Optimizing the Asset Replacement Investment on the Power Transmission Grid

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***Abstract*— Nowadays, utilities need to invest intensively in the grid in order to ensure the service quality and security of supply, while fulfilling budget constraints. The replacement wave problem arises from this situation, where a utility must level the investment on asset's replacement, while ensuring the operation's reliability. This work describes a solution for the replacement wave issue, applying the state-of-the-art asset management practices, to produce an optimal schedule for replacement investment of end-of-life assets. The optimal scheduling is achieved through a combinatorial optimization algorithm that selects investments.**

A theoretical case study was carried out, to show the applicability of the proposed method. The cases were built employing Monte Carlo Method. In order to keep as realistic as possible, public information was gathered from several Transmission System Operators (TSO) of electricity.

The results confirmed how pertinent the adoption of a scheduling methodology is, for efficient investment in grid's modernization. An approach is presented, in order to support the assets replacement planning, taking into account the grid's reliability and financial constraints.

Keywords—asset management, optimal scheduling, replacement wave, risk-based maintenance

I. Introduction

The soar of renewable energy sources in the power system, alongside with the liberalization of utilities, in the beginning of the XXI century, created many challenges to Transmission System Operators (TSO) [1, 2]. The liberalization induced an organizational change, by the unbundling and privatization, urging TSOs to be economically efficient. At the same time, the renewable energy revolution and the electricity markets integration needed high levels of investment.

Coupled with this situation, in most of developed countries, the bulk of the grid was developed in the 1970-1980 period [3]. This way, most TSOs are noticing they must prepare to accommodate massive asset replacement and refurbishment, if time is used as a decision variable [4].

Given financial constraints that TSOs, as regulated companies, have to comply [5], this modernization must be executed in an efficient and effective way [6]. Efficient, to allow financial sustainability on the long term, and effective to assure system's reliability is preserved through this process.

It is expected that an optimal modernization schedule, allows such to happen, as would smoothen the investment effort. To understand how this planning is to be made, while having such properties, a wide review on multiple topics and domains is needed.

II. State of the Art

A. Regulatory Developments

As most TSO's operate a natural monopoly, its activity is highly regulated. Reason why is quite important to understand how regulation is defined [7].

Nowadays the regulatory framework is evolving [8, 9] from an accepted-cost perspective to an incentive-based one. The accepted-cost framework evaluates directly if an investment is efficiently executed [10]. The incentive-based framework rewards the TSO on a more systematic level, and for the end-result of an investment decision [11].

This policy leads to an innovative [12] and efficient [13] activity, as the Ofgem[1] experience shows in the UK [14]. Such innovation and efficiency breeds naturally from this de-regulated environment. However, to have this success, the TSO must adapt its structure and management to attain all those advantages.

B. Asset Management

The TSO value proposition is quite dependent on physical assets, which have a long life cycle (10 to 30 years) [15]. These assets need intensive Capex, and regulators make pressure to justify costs and spending [16], [17]. Having a thoughtful Asset Management (AM) strategy is vital to succeed in this new environment.

To provide a framework to implement this strategy, several standards arose. EPRI [18] and CIGRE [19] developed their own framework for electrical related activities. The Institute of Asset Management (IAM)[2] [6], [20], released PAS 55 framework, which gave for the first time an AM standard for all physical assets. From 2014 the ISO 5500X standard series was presented [20], [21]. This standard attains all types of assets to be managed, reason why motivated most of utilities to pursue such certification.

[1] Office of Gas and Electricity Markets (Ofgem), TSO regulator in UK.

[2] Institute of Asset Management. A professional body for those involved in acquisition, operation and care of physical assets, especially critical infrastructure.

These new standards pave the way to introduce novelties in this field. Those trends may be related to different parts of the asset management structure [6], [16], [18], [22]. This structure is depicted in Fig. 1, where in the 1st level the operation tier is found. The 2nd is the tactical tier, and 3rd constitutes the strategic one. Each tier has one or two scopes.

To solve the replacement wave problem, these three tiers must be interconnected, in order to provide a long-term solution that covers both technical and economical scopes [21], [23]. A decision model ought to be implemented to address problems and situations that may arise from different tiers and scopes. [24].

To have effective and efficient decisions, it is critical that assets' lifecycle is known [25], [26], as to understand its impact on operational level.

To comprehend how such changes may be executed, it is wise to review existent maintenances policies. How they may be executed, and what is the rationale for investment, on each policy.

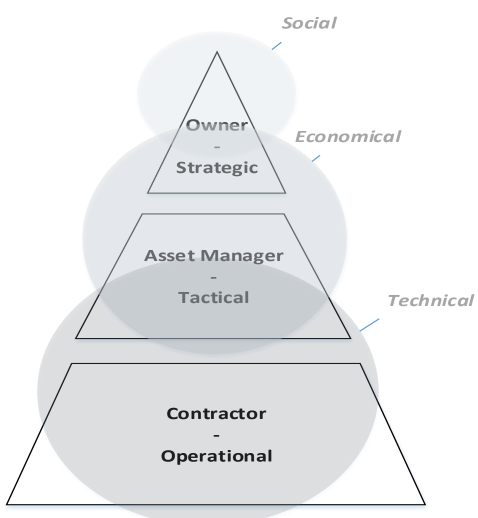


Fig. 1 – Organisational structure for Asset Management implementation. Adapted from *[7] [27]*

C. Maintenance Policies

The maintenance policies are critical to comprehend how the operation's reliability is properly sustained on a regular basis [7]. Given so, the asset replacement strategy is highly dependent on the maintenance policy chosen for a certain asset.

The maintenance policies are nowadays grouped in 4 options:

- Corrective Maintenance (CM) – An asset is intervened, only if it fails [28], [29].
- Time Based Maintenance (TBM) – There are periodical inspections and maintenance is executed [7], [29].
- Condition Based Maintenance (CBM) – The asset's condition is intensively monitored and is intervened only when needed [7], [29].
- Reliability Centered Maintenance (RCM) – The system's reliability is taken into account [7]. Within RCM, the Risk Based Maintenance (RBM) is quite used, as a correlation between fail probability and consequence is computed, which is a good indicator to assess the system reliability [30] - [34].

As can be perceived, the RCM and RBM policies are being quite used and actively recommended by ISO 5500X [20] and PA55 [6] standards. Although not every asset may be eligible to pursue such policy [25], [26], the critical and most expensive ones[3] can use this novelty.

The usage of RCM/RBM requires a high investment. Not only is required to have a dedicated system to decide when the assets should be intervened, but to provide a risk calculation methodology [32]. This computation is based on (1), as the risk of a certain event i, is the product between the consequence c of such happening with its probability p.

$$r(i) = c(i) \cdot p(i) \qquad (1)$$

Most of this investment is related with new methodologies which may relate several data[4] not only to calculate risk, but as well to decide to maintain, reinvest or dispose a certain asset on the computed risk [35].

Even if risk is being employed as a decision method to perform maintenance, it is important to understand other investment strategies. How is this decision executed, in accordance with these developments? Which variables (economical, environmental or technical) are used?

D. Investment Strategies

An investment is intended to give a certain return in the future. This return may be a certain benefit, or an actual monetary dividend. Thus, one question is natural, how is supposed to compare between a certain benefit, and a monetary value?

To answer this question, a framework based on Cost-Benefit Analysis (CBA) is provided, combined with the Multi-Criteria Analysis (MCA). It is expected that both benefits and costs can be monetized, easing a supposedly intricate analysis, into a single objective variable. MCA has been widely studied and applied for decision aid of energy plans [36].

Most investments are required to be evaluated using both methodologies by several stakeholders [37] - [39]. Another approach is based on Risk Optimization, which might complement the Multi-Criteria analysis [32].

Considering the scope of this paper, the method that evaluates the most suitable investment to modernize a certain asset portfolio should be risk-based. Doing so, it ensures and effective investment decision, leading to an efficient activity.

[3] The reason is both technical and economical. Certain assets do not require constant or regular monitoring, or is impossible doing so. While for others the cost of pursuing such policy is quite greater than the benefits.

[4] Each asset must have a certain analysis based on its specifications. Given several types and kind of assets, such analysis is a costly investment.

III. Financial Analysis

A risk-based investment decision certifies the effectiveness of a certain investment. To assess efficiency, a financial analysis ought to be performed.

When choosing investments, a manager tries to understand which project brings the most value to a certain organization [40]. To evaluate financially, three steps are needed [41]:

- Estimate Cash Flows
- Determine and calculate a merit figure
- Compare the merit figure, with an acceptance criterion.

Although there are some financial models, the most used ones, take into account time value of money. Those models are called Discounted Cash Flows (DCF) [42]. One of the most important ones are the Net Present Value (NPV). The NPV is quite simple to compute, as (2) shows.

$$NPV = PV - C_0 = \sum_{t=1}^{T} \frac{\mathrm{M_t}}{(1+r)^t} - C_0 \tag{2}$$

What maybe intricate and elaborate to provide, are an accurate CF figure for each year. Here one can relate the importunateness of the regulation sector, as this actor defines the expected CF a utility may receive for a certain asset. There are other tools related to DCF, such as Benefit/Cost (B/C) [42], Internal Rate of Return (IRR) [43], or the Modified Internal Rate of Return (MIRR) [44], [45]. IRR and MIRR tools use the rate of return (%) as merit figure, while NPV provides absolute values (€), and B/C returns a relative value between the benefits and costs of the project.

There are other financial methods aside from DCF. Some stochastic based methods such as Real Options (RO), or Value at Risk (VaR) provide a unique insight. RO is used for large investment projects where several possibilities may be explored during the project's lifetime [46] - [48]. The VaR can, alongside with a risk-based investment strategy, monetize the risk a certain asset portfolio has [49], [50]. Both these methods need, however, an intricate and expensive analysis. If ill-comprehended they may lead to erroneous conclusions.

It is defined how an investment may be selected, based on effectiveness and efficiency. One must understand how this selection is mathematically conducted.

IV. Optimization Algorithms

A successful modernization can be only attained if it is properly optimized, given a certain merit figure. This problem can be easily related with combinatorial problems, for the following reasons, related with usual modernization investments:

- Each project is to be allocated in a single year.
- One project is not allowed to be partitioned.

These statements lead to binary decisions, if the project is going to be executed or not in a certain time-frame. Such description motivates a deeper understanding of combinatorial problems. Not only defining their formulation, as comprehending ways to provide a solution.

A. Modelling of Combinatorial Problems

The combinatorial problems apply for situations where the variable may only take integer values. Such constraint, usually makes a problem NP-Hard, meaning it is computing intensive [51], [52].

These types of problems may be modelled as a Mixed Integer Linear Programming (MILP). This model takes integrally the Linear Programming (LP) rational, the difference being the objective variable takes only certain integer values [53].

Although a LP can be easily solved[5], a MILP, being a Combinatorial Problem, is usually a challenge to unravel. The problem lies with the exponential computing time that most algorithms need, to provide the global optimum [54].

$$\min_{x \in \mathrm{X}} f^T x \tag{3}$$

Subject to:

$$Ax \leq b \tag{i}$$

$$A_{eq}x = b_{eq} \tag{ii}$$

$$x \text{ is integer} \tag{iii}$$

To understand how is this search conducted, it is interesting to study which algorithms may be used, and its perks and advantages.

B. Exact Algorithms

As already stated, combinatorial problems take exponential time to be solved, if a global optimum is to be reached. Exact Algorithms try to attain that objective, while trying to diminish search time [55].

There are two kinds of Exact Algorithms extensively used to solve combinatorial problems, the Dynamic Programming (DP) [56], and the Branch & Bound (BB) [53].

C. Meta-Heuristics

Even with some innovative approaches, the search for a global minimum may be ill-fated, given the core characteristics of a problem of this kind, to be solved with exact algorithms. Another completely different approach is based on a random search to find a suitable optimum for a given problem.

While the solution may not be a global optimum, but a sufficient and practical one (heuristic), the problem does not require a complicated reformulation to be solved. This way, this algorithm can be executed for a wide range of problems (meta) [57].

[5] As this problem is convex, Simplex algorithm is used, solving it in polynomial time.

Meta-Heuristics algorithms are mainly based on natural phenomena, reason why there are a large quantity [58]. As it can be perceived, there are some methods that already met intensive research for some specific problems [59].

As perceived by [60] there are several MH which can be obtained, when mechanics of the algorithm are combined in between. An example may be EPSO and DEEPSO algorithms, used to solve combinatorial problems [35], [61], [62].

V. Method to optimally schedule modernization

A. Problem Formulation

As already stated, the method to schedule grid's modernization must be efficient and effective. To reach both objectives, and given the theoretical study around AM practices, a proper execution shall be provided, as in table I.

TABLE I. Objectives realization

Objective	Execution
Effectiveness	Risk-based Optimal priority
Efficiency	Investment Limitation

To execute both objectives, the schedule must be implemented having the following points:

A. The budget limitation must be accountable. This way a replacement wave is averted, ensuring TSO's future financial sustainability

B. Ensure assets' replacement which are a threat to reliability, through risk management.

To translate those points into a mathematical formulation, quantitative and qualitative evaluations are needed. This evaluation ought to provide both systemic and item-based insight.

TABLE II. Point's implementation

Point	Qualitative-System	Qualitative-Item	Quantitative unit
A	Budget	Investment needed	Capex [€]
B	Reliability, Integrity, security	Intervention's urgency	Risk Index (RI)

The Capex is an investment figure, thus is a monetary value (here in €). However, the risk index does not have a defined figure, as it is dependent on the purpose it serves. To describe how the risk index is awarded, the basis is taken from (1). The Health index is an image of the likelihood of an asset to fail, thus is associated with the probability to fail. The Criticality index states the consequence of a such fail.

Both indexes are discrete, and tables II and III show how the value attribution is realized.

TABLE III. Health index possible notation and meaning

Notation	Meaning
1	The asset's age is less than 15 years
2	The asset's age is between 15 and 30 years
3	The asset's age is higher than 30 years

TABLE IV. Criticality index possible notation and meaning

Notation	Meaning
1	Facility sited in a grid area with flexibility
2	Facility sited in a grid area with limited flexibility
3	Facility sited in a critical grid area

To create a risk index, theoretically the next step would be applying (1). Another proposal is here considered as (3) states. Mathematically it can be comprehended as applying a logarithmic on both branches of (1). The advantages of doing so can be stated on table V, as linear and clearly defined risk zones are obtained, as seen in [23].

$$RI = CI + HI \tag{3}$$

TABLE V. Possible risk index (RI) values, the darker the risky.

RI	CI			
	+	1	2	3
HI	1	2	3	4
	2	3	4	5
	3	4	5	6

For the problem to be completely formulated, an objective function is expected to be written, in order to find a suitable optimization algorithm. Is waited that an optimal schedule can be generated.

B. Objective Function

As stated by table I, there are 2 distinct objectives to be attained, thus 2 optimization exercises to be performed. Each having its own formulation.

To define the objective functions, it is wise to understand how the objective variable is depicted. As stated, the objective is to understand if a project is to be executed and in which year. That leads to a binary interpretation, on a first level. So if N projects are considered, then x will be a vector with N entries, representing each vector.

However, a project may be allocated in any T year, a vector with N entries won't be enough. To provide sufficient information, there may be as many vector as T years. Such description leads to consider $x_{i,k}$ as entry of a matrix X of $N \cdot T$ dimension.

The risk-based Optimization is formulated by (4)., taking into account the risk priority. The objective is to perform the greatest number of renovations for a given group of projects. This rationale was adopted, as a project with the same risk index, supposedly, has the same impact on the portfolio reliability Thus performing a high number of projects with an elevated risk index, would further ensure the needed reliability.

So the sooner a project is allocated, the better. Having in mind this description, and the project indivisibility between years, a yearly optimization makes sense.

Mathematically, such description can be attained by (4):

$$\max_{i\in \mathrm{N},k\in \mathrm{T}} \sum_{i=0}^{N} y_k \cdot x_{i,k} \tag{4}$$

Subject to:

$$\sum_{i=0}^{N} x_{i,k} CAPEX_i \leq Budget_{M,k}, \forall\, k\ \in T \quad \text{(i)}$$

$$y_k = 1 \quad \text{(ii)}$$

$$x_{i,k} = \{0,1\} \in \mathbb{N} \quad \text{(iii)}$$

$$\left.\begin{array}{l} k = \{0, T\} \in\ \mathbb{N}^+ \\ i =\ \{0, N\} \in \mathbb{N}^+ \end{array}\right. \quad \text{(iv)}$$

Where the restriction (i) bounds the investment for a cap value. Constraint (ii) states every project, for the same risk group has the same urgency. The objective variable is bounded by (iii). Restriction (iv) ensures that one project may only be executed once, thus it can only appear on a year. The final restriction, is in reality a domain reference for the possible years and projects, this formulation can work on.

For this formulation to provide the desired results, when each yearly optimization is performed, the project domain has to be updated. Meaning already allocated projects won't be considered again.

When taking into account economic-financial optimization, is important to keep the investment as low as possible. Doing so, the replacement wave is averted, as reliability is assured, while financially the costs are leveled.

To have this objective attained, is important to consider all the calendar at once. Formulation (5) ensures that.

$$\min_{i\in \mathrm{N},k\in \mathrm{P}} \sum_{k=0}^{P} \sum_{i=0}^{L} x_{i,k} CAPEX_i \tag{5}$$

Subject to:

$$\sum_{i=0}^{L} x_{i,k} CAPEX_i \leq Budget^*_{M,k}, \forall\, k\ \in P \quad \text{(i)}$$

$$\sum_{i=0}^{L} x_{i,k} CAPEX_i \geq Budget^*_{m,k}, \forall\, k\ \in P \quad \text{(ii)}$$

$$x_{i,k} = \{0,1\} \in \mathbb{N} \quad \text{(iii)}$$

$$\sum_{k=0}^{P} x_{i,k} \leq 1 \quad \text{(iv)}$$

$$\left.\begin{array}{l} k = \{0, P\} \in\ \mathbb{N}^+ \\ i =\ \{0, L\} \in \gamma \end{array}\right. \quad \text{(v)}$$

The restrictions (i) and (ii) bound the investment to be made between a maximum and minimum value. Restriction (iii) refers to the objective variable as a binomial one, where a project may or may not be done. Restriction (iv) ensures that one project may only be executed once, thus it can only appear on a year. The final restriction, is in reality a domain reference for the possible years and projects, this formulation can work on. Different domains are represented, as this formulation will only consider years which minimum budget wasn't surpassed, and projects which weren't allocated so far.

This domain restriction reduces the number of variables, which is quite important to diminish the computation time, given the chosen algorithm.

C. *Optimization Algorithm*

Having both problems mathematically defined, the next step is to provide an algorithm which delivers a solution, attaining the objectives in table I.

To do so, considering the formulations are quite identical, one may use combinatorial algorithms to provide a solution. In this case, an Exact Algorithm will be used by the following reasons:

- The information is static.
- The algorithm must find a global minimum, given the importance it has to accomplish financial sustainability
- There is no need for a quick computation
- As the problem is divided in smaller ones, computing time is severely reduced.
- If necessary, there are ways to induce heuristics into the algorithm.

As both formulations are MILP, the Branch and Bound algorithm is easily applicable. That is observable, when inspecting Matlab optimization Toolbox. There is an optimization algorithm named intlinprog, that successfully solves both presented formulations.

The optimization algorithm alone does not provide the necessary answer. It is necessary to embed other functionalities to produce a comprehensive scheduling algorithm. It is expected a schedule which defines the assets to be replaced, or to be maintained.

D. *Schedule Algorithm*

This schedule algorithm must have the following features:

a. Project list acceptance and translation.

b. Definition of optimization exercises scope

c. Connection and constraint reformulation in between optimization exercises.

d. Translation between optimization results and allocated projects.

The feature a). is done by reading a list or generating a project[6] list. Afterwards the information there must be translated to suit the needs of the algorithm.

[6] For simulation purpose, a list project may be generated to test the schedule Algorithm, per example.

The feature b). is quite important for this algorithm success. First is to be understood there are several optimization exercises to be performed. Those exercises will cover each risk group as defined in Table V. For extremely and very risky projects, a risk-based priority optimization (3) is mandatory.

Afterwards, as reliability is in principle assured, the objective now is to guarantee financial sustainability. Thus projects with medium risk, firstly are allocated based on economic-financial optimization (5). From this step, two distinct situations may arise:

The calendar is all filled with medium risk projects, in an optimal fashion. If such happens the algorithm terminates, and won't even consider lower risk investments.

Another situation appears when the medium risk group cannot provide a feasible solution within (5). To deal with this situation the following approach is used:

- For medium risk projects is considered a risk optimization process where the cap for each year is the minimum plus a certain
- After all medium risk projects were allocated the rest of the schedule is assigned through low risk project allocation. To perform such action an economic-financial optimization (5) is used for available years and projects.

As already noted, having separate optimization exercises, that run dynamically according to the input, may compromise the algorithm as a whole. To manage this situation, feature c). was added. This feature allows problem restriction to change within the algorithm. Such permits the constraints of the problem as a whole to be respected, ensuring the accomplishment of the announced objectives.

At the end, the results for each optimization exercise must be grouped and translated successfully into a schedule. Such is quite related with feature d).

To comprehend the algorithm's logic, in the appendix a flowchart is shown.

E. Formulation Adaptation

Both formulations (4) and (5), have to be properly defined. This way a correct result and interpretation is expected from the Matlab code.

Firstly, the objective function as to be defined as (3). Afterwards the objective variable, has to be a vector. This vector describes projects which can be allocated. As stated before, at the beginning of subchapter B.

Formulation (4) does not need much adaptation. Based on a yearly iteration, the vector x is considered the objective variable. Inspecting (4-ii), the objective function which the algorithm will considered

$$f_{5.10}^{T} \cdot x = [\,1 \cdots 1\,] \cdot \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \tag{6}$$

Reviewing (4), there is one inequality to be considered, defined by (i). Such inequality must simple be posed as (3) requires.

$$[Capex_1 \cdots Capex_n] \cdot \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \leq Budget_M \tag{7}$$

With (4) adapted to be used by the algorithm, one shall adjust (5). Firstly, the objective variable must be rewritten. As previously indicated, this input must be defined as a vector, although it was initially posed as a matrix.

$$X = \begin{bmatrix} x_{1,1} & \cdots & x_{1,T} \\ \vdots & \ddots & \vdots \\ x_{n,1} & \cdots & x_{n,T} \end{bmatrix} \longrightarrow [x_1] \cdots [x_T]$$

$$[x_1] \cdots [x_T] \longrightarrow \begin{bmatrix} [x_1] \\ \vdots \\ [x_T] \end{bmatrix} = \begin{bmatrix} x_{1,1} \\ \vdots \\ x_{n,1} \\ \vdots \\ x_{1,T} \\ \vdots \\ x_{n,T} \end{bmatrix} = X_v \tag{8}$$

Afterwards vectorization was performed, represented by X_v, both objective functions and restrictions can be properly defined. As it can be noticed this formulation has 3 inequality constraints (i,ii,iv).

Firstly, constraint (iv) is defined. As it can be noticed by (3), the constraint must be defined by a matrix A, the objective variable vector x. The product between those entities should always be lesser or equal than a vector b.

Considering (iv) and (3), for a vector x (thus a single year), the following matrix relationship is obtained.

$$[A_{iv}] \begin{bmatrix} x_{1,1} \\ \vdots \\ x_{n,1} \end{bmatrix} \leq [b_{iv}] \quad \longrightarrow [I] \cdot [x_1] \leq [1] \tag{9}$$

However, formulation (5) deals with multiple years at once. Thus (9) has to be extended for a situation where the objective variable is X_v

$$[I] \cdot [x_1] \leq [1] \longrightarrow [I_1 \cdots I_T] \cdot \begin{bmatrix} [x_1] \\ \vdots \\ [x_T] \end{bmatrix} \leq \begin{bmatrix} [1] \\ \vdots \\ [1] \end{bmatrix} \tag{10}$$

For restriction (i), the same logic is used as in-between (9) and (10). Taking into account (7), and employing that restriction for multiple T years, (11) is obtained.

$$\begin{bmatrix} [Capex] & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & [Capex] \end{bmatrix} \cdot \begin{bmatrix} [x_1] \\ \vdots \\ [x_T] \end{bmatrix} \leq \begin{bmatrix} Budget_{M,1} \\ \vdots \\ Budget_{M,T} \end{bmatrix} \tag{11}$$

As restriction (ii) is the same as (i), except for the opposite A and b signals, its inequality is nearly direct to be obtained from (11).

$$\begin{bmatrix} -[Capex] & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & -[Capex] \end{bmatrix} \cdot \begin{bmatrix} [x_1] \\ \vdots \\ [x_T] \end{bmatrix} \leq \begin{bmatrix} -Budget_{m,1} \\ \vdots \\ -Budget_{m,T} \end{bmatrix} \tag{12}$$

With all inequalities defined, for each constraint, they need to be grouped in order to respect formulation (3), as (13) depicts.

$$\begin{bmatrix}[A_i]\\ [A_{ii}]\\ [A_{iv}]\end{bmatrix}\cdot\begin{bmatrix}[x_1]\\ \vdots\\ [x_T]\end{bmatrix}\leq\begin{bmatrix}[b_i]\\ [b_{ii}]\\ [b_{iv}]\end{bmatrix} \tag{13}$$

Such operation can be translated in (14).

$$\begin{bmatrix} I_1 & \cdots & I_T\\ [Capex] & 0 & 0\\ 0 & \ddots & 0\\ 0 & 0 & [Capex]\\ -[Capex] & 0 & 0\\ 0 & \ddots & 0\\ 0 & 0 & -[Capex]\end{bmatrix}\cdot\begin{bmatrix}[x_1]\\ \vdots\\ [x_T]\end{bmatrix}\leq\begin{bmatrix}[1]\\ \vdots\\ [1]\\ Budget_{M,1}\\ \vdots\\ Budget_{M,T}\\ -Budget_{m,1}\\ \vdots\\ -Budget_{m,T}\end{bmatrix} \tag{14}$$

The inequality constrain is correctly defined to depict the constraints in (5). To describe the objective function of (5), (15) is provided.

$$f_{5.13}^{T}\cdot X_v=\big[[Capex]\cdots[Capex]\big]\cdot\begin{bmatrix}[x_1]\\ \vdots\\ [x_T]\end{bmatrix} \tag{15}$$

After all important aspects of the method were characterized, one shall test and perform a Case study. Such performance is to be analyzed to infer if the proposed objectives were attained.

VI. CASE STUDY

A. *Electric Grid's Characterization*

Given the indication in Chapter V, the grid's assets must be properly categorized following their condition index, critical index and expected Capex to perform the reinvestment.

The grid can be spited in two kinds of facilities:

- Linear (LF), which comprises assets related to transmission lines, and
- Nonlinear(NLF), which relates assets to be found in substations.

As $[x]$ delivers, it is possible to compute Condition and Criticality indexes' probability distribution function, in accordance to Chapter V developments.

The installation health index data was obtained from [62] and the critical index information was collected from [63].

TABLE VI. INSTALLATION'S HEALTH INDEX PDF.

Health Index (HI)		1	2	3
Facilities	Linear [%]	38,7	31,4	30,0
	Non-linear [%]	68,3	21,0	10,7

TABLE VII. INSTALLATION'S CRITICAL INDEX PDF.

Criticality Index (CI)		1	2	3
Facilities	Linear [%]	25,0	50,0	25,0
	Non-linear [%]	8,8	42,1	49,1

With this information, a risk index pdf can be constructed, following (3). After developing several MC simulations, the pdf, in table VIII was used.

TABLE VIII. INSTALLATION'S RISK INDEX PDF.

Risk Index (RI)		2	3	4	5	6
Facilities	Linear [%]	9,5	27,4	32,8	22,8	7,4
	Nonlinear[%]	5,9	30,8	43,3	14,8	5,3

Complementary, a Capex distribution is provided. This Capex distribution is a Pareto-based, to emulate many non-expensive interventions, while existing some which represent a heavy burden to cope. Afterwards it is possible to construct a project list, based on these probabilistic distributions.

TABLE IX. MODEL OF PARETO PDF PARAMETERS

Facility	a	k	μ[M€]
Linear	1,05	1,5	3,15
Non-Linear	1,15	1,5	3,45

$$pdf_{pareto}(x)\begin{cases}=\dfrac{a^d\cdot d}{x^{a+1}}, x>a\\ 0, x\leq a\end{cases} \tag{16}$$

$$cdf_{pareto}(x)=1-\left(\frac{d}{x}\right)^a \tag{17}$$

$$\mu_{pareto}=\frac{a\cdot d}{a-1} \tag{18}$$

These values were defined from several data comprising reinvestments on [64]. It is possible from [65], [66] realize a generalization of reinvestment project cost.

B. *Project Generation*

The project generation is based on the RI and Capex probabilistic distributions. To have a project list as similar as a real one, a TYNDP was considered [63]. For this period, around 130 replacement investment projects are considered, taking into attention the different kinds of assets.

As the schedule to be tested will have a time-span of 5 years, half those projects will be taken into consideration[7]

TABLE X. INITIAL SET OF VALUES TO BE CONSIDERED FOR METHOD'S EMPLOYMENT

Parameter	T	Max Capex [M€]	Min Capex [M€]	#LF	#NLF
Amount	5	40	20	29	36

Having in mind how risk is important for this method's result, a risk distribution of this Case Study is showed by table XI.

[7] Although there wouldn't be any difference to have 130 projects, aside from computation time and algorithm flow, for simulation and analysis reason only 65 were considered.

TABLE XI. PROJECTS AND CAPEX DISTRIBUTION, BY RI.

RI	2	3	4	5	6	Total
Capex [M€]	7,2	55,2	70,9	50,8	1,3	185,4
#Project	4	20	26	14	1	65

Considering the obtained projects, a scheduling shall be performed

C. Scheduling Simulation Analysis

In order to assess if the method offers a schedule which translates into an efficient and effective investment, several figures have to be estimated.

Two values have the upmost importance: The Capex that is going to be spent, and the investment's risk.

Figure 1 shows the expected evolution of Capex, through the next 5 years. In the same figure, it is possible to understand how the risk evolves. In the first year a major investment is performed, as urgent or extremely urgent projects are considered to guarantee reliability. The next years are used to allocate projects which have a medium level of risk.

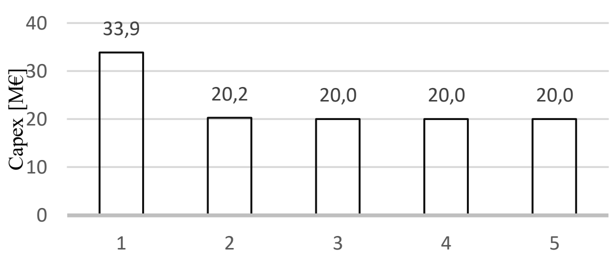


Fig. 2 – Yearly Capex allocation, considering the scheduling and planning realized by the method. The investment cap is located at 20M€, while the floor at 40M€.

To have a better insight how this method allocated the projects, Table XII and Table XIII give another important view. Table XII shows how many projects, and how much Capex was spent in relation with IR groups. As can be perceived from Figure 1, and Table XII the riskiest investments were allocated as sooner as possible. As inspected only a fraction of all possible investments were in fact allocated (61,6%).

Although the first year had heavier investment than the others it can be seen that all years respect the budget restrictions, and in most cases, the invested amount will be nearly the minimum.

Such means efficiency is guaranteed as financial sustainability is ensured.

The effectiveness is assured, as risky investment was allocated, and the most were planned to start as soon as possible.

TABLE XII. PROJECTS AND CAPEX DISTRIBUTION, BY RI.

RI	2	3	4	5	6	Total Schedule [%]
Capex [%]	0	0	87,6	100	100	61,6
#Projects [%]	0	0	73,1	100	100	65,2

[8] As this work only covers modernization investment drive, it depends on others drive's performance to assess if the investment financial sustainability for a TSO is accomplished or not

TABLE XIII. RI AVERAGE FIGURE, IN TERMS OF ALLOCATED PROJECTS AND CAPEX, THROUGHOUT DIFFERENT YEARS.

Years	1	2	3	4	5	Effective
$\overline{IR}_{proj}$	5,1	4,7	4,0	4,0	4,0	Yes

VII. CONCLUSION

Both main objectives were attained. The scheduling was efficient, as financial sustainability is, in principle[8], ensured, and effective, as the riskiest projects were allocated, and the most urgent were allocated as earlier as possible in the produced schedule extensions.

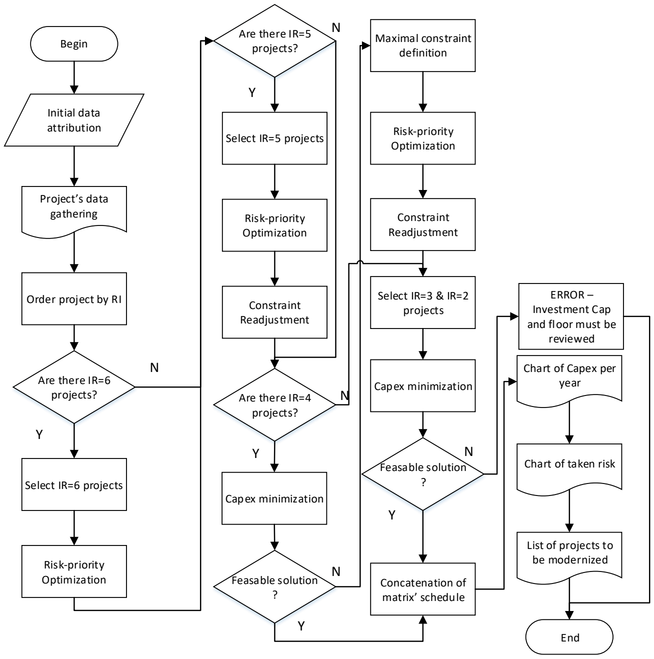
This results propel future works, where there are a wide room for applications, as improvements that may be considered. Regarding other applications, this method could be applied for other utilities. Not only in other electrical grids (Distribution), but for Natural Gas, Water, Telecom and Transportation. All those economic activities are facing similar business conditions, regarding budget constraints and physical asset aging.

To allow such to happen, a well-defined risk-scoring methodology should be determined to enhance the employment of the proposed method.

Regarding improvements of this method, the economic efficiency of this process, can be defined by the NPV. This way the proposed method would maximize this figure, while considering financial sustainability and technical reliability.

Another future work, to assess financial sustainability would be considering Totex. This figure allows a more comprehensive estimation of the financial impact which an investment may have, not only considering the moment of acquisition, but the operational expense that it might bring throughout its lifetime.

ANNEX – LOGIC OF THE OPTIMIZATION ALGORITHM



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