PANAMA

PRESCRIPTIVE SOLAR ANALYTICS & ADVANCED WORKFORCE MANAGEMENT

D3.4

Optimization Tool

Responsible Partner	University of Western Macedonia
Prepared by	Ioannis Panapakidis Despoina Kothona
Checked by WP Leader	Georgios Christoforidis
Verified by Reviewer #1	
Verified by Reviewer #2	
Approved by Project Coordinator	

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Definition of Acronyms

GAMS	General Algebraic Modeling System
PV	Photovoltaic
MINLP	Mixed-Integer Non - Linear Programming
MCDA	Multi-Criteria Decision Analysis

Note: Mathematical symbols and terms are explained directly in the corresponding sections.

EXECUTIVE SUMMARY

This deliverable aims to provide a detailed description of the integrated optimization tool, that provides a plan for the maintenance actions that should be followed in order to retore the functionality of faulty PV systems. The integrated prescriptive maintenance tool consists of two models: a) MINLP model and b) MCDA tool and exploits the benefits of both models. The document follows the projects’ structure and recalls the following tasks:

- D3.2: “PV generation forecasting models”
- D3.3: “Decision analysis and results”

The deliverable is separated into three main sections. At the first section, the development of the MINLP is presented. Specifically, the input parameters, the variables and the constraints of the model are presented. The model provides an optimal maintenance plan considering the minimization of the travelling cost, the energy losses due to abnormal operation of the systems and the salary of the personnel. At the second section, the methodology and implementation of the TOPSIS method, which is a widely used MCDA technique, is presented. Finally, at the last section, the results of the individual models as well as the results of the proposed integrated tool are illustrated.

1 INTRODUCTION

The installation of a PV plant is a considerable investment and the maintenance procedures that should be followed are essential to ensure its viability. The deployment of business analytics is a promising solution to assure the profit maximization of the investment. The concept is presented in Figure 1. However, only two out of the three business analytics types are widely used: a) the descriptive analytics and b) the predictive analytics. The former focuses on the data analysis in order to describe the current state of the system and answers to the following questions: a) “What has happened?” and b) “What is happening now?”. An extension of the descriptive analytics is the diagnostic analytics that focuses on the cause and answers to the question “Why did it happened?”. On the other hand, the predictive analytics aims to describe the future state of the system answering to the questions “What will happen?” and “Why it will happen?” [1].

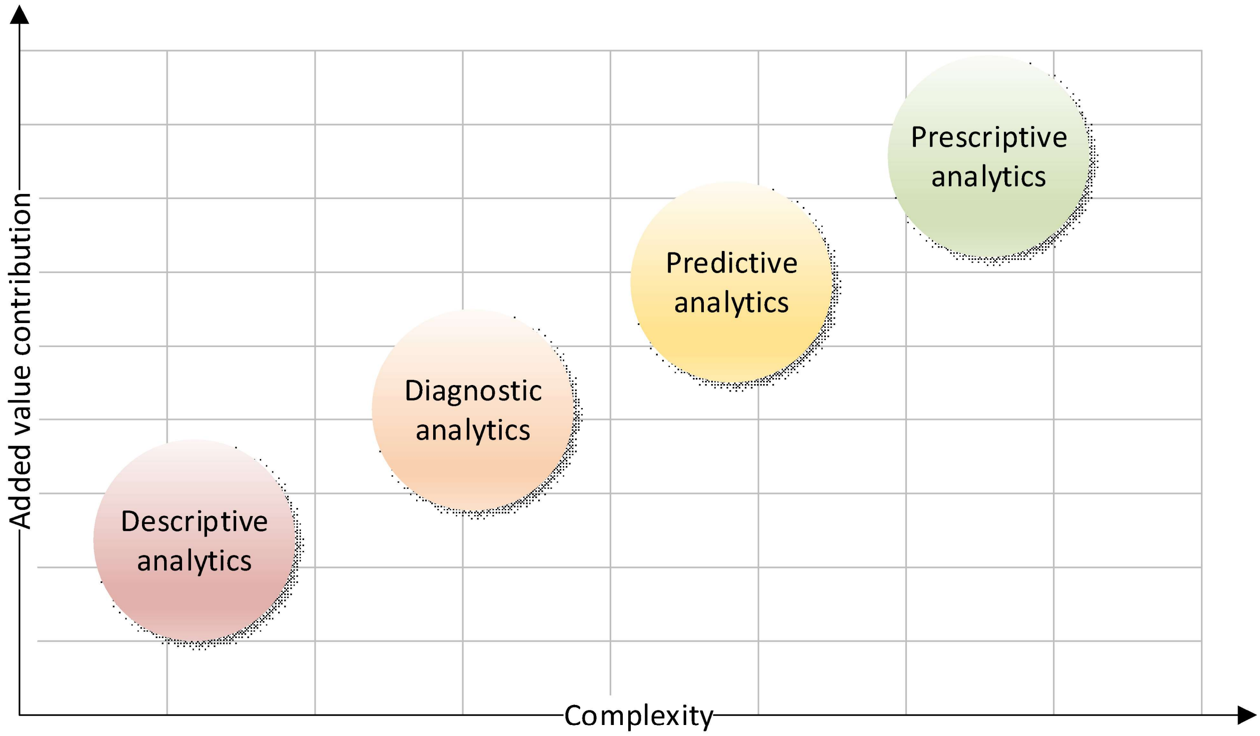

Figure 1. Description of business analytics.

The immediate detection of the faults is essential to minimize the time required to restore the functionality of the plant and consequently to minimize the cost due to the energy losses. However, in order to assure the profit maximization of the system, the deployment of the prescriptive analytics, the third type of the business analytics, is vital. The prescriptive maintenance is focused on the actions that should be followed after the occurrence of a fault and answers to the questions “What should I do?” and “Why should I do it?” [1]. These questions can become even more complicated when several faults are detected in different PV sites.

Considering this, at the present Deliverable, the development of an integrated optimization tool, that provides a maintenance plan when multiple systems are under faulty conditions, is presented. Specifically, the tool consists of two models: a) a MINLP model and b) MCDA model. On the one hand, the MINLP model provides an optimal plan for the maintenance activities based on the minimization of the fuel cost, the cost of the energy losses and the salary of the personnel. However, the main drawback of the model is its inability to receive as inputs qualitative variables, meaning that it does not take into account significant information referring to the expertise of the personnel, the type of road to the PV site and others. On the other hand, the MCDA tool is widely used in decision-making problems due to its flexibility to handle both quantitative and qualitative criteria. However, the model does not provide an optimal solution but a ranking number for each feasible solution which is mainly affected by the knowledge of the expert. The proposed model is able to exploit the merits of both methods and it is able to sufficient manage the available human sources, so that to maximize the profit of the investors and minimize the operational costs of the enterprise.

2 MINLP MODEL

The optimization tool has been developed in GAMS^{TM} and addresses the problem of the optimal PV maintenance scheduling, when multiple systems are under fault conditions. Specifically, it provides a maintenance plan that refers to the daily maintenance activities of the technicians, within the scheduling period. The maintenance plan is updated each time a new fault occurs and the prioritization of the systems' repairment is determined considering the minimum travelling distance between the PV sites, the nominal capacity of the systems, the forecasted PV power, the faults' severities as well as the severities of meteorological conditions. The general process of the MINLP model is presented in Figure 2.

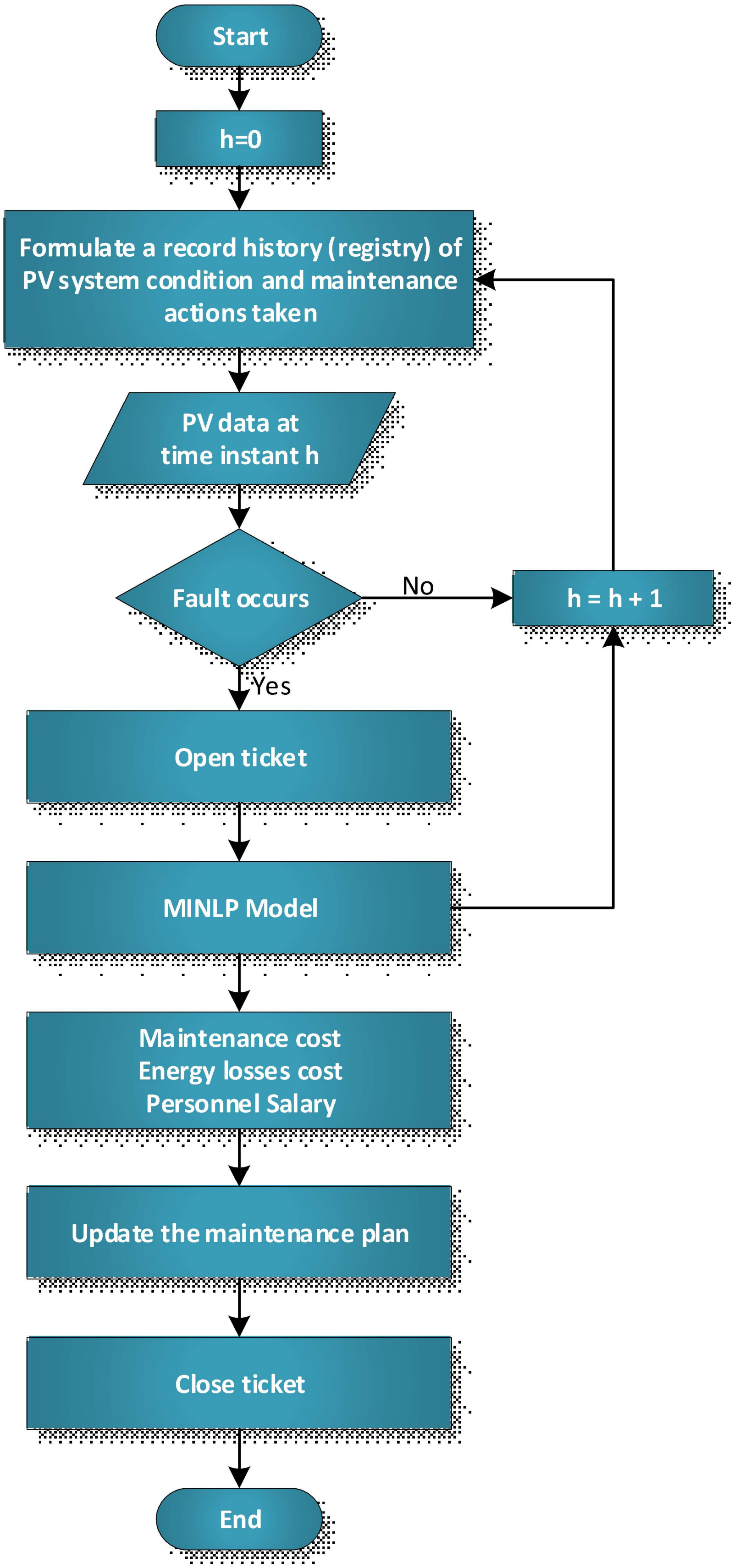

Figure 2. General process of the MINLP model.

2.1 Input parameters

The sets and the parameters of the model are presented in Table 1. Specifically, the mathematical formulation of the problem is based on the following sets:

1. The teams that are available to undertake the systems' maintenance are defined with the set $p=\{1,2,...P\}$, where P denotes the total number of the teams. In order to formulate the problem without ambiguity, set p_1 is a second name given for set p .
2. The considered time horizon for the maintenance schedule is defined with the set d , where $d=\{0,1,..,D\}$. Here D denotes the total number of days of the maintenance plan. Other indicators used for the same set is d_1 .
3. The sites of the PV systems are defined with set c , where $c=\{0,1,..,N\}$. Here N refers to the total number of the systems' locations. Other indicators used for the same set are c_1 , c_2 , c_3 , c_4 and c_5 .
4. The time instant, i.e., time slot, of the current day is defined with set h, where $h=\{0,1,..,H\}$. Here H is the number of total time slots and is equal to the total daily observations obtained from each PV system. The time instants can be defined with set h_1 as well.

Table 1. Input parameters of the MINLP model.

Sets	
c,c_1,c_2,c_3,c_4,c_5	Sets used to define the locations, $(c,c\_1,c\_3,c\_4,c\_5)=\{0,1,..,N\}$
N	Defines the total number of locations
h,h_1	Sets used to define the time slot, $h=\{0,1,..,H\}$ and $c\_1=\{0,1,..,H\}$
H	Defines the total number of time slots
d,d_1	Sets used to define the day of the maintenance, $d=\{0,1,..,D\}$ and $d\_1=\{0,1,..,D\}$
D	Defines the total number of days
p,p_1	Sets used to define the team of technicians, $(p,p\_1)=\{0,1,..,P\}$
P	Defines the total number of teams
Parameters	
$detection_c$	Is equal to 1 if a fault occurs at location c
$days_c$	Total days of faulty operation of system at location c

$mntT_c$	Time required to restore the functionality of the system at location c
$mntT\_slots_c$	Total time slots required to restore the functionality of the system at location c
$severityF_c$	Fault severity of the system at location c
$loss\_rate_c$	Power loss rate of system c considering the type of fault
$severityW_{c,d}$	Severity of weather conditions of the system at location c
$unavailabilityD_c$	Number of days required for the delivery of missing spare parts at location c
$unavailabilityT_c$	Defines the time slots when the spare parts at location c will be available
$unavailabilityP_p$	Integer value denoting the h^{th} time slot when the technicians of team p will become available for the next repairment
$working\_hours_p$	Continues variable denoting how many hours technicians of team p have worked at the day of the model's execution
$dist_{c,c\_1}$	Distance from location c to location c_1 (km)
$time_{c,c\_1}$	Travelling time from location c to location c_1 (hours)
$time\_slots_{c,c\_1}$	Total travelling time slots from location c to location c_1
mAg_c	Is equal to 1 if the maintenance agency is located in c
$forecast_{c,h,d}$	Forecasted power of system located in c at the h^{th} time slot at day d
$location_{p,c,d}$	Is equal to 1 if the technicians of team p are at location c at day d
Scalars	
$sunrise$	Integer value denoting the h^{th} time slot of the sunrise
$sunset$	Integer value denoting the h^{th} time slot of the sunset
ex_time	Integer value denoting the h^{th} time slot when the model is executed
t	Number of technicians
s	Per hour salary of the personnel (€/h)
$overtime\_rate$	Rate of per hour salary increment for each hour in addition to the eight-hour working
$energy\_price$	Energy price per kWh (€/kWh)
$fuel$	Fuel cost per km (€/km)

The model's objective is to minimize the energy losses, due to faulty systems, the travelling cost and the cost of the personnel's salary. The former refers to the cost of the trips and its assessment is based on:

- The fuel cost, $fuel$ (€/km), which is a scalar parameter.
- The distances between the PV plants, defined as $dist_{c,c\_1}$
- The current location of the teams, i.e., the location of the teams the time the model is executed, denoted as $location_c$. The $location_c$ parameter is essential to define the start point of the trip.
- The location of the maintenance agency, denoted as mAg_c. The mAg_c parameter is essential to define the end point of the daily trip.

Additionally, the estimation of the energy losses is based on:

- The energy price ($energy\_price$) (€/kWh)
- The daily forecasted power ($forecast_{c,h,d}$) (kW)
- The loss rate parameter ($loss\_rate_c$) considering the type of fault

It should be noted that the time resolution of the forecasts, i.e., the length of set h, depends on the recording frequency of the monitoring system, installed at each system. The forecasts derive from the day-ahead forecasting model that has been implemented in Deliverable D3.2. However, since the maintenance plan is possible to be formulated for several days ahead, in Figure 3 and Figure 4 an example is presented that illustrates the inputs of the day-ahead-model when we attempt to forecast the PV power production one and two days ahead, respectively.

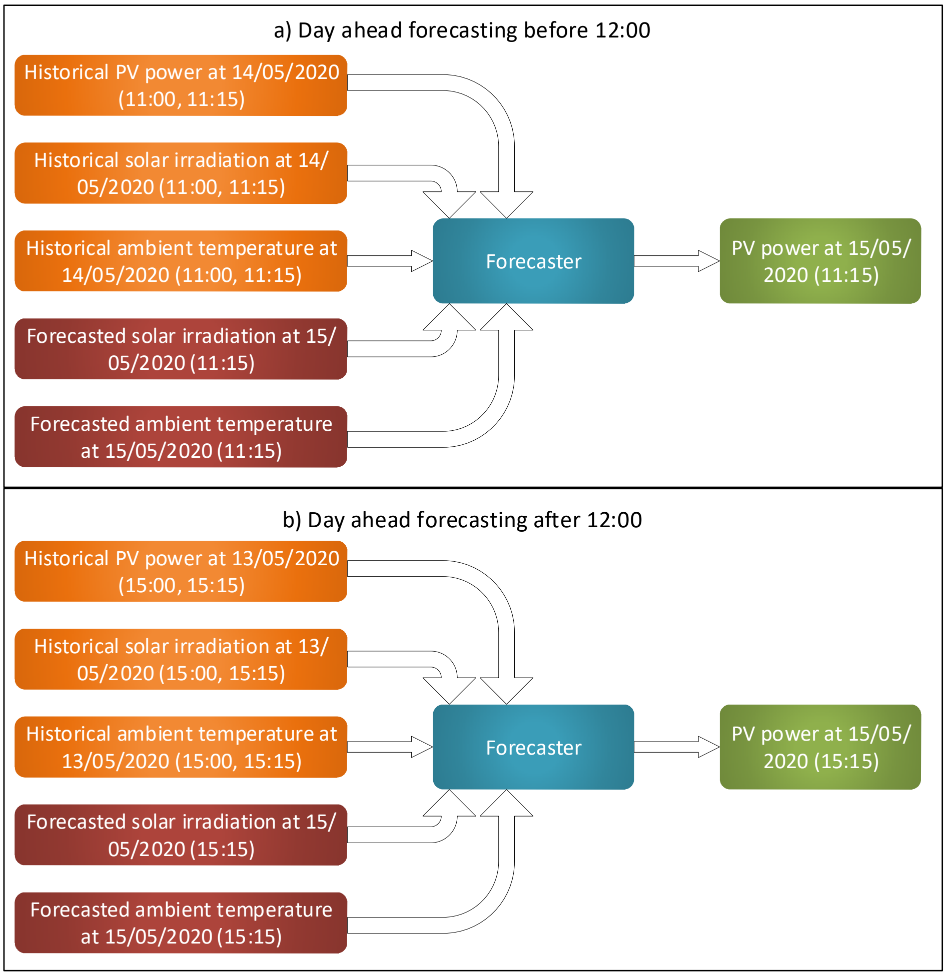

Figure 3. Day ahead PV power forecasting process a) before 12:00, b) after 12:00.

Finally, for the assessment and minimization of the personnel's salary, the daily working hours of the personnel, including the time required for the systems' repairment ($mntT_c$) and the total travelling time between the locations ($time_{c,c\_1}$) have been considered. Specifically, when the working hours exceed the 8-hour working day, the per hour salary is increased. Additionally, the number of technicians t is included in the estimation of the salary.

Apart from the estimation of technicians' working hours, parameters $mntT_c$ and $time_{c,c\_1}$ are also used to calculate the start and the end time of systems' maintenance. Since both parameters are defined in hours, we used the parameters $mntT\_slots_c$ and $time\_slots_{c,c\_1}$ that define the total time slots required for the repairment of the systems and the traveling between the locations, respectively.

The estimation of the repairment time for each type of faults is a relatively difficult procedure. However, in the Solar Bankability project an analysis was conducted, based on failure records of 746 PV plants [2]. Table 2 presents the time required for the faults' repairment, based on the analysis' results. Since there are faults that require more than eight hours to be repaired, we separate the repairment time into maintenance intervals. For instance, for the repairment of a broken transformer, 48 hours are needed. In this case, we separate the fault into six sub-maintenance activities. Each activity requires eight hours for its completion. After the completion of the first activity, the second activity should be scheduled and the model is executed again. This procedure is executed iteratively until all sub-maintenance activities are completed.

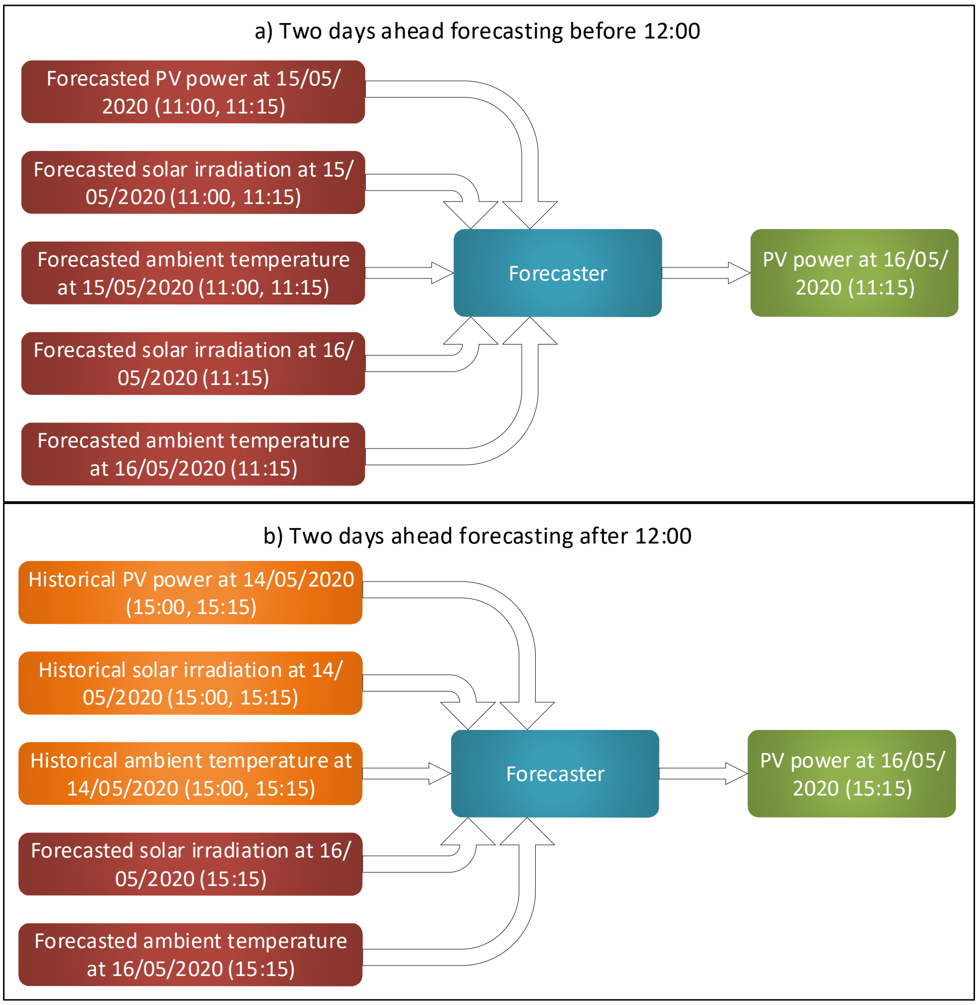

Figure 4. Two days ahead PV power forecasting process: a) before 12:00, b) after 12:00.

Despite the cost minimization, the prioritization or not of the maintenance activities should be defined considering two additional parameters: a) The of the fault ($severityF_c$) and b) the severity of the weather conditions ($severityW_{c,d}$). Both terms are subjective to the experts' experience and four levels of severity have been defined based on [3]: a) Catastrophic, b) Critical, c) Marginal and d) Negligible. The high severity level of the former indicates that the fault occurrence leads to extensive energy losses. Thus, the system's maintenance should be prioritized. However, the high severity level of meteorological conditions indicates that the maintenance activities should be postponed in order to ensure the personnel safety and prevent the maintenance activities under unfavorable weather conditions. The severity levels defined for each type of fault are presented in Table 2 and have been defined considering the power losses. Table 3 includes the severity levels defined for the weather conditions.

Table 2. Repairment time for each type of fault.

	Failures	**Repair time (h)**	**Severity code**	**Power loss per inverter (%)**	**Severity level**
Modules	Hotspot	2	Negligible	2	1
	Delamination	2	Negligible	1	1
	Glass breakage	2	Marginal	10	3
	Soiling	0.01	Marginal	10	1
	Shading	0.01	Marginal	10	1
	Snail track	2	Negligible	1	1
	Cell cracks	2	Negligible	1	2
	Defective backsheet	2	Negligible	1	2
	Overheating junction box	2	Negligible	1	2
	PID = Pontetial Induced Degradation	2	Marginal	10	1
	Failure bypass diode and junction box	2	Marginal	33	2
	Corrosion in the junction box	2	Negligible	1	2
	EVA discoloration	0	Negligible	0	1
	Theft of modules	0.5	Catastrophic	100	3
	Broken module	2	Catastrophic	100	3
	Damage by snow	2	Catastrophic	100	3
	Corrosion of cell connectors	2	Negligible	1	3
	Improperly installed	2	Negligible	5	2
	Missing modules	2	Catastrophic	100	3
Inverter	Fan failure and overheating	4	Marginal	20	3
	Switch failure/damage	4	Catastrophic	100	3
	Inverter firmware issue	4	Negligible	0	3
	Polluted air filter – derating	4	Marginal	20	3
	Inverter pollution	4	Negligible	1	3
	Data entry broken	4	Negligible	0	3
	Display off	4	Negligible	0	3
	Wrong connection	4	Negligible	5	3
	Burned supply cable and/or socket	4	Catastrophic	100	2
	Inverter wrongly sized	4	Marginal	10	2
	Wrong installation	4	Marginal	10	3
Mou ntin	Tracker failure	5	Critical	50	2
	Not proper installation	48	Negligible	0	2

	Corrosion of module clamps	0.5	Negligible	0	2
	Disallignment caused by ground instability	48	Negligible	1	2
	Corrosion	24	Negligible	0	2
	Oil leakage	5	Negligible	0	2
Combiner boxes	IP failure	24	Negligible	0	2
	Main switch open and does not reclose again	1	Catastrophic	100	3
	Broken/Wrong general switch	1	Catastrophic	100	4
	Wrong wiring	24	Negligible	0.1	4
	General switch off	1	Catastrophic	100	4
	Wrong/Missing labeling	1	Negligible	0	2
	Incorrect installation	24	Negligible	0	4
	Overcurrent protection and correctly sized	4	Negligible	0	4
	Broken, missing or corroded cover	1	Negligible	0	3
	Missing protection against electric shock	1	Negligible	0	1
Cabling	UV aging	2	Negligible	1	
	Theft cables	24	Catastrophic	100	4
	Broken cable ties	1	Negligible	0.01	4
	Wrong connection, isolation and/or settings	0.5	Negligible	0.01	4
	Broken/Burned connectors	0.5	Catastrophic	100	4
	Wrong/Absent cables connection		Negligible	5	4
	Wrong wiring	0.5	Negligible	1	4
	Cables undersized	48	Negligible	1	4
	Damage cable	1	Marginal	15	2
	Improper installation	1	Negligible	4	2
	Conduit failure	2	Negligible	0.1	3
	Broken transformer	48	Catastrophic	100	4

Table 3. Severity assessment for weather conditions.

Weather Condition	Severity code	Severity level
Lightning	Catastrophic	4
Strong Winds	Marginal	2
Heat	Marginal	2
Snow	Critical	3
Hail	Critical	3

Furthermore, the unavailability of the spare components ($unvailability_c$) needed for the repairment of the systems as well as the unavailability of the personnel ($unavailabilityP$) are used for the formulation of the maintenance plan. Additionally, in case a component is unavailable, we need to specify the days ($deliveryD_c$) and the time instants ($deliveryH_c$) required for the delivery.

2.2 Variables

MINLP model provides an optimal maintenance plan ($plan_{p,c,c\_1,d}$) and is executed when a new ticket opens. The variable $plan_{p,c,c\_1,d}$ is a 4-dimension array defined as:

$$plan_{p,c,c\_1,d} = \begin{bmatrix} & p1.d1 & \cdots & p1.dD & p2.d1 & p2.d2 & \cdots & pP.dD \\ c1.c1 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ c1.c2 & 1 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ c1.c3 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c2.c1 & 1 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c3.c1 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ cN.cN & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \quad (1)$$

Assuming that two open tickets refer to the systems cited in $c2$ and $c3$, respectively, and the location of the maintenance agency is in $c1$, then according to the plan in (1), the technicians of team $p1$ have to travel from location $c1$ to location $c2$ at the day $d1$, in order to repair the system cited in $c2$. Additionally, the technicians of team $p2$ have to travel from location $c1$ to location $c3$ at day $d1$ to restore the systems' functionalities.

Table 4. Variables of MINLP model.

Integer Variables	
$start\_mntT_c$	Denotes the h^{th} time slot when the technicians start travelling to the system located in c
end_mntT_c	Denotes the h^{th} time slot when the functionality of the system located in c is restored
$off\_service_{c,d}$	Denotes the total time slots per day the system at location c_1 has not been repaired
Continuous Variables	
$total\_working\_hours_{p,d}$	Total working hours of technicians of team p at day d
$overtime_{p,d}$	Total hours that exceed the eight-hour working per day
$Energy\_cost$	Total energy losses of the faulty systems
$Fuel\_cost$	Total fuel cost

$Severity\_cost$	Penalty factor to prioritize or not the maintenance activities considering the severity of the fault and the weather conditions
$Salary$	Total salary of the personnel
$Total\_maintenance\_Cost$	Total cost considering the energy cost, the fuel cost and the salary of the personnel
OF	The objective function to be minimized
Binary variables	
$plan_{p,c,c\_1,d}$	Is equal to 1 if the technicians of team p travel from location c to location c_1 at day d
$off\_serviceBin_{c,h,d}$	Is equal to 1 if the system located in c, at the h^{th} at day d is out of service
$eight\_hours_{p,d}$	Is equal to 1 if the technicians of team p will work more than eight hours at day d

The variables of MINLP model are presented in Table 4. Despite the maintenance plan the model provides additional information. Specifically, it provides information referring to the start time ($start\_mntT_c$) of the maintenance activities at each system as well as the time when the repairment is expected to be completed (end_mntT_c).

Furthermore, $off\_serviceBin_{c,h,d}$ variable specifies the time slots, when the system cited in c operates under faulty conditions or is out of service, while $off\_service_{c,d}$ is used to specify the total time slots per day d that system at location c has not been repaired. For the estimation of $off\_service_{c,d}$ the variables $start\_mntT_c$, end_mntT_c and the ex_time parameter are used.

Regarding the salary of the personnel, the model estimates not only the total cost of the technicians but also specifies the total working hours for each team per day ($total\_working\_hours_{p,d}$), the teams that is planned to work over eight hours at day d ($eight\_hours_{p,d}$), as well as the total hours that exceed the eight-hour working per day ($overtime_{p,d}$).

Also, the total cost, i.e., the sum between of the energy losses cost ($Energy\_cost$), the travelling cost ($Fuel\_cost$) and the salary of the personnel ($Salary$), of the optimal plan is estimated.

2.3 Constraints

For the formulation of the problem several constraints have been taken into account. At first, in order to ensure that the maintenance plan is determined considering only faulty PV systems we must assure that normal operating systems will not be visited. This is expressed in equations (2) – (4).

$$plan_{p,c,c\_1,d} = 0, when \begin{cases} c = c\_1 \\ and \\ location_{p,c,d} = 0 \end{cases} \quad (2)$$

$$plan_{p,c,c\_1,d} = 0,\ when\ location_{p,c\_1,d} \neq mAg_{c\_1} \quad (3)$$

$$\sum_{c}^{C} plan_{p,c,c\_1,d} + \sum_{c}^{C} plan_{p,c\_1,c,d} = 0,\ when \begin{cases} detection_{c} = 0 \\ and \\ mAg_{c} = 0 \\ and \\ location_{p,c,d} = 0 \end{cases} \quad (4)$$

Accordingly, equations (5) and (6) are used in order to assure that all tickets will be handled within the time period determined by the maintenance plan.

$$\sum_{p}^{P}\sum_{c}^{C}\sum_{d}^{D} plan_{p,c,c\_1,d} = detection_{c\_1} \quad (5)$$

$$\sum_{p}^{P}\sum_{c}^{C}\sum_{d}^{D} plan_{p,c\_1,c,d} = detection_{c\_1} \quad (6)$$

Since the term $plan_{p,c,c\_1,d}$ describes the trip of the technicians, the constraints in equations (7) and (8) are used to create a valid trip. Both equations, i.e., equation (7) and equation (8), indicate that the technicians cannot return to a PV system that has been already repaired.

$$plan_{p,c,c\_1,d} + plan_{p,c\_1,c,d} \leq 1 \begin{cases} detection_{c\_1} = 1 \\ and \\ location_{p,c,d} = 0 \end{cases} \quad (7)$$

$$plan_{c,c\_1,d} + plan_{c\_1,c\_2,d} + plan_{c\_2,c,d} \leq 2, when \begin{cases} detection_{c} = 1 \\ and \\ detection_{c\_1} = 1 \\ and \\ detection_{c\_2} = 1 \end{cases} \quad (8)$$

Additionally, the unavailability of spare parts makes the repairment process infeasible, as it is expressed in equation (9).

$$\sum_{c}^{C}\sum_{d}^{D} plan_{c,c\_1,d} = 0, when \begin{cases} d \leq deliveryD_{c\_1} \\ and \\ c \neq c\_1 \end{cases} \quad (9)$$

The last constraints of $plan_{p,c,c\_1,d}$ variable are expressed in equations (10) and (11) and are used to make sure that teams return to location c at the end of the daily repairment activities.

$$\sum_{c}^{C}\sum_{c\_1}^{C} plan_{p,c,c\_1,d} \leq 1, when\ mAg_c = 1 \tag{10}$$

$$plan_{p,c,c\_1,d} = 0, when \begin{cases} mAg_c = 1 \\ and \\ detection_c = 0 \\ and \\ location_{p,c,d} = 0 \end{cases} \tag{11}$$

Regarding the maintenance activities, equation (12) is used in order to ensure that all the scheduled maintenance procedures will be completes within the day.

$$\sum_{c}^{C}\sum_{c\_1}^{C}\left(time\_slots_{c,c\_1} plan_{p,c,c\_1,d} + mntT\_slots_{c\_1} plan_{p,c,c\_1,d}\right) \leq \begin{cases} H,\ when\ d > 1 \\ H - unavailabilityP_p\ when\ d = 1 \end{cases}$$

(12)

The estimation of start time of maintenance procedures for each faulty system are reformulated, as:

$$start\_mntT_{p,c\_4} \geq \begin{cases} \begin{pmatrix} unavailabilitP(p) + mnt\_slots_{c\_3} + time\_slots_{c\_2,c\_3} \\ + mnt\_slots_{c\_2} + time\_slots_{c\_1,c\_2} \\ + mnt\_slots_{c\_1} + time\_slots_{c,c\_1} \end{pmatrix} plan_{p,c\_3,c\_4,d}\, plan_{p,c\_2,c\_3,d}\, plan_{p,c\_1,c\_2,d}\, plan_{p,c\_,c\_1,d}, when \begin{cases} location_c = 1 \\ or \\ mAg_c = 1 \end{cases} \\ \begin{pmatrix} unavailabilitP(p) + mnt\_slots_{c\_3} + time\_slots_{c\_2,c\_3} \\ + mnt\_slots_{c\_2} + time\_slots_{c\_1,c\_2} \end{pmatrix} plan_{p,c\_3,c\_4,d}\, plan_{p,c\_2,c\_3,d}\, plan_{p,c\_1,c\_2,d}, when \begin{cases} location_{c\_1} = 1 \\ or \\ mAg_{c\_1} = 1 \end{cases} \\ \left(unavailabilitP(p) + mnt\_slots_{c\_3} + time\_slots_{c\_2,c\_3}\right) plan_{p,c\_3,c\_4,d}\, plan_{p,c\_2,c\_3,d}, when \begin{cases} location_{c\_2} = 1 \\ or \\ mAg_{c\_2} = 1 \end{cases} \\ \left(unavailabilitP(p)\right) plan_{p,c\_3,c\_4,d}, when \begin{cases} location_{c\_3} = 1 \\ or \\ mAg_{c\_3} = 1 \end{cases} \end{cases}$$

(13)

$$start\_mntT_{p,c\_4} \geq \begin{cases} \begin{pmatrix} sunrise + mnt\_slots_{c\_3} + time\_slots_{c\_2,c\_3} \\ + mnt\_slots_{c\_2} + time\_slots_{c\_1,c\_2} \\ + mnt\_slots_{c\_1} + time\_slots_{c,c\_1} \end{pmatrix} plan_{p,c\_3,c\_4,d}\, plan_{p,c\_2,c\_3,d}\, plan_{p,c\_1,c\_2,d}\, plan_{p,c\_,c\_1,d}, \begin{cases} location_{c} = 1 \\ or \\ mAg_{c} = 1 \end{cases} \\ \begin{pmatrix} sunrise + mnt\_slots_{c\_3} + time\_slots_{c\_2,c\_3} \\ + mnt\_slots_{c\_2} + time\_slots_{c\_1,c\_2} \end{pmatrix} plan_{p,c\_3,c\_4,d}\, plan_{p,c\_2,c\_3,d}\, plan_{p,c\_1,c\_2,d}, \begin{cases} location_{c\_1} = 1 \\ or \\ mAg_{c\_1} = 1 \end{cases} \\ \left(sunrise + mnt\_slots_{c\_3} + time\_slots_{c\_2,c\_3} \right) plan_{p,c\_3,c\_4,d}\, plan_{p,c\_2,c\_3,d}, \begin{cases} location_{c\_2} = 1 \\ or \\ mAg_{c\_2} = 1 \end{cases} \\ \left(sunrise \right) plan_{p,c\_3,c\_4,d}, \begin{cases} location_{c\_3} = 1 \\ or \\ mAg_{c\_3} = 1 \end{cases} \end{cases} \quad (14)$$

Moreover, the starting time of maintenance activities depends on the spare parts availability, meaning that no maintenance procedures can be scheduled at time h until all required missing parts are available, as expressed in equation (15).

$$start\_mntT_{c\_1} \geq deliveryH_{c\_1},\ unavailabilityT_{c\_1} = 1 \quad (15)$$

Accordingly, based on the start maintenance time the end maintenance time for each system located in c is defined as:

$$end\_mntT_{c\_1} \geq start\_mntT_{c\_1} + mntT\_slots_{c\_1} + time\_slots_{c,c\_1} \sum_{d}^{D} plan_{c,c\_1,d} \quad (16)$$

Another constraint that refers to the end of the maintenance, corresponds to the daily timeslots. Specifically, the maintenance activities for each system c should be complete until the end of the day, as equation (17) denotes.

$$end\_mntT_{c\_1} \leq H \quad (17)$$

The estimation of end_mntT_{c} is used to asses the $off\_service_{c,d}$ variable, that denotes the total time slots until system's c repairment. The assessment of $off\_service_{c,d}$ is denoted in equation (18). Additionally, for the assessment of energy losses, the time slots when each system is out of service or operates under faulty conditions should be specified. This is achieved with the utilization of the $off\_serviceBin_{c,h,d}$ variable. The $off\_serviceBin_{c,h,d}$ is a binary variable, subjective to $off\_service_{c,d}$, as it is expressed in equation (19), and the constraints for its valid formulation are presented in equations (20) and (21).

$$off\_service_{c\_1,d} = \begin{cases} \left(end\_mntT_{c\_1} - ex\_time \right) \sum_{c}^{C} plan_{c,c\_1,d},\ \forall d = 1 \\ end\_mntT_{c\_1} \sum_{c}^{C} plan_{c,c\_1,d} + H \sum_{c}^{C} \sum_{d\_1}^{D} plan_{c,c\_1,d},\ \forall d > 1, d\_1 > d,\ c \neq c\_1 \\ end\_mntT_{c\_1} \sum_{c}^{C} plan_{c,c\_1,d} + \left(H - ex\_time \right) \sum_{c}^{C} \sum_{d\_1}^{D} plan_{c,c\_1,d},\ \forall d = 1,\ d\_1 > d,\ c \neq c\_1 \end{cases}$$

(18)

$$\sum_{h}^{H} off\_serviceBin_{c\_1,h,d} = off\_service_{c\_1} \tag{19}$$

$$off\_serviceBin_{c\_1,h,d} = 0, \forall h < ex\_time \tag{20}$$

$$off\_serviceBin_{c\_1,h,d} \leq \begin{cases} off\_serviceBin_{c\_1,h-1,d}, \forall d > 1,\ h > 1 \\ off\_serviceBin_{c\_1,h-1,d}, \forall d = 1,\ h > ex\_time \end{cases} \tag{21}$$

Finally, variables $total\_working\_hours_{p,d}$, $overtime_{p,d}$ and $eight\_hours_{p,d}$ are used for the salaries estimations and are subjective to the following constraints.

$$eight\_hours_{p,d} \leq total\_working\_hours_{p,d} / 8 \tag{22}$$

$$total\_working\_hours_{p,d} = \begin{cases} \sum_{c}^{C}\sum_{c\_1}^{C} plan_{p,c,c\_1,d} time_{c,c\_1} + mntT_{c\_1} + working\_hours_{p},\ d = 1 \\ \sum_{c}^{C}\sum_{c\_1}^{C} plan_{p,c,c\_1,d} time_{c,c\_1} + mntT_{c\_1},\ d > 1 \end{cases} \tag{23}$$

$$total\_working\_hours_{p,d} \leq 8 \cdot eight\_hours_{p,d} + overtime_{p,d} \tag{24}$$

2.4 Objective function

Considering the constraints, presented in the previous subsection, the objective function to be minimized is formulated as follows:

$$OF = Fuel\_cost + Energy\_cost + Salary + Severity\_cost \tag{25}$$

The assessment of $Fuel\_cost$, $Energy\_cost$ and $Salary$ are expressed in equations (26), (27) and (28), respectively. Moreover, the $Severity\_cost$ term is used as a penalty term in order to prioritize or not the repairment of a system, in regarding to weather conditions and fault's severity, as equation (29) indicates.

$$Fuel\_cost = fuel \cdot \sum_{p}^{P}\sum_{c}^{N}\sum_{c\_1}^{N}\sum_{d}^{D} plan_{p,c,c\_1,d} dist_{c,c\_1} \tag{26}$$

$$Energy\_cost = energy\_price \sum_{c}^{C}\sum_{d}^{D}\sum_{h}^{H} \left(forecasted_{c\_1,t,d} off\_serviceBin_{c\_1,t,d} \right) \tag{27}$$

$$Salary = s \cdot t \sum_{p}^{P}\sum_{d}^{D} \left(total\_working\_hours_{p,d} + eight\_hours_{p,d} overtime_{p,d} overtime\_rate \right) \tag{28}$$

$$\begin{aligned} Severity\_cost = M \cdot \sum_{p}^{P}\sum_{c}^{C}\sum_{c\_1}^{C}\sum_{d}^{D} severityF_{c\_1} \left(d \cdot plan_{c,c\_1,d\_1} + days_{c\_1} - 1 \right) + \\ + \sum_{c\_1}^{C}\sum_{d}^{D} \left(severityW_{c\_1,d} \sum_{c}^{N} plan_{c,c\_1,d} \right) \end{aligned} \tag{29}$$

3 MCDA TOOL

The actions that should be followed so that to restore the functionality of the faulty PV systems, such as the selections of the route, the personnel team and the system's repairment order, is a decision-making problem. Considering the previous, the MCDA tool, which is a widely used decision-making tool, is employed to address the problem of the PV systems' maintenance scheduling. The MCDA does not provide an optimal solution of the problem, but it has the ability to provide a ranking number for each alternative, i.e., for each feasible solution of the problem, by estimating several conflicting criteria, that can be either qualitative or quantitative. In this way, the experts have the opportunity to consider the results of the method and decide whether the best alternative will be accepted or rejected. There are several MCDA techniques, however, in the specific case, the TOPSIS method is selected due to its simplicity and flexibility [4].

3.1 TOSPIS METHOD

The TOPSIS method is based on the evaluation of the available alternatives, considering several criteria. In this case, the alternatives are the maintenance schedules that the technicians can follow, when the opened tickets refer to the different PV systems. The criteria are the parameters that affect the cost of the maintenance activities. The method's implementation is based on the assessment of two solutions, namely the ideal and anti-ideal, respectively. Additionally, the distances of each alternative from the ideal and anti-ideal solutions are estimated. Let A_i, $i = 1, 2, ..., m$ be the alternatives and z_j, $j = 1, 2, ..., n$ the criteria. The implementation of the TOPSIS method is based on the following steps:

Step#1. Build the decision matrix X with m alternative solutions and n criteria. The intersection of each criterion and alternative is denoted with x_{ij}:

$$X = \begin{bmatrix} & z_1 & z_2 & \cdots & z_n \\ A_1 & x_{11} & x_{12} & \cdots & x_{1n} \\ A_2 & x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ A_m & x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (30)$$

Step#2. Construct the $R = \left(r_{i,j}\right)_{m \times n}$ matrix, which is the normalized matrix X. Each $r_{i,j}$ element is denoted as:

$$r_{i,j} = \frac{x_{i,j}}{\sqrt{\sum_{k=1}^{m} x_{k,j}^2}}, \; i = 1, 2, ..., m, \; j = 1, 2, ..., n \quad (31)$$

Step#3. Construct the weighted normalized decision matrix V as:

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix} \tag{32}$$

where each element $v_{i,j}$ is denoted as:

$$v_{i,j} = w_{i,j} r_{i,j} \tag{33}$$

where, $w_{i,j}$ is the weight assigned to the connection of solution $i\,(A_i)$ with criterion $j\,(z_j)$. The weights are defined according to the knowledge of the expert, directly affects the results of the process and their sum must be equal to 1. The user can alternate the weights of each criterion so to satisfy his/her needs. Calculate the ideal (V^+) and the inti-ideal (V^-) alternative as:

$$A^+ = \left\{ \left\langle \max v_{i,j} \middle| j \in J \right\rangle, \left\langle \min v_{i,j} \middle| j \in J' \right\rangle \right\} \tag{34}$$

$$A^- = \left\{ \left\langle \min v_{i,j} \middle| j \in J \right\rangle, \left\langle \max v_{i,j} \middle| j \in J' \right\rangle \right\} \tag{35}$$

where $J = \{1, 2, ..., n\}$ denote the criteria having a positive impact to the solution and $J' = \{1, 2, ..., n\}$ are the criteria having a negative impact to the solution. Considering this, the ideal solution is the maximum value of the positive impact and the minimum of the negative impact. On the contrary, the anti-ideal solution is the minimum value of the positive impact and the maximum value of the negative impact.

Step#4. Calculate the distances between each alternative i and: a) the ideal-solution and b) the anti-deal solution.

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{i,j} - A^+ \right)^2},\ i = 1, 2, ..., m \tag{36}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{i,j} - A^i \right)^2},\ i = 1, 2, ..., m \tag{37}$$

Step#5. Calculate the relative proximity of each alterative i to the positive ideal solution

$$RC_i = \frac{d^-}{d^- + d^+} \tag{38}$$

Step#6. Sort the alternatives i according to the values of RC_i.

3.2 MCDA concept design

For the development of the TOPSIS method 14 criteria have been considered as presented in Table 5.

Table 5. MCDA criteria.

Code	MCDA criteria	Quantitative	Qualitative

z1	Distance between the locations	✓	
z2	Time needed to travel between the locations	✓	
z3	Type of route to the PV site		✓
z4	History of fault occurrences on the PV site		✓
z5	System complexity		✓
z6	Level of personnel expertise		✓
z7	Urgency		✓
z8	Unavailability of personnel	✓	
z9	Working hours	✓	
z10	End of maintenance activities	✓	
z11	Transportation time of spare parts	✓	
z12	Forecasted PV power		✓
z13	Severity of fault		✓
z14	Severity of weather conditions		✓

The qualitative criteria can be separated into categories, as they are presented in Table 6. Since several categories can lie under the same criterion, we have separated them into levels and each level corresponds to a value within the range of [1,9]. The ranged values are used for the construction of the decision matrix. In criteria 1, 4 and 8, higher values of levels denote more favorable conditions. However, in criteria 2, 3, 5, 6 and 7, higher values of levels indicate that the faults should be repaired as soon as possible.

Table 6. Description of qualitative criteria.

No.	Criterion	Categories	Levels	Values in range 1-9
1	Type of route to the PV site	Earthen	Low	3
		Gravel	Medium	5
		Asphalt	High	8
2	History of fault occurrences on the PV site	Rarely	Low	3
		Often	Medium	5
		Most often	High	8
3	System`s complexity	Low	Low	3
		Medium	Medium	5
		High	High	8
4	Level of personnel1s	Novice	Low	3
		Advanced beginner		

	expertise	Competent	Medium	5
		Proficient	High	8
		Expert		
5	Urgency	The system will be repaired two days after	High	3
		The system will be repaired the next day	Medium	5
		The system will be repaired within the current day	Low	8
6	Forecasted PV power	Average forecasted power < Average capacity	Low	3
		Average forecasted power = Average capacity	Medium	5
		Average forecasted power > Average capacity	High	8
7	Severity of fault	The level for each type of fault is presented in Table 2.	Negligible	2
			Marginal	4
			Critical	6
			Catastrophic	8
8	Severity of weather conditions	Sunny	Sunny	9
		Cloudy	Cloudy	7
		Rainy	Rainy	5
		Stormy	Stormy	3
		Snowy	Snowy	1

For the construction of the decision matrix the qualitative criteria should be assigned to values within the range of [1,9]. In order to achieve this, we use the minimum and the maximum value of the criterion. Additionally, we consider whether the criterion belongs benefit or cost criteria since higher values denotes more beneficial conditions. For example, the distance between the locations corresponds to a cost criterion since long distances has as a result the increment of fuel cost. In Table 7, the pseudocode for the assignment of the quantitate criteria to the ranged values is presented.

Table 7. Assignment of criteria values within the range of [1, 9].

Convert criterion values into ranged values

```
criterion_values = values of alternatives for the specific criterion
length = total alternatives

minimum = minimum value of criterion_values
maximum = maximum value of criterion_values
step = (minimum – maximum) / 9

bin = array(9x2)
ranged_criterion_values = array(length x 1)

bin[1][1] = minimum
bin[1][2] = maximum

for j=2 to 9:
    for i=1 to 2:
        if j<9 or i=1:
            bin[j][i] = bin[j-1][i] + step
            else:
            bin[j][i] = bin[j-1][i] + step + 1

for j=1 to length:
    for i=1 to 9:
        if i=1:
            if criterion_values[j] >= bin[i][1] and criterion_values[j] <= bin[i][2]:
                ranged_criterion_values[j] = 9 – i
        else:
            if criterion_values[j] > bin[i][1] and criterion_values[j] <= bin[i][2]:
                ranged_criterion_values[j] = 9 – i
```

A significant criterion of the model is the working hours (z9). Based on the 8-hour working day, when the working hours exceed the 8-hour period, the technicians need to work overtime. In this case, the real values are assigned to ranged values less than. However, when the working hours are less or equal to eight, then the real values of criterion are set equal to 9. Finally, in case the working hours per day exceed twelve, then the criterion is assigned to the minimum value of the range, i.e., 1.

Additionally, significant attention should be paid at criterion z10, that examines whether the systems' repayment has been completed by the end of the day. The value of the criterion is set to 0, if the maintenance activities are completed within the same day, or 1, if the maintenance activities are completed the next day.

4 INTEGRATED MODEL

One of the main differences between MINLP and TOPSIS refers to the input parameters, as they are illustrated in Table 8. From Table 8 it is clear that the difference lies at the type of the parameters, since qualitative criteria can be additionally used in TOSPIS method. This is the main advantage of the TOPSIS method over the MILP model, since the latter provides an optimal maintenance plan without considering significant parameters, such as the system's complexity, the level of personnel expertise, etc.

One of the main drawbacks of TOPSIS method is that the ranking number of each alternative is derived based on the weights that are assigned to each criterion. So, the results provided by the tool are subjective to the expertise knowledge, since the model requires the assignment of weights for each criterion. Additionally, for the assessment of the ranking number the fuel cost and the cost of the energy losses are not considered.

Table 8. Input parameters/ criteria of MILP and MCDA model.

Inputs/Criteria	MILP	MCDA
Distance between the locations	✓	✓
Time needed to travel between the locations	✓	✓
Type of route to the PV site	×	✓
History of fault occurrences on the PV site	×	✓
System`s complexity	×	✓
Level of personnel`s expertise	×	✓
Urgency	×	✓
Unavailability of personnel	✓	✓
Working hours	✓	✓
End of maintenance activities	✓	✓
Transportation time of spare parts	✓	✓
Forecasted PV power	✓	✓
Severity of fault	✓	✓
Severity of weather conditions	✓	✓

4.1 Concept design of integrated model

In order to exploit the advantages of the MINLP model and the TOSPIS method and deal with their drawbacks, an integrated optimization tool has been developed. Figure 5 illustrates the general structure of the integrated tool. MINLP and MCDA, are executed in parallel, when a new ticket opens. The MINLP model provides an optimal maintenance plan, considering the cost minimization, and estimates the maintenance cost. In contrast, the TOPSIS method provides a ranking number for each alternative. Afterwards, the user selects a solution, considering the ranking number, and the cost of the maintenance plan is estimated. Accordingly, the maintenance cost provided by the MINLP model and the cost derived from the selected solution of the MCDA method are compared. From the comparison the maintenance schedule is selected. In this way, we can ensure that the maintenance cost of the selected maintenance plan is not excessively higher than the minimum cost provided by the MILP model.

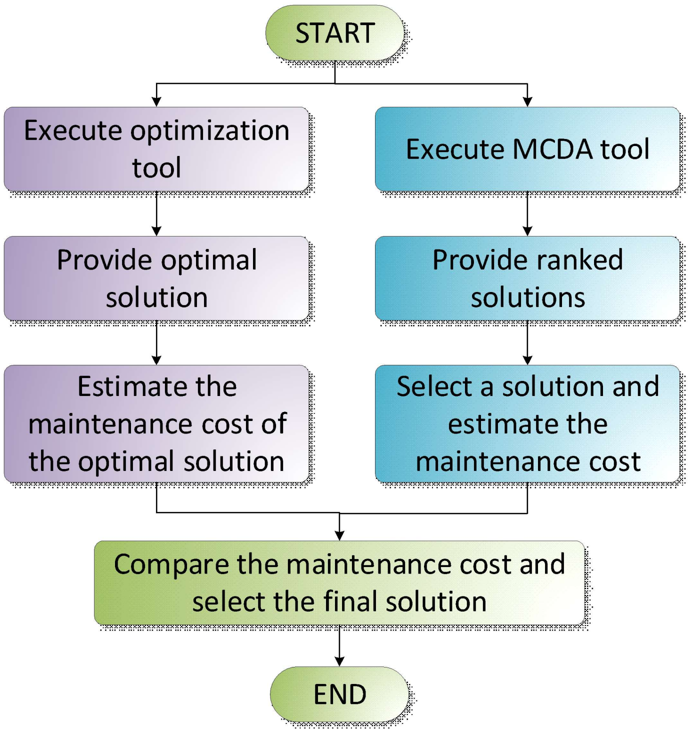

Figure 5. General structure of the integrated tool.

5 Conclusions

At the present Deliverable, an integrated tool, consisting of the MINLP model and the MCDA method, as well as the formulation of the MINLP model, i.e., the parameters, the variables, the constraints and the objective function of the model, have been presented. The structure of the integrated model has been defined to exploit the merits of the MINLP and MCDA, and eliminate their drawbacks. The results of the integrated tool will be presented in the next deliverable that is dedicated to the technoeconomic assessment of the maintenance tool.

6 References

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