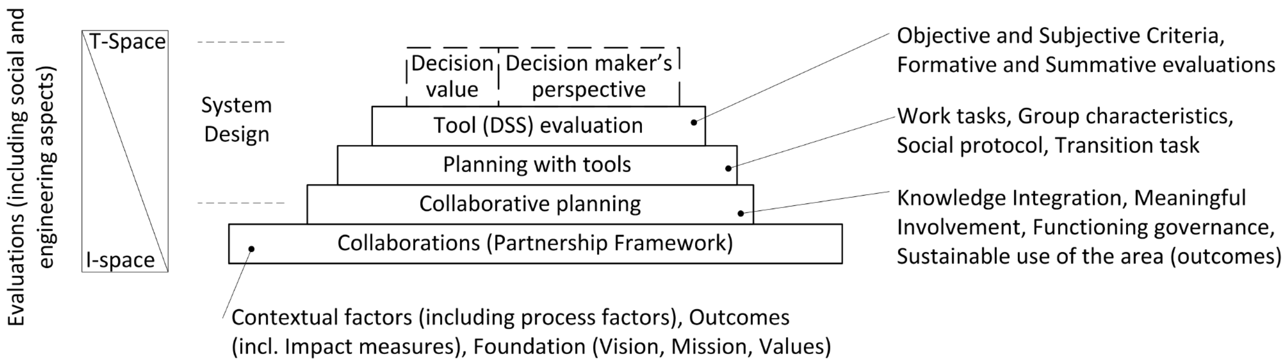


Figure 6. Evaluation continuum: evaluation aspects and system design

The outlined inter-relations in combination with resilience management steps mentioned in subsection 2.1 can be utilized as follows. To devise a state-of-the-art workshop or a gaming session, the organizer might consider which features of a solution and the anticipated effects it should investigate. This concerns which factors and which context are of interest. Using the structure the organizer can devise questionnaires for the session or workshop. Specifically, design science principles might assist in position test sessions within the development efforts, while the evaluation frameworks can guide the efforts to devise questions for these sessions. The organizer might consider the following steps.

First, some complex constructs, such as resilience need to be elaborated. As mentioned, such complex constructs (e.g., Engineering resilience, Ecological/ecosystem resilience and social resilience, or Socio-ecological resilience) can be applied differently in a variety of context. For instance, the overall resilience plans and strategies can include activities, such as response and recovery, and education and training. This implies different actions. Internally, companies might also have different business continuity and planning continuity actions, as well as operate and interact with each other in a variety of ways. This can result in confusion on its meanings and hamper understanding of its meaning in a specific context.

Afterwards, the planning process might be specified. Knowledge integration, involvement and other relevant features of the process can be elaborated. The interfaces between the process and the desired tools are to be detailed. Features of the tools should be outlined and metrics assigned to them. Additionally, as evaluation of some features can be complicated, e.g., due to the need for stakeholders with a specified expertise, ways how to devise these metrics need to be outlined.

System design and systems engineering methods can further assist in specifying evaluation sessions. The expertise of participants of gaming sessions and stakeholder workshops might be related to questions to be asked. For instance, less experienced participants of such sessions can provide their view on how a system operates as a whole (‘system test’ characteristic). Questions related to the scalability of solutions and the limits of applications of artifacts can be asked to more experienced practitioners.

To evaluate a constructed system from a DSS perspective, a combination of objective and subjective factors might be considered. If necessary, some relevant indicators can be introduced. Appendix B illustrates how a specialized factor to evaluate value of the decision was developed and applied to the IRENE energy prediction and response tool, which in turn is described in [45].

Importantly, the aspects of this continuum are complementary, but at times overlap. For instance, several evaluation steps of DSS evaluation are directly related to system (re)engineering, but the ‘evaluation of Outcome’ has no counterpart. Similarly, separating DSS evaluation as tasks related to objective and subjective factors can complement other characterizations.

All in all, the design of questionnaires for stakeholder sessions and gaming workshops might benefit from justifiably specifying which questions should be included. The continuum aims to provide a reference knowledge base for such a decision. The IRENE project will employ it for this purpose. The feedback collected during stakeholder workshops and student gaming sessions will be used for validating the tools. This will consider the evaluation from the perspective of decision makers. Special indicators, such as the one mentioned in Appendix B and in Chapter 5, will account for evaluating decision values. The calculation of the latter indicator is a sophisticated approach to evaluate improvements in urban grids and can be potentially applied not only to a specific IRENE tool, but to the large scope of other tools.

In addition to the outlined evaluation continuum, the task of designing questionnaires will consider best practices available in the domain of microgrid modelling. These practices are described next.

4 SURVEYING MICROGRID MODELING TOOLS AND GENERIC SUGGESTED FUNCTIONALITIES

In this section, we overview several tools for modelling and controlling smart grids and outline features that can be expected from a state-of-the-art tool. These aspects are relevant to evaluating limits and possible overlaps in functionality of the IRENE solutions. They point out at boundaries of reasonably expected scalability of these solutions. First, we review relevant tools and services and cross-relate their functionality. Then, we look at high-level requirements and conclude with the overview of the desired functionality of smart grid modeling tools. The corresponding list aims to provide developers with a view of functionality expected from advanced tools.

This review was performed to ensure that the development of the grid optimization model in D4.1 is well-aligned with standard core functionalities of existing tools. Taking into account the identified functional limitations of existing tools, a novel IRENE optimization tool is currently under development. As a subtask, the review also aims to identify functionalities that can be represented to users. These improvements in the interface can be studied in terms of the readability, the way how the output results presented, whether the tool provides a clear implication (positive or negative aspects) to users, and how it suits the users' needs and requirements with respect to the output results.

4.1 TOOLS AND SERVICES AVAILABLE

4.1.1 DNV GL's Microgrid Optimization tool

DNV GL, the international certification body has developed a microgrid mathematical optimization tool [52] to evaluate the full integration of distributed generations, electrical, thermal storages, new innovative technological updates, building automation and customers' behavioral usages. The mathematical software module also includes the detailed policy drives, climate, technology cost projections and tariffs at which referring specifically to a particular geographical location. The simulation is holistic-based and aims at maximizing the economic value and reliability of electrical system and power. The whole model simulates the day-ahead energy prices, demand forecasts, weather forecasts, dynamic performance of the buildings, storage, and distributed generation, and management of the controllable resources (CHP, storage, and Demand Response (DR)) that optimize the energy economics during the day. The optimization problem is formulated through the Mixed Integer Linear Programming Approach. The end results are further used in simulations of DR, ancillary service for the participation of energy markets, and islanded mode. The overall reliability of the grid is assessed by perturbing the grid with outages or contingencies through the relevant utility statistics (SAIDI, SAIFI).

The optimization tool is capable of shifting its operational module from optimizing energy economics to maximizing the uninterruptable and critical load that can be served from available resources during the outage period. Three types of results are demonstrated upon the simulation which are: 1) Prioritized load curtailment optimization based on DR; 2) curtailed/added loads during islanded operation; 3) and forecast results of energy prices. The tool is also capable of computing the zero net energy economics of energy such as cash flow, and Return on investments (ROI), and emissions reduction.

4.1.2 Massachusetts Institute of Technology (MIT)

The MIT has built a laboratory-scale microgrid to investigate questions based on the earlier model from computer simulation studies [53]. The institute aims to evaluate the transition of voltage that may lead to voltage instability (E.g. when the node is either disconnected or reconnected to the central power grid). The project focuses on a small-scale power system that combines the energy generation and storage devices to serve local customers at low level grid. Using off-the-shelf equipment and computer programming, devices are developed that behave like generators in the real field such as wind and solar energy system, storage devices and customer loads.

4.1.3 Masdar Institute

The Masdar Institute corporates with MIT by concentrating on developing an analytical-based weighted multi-objective optimization within the Microgrid [53]. The analytical methods analyses the two factors (system configuration and operation planning) simultaneously that determines the costs and emissions. The method generates a set of optimal planning/designs and operating strategies that minimizes costs and emissions. As system configuration and operations planning are interdependent, the two factors can be evaluated simultaneously, unlike the traditional approach which allows only single sequence of task evaluation and then following by the subsequent task, which leads to huge trade-offs between two interdependencies. The costs and emissions are analyzed simultaneously and sets of optimal designs and operating strategies are generated that will minimize costs and emissions, through different weighting on two objective functions.

4.1.4 Siemens Power Technologies International (PTI)

Siemens PTI provides a consulting, software and training program to optimize system networks for generation, transmission and distribution and power plants for smart grids [54]. The consulting services offer expertise in power system studies. This includes the system dynamics and threat analysis, energy markets and regulation, control systems, power quality, and steady-state and dynamic system evaluations. The software solutions with completed power system analysis tools include PSS®E, PSS®SINCAL PSS®NETOMAC, PSS®ODMS, PSS®MUST, and MOD®. The Value proposition considered in Smart grid are: Reliability, fuel savings, and environmental benefits.

4.1.5 Etap Grid

Microgrid Master Controller software [55][56] developed by Etap Grid performs the detailed modelling, simulation and optimization of electrical systems. The software controller is capable of predicting and forecasting energy generations and loads. The controller also integrates and automatically control (automated load shedding and generation) of microgrid elements, such as PVs, energy storages, back-up generations, wind, gas turbines, CHP, fuel cells, and demand management. The software automatically manages and optimizes the load during grid-connected or islanded grid operations. The economic cost value is the main value proposition in Etap Grid, while the software aims to lower the total cost of ownership by reducing the average cost of electricity from the national electricity price. The fuel cost is minimized due to using distributed energy resources and the optimization of generation dispatches.

4.1.6 Argonne National Laboratory

Argonne National Laboratory offers a range of resilient-based tools, techniques, and engineering methods to optimize the interdependencies of energy and global security needs [57], including:

- Electrical Power Network Modelling (EPfast). EPfast is an electric power infrastructure modelling tool that inspects the impact of power outages in the large grid. The tool models the tendency of islanding operations, either synthetic based or natural threats. Example of applications include: identification of system vulnerabilities and implementation of preventative measures; critical power infrastructure, resiliency analysis; and system dependency/interdependency analysis with non-power infrastructure systems. As [21] illustrated, such dependencies can be of significant complexity.

- Electric Grid Resilience Improvement Program (EPGRIP). EPGRIP is an integrated power system restoration optimization tool combined with AC power flow-based cascading failure/outage. The integrated system restoration optimization module supports restoration planning and operational decision-making in the transmission and distribution systems. Examples of applications include the optimization of black-start restoration plan, generator start-up recovery plan, re-routing power in a damaged distribution network, and prioritizing the critical loads in the restoration plan. The cascading failure module considers system monitoring, protection, control and further simulates the most important cascading techniques. The module further provides cascading risk analysis and generates credible cascading scenarios for restoration purposes.

4.1.7 Summary of Functionalities of Smart Grid Modelling Tools

Table 5 summarizes analysis of the modelling tools, as well lists capabilities of the IRENE WP4 tool. This tool is designed and implemented in tasks T4.1&4.2, which are reported in deliverable D4.1. In line with IEC, it does not only provide the simulation of electricity continuity planning (adding/removing alternate generation sources) from the technical perspective, but also ensure the cost concerned through the interventions for benefits of business planning. Besides, the user interface might account for acquiring inputs from users, simulating outage and islanding operation, and performing the resilience analysis. The users might manipulate/control the tool and to provide varieties of resilience coefficient metric whenever a new case/scenario is applied (i.e., adding or remove a local generator).

The outlined functionality analysis is related to task T5.2 that involves designing a method for evaluating the practicability, efficiency and the impact mitigation approaches and policies developed by IRENE. On one side, questionnaires will take into account the ‘evaluation continuum’ outlined earlier. On another side, they will deal with specific IRENE tasks that concern:

- D1.1: T1.1 – Accounting for the relevancy of the scenario description developed;
- D1.1: T1.3 – Considering policies in relation to requirement from fellow stakeholders;
- D2.1: T2.1&2.2 Practicality of threat identification, ranking, risk and mitigation approaches;
- D3.1: T3.1 – Practicality of the Grid topology used in System Architecture Design;
- D3.1: T3.2– Effectiveness of Supply Demand Prediction, Planning, optimization algorithms;
- D4.1: T4.1 & 4.2 – Ease of use and practicality of the user-interface tool.

The questionnaires will be disseminated during workshop organized to evaluating the IRENE solutions.

Table 5. Analysis summary of microgrids modelling tools and services

Tool		Mathematical Optimisation module	Laboratory -scale Microgrid	Weighted multi-objective optimisation tool	Optimisation of system network	Microgrid Master Controller	Electric power infrastruc-ture modelling tool (EPfast)	Integrated power system restoration optimiza-tion tool (EPGRIP)	IRENE WP4 tool	IRENE Task (Deliverables and Task number)
Institution		DNV GL	MIT	Masdar Institute	Siemen's PTI	ETAP Grid	Argonne National Laboratory	Argonne National Laboratory		
	Mathematical Optimisation	✓		✓	✓	✓		✓	✓	D3.1 – T3.1 & 3.2
	User interface ready	✓			✓				✓[2]	D1.1 – T1.1 – 1.3 D3.1 – T3.1 &3.2 D4.1 - T4.1 & 4.2
	Grid topology ready				✓				✓	D3.1 – T3.1 D4.1 - T4.1
	Prototype based		✓							
	Demand forecasts	✓				✓			✓	D3.1 – T3.2 D4.1 – T4.2
	Control resources (e.g. generating sources, demand response)	✓	✓	✓	✓	✓		✓	✓	D1.1 - T1.1 D3.1 – T3.1 & 3.2 D4.1 – T4.2

[2] Based on inputs from WP1 on how the stakeholders might collaborate and what requirements can be derived; methodologies from WP3

Functionality of the tool	Include modelling of generation and storage	✓	✓	✓	✓	✓		✓	✓	D1.1 - T1.1 D3.1 – T3.1 & 3.2 D4.1 – T4.2
	Maximise economic value (cost of reduced/added loads)	✓		✓	✓	✓			✓	D1.1 - T1.1 D3.1 – T3.1 & 3.2 D4.1 – T4.2
	Maximise emission savings			✓						
	Maximise critical loads	✓						✓	✓	D1.1 – T1.2 D3.1 – T3.1 & 3.2 D3.2 – T3.3 D4.1 – T4.2
	Identify system threats						✓		✓[3]	D2.1 – T2.1 D2.2 – T2.2 D4.1 – T4.2
	Capable of islanding operation	✓				✓		✓	✓	D3.1 – T3.2 D4.1 – T4.2
	Apply scenario/case studies	✓	✓		✓	✓			✓	D2 D3.1 – T3.1 & 3.2 D4.1 – T4.1 & 4.2
	Outage/contingency simulation	✓			✓	✓	✓	✓	✓	D3.1 – T3.2

[3] Upon the tool simulation – list of potential threats will be displayed in output window

	Cost analysis	✓		✓	✓	✓			✓	D3.1 – T3.2
	Emissions analysis	✓		✓						
	Resilient analysis						✓	✓	✓[4]	D3.1 – T3.2 D4.1 – T4.1 & 4.2
	Reliability analysis	✓	✓	✓	✓		✓			
	Power flow analysis		✓		✓	✓	✓			
	Apply preventive measures/restoration plan						✓	✓	✓	D3.1-T3.2[5]
Service offered	Consultation	✓			✓				✓[6]	D5.2 – T5.3
	Certification	✓								
	Software training				✓				✓[7]	D5.2 - T5.3

[4] Resilience coefficient metric from WP3 methodology will be displayed in the output window

[5] Available generators will compensate the deviation of demand during a contingency event

[6] Considering feedbacks from stakeholder workshops

[7] Gaming simulation with students

4.2 Brief Review of Microgrid Modelling Challenges

A number of generic suggestions developed by standardized bodies and authorities outline functionalities that a modeling tool might address in general. This subsection reviews important challenges that should be considered for improving resilience of Smart (Micro) Grids during contingency events. This survey findings complement the overview of the tools described in the previous subsection.

4.2.1 International Electrotechnical Commission (IEC)

The IEC has classified [58] several grid planning challenges relevant to aid the recovery of grid outages, which concern both business planning and technical aspects:

- *Quality of planning*. This outlines the degree to which an organization is prepared to respond to grid outages. The response accounts for minimizing or avoiding the loss of electricity supply after a disaster and the robust recovery strategy in case of outages. The quality of planning should begin with a standardized classification of the potential damage from various disasters. Subsequently, measurement analysis and critical rating of electrical infrastructures follow, concluded by the preparation of detailed plans for grid recovery;
- *Continuity of planning*. The continuity of planning emphasizes how the strategic planning would respond to particular external events (sudden catastrophic events). The continuity plan ensures the successful recovery of planning as quickly as possible following a disaster. This may include the business-based continuity planning that identifies critical and non-critical outage functions. **Risk and threat analysis** are further performed to identify potential threats and followed by recovery steps;
- *Electricity continuity planning*. As the business continuity planning stresses the maintenance and restoration of the power grid, the electricity continuity planning is needed that handles the detailed electrical system and advanced electrical technologies. The electrical continuity planning emphasizes the speedy and continuous restoration of electrical supply through distributed generation or any other technologies. The electricity continuity planning includes:
    - The use of alternate generation sources such as backup generation;
    - The dependencies with the electrical component, such as the availability/ committable state of backup generators;
    - The risks of using particular generators associated to disaster situations.

The electricity continuity planning classifies outage events in detail further to the main classification from the business continuity planning. Classifications cover disaster metrics such as flood heights, wind strength, earthquake intensity, lightning frequency, tsunami height, and also duration of such disaster.

To consider load failure, one should know how a failure can be linked to a load. To cope with major's infrastructure single point of failure, N-1 contingency should be taken into account. The classification of load properties is also essential for planning, as different loads serve different functions with different levels of power quality. This is relevant to the length of supply failure that will not lead to significant negative economic and social impacts. Energy loads should be classified based on metrics such as:

- Acceptable supply interruption duration;
- Acceptable supply voltage range;
- Acceptable supply frequency range.

Energy Management System (EMS) or a master controller can clearly benefit from prioritizing loads (from critical to non-critical loads). This will ensure that the highest priority in continuous supplying power to critical loads (e.g. hospitals, telecommunication nodes) is maintained, thus leading to maximizing social welfare.

- *The consumer market of electricity continuity and disaster mitigation functions*. With microgrids enabling new ways to handle outages, consumers can benefit from employing distributed generation during grid outages. Distributed generations installed within households enable the automatic switching of electrical systems in the case of outages. In principle, consumers are not expected to respond to the sudden perturbation of normal grid operation. Therefore, in the event of an outage, the grid and microgrid functions must be unlinked (and later reconnected back to the grid) automatically.

Well-balanced configurations of wind, PV, battery and EV can then be used to continue supply consumers with electricity. Still, introduction of renewables is a complex task [24]. Noticeably, while renewable generation can ensure the correct penetration rate of microgrids, over-penetration of microgrids may bring the instability of the overall grid (voltage irregularities). Importantly, critical infrastructure facilities (e.g., telecommunication systems, medical facilities, data management centers and production facilities) must have continuous power supply during prolonged outages.

4.2.2 New York State Energy Research and Development Authority (NYSERDA)

NYSERDA outlined challenges related to microgrids that can support critical facilities with installed backup generations [59].

Overall, the ability to operate backup generation at critical facilities for prolonged periods depends on the availability of fuel. Typically, facilities store only enough fuel on-site to operate backup generations up to maximum of four days, and rely on contracts with private vendors to replenish energy supply. To relax this dependency, the deployment of microgrid within critical facilities and areas with highly-frequent disasters/outages should be prioritized. Given that small critical facilities can be clustered in close proximity (within a half-mile radius), satisfying their energy demand with micrograms appears to be adequate.

The need to provide enough power to critical loads during islanding may demand additional *redundant generators.* They can provide solutions if one or more generators fail. It is important to identify *critical loads* during emergencies in order to prioritize and support "must-run" facilities. Furthermore, in order to enhance the uninterrupted service during emergencies, the installation of UPS such as *battery storage* is necessary. Furthermore, established preventive maintenance systems are needed (e.g. distributed generations such as battery storage may degrade over time and might need maintenance).

NYSERDA [59] emphasizes that there must be an important distinction of distributed generations (DG), whether it is emergency, base load, or intermittent generation. For example: emergency generators: Diesel generators; base load generators: CCGT, Fuel cells, biomass, geothermal; Intermittent generators: wind and solar. This is needed because a microgrid relying exclusively on renewable energy resources currently cannot provide electric power during grid outages with the level of reliability required for emergency loads.

Despite advantages that distributed generation can provide during outages, if such a microgrid runs only when the local utility is interrupted, it is difficult to be justified economically. Thus, considering how the microgrid can operate within utility distribution networks is important. There is a need to *standardize* (realistic) grid models to ensure effective microgrid integration with existing utility distribution networks, multiple points of common coupling with the utility system, and the overall interoperability purposes. While the integration of standby generators into a microgrid can enhance the reliability of backup service, this may, however, call for the high cost of designing and installing the control, communication, and electrical infrastructure. Hence, more case studies focused on the costs are needed to prove the economic operation of microgrid at particular instant or event.

4.3 CONCLUSIONS ON DESIRED FUNCTIONALITY OF MICROGRID TOOLS

Previous subsections overviewed tools and services available for modeling microgrids, as well as challenges such tools should handle. A (non-exhaustive) reference list of desired functionality of such tools can therefore be combined as follows:

1. Smart grid topologies must reflect standardized (realistic) grid models to enable grid simulation and analysis. IEEE 14 bus system, as well as other similar approaches, can provide input for such cases (see Appendix A for a reasoning of using IEEE 14 bus for modeling a microgrid).
2. Tools might support value propositions relevant to Smart Grids. This include reliability, fuel cost savings, and environmental benefits. The optimization module might enable sets of optimal designs, strategies and solutions that maximizes the economic and environmental benefits, as well as the reliability and security of power system. A mathematical optimization software module with objective function(s) is the common approach for optimizing the economic benefits (minimize the costs of generation and dispatch by proper utilization of generation sources) and power reliability (continuous power supply when there is an outage).
3. To integrate tools into an organization context they might consider the electricity continuity planning, continuity of the consumer market, and disaster mitigation functions. This should provide a link to quality and continuity of planning. Scenarios outlining policy details, methodologies, and assumptions are critical for a realistic modelling tool.
4. The modelling of (additional redundant) generation sources and storage (e.g., batteries) is necessary.
5. Predictive analysis and forecast of loads and generations should be considered. Modules should account for integration of demand profiles (end-users' behavior of energy usage), distributed generations, electricity connection, and storages.
6. The automated optimization (load balancing) of grid-connected or islanded operation is needed.
7. To evaluate the robustness of the electricity network to any type of outage events, different outage causes should be considered.
8. The resilience metric is a grid performance metric that should be considered to evaluate the overall resilience integration of a grid. The resilience metric is helpful for city planners to know the overall performance index of the grid where a particular smart intervention is applied.

Several aspects should be considered to make these aspects possible. They include:

- A graphical user interface is essential to assist users in learning, planning, and assessing the grid development.
- Training should be provided to the users who are to be familiarized with the software tool.

This list and the overview provided in this section are relevant for surveying functionalities of microgrid tools and cross-relating them to each other. This section builds on and contributes to other tasks of the IRENE. Specifically, tasks related to work packages WP4 and WP5: T4.1 Design and develop a modeling tool and T5.3 Evaluation of IRENE methods, frameworks, and tools.

Having state-of-the-art in evaluation and modeling tools overviewed, the IRENE project will devise workshop sessions to consider the use of developed IRENE solutions. At the same time, a rigorous approach should be applied to account whether the application of the tool resulted in improved functionality of a microgrid. For this purpose, the IRENE project will employ model-based assessment. An introduction to this approach is provided in the next section.

5 MODEL-BASED ASSESSMENT TECHNIQUES

For the evaluation of critical systems, modelling is a valuable tool because it helps to avoid experimenting on a real instance of the system, which may be costly, dangerous or simply unfeasible. Model-based evaluation allow system architects to understand and learn about specific aspects of the system. As a fault-forecasting technique, it allows: detecting possible design weak points or bottlenecks, performing early validation of dependability requirements, or suggesting solutions for future releases or modifications of the systems.

In general, within model-based evaluation [60] a model is an abstraction of a system. This abstraction highlights important features of the system and provides ways of quantifying its properties. It allows to neglect details that are relevant for the actual implementation, but that are marginal for the objective of the study. Models play a primary role in dependability and performability assessment of modern computing systems.

Modelling is composed of two phases: 1. the construction of a model of the system; and 2. the processing of the model to obtain evaluate the desired metrics or properties. Research in dependability analysis has led to a variety of modeling formalisms. Each of these techniques has its own strengths and weaknesses in terms of accessibility, ease of construction, efficiency and accuracy of solution algorithms, and availability of supporting software tools. The choice of the most appropriate model depends upon the complexity of the system, the questions to be answered, the accuracy required, and the resources available to the study.

In this section, we provide an overview of modeling formalisms, techniques, and tools that are most common in model-based evaluation of dependable systems. This overview of state-of-the-art solutions provides a sophisticated introduction into the domain. It includes aspects of modeling smart grid evolution, which form the basis for evaluations to be conducted within work package WP5 of the IRENE project.

5.1 REVIEW OF MODELLING FORMALISMS AND TECHNIQUES

Modelling formalisms can be broadly classified into combinatorial (non-state-space) models and state-space models. Combinatorial models, in contrast with state-space models, do not enumerate all possible system states to obtain a solution.

5.1.1 Combinatorial models

To study the dependability of systems, several approaches were developed. Reliability block diagrams (RBD), fault trees (FT), and reliability graphs (RG) are non-state-space models that are commonly used. They are concise, easy to understand, and have efficient solution methods. However, some realistic features cannot be captured by these models, in particular the interrelated behavior of components, imperfect coverage, nonzero reconfiguration delays, and the combination with performance (performability, [61]).

These aspects have led to the development of extensions to specific formalisms, such as dynamic fault trees (DFT) and dynamic reliability block diagrams (DRBD) that allows to model reliability interactions among components or subsystems. A brief overview of traditional non-state-space models can be found in [1], while some of their “dynamic” extensions are outlined in [62]. It is worth noting that there are strong differences between different “dynamic” formalizations, which may lead to compatibility problems and unexpected results [63].

5.1.2 State-based models

State-space models, in particular homogeneous continuous time Markov chains (e.g., see [64] for full details) are commonly used for dependability modelling of computing systems. They are able to capture various functional and stochastic dependencies among components. In addition, they allow evaluation of various measures related to dependability and performance (performability) based on the same model, when a reward structure is associated to them. Unfortunately, as some processes require the strong assumption that the holding time in any state of the system is exponentially distributed, not all existing systems and their features can be captured properly by Markov processes.

In some cases this assumption may be very unrealistic. If so, to properly represent the system behavior more general processes (e.g., semi-Markov, Markov Regenerative or even non-Markovian processes) must be used. When dealing with such processes, complex and costly analytical solution techniques may be needed. If analytic solution methods do not exist, discrete-event simulation must be used to solve the models thus providing only estimates of the measures of interest. If dependability metrics such as reliability and availability are concerned, simulation may be time consuming because of the rare event problem: events of interest occur so rarely that very lengthy simulations are necessary to obtain reliable results.

To facilitate the generation of state-space models based on Markov chains and their extensions, higher-level modelling formalisms like Stochastic Petri Nets (SPN) are commonly used. These formalisms allow a more compact model representation of the state-space because they support concurrency. In [65], the authors explore and discuss a hierarchy of SPN classes where modelling power is reduced in exchange for an increasingly efficient solution. These solutions concern Generalized Stochastic Petri Nets (GSPN), Deterministic and Stochastic Petri Nets (DSPN), Semi-Markovian Stochastic Petri Nets (SMSPN), Timed Petri Nets (TPN), and Generalized Timed Petri Nets (GTPN). Other widely used modelling formalisms are Stochastic Reward Nets [66], Stochastic Activity Networks (SAN) [67] and Markov Regenerative Stochastic Petri Nets (MRSPN) [68].

Other modelling formalism that allow specifying Markov processes include Stochastic Automata Networks [69] or models based on Stochastic Process Algebras. Such formalisms are extensions of basic Process Algebras, which are enriched with the ability to associate probabilities and/or time delays to the execution of actions. These extensions allow performing quantitative analysis on the model. Several stochastic process algebra languages have been introduced. The most influencing one in dependability analysis has been Performance Evaluation Process Algebra (PEPA) [70]. Similarly to Petri Net extensions, some of these formalisms are Markovian, e.g., PEPA, or Markovian Time Processes for Performance Evaluation (MTIPP) [71]. These evaluation techniques rely on Markov chains. Other formalisms allow more general probability distributions, e.g., SPADES [72] or MoDeSt [73], and therefore have evaluation techniques that rely on more general stochastic processes, or discrete-event simulation.

5.2 MODELLING METHODOLOGIES

The main problem in using state-based models to realistically represent the behavior of a complex system is the explosion in the number of states (often referred to as state-space explosion problem). Significant progress has been made in addressing the challenges raised by the large size of models both in the model construction and model solution phase. A combination of such techniques can be categorized with respect to their purpose: largeness avoidance or largeness tolerance. See [1], [74] for two comprehensive surveys.

5.2.1 Reducing model complexity

Largeness avoidance techniques try to circumvent the generation of large models. This can be achieved by employing, for example, state truncation methods [75], state lumping techniques [76], hierarchical model solution methods [77], fixed point iterations [78], hybrid models that judiciously combine different model types [79], and the fluid flow approximation [80][81].

However, these techniques may not be sufficient as the resulting model may still be large. Thus, largeness tolerance techniques are needed to facilitate the generation and the solution of large state space models. Largeness tolerance techniques propose new algorithms and/or data structures to reduce the space and time requirements of the model. This is usually achieved through the use of structured model composition approaches, where the basic idea is to build the system model from the composition of sub-models describing system components and their interactions. Generic rules are then defined for the elaboration of the sub-models and their interconnection. Following the approach proposed in [82], for example, the generator matrix of a CTMC is not entirely stored, but it is implicitly represented as Kronecker product of a number of smaller matrices. In [83] largeness is tolerated using Multivalued Decision Diagram (MDD) data structures to efficiently explore large state spaces.

Other techniques try to reduce the complexity of the model. Relevant concepts can be borrowed from the model checking theory. For example, the approach in [84] combines process algebras with Markov chains to take advantage of their powerful and well-defined composition operators, leading to the Input/Output Interactive Markov Chains (I/O-IMC) formalism.

Rather than focusing on model composition, another approach concentrates on the definition of the dependability measures of interest to be evaluated. In fact, many sophisticated formalisms exist for specifying complex system behaviors, but methods for specifying performance and dependability variables remain quite primitive. To cope with this problem, modelers often must augment system models with extra state information and event types to support particular variables. To address this problem the so-called path-based reward variables have been introduced [85]. Numerical methods to compute such reward variables, defined with the Continuous Stochastic Logic (CSL), are given in [86]. In another work [87] the model checking approach is illustrated through a workstations cluster example.

Other approaches try to tolerate model largeness using model decomposition and aggregation of the partial results. The basic idea is to decouple the model into simpler and more tractable sub-models. The measures obtained from the solution of the sub-models are then aggregated to compute those concerning the overall model. A survey on decomposition/aggregation approaches can be found in [88]. In the same paper, the authors also propose a general modelling framework that adopts three different types of decomposition techniques to deal with model complexity: at functional, temporal, and model-level. The key point is that the approach is non-domain-specific, i.e., not specifically developed for a particular class of systems or tailored for a specific modelling formalism or solution technique. Other existing largeness tolerance techniques include, for instance, disk-based approaches [89] (the model structure is stored in the disk thus allowing larger models to be solved) or on-the-fly approaches [90] (to completely avoid the storage of structures in memory, generating them iteratively while computing the solution).

Even if these techniques are used, solving large state-space models is still a difficult task. Moreover, under certain conditions model solution may be a challenge even for models having only a few states. In particular, a large difference between the rates of occurrences of events leads to the stiffness problem. Stiff models cause problems in the numerical solution, because they require the use of an integration step of the order of the smallest time constants even though the analysis is to be carried out for an interval consistent with the largest time constants. Stiffness may be avoided using aggregation and decomposition techniques in which the resulting sub-problems are non-stiff (e.g., see [91]), or it may be tolerated using special numerical solvers (e.g., see [92][93]).

It is important to note that all the above techniques are complementary and all may be needed at the model construction and model solution levels. This concerns settings when detailed and large dependability models need to be generated and processed to evaluate metrics characterizing the resilience of real life systems.

5.2.2 Model-driven engineering techniques

The emergence of model-driven engineering methodologies and the elaboration of automated model transformation techniques have opened up new ways to integrate model-based assessment into the development process. Model-Driven Engineering (MDE) refers to the systematic use of models as primary artefacts throughout the engineering lifecycle [94]. Precise, albeit informal or semi-formal engineering languages (like UML, BPEL, AADL, etc.) allow not only a reasonable unambiguous specification and design, but also serve as the input for subsequent development steps like code generation, formal verification, evaluation, and testing. One of the core technologies supporting model-based engineering is *model transformation* [95]. Transformations can be used to refine models, apply design patterns, and project design models to various mathematical analysis domains in a precise and automated way.

These initiatives and technologies influenced model-based assessment, since they offered an efficient and integrated approach to *derive dependability analysis models from engineering models*. Resilience assessment requires specific support for the specification and description of non-functional aspects of the system (like reliability, safety), which are not properly covered by the common engineering languages, as these focus primarily on functional aspects. Recently, significant effort has been spent in the definition of standard languages that support the high-level specification of non-functional properties of systems; the UML profile for QoS and fault tolerance [96], the UML profile for Modeling and Analysis of Real-Time and Embedded systems (MARTE) [97], the Error Model Annex for AADL [98] are the most notable examples.

Different approaches for the automated derivation of dependability models have appeared in literature, often using ad-hoc language extensions. A survey can be found in [99].

- *Direct modelling of dependability related behavior*: System designers use the extended engineering language to directly describe failure and repair/recovery processes (e.g., occurrence of different failure modes, error propagation) and also the corresponding properties of components (e.g., error rates, propagation probabilities). A good example is the usage of the AADL Error Model Annex: the behavior of the components can be described in presence of internal faults and repair events, as well as in presence of external propagations. The dependability evaluation toolset constructs the analysis models by mapping the dependability related behavior to the analysis formalism and then computes system-level dependability measures. A stepwise approach for GSPN dependability modelling on the basis of AADL is presented in [100]. As another example, in [101] UML is used as a language to describe error propagation and module substitution, that is then mapped to dynamic fault trees.
- *Modular construction of system-level models using predefined generic sub-models*: Dependability experts construct *analysis sub-models* that represent the generic structure of

both the failure/recovery processes of the different types of components and the error propagation among them. System designers use the language extensions just to identify the component types and assign local dependability parameters to hardware and software artefacts in the engineering model. These dependability parameters (typically available from component handbooks or from component level evaluation) are used to parameterize the generic sub-models. The dependability model construction tools (1) apply pattern matching and model transformation to assemble the relevant parameterized sub-models in a modular way on the basis of the architecture design, and then (2) invoke solution algorithms to solve the system level model. In a UML based approach [102], language extensions are defined as a UML profile (stereotypes and tagged values), analysis sub-models are assigned to architectural components and relations, and then composed as a system level Stochastic Reward Net (SRN). Modular model construction is supported by automated tools [103]. In case of web service based process models [104], web service language extensions are utilized, the services are mapped to DSPN sub-models, and then integrated into a Multiple Phased System model. An MDE transformation workflow for the quantitative evaluation of dependability-related metrics has been presented in [105]. The workflow is integrated in a more comprehensive modelling framework that is currently developed within the CHESS project (https://www.polarsys.org/projects/polarsys.chess), which combines MDE philosophy with component-based development techniques.

- *Integration of various aspects from different models*: In complex, dynamic distributed systems the dependability model shall be constructed from several engineering models that capture various aspects of the system at different hierarchy levels. Typically, user, application, architecture and network levels are distinguished. For example, in case of large, critical mobile systems and infrastructures [106], the construction of the dependability model for computing user-level dependability attributes is based on (1) the workflow model of the user activities, (2) the topology models of the network connections in the various phases of the user activities (also constructed automatically from user mobility traces), and (3) the application-service-resource dependency models. This way a complex evaluation tool-chain is required to integrate the different mapping, abstraction, model transformation, and solution steps [107].

The automated derivation of dependability analysis models from the engineering models (that were created during the model based development process) has its advantage. Specifically, besides the application of a limited set of model extensions, there is no need to learn and use specific dependability analysis formalisms. Thus, modelling efforts can be saved. This is definitely a benefit if dependability analysis necessitates the creation of state-based dependability models in complex systems. Often, these models require higher learning and modelling effort than traditional combinatorial methods.

5.2.3 Supporting tools

Several software tools have been developed to address dependability and performability modelling and evaluation. Extensive surveys of the problems related to techniques and tools for dependability and performance evaluation can be found for example in [108][109][110]. Tools for the evaluation of dependability and performance models are often broadly grouped in two main categories.

- Single-formalism/multi-solution tools are built around a single formalism and one or more solution techniques. They are very useful inside a specific domain, but their major limitation is that all parts of a model must be built in the single formalism supported by the tool. A number of tools is based on the Stochastic Petri Nets formalism and its extensions; some examples are DSPNexpress [111], GreatSPN [112], SURF-2 [113], DEEM [114], TimeNET [115]. Other tools are instead based on stochastic process algebras; they provide numerical solutions and in some cases simulation-based results as well. This set includes, for example, the PEPA Eclipse Plugin [116], CASPA [117], PEPS [118], and PRISM [119]. All the above tools provide analytic/numerical solvers for a generated state-level representation and, in some cases, support simulation-based solution as well. Other tools use other model specification approaches, sometimes tailored to a particular application domain, e.g., HIMAP [120] and TANGRAM-II [121].

- Multi-formalism/multi-solution tools support multiple modelling formalisms, multiple model solution methods, and several ways to combine the models, also expressed in different formalisms. They can be distinguished with respect to the level of integration between formalisms and solution methods they provide. In particular, some tools provide the infrastructure to unify different single formalism modelling tools into a unique software environment; examples in this category are IDEAS [122], FREUD [123], and DRAWNET++ [124]. Other tools actually implement new formalisms, composition operators and solvers within a unique comprehensive framework. Though more difficult than building a software environment out of existing tools, this approach has the potential to much more closely integrate models expressed in different modelling formalisms. To the best of our knowledge, SHARPE [125], SMART [126], DEDS [127], OsMoSys [128], POEMS [129] and Möbius [130] are the main tools falling in this category.

With the advancement of model-driven engineering techniques and infrastructures, novel tools can also perform automated derivation and evaluation of dependability models from architectural model. The ADAPT tool [131] and the CHESS State-Based Analysis plugin [132] are two notable examples.

As shown, the domain of modeling methodologies is well developed and a number of advances tools are currently available. At the same time, to model smart grids additional efforts should be invested. Suitable approaches should account for grid specifics, including interrelations of electric and IT networks. In the rest of this document we introduce how such steps can be performed. These steps will be applied for analyzing outputs of stakeholder workshops and gaming sessions within work package WP5 of the IRENE project.

5.3 A Model-Based Approach to Support Smart Grid Evolution

To model Smart Grids one should account that Smart Grids evolve in terms of their physical infrastructure, as well as their controlling (ICT) infrastructure. Importantly, compared to traditional power grid systems, which evolve very slowly during time, smart grids are subject to a higher degree of dynamicity and evolution due to a number of reasons. These reasons include: 1. business motives, 2. failures, 3. effects of islanding mechanisms, 4. planned maintenance operations and other routine work, and 5. grid and ICT reconfiguration. The latter can be particularly related to temporary quarantining or outcomes of failed cyber-attacks.

To consider when and how to apply relevant modifications is a non-trivial problem, as one might select actions from a large list of possible alternatives. Greatest challenges are related to the number of variables involved in such decisions and the need to create different analysis models for each configuration. The approach proposed in this section aims to address this problem.

5.3.1 Role of the Model-Based Analysis

The evolution of a Smart Grid leads to a modification of the system architecture. The "event" that caused it can be seen as having a broad meaning. For example, it can be the beginning of a (large) set of maintenance operations. In response to a given event, different changes possible. They might involve grid components (generators, substations, power lines, and loads), grid topology, ICT infrastructure, and available failure mitigation capabilities.

Often, decisions on which changes should be applied have to be taken by humans. Those people should account for conflicting requirements, e.g., reliability, safety, security, performance, and cost. This raises several challenges to a proper operation of the Smart Grid. First of all, in the absence of reference metrics, human decisions are subjective: different individuals would make different choices, based on their background and experience. Besides, human activities are subject to errors, which become increasingly possible when facing the complexity of the system architecture and interactions. Finally, deciding on a grid evolution step is not an isolated decision. Based on the current state of the Smart Grid, it may result in further modifications to the system, which – if wrong decisions are made – may result in cascading or escalading failures possibly leading to major outages.

An automated decision support is therefore needed. It can provide humans with objective metrics based on which they can compare different evolution scenarios and select the most convenient one, according to some criteria. In the next section we define a model-based methodology to quantitatively assess possible evolution scenarios in terms of availability, reliability, performability, safety, etc. We aim at developing a modular and reusable solution, since many different variations of the system architecture needs to be evaluated to support decision makers in their tasks.

5.4 THE MODELLING APPROACH

The approach is based on the concept of template models, which was introduced in [133]. A set of generic "template" models are selected from a model library and automatically composted together based on the scenario to be represented. The workflow is presented in more details in the subsection below. The main concepts then introduced.

5.4.1 The Workflow

The high-level view of the proposed approach is illustrated in Figure 7. The workflow takes as input a detailed description of an Evolution Scenario (e.g., recovery from a failure, planned maintenance activities, etc.). Afterwards, it provides a set of metrics as output. These metrics can be used by the decision maker to decide if the evolution scenario is to be implemented or not.

A preliminary step consists in analyzing the Evolution Scenario to retrieve the information that is relevant to the decision process. This includes identifying the relevant characteristics of the system modifications that are foreseen, e.g., the kind and location of an occurred failure, or the details of a sequence of maintenance activities. At the same time, the Evolution Scenario also identifies the Smart Grid components that are relevant for the scenario under analysis. The effort required to perform this activity depends on the actual representation of the Evolution Scenario; a *Scenario Analysis* step is performed to extract the required information. Here we assume that the needed information, consisting in the *Relevant Components* and the *Relevant Evolution Characteristics* has already been extracted from the Evolution Scenario.

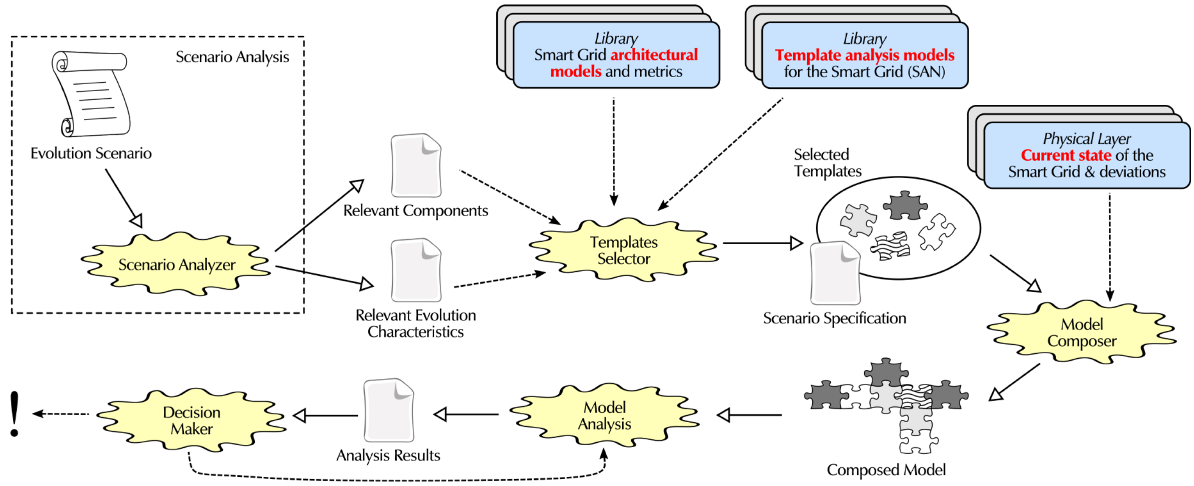


Figure 7. Workflow of the proposed methodology for building a decision support system

The extracted information is processed by the *Templates Selector* module (1), which, based on the architectural models of the involved components and on the specificities of the scenario, identifies the template models that need to be retrieved from a model library, and how they should be interconnected. The complete composite model for evaluating the Evolution Scenario of interest is then assembled by the *Model Composer* module (2). The model composer also receives as input the current state of the physical layer of the Smart Grid. This concerns, e.g., the current flow, the generated power, the voltage, and other physical properties of the involved components. Such values, which are used as the initial state for model evaluation, can be retrieved from different sources, e.g., assumptions provided in the Evolution Scenario, simulations of the physical layer, or actual sensors on the real system.

The next step is to evaluate the model and obtain the numerical results for the metrics of interest (3). Such results are then presented, possibly accompanied by warning messages, to the decision maker (4), which then ultimately decides whether to accept the given Evolution Scenario or not. Before taking the final decision, he/she can request additional evaluations of the model, for example to perform sensitivity analysis on some key parameters or to perform "what-if" analysis with respect to conditions that are judged to be particularly critical.

5.4.2 Template Models Concepts

The basic building blocks of the proposed approach are *model templates* based on Stochastic Petri Nets and their extensions [133]. Model templates realize one or more *interfaces*, which specify how they can be connected to other model templates, and a set of *parameters*, which specify variable elements in the model (e.g., the initial number of tokens in a certain place). Model templates can be either *atomic templates* or *composite templates*. A set of model templates constitutes a *library*.

Atomic templates are associated to an *implementation* in the selected state-based formalism (e.g., a PNML file, or a tool-specific format like the XML-based format used by Möbius [130]). Composite templates define how a set of sub models are composed together. For the referenced sub models a *multiplicity* attribute may be specified. Composite templates can have parameters as well, which allow for example parametric multiplicity values to be specified. Composite templates include a set of *composition rules*, which specify the patterns for connecting the interfaces of their sub models.

A *model variant* is obtained from a model template by associating concrete values to its parameters. An *atomic variant* is defined by a reference to an atomic template, and possibly a set of values for its parameters. Similarly, a *composite variant* is a reference to a composite template, and possibly a set of values for its parameters. In addition to the set of values for its parameters, a composite variant also defines which other model variants are used to implement its sub models, provided that they are compatible with the specification of the template.

A model variant can be used more than once in the overall composed system model, e.g., in case multiple identical elements are present in the system. A *model instance* is an individual instance (copy) of a model variant. An *atomic instance* is a copy of the template implementation, where all the parameters have been set as specified by the atomic variant. A composite instance is an instance of a composite variant, i.e., a collection of model instances composed according the specified rules.

Model templates reside in the library of Figure 7. Model variants are used to define the scenario to be evaluated. Model instances are automatically generated by the model composer, and are the concrete stochastic models on which the evaluation is finally performed. The key points of this approach are: 1. as opposed to traditional modelling approaches, templates are reusable and need to be defined only once by experts; 2. the model composer automatically generates the needed model instances based on a description of the scenario of interest, which is given in terms of the needed model variants. To specify model templates and model variants, the ad-hoc Template Models Description Language (TMDL) has been defined in [133].

5.5 Initial Applications To Simplified Scenarios

In this section we provide an overview of the concept of model template in the context of a Smart Grid. The idea is to separate, for each component, the *physical layer* (i.e., electric behavior) from the *information layer*. Models of the two layers should interact only in precise and predefined ways, so that each of them can be refined and/or replaced in isolation without affecting the other, thus improving models re-usability.

This approach is schematized in Figure 8. Each component may communicate with the others at the information layer, at the physical layer, or both. Changes in the information layer that may have an impact on the physical status of the grid (e.g. reconfigurations, failures, recoveries) are notified to the physical layer. The physical layer performs a "Grid Status Update", i.e., new physical parameters are computed by considering the current system state (e.g., number of connected generators, status of transmission lines, on/off status of loads). The new physical parameters could be obtained in different ways. For instance, by using external simulators of the physical layer, acquired by actual sensors on the real system, or solving simplified analytic equations as in [140]. The physical layer provides an aggregated view of its status to the information layer, in the form of states or events that are relevant for the functioning of the component.

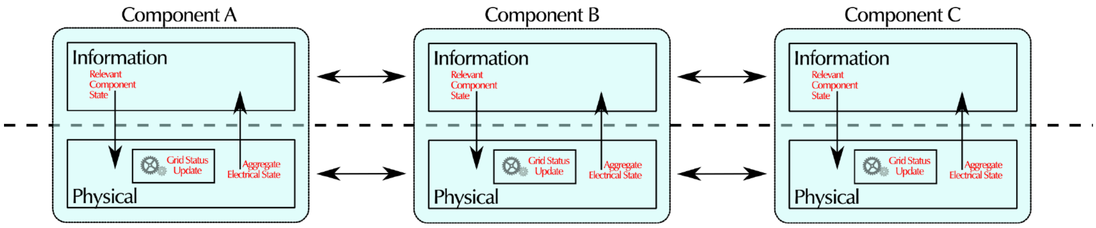


Figure 8. Overview of the modelling approach[8]

[8] For each component the information and the physical layers are modelled separately

As a simple example, we consider three different components of a Smart Grid system: a *generator*, a *transmission line*, and a *load*. For each of them we consider the physical and information layers, thus yielding six simple model templates, which are detailed in the following:

- Generator – Information;
- Generator – Physical;
- Transmission – Information;
- Transmission – Physical;
- Load – Information;
- Load – Physical.

It should be noted that those templates are examples and will be refined in the remaining part of the IRENE project. These initial models have been inspired by the work in [134] and [135].

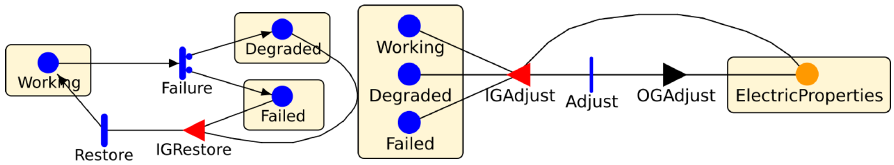
5.5.1 Generator

The two model templates that constitute a generator are depicted in Figure 9: the one for the information layer on the left, and the one for the physical layer on the right. The model interfaces are highlighted in yellow.

The information layer determines the current working state of the generator. Initially, the generator is in the *Working* state. With a random delay a failure occurs (*Failure* activity), which may bring the generator in the degraded state or in the failed state. Restoration (*Restore* activity) also occurs with a random delay.

The interface between the information and physical layer are the three places *Working*, *Degraded*, and *Failed*, which represent the current working state of the generator. The physical layer uses the information in those places to adjust the physical parameters of the generator. For example, when the generator is in the *Degraded* state, only a portion of the maximum power can be generated. Physical properties of the generator (e.g., generated power, voltage, etc.) are kept in the *ElectricProperties* extended place; an extended place can contain structured data in the form of C++ structures. The *Adjust* activity fires when the current working state of the generator changes, thus updating the current physical parameters.

The extended place *ElectricProperties* is also an interface with the rest of the model, in particular with the model of the physical layer of the component(s) connected to the generator.



Parameter	Description
MTTF	Mean time to failure of the generator
pDegraded	Probability to have a degradation following a failure
MTTR	Mean time to repair of the generator

Figure 9. Model template for a generator

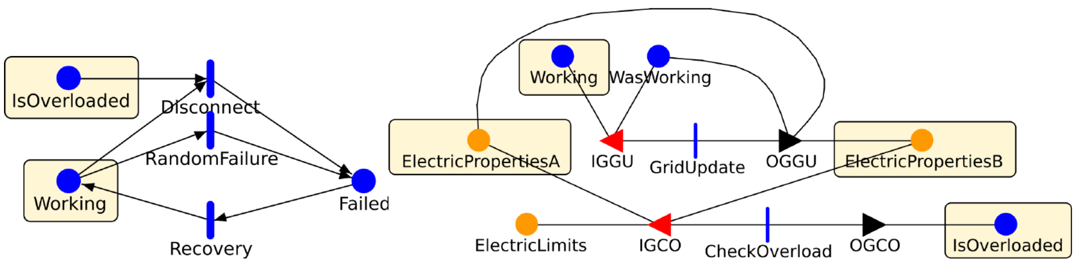
5.5.2 Transmission

The two model templates that constitute a transmission line are depicted in Figure 10; the one for the information layer on the left, and the one for the physical layer on the right. The model interfaces are highlighted in yellow.

At the information level a transmission line may be in the *Working* or *Failed* states. A random failure (activity *RandomFailure*) may bring the line in the *Failed* state. After a given amount of time a recovery may occur (activity *Recovery*), bringing back the line to the *Working* state. A line may also fail if it becomes overloaded; if a line becomes overloaded a token is added in the *IsOverloaded* place by the physical layer. This enables the *Disconnect* activity, which will fire after a predefined delay. Together with the *Working* place, the *isOverloaded* place is an interface to the model of the physical layer.

In addition to the interfaces with the information layer, the physical layer contains three places: *ElectricPropertiesA* and *ElectricPropertiesB*, which keep the physical properties of the two endpoints of the transmission line, and *ElectricLimits*, which keeps a description of the physical limits that the transmission line can sustain (e.g., maximum current intensity). *ElectricPropertiesA* and *ElectricPropertiesB* are interfaces with the models of the components connected to the line.

When the status of the line changes from *Working* to *Failed*, or-vice versa (i.e., when places *Working* and *WasWorking* differ), the *GridUpdate* activity is enabled and fires, performing a Grid Status Update as discussed above. Then, the activity updates the *WasWorking* place, to the current *Working* state of the line. This allows the model to keep track of when an update is needed. The *CheckOverload* activity checks for physical parameters not to exceed the established limits. If it occurs, then a token is added in place *IsOverloaded*, signaling an overload to the information layer. From there, different actions can be undertaken; in this example, the line will be simply disconnected (*Disconnect* activity in the information layer).



Parameter	Description
MTTF	Mean time to failure of the transmission line
MTTR	Mean time to repair of the transmission line
ElectricLimits	Limits for the physical properties of the transmission line

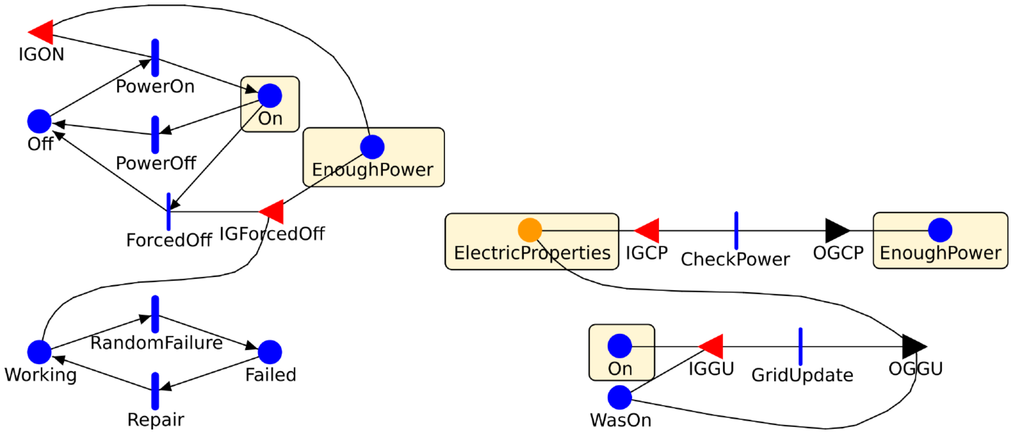
Figure 10. Model template for a transmission line

5.5.3 Load

The two model templates that constitute a load are depicted in Figure 11. The model interfaces are highlighted in yellow. The model has a single interface, *AvailablePower*, which represents the power that the load receives from the power grid. It is assumed that the load follows an on/off cycle with random delays, and that it is powered off if it does not receive enough power from the grid. This is the behavior, for example, of workstations supported by small uninterruptible power supply devices.

The on/off cycle is modelled by the *PowerOn* and *PowerOff* activities and the *On* and *Off* places. In order for the load to power on, it is necessary that enough power is supplied by the Smart Grid. This is controlled by the physical layer, which keeps a token in place *EnoughPower* until enough power is available. If the load is in the *On* state and the *EnoughPower* becomes empty, the *ForcedOff* activity is triggered, bringing the load in the *Off* state. The load may also fail with a random delay (*RandomFaiilure* activity); when this happens a token is removed from the *Working* place and one added to *Failed*. This also triggers the *ForcedOff* activity, to represent that the load is powered off following the failure. After a given amount of time, the load can be repaired (*Repair* activity).

Places *On* and *EnoughPower* are interfaces with the model of the physical layer of the load. The model also contains the place *ElectricProperties*, which contains the current electrical properties of the load, and it is the interface with the rest of the Smart Grid model: it is shared with the line to which the load is connected. The activity *CheckPower* checks if the *ElectricProperties* of the line to which the load is connected are able to provide enough power to make the load work as needed; if it is so, a token is kept in place *EnoughPower*, otherwise the place emptied. The required power is given by the *NeededPower* variable of the model. When the load switches from the *On* to the *Off* state and vice-versa, a Grid Status Update needs to be triggered as well; this is performed by the *GridUpdate* activity, which is enabled and fires when places *On* and *WasOn* differ.



Parameter	Description
MTTF	Mean time to failure of the load
MTTR	Mean time to repair of the load
OnPeriod	Average duration of the “On” period
OffPeriod	Average duration of the “Off” period
NeededPower	Power needed by the load in order to function

Figure 11. Model template for a load

5.5.4 Composition

Composition of the above templates is straightforward. The connections between physical and information layers have been already described in the previous sections. Models of different components are connected composing their physical layer models, based on the topology of the Smart Grid. In particular, *ElectricProperties* places are shared between models of components that are connected each other.

Such simple set of templates already allow a number of interesting questions to be answered about the reliability and availability of the system and its components. For example:

- How does the reliability/availability of a given load changes based on the number of transmission lines that are used?
- Which is the average power that is required by a given load, given its on/off profile?
- What is the probability that the load X will experience a lack of power within one month?

5.5.5 Next Steps

The above models are very simple, and serve the purpose of contextualizing the approach to Smart Grid systems. Next steps consist on refining the models for a more realistic representation of Smart Grids behavior, and to be able to analyze more aspects of their functioning, for both the information and the physical layers. For this objective, different directions can be pursued: the development of more detailed Stochastic Petri Nets models (e.g., [136], [140]), the adoption of simple flow models (e.g., [137]), or the combination of stochastic models with ad-hoc power simulators (e.g., Xyce [138]), using an approach similar to the one in [139].

6 CONCLUSIONS

This document introduced a number of constructs useful for assessing tools and methods developed within the IRENE project. We reviewed evaluation approaches with the aim to assist in devising questionnaires. The questionnaires will cover decision maker's perspectives. The described functionality of existing state-of-the-art tools will serve as a reference baseline for questionnaires. The output of IRENE modeling sessions will be evaluated using model-based assessment techniques.

The design of stakeholder workshops and gaming sessions, which is a consequent task within work package 5 of the IRENE project, will build on the state-of-the-art approaches outlined in this document. That task will concentrate on designing a method for evaluating the practicability and efficiency of approaches developed by IRENE. The resulting evaluation method and the results obtained during stakeholder workshops and gaming sessions will be reported in IRENE deliverable D5.2.

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A APPENDIX: EMPLOYING IEEE 14 BUS FOR DESCRIBING A MICROGRID

Other IRENE deliverables, namely D3.1 and D4.1, deal with scientific contributions how to models microgrids. This appendix briefly recaps reasoning why those novel contributions, which currently can be seen as state-of-the-art in the domain, build on employing IEEE 14 bus system to describe a microgrid.

A smart grid topology adequately defined for realistic grid simulation and analysis requires certain level of details. First, this level should be connected to state-of-the art simulations, including acknowledged approaches in the engineering domain. Second, the level should be linked to a real-world and to a level of complexity that can be comprehended by people from different backgrounds. It should support comprehending realistic scenarios with proper policy details, methodologies, and assumptions. Besides, best practice in modelling and design requirement should be considered to account for a state-of-the art Microgrid. Some of features that DG needs to support critical infrastructures are described in subsection 2.1 of D3.1 “Islanding: needed features and the process”.

Employing an IEEE-14 bus satisfies the both mentioned criteria. At outlined in Deliverable 3.1 of the IRENE project, the IEEE 14 bus system can be effectively used as the fundamental representation of grid architectural topology. Loads (including end-consumer loads at low voltage level) and voltage sources (such as generators at low- and mid-voltage level) are connected to busses, which are in tern linked to each other. In the scope of IRENE, this network topology can be employed to describe relations between the grid- and microgrid networks. Figure 12 describes an architecture consisting of mid and low-voltage distribution network components.

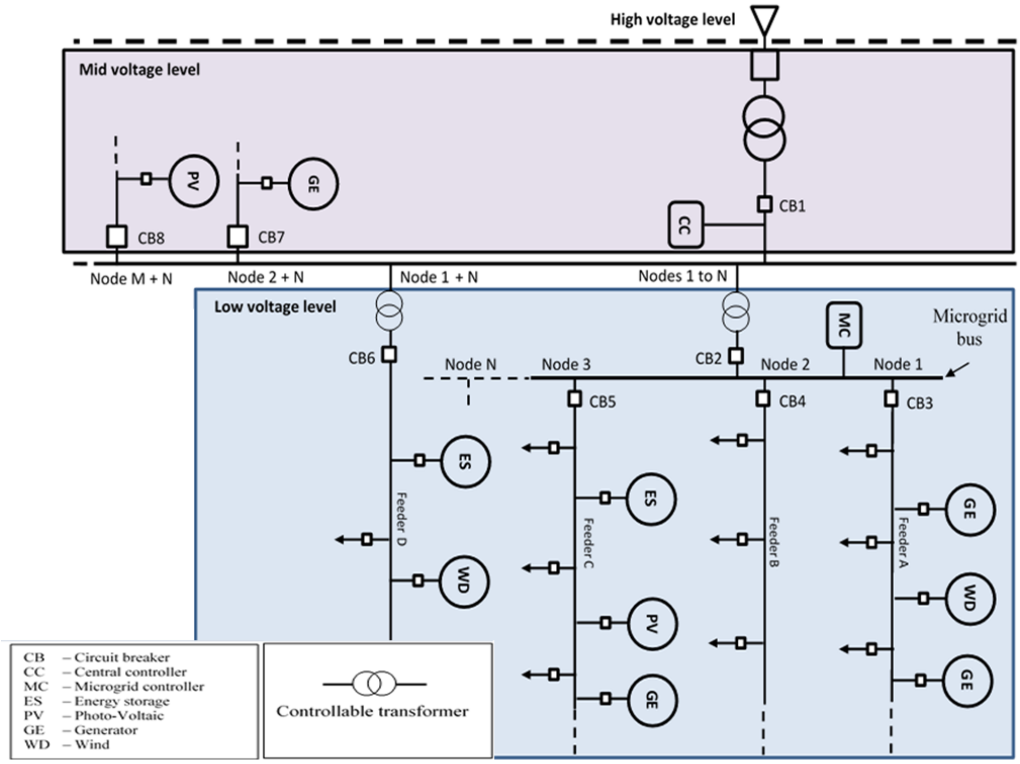

Figure 12. A grid configuration. Adapted and modified from IRENE D5.1

B APPENDIX: DEMAND SIDE MANAGEMENT AND GRID AUTONOMY FACTOR

Demand Side Management (DSM) consists of a number of techniques to modify the energy consumption of users. One possibility is to allow the utility or grid network operator to directly control (or shed) the loads when the network operates under pressure. In such emergency cases economic considerations of DSM are less relevant, as the overall goal is to satisfy critical loads. Prior analysis should identify which loads are critical or interruptible, as well as what rules should handle certain types of loads during an outage. Such rules should specify, for instance, whether heating, cooling, or EV charging shall be interrupted for that type of building.

DSM in the IRENE project is performed to clarify whether the considered grid region requires black start capability after the failure. IRENE does not address short times scales, transient phenomena, and instabilities due to reactive power or voltage collapse. The discussed mechanisms start at larger time scales where additional generation may be activated or demand can be shed.

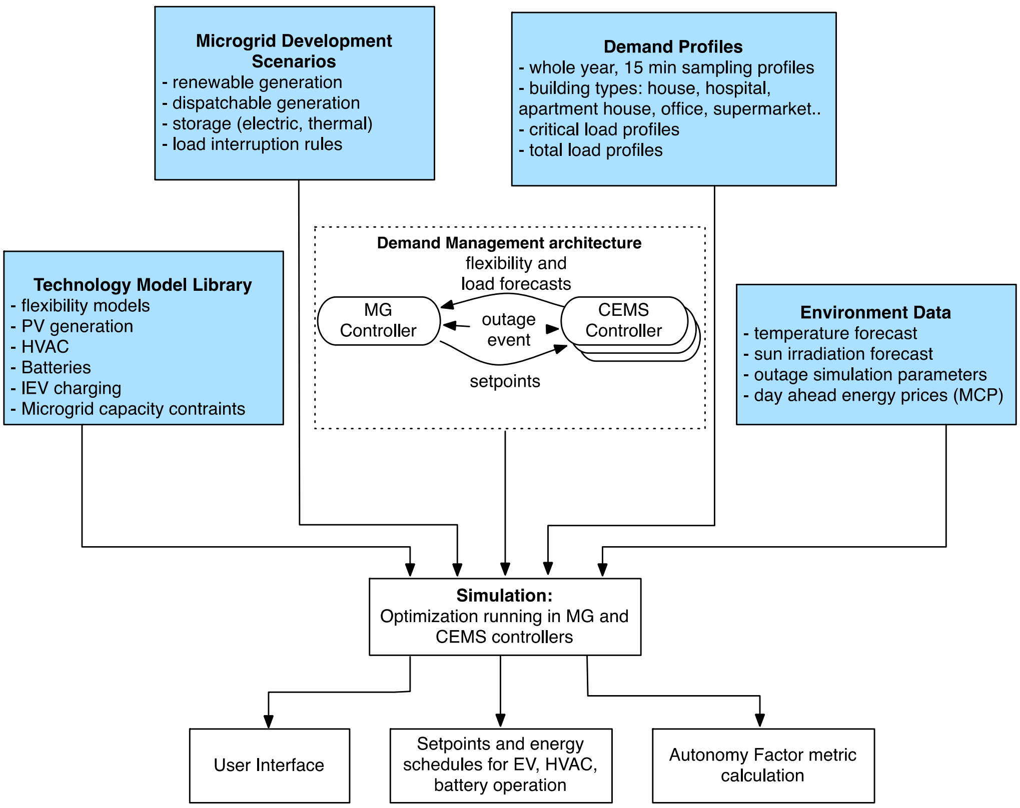

Figure 13. IRENE Microgrid planning and simulation process

Deliverable D3.1 demonstrated how a DSM can be employed to handle a crisis situation. Figure 13 summarizes the simulation process to determine the consumption of a microgrid prior and during an outage. These efforts formed a novel contribution demonstrated the application a state-of-the-art DSM simulation. The grid was constructed by selecting a number of building types with known load profiles for heating, cooling, ICT equipment, fan, facility, etc. Additionally, Battery Storage, Electric Vehicle charging stations, and Photovoltaic generation were added to the grid. Simulation environment parameters were set to obtain the consumption profiles and determine the required local generation in case islanding should be provided.

In addition to simulating grid behaviour during an outage in deliverable D3.1, to assess the effect of parameter changes of the microgrid we defined a quantitative measure named "grid autonomy factor". With a value between 0 and 1, the autonomy factor characterizes a grid behaviour during an outage scenario. The outage scenario concerns date and time of the outage event, outage length, grid configuration, and other input data.

The way the grid autonomy factor is calculated incorporates main features of a smart grid relevant to mitigating outages as follows. Let E^o_{in} be energy supplied to the microgrid during an outage. The demand of the microgrid during normal operation D^n is the sum of critical, interruptible demand, whereas the energy difference in the storage at the end of the considered interval ESS^n_{diff}: $D^n = E_{crit} + E_{interr} + ESS^n_{diff}$.

The demand D^n has to be satisfied by the renewable generation E_{RES} and the power injected into the microgrid E^n_{in}: $D^n = E^n_{in} + E_{RES}$. Similarly, in outage mode $D^o = E_{crit} + ESS_{diff}^o$ and $D^o = E^o_{in} + E_{RES}$. The autonomy factor is: $\alpha = 1 - \frac{E^o_{in}}{D^n} = 1 - \frac{E^o_{in}}{E^n_{in} + E_{RES}}$. Using the definitions above, we obtain $\alpha = \frac{E_{interr} + (ESS^n_{diff} - ESS^o_{diff}) + E_{RES}}{E_{crit} + E_{interr} + ESS^n_{diff}}$.

For a non-smart grid where all the loads are considered critical, $E_{interr}=0$, no renewable $E_{RES}=0$, $\alpha \approx 0$. Increasing E_{RES} can theoretically achieve a self-sufficient microgrid. In reality the renewable power fluctuates strongly, therefore dispatchable generation must be used. The autonomy factor was calculated for a benchmark grid. In the baseline scenario the outage duration is 24 hours, each small office has 50m^2 PV panels, and each residential house has a 10kWh battery. The other scenarios are compared to this baseline

Table 6 shows the results of simulations. More PV generation clearly improves the autonomy factor (see the difference between the scenario NoPV, and the baseline. Also, the outage duration and its timing directly impact the autonomy factor: thus, an outage of only 6h (9am to 3pm) increases α from 0.58 (the value for 24h) to 0.67. Also, the power constraint has been set to 120kW (was previously 200kW) to limit the load during the outage. This feature is relevant if a certain amount of dispatchable generation has been installed. This reduction lead to an expected decrease of α.

Table 6. Impact of the system parameters on the autonomy factor

Scenario	E^n_{in}, MWh	E^o_{in}, MWh	E^n_{RES}, MWh	α
Baseline	4.675	2.46	1.15	0.58
NoPV (offices)	5.11	2.90	0.71	0.50
Less Storage	4.77	2.40	1.04	0.58
6h Outage	1.23	0.55	0.47	0.67
24h Outage-120kW	4.675	2.39	1.15	0.54
6h Outage-120kW	1.23	0.59	0.47	0.65

C APPENDIX: SCENARIO PLANNING AS A STRATEGIC TOOL

For envisioning the future one can employ scenario planning as an instrument of strategic planning. D1.1 provides an adequate support for it, as in D1.1 we approached scenario development as a plausible exploration of the future. It is to be used in combination with other scenarios to explore the robustness of diverse models and choices.

Pierre Wack demonstrated in [46][47] that scenario planning as an instrument can indeed assist in explicating certain assumptions, challenging them, and explore opportunities for future decisions making. Also, it can act as a "complexity reducer" and as a convincing argument related to pursuing specific actions. These benefits of using scenario planning for strategic decisions led to adopting it as a strategic tool at Royal Dutch/Shell.

By adopting a 2x2 matrix, not unlike the one described in D1.1, Wack explored possible futures of countries by mapping them on two axis according to their absorptive capacity (ample or limited) and oil reserves (ample or limited). Then, some scenarios were developed to focus on understanding the forces that would eventually compel an outcome [46]. Scenarios expressed and communicated the common view of the new world to reach a shared understanding of the new realities to all parties of the organization. In this, they provided managers with the ability to re-perceive reality [47].

For the case of urban grids, the adequacy of this tool it is supported by the warrant that the task of city resilience planning is closely linked to the ultimate purpose of the scenario planner, which is "to create a more adaptive organization which recognizes change and uncertainty, and uses it to its advantage" [48].

D APPENDIX: DIFFERENCES BETWEEN DSS AND SERIOUS GAMES FROM THE POINT OF VIEW OF THE EVALUATION CONTINUUM

The outlined ‘evaluation continuum’ draws on advances in evaluating advanced modelling tools and methods during stakeholder workshops and gaming sessions. Despite that such efforts might occur in settings similar to serious gaming, an important feature should be mentioned how a DSS as an object of study differ form a serious game.

In general, serious games can be effectively employed for a number of purposes, including tactical- and strategic decision making in the safety domain [49] or for studying interrelations between infrastructure networks and urban growth [50]. Additionally, some visualization environments can combine the functionality of reflecting real world and providing opportunities for training [51].

However, the focus of serious gaming sessions is not necessarily linked to the purpose of validating (and possibly evaluating) the tool in a close-to-real-world context. Serious games are primarily designed as being games for purposes other than pure entertainment. In this way, they differ in their purpose from tools to address specific real-world contextual problems. Due to their goal, in serious games some aspects related to entertainment can be overemphasizes and others, which aim to reflect reality, can be tuned down. Thus, playing serious games is more linked to the added pedagogical value of fun and competition. This accent may lack in sessions of evaluating tools to find solutions to real-world problems. Further research might outline a more specific relations between the constructs from the ‘evaluation continuum’ and serious games at large.