PANAMA

PRESCRIPTIVE SOLAR ANALYTICS & ADVANCED WORKFORCE MANAGEMENT

D3.5

Techno-economic assessment

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

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Definition of Acronyms

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 present the technoeconomic assessment of the integrated model, that provides a plan for the maintenance actions that should be followed in order to retore the functionality of faulty PV systems. The document follows the project`s structure and recalls the following tasks:

- D3.2: “PV generation forecasting models”
- D3.3: “Decision analysis and results”
- D3.4: “Integrated optimization tool”

The deliverable is separated into three main sections. At the first section, a short description of the integrated model is presented. The second section includes the formulation of the examined scenario for the model’s evaluation, while at the final section the technoeconomic assessment is presented.

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].

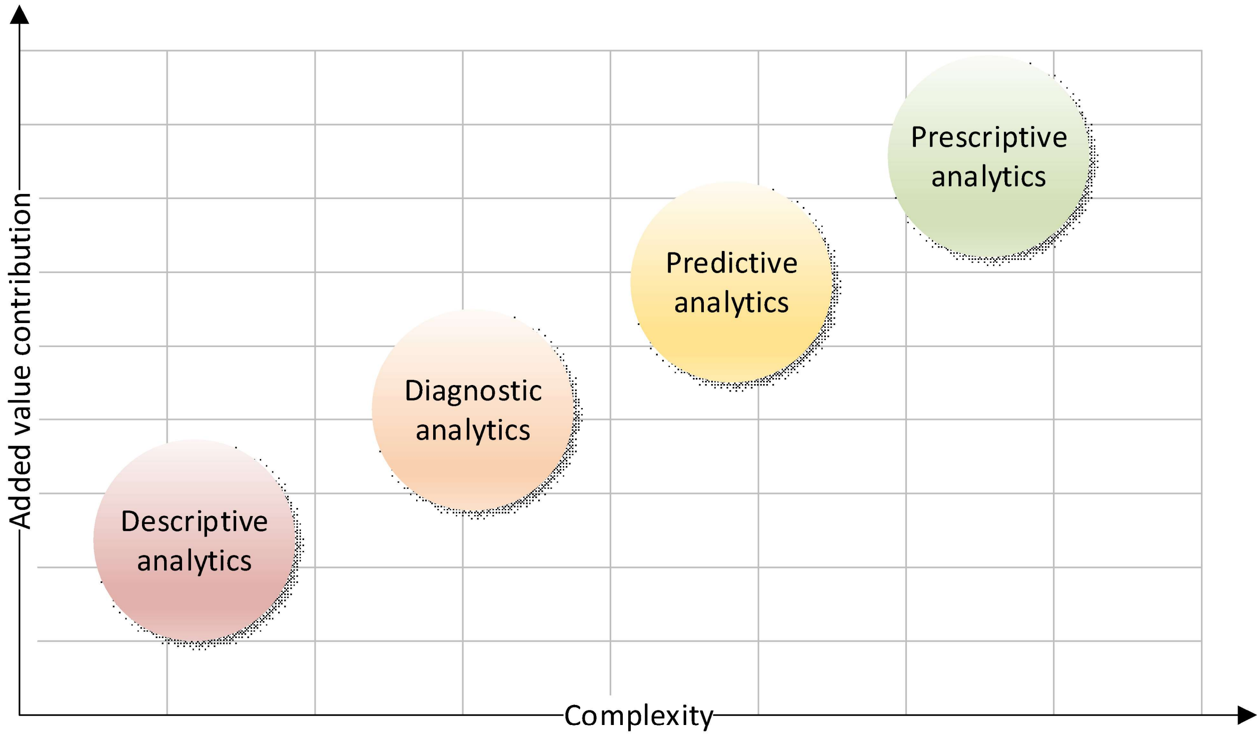

Figure 1. Description of business analytics.

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, the present Deliverable highlights the necessity of prescriptive analytics deployment, by presenting the technoeconomic assessment of an integrated optimization tool, that consists of the MINLP model and the MCDA method and provides a maintenance plan when multiple systems are under faulty conditions. The results indicate that that the model’s deployment can significantly reduce the cost of the maintenance activities.

2 INTEGRATED TOOL DESCRIPTION

The implementation of the integrated model has been described in Deliverable 3.4. The integrated tool comprises of the MINLP model and the MCDA method, which are executed concurrently, each time a new fault occurs as it is presented in Figure 2.

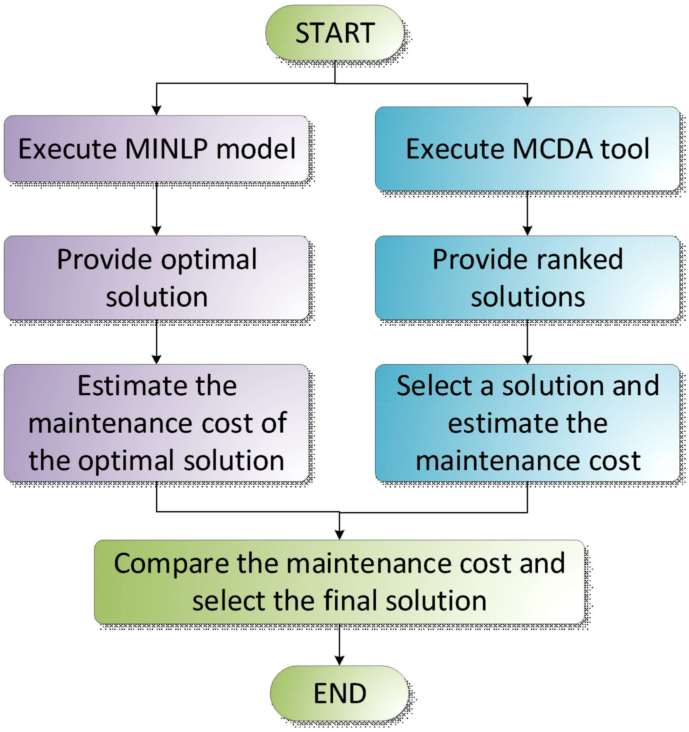

Figure 2. General structure of integrated tool.

The MINLP model is executed and provides an optimal solution in terms of minimizing the fuel cost ($Fuel\_cost$), the salary of the personnel ($Salary$) and the energy losses ($Energy\_cost$) due to faults. Additionally, a penalty term ($Severity\_cost$) is used in order to prioritize or not the maintenance activities considering the severity of fault and the meteorological conditions at the PV site. The objective function to be minimized is presented in Equation (1). On the other hand, the MCDA tool does not provide an optimal solution but ranking numbers for each feasible solution. The development of the MINLP model and the MCDA method have been presented in Deliverables 3.4 and 3.3, respectively.

$$OF = Fuel\_cost + Energy\_cost + Salary + Severity\_cost \quad (1)$$

Although the MCDA method does not provide the optimal solution, it overcomes the main drawback of the MINLP model and has the ability to get not only quantitative but also qualitative criteria, as they are presented in Table 1. In this way the ranking number of each solution derives considering significant information such as the level of personnel expertise, the type of road etc. After the execution of the MCDA method, the user has to select a solution and compare its maintenance cost with the maintenance cost derived from the MINLP model. In this way the integrated model ensures that the cost of the selected maintenance plan is not extremely higher that the optimal cost provided by the MINLP model.

Table 1. 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	✓	✓

3 DATA DESCRIPTION

For the estimation of the results the data of the project has been utilized. Specifically, the data refers to eight PV plants with nominal DC power 1,115 kW, and includes data series of produced power, solar irradiation, modules' temperature and ambient temperature, with recording frequency of 15 min. The detailed information of the project's data is presented in Table 2. For each plant a system code has been set for its identification.

Table 2. PV systems' information.

PV system	Location	System/Location code	Nominal capacity (kW)	Recording frequency
Eragro_9	Guragac	$c1$	1155,00	15 min
Girayhan_3	Guragac	$c2$	1155,00	15 min
Eragro_8	Karasinir	$c3$	1149,00	15 min
Eragro_5	Secme	$c4$	1155,00	15 min
Eragro_7	Yenimescit	$c5$	1149,00	15 min
Eragro_6	Yenimescit	$c6$	1149,00	15 min

In order to estimate the power losses in terms of fault's type the following assumptions have been made about the structure of the plants, based on the structure of a real PV plant of 1 MW capacity:

1. Eight inverters have been installed consisting of 10 MPPTs and 20 input strings, meaning that two strings can be connected to each MPPT.
2. Each system comprises of 1850 panels with nominal capacity 540 Wp.

Additionally, since the number of modules, connected to each string, is a key factor to estimate the power losses at string level, two different connections have been assumed, as they are presented in Table 3. More specifically, at the first structure 232 modules are connected to seven out of ten inverter's MPPTs and two strings are connected to each MPPT. This connection has been implemented to five string inverters. On the other hand, at the second structure, 230 modules are connected to the inverter. As previous, seven out of ten MPPTs are used and two strings are connected to each MPPT channel. This connection has been implemented to three out of eight inverters.

Table 3. Connection of modules to inverter.

	Structure 1		Structure 2	
	Number of strings	**Number of modules per string**	**Number of strings**	**Number of modules per string**
MPPT1	2	17	2	17
MPPT2	2	17	2	17
MPPT3	2	17	2	17
MPPT4	2	17	2	16
MPPT5	2	16	2	16
MPPT6	2	16	2	16
MPPT7	2	16	2	16
MPPT8	-	-	-	-
MPPT9	-	-	-	-
MPPT10	-	-	-	-

Since the location of the maintenance agency should be specified, it is assumed that is cited in Secme. The code of the location has been set to *c7*. Based on this, the distances between the locations as well as the travelling time between the locations are presented in Table 4 and Table 5, respectively.

Table 4. Distances between the systems (km).

	c1	***c2***	***c3***	***c4***	***c5***	***c6***	***c7***
c1			6,3	52,4	26,4	26,4	6,3
c2			6,3	52,4	26,4	26,4	6,3
c3	6,3	6,3		52,2	27,3	27,3	
c4	52,4	52,4	52,2		46,2	46,2	52,2
c5	26,4	26,4	27,3	46,2			27,3
c6	26,4	26,4	27,3	46,2			27,3
c7	6,3	6,3		52,2	27,3	27,3	

Table 5. Travelling time between the locations (min).

	c1	c2	c3	c4	c5	c6	c7
c1			12	41	39	39	12
c2			12	41	39	39	12
c3	12	12		43	41	41	0
c4	41	41	43		40	40	43
c5	39	39	41	40			41
c6	39	39	41	40			41
c7	12	12	0	43	41	41	

4 FORMULTION OF THE EXAMINED SCANARIO

For the validation of the integrated tool an examined scenario has been developed consisting of four test cases. The detailed information of the tickets included in each test case are presented in Table 6, 7, 8 and 9.

Table 6. Test_case#1: Tickets description.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_6	c6	26/2/2021 9:30	Main switch open and does not reclose again	1	12.5	3
Eragro_7	c5	26/2/2021 9:40	Six Broken/Burned Connectors at a combiner box	5	5.36	2
Eragro_9	c1	26/2/2021 17:32	Polluted air filter - derating	4	2.5	1
Erago_7	c5	26/2/2021 17:42	Main switch open and does not reclose again	1	12.5	3
Eragro_6	c6	27/2/2021 10:03	Fan failure and overheating	4	2.5	1
Eragro_5	c4	27/2/2021 10:04	Switch failure/damage	4	12.5	3
Eragro_9	c1	27/2/2021 10:15	Switch failure/damage	4	12.5	3

Table 7. Test_case#2: Tickets description.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_6	c6	15/5/2021 17:17	Switch failure/damage	4	12.5	3
Eragro_7	c5	15/5/2021 17:27	Fan failure and overheating	4	2.5	1
Eragro_9	c1	15/5/2021 18:46	Main switch open and does not reclose again	1	12.5	3
Girayhan_3	c2	15/5/2021 18:59	Switch failure/damage	4	12.5	3
Eragro_8	c3	15/5/2021 19:15	Polluted air filter - derating	4	2.5	1
Erago_5	c4	15/5/2021 19:23	Main switch open and does not reclose again	1	12.5	3

Table 8. Test_case#3: Tickets description.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_6	c5	17/6/2020 13:01	Main switch open and does not reclose again	1	12.5	3
Eragro_7	c6	17/6/2020 13:10	Fan failure and overheating	4	2.5	1
Eragro_9	c1	17/6/2020 17:17	Switch failure/damage	4	12.5	3
Girayhan_3	c2	17/6/2020 17:24	Switch failure/damage	4	12.5	3

Table 9. Test_case#4: Tickets description.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Erago_5	c4	23/9/2020 9:38	Fan failure and overheating	4	2.5	1
Eragro_9	c1	23/9/2020 9:41	Main switch open and does not reclose	1	12.5	3

			again			
Eragro_6	c6	23/9/2020 9:41	Two Broken/Burned Connectors	3	5.36	2
Eragro_7	c5	23/9/2020 9:47	Polluted air filter - derating	4	2.5	1
Girayhan_3	c2	23/9/2020 12:22	Main switch open and does not reclose again	1	12.5	3
Eragro_8	c3	23/9/2020 12:25	Switch failure/damage	4	12.5	3

For the execution of the MCDA tool, the user should define the weights of the criteria. In Table 10 the weight that have been set for each criterion are presented. Moreover, Table 11 includes the values of the qualitative criteria referring to system's complexity and history of fault occurrences to the PV site, while in Table 12 the expertise of each team is defined. Finally, the type of road between the locations is included in Table 13.

Table 10. Weight assignment per criterion.

MCDA criteria	Weight
Distance between the locations	**0,06**
Time needed to travel between the locations	0,06
Type of route to the PV site	0,06
History of fault occurrences on the PV site	0,06
Time needed to repair faulty PV plants	0,02
System complexity	0,07
Level of personnel expertise	0,09
Urgency	0,09
Availability of personnel	0,08
Working hours	0,08
Spare parts availability	0,08
Forecasted PV power	0,08
Severity of fault	0,09
Severity of weather conditions	0,08
total	**1**

Table 11. Systems' complexity and history of fault occurrences.

PV system	System-Location code	History of fault occurrences	System complexity
Eragro_9	*c*1	Medium	High
Girayhan_3	*c*2	Low	Medium
Eragro_8	*c*3	Low	Low
Eragro_5	*c*4	High	Medium
Eragro_7	*c*5	High	High
Eragro_6	*c*6	Medium	Medium

Table 12. Personnel expertise.

Team	Level of expertise
*p*1	Competent
*p*2	Expert

Table 13. Type of road between the locations.

	*c*1	*c*2	*c*3	*c*4	*c*5	*c*6	*c*7
*c*1			Asphalt	Asphalt	Asphalt	Asphalt	Asphalt
*c*2			Asphalt	Asphalt	Asphalt	Asphalt	Asphalt
*c*3	Asphalt	Asphalt		Asphalt	Asphalt	Asphalt	Asphalt
*c*4	Asphalt	Asphalt	Asphalt		Asphalt	Asphalt	Asphalt
*c*5	Asphalt	Asphalt	Asphalt	Asphalt			Asphalt
*c*6	Asphalt	Asphalt	Asphalt	Asphalt			Asphalt
*c*7	Asphalt	Asphalt		Asphalt	Asphalt	Asphalt	

5 Results

The results presented in the following subsections include detailed information about the maintenance cost each time the MINLP model and the MCDA method are executed. Additionally, the cost of the base model is included. The base model refers to the maintenance activities that are executed without the deployment of the integrated tool. Specifically, the prioritization of maintenance is based on the following assumptions:

1. The faults are prioritized considering the faults severity.
2. In case the severity of two faults is equal then the priority is based on the system's nominal capacity.
3. In case the severity of two tickets is equal and the nominal capacity of the systems is equal then the priority is based on the time the ticket opens.

5.1 Test_case#1

5.1.1 Iteration#1

At Iteration#1 two tickets open referring to system *c*5 and *c*6, as presented in Table 14. Specifically, the fault detected in *c*5 refers to six broken interconnections between the strings and the inverter. However, there are two different string structures, i.e., string consisting of 17 or 16 modules, with nominal DC power 9.180 kW and 8.640 kW. Considering the small deviation between the two structures, for shake of simplicity we assume that a broken interconnection result to 0.89% energy losses, as it is defined in equation (2).

$$Losses(\%) = \left(\frac{1}{(Number\ of\ inverters) \cdot (Number\ of\ strings)} \right) \cdot 100\% \quad (2)$$

Table 14. Test_case#1 Iteration#1: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_6	*c*6	26/2/2021 9:30	Main switch open and does not reclose again	1	12.5	3
Eragro_7	*c*5	26/2/2021 9:40	Six Broken/Burned Connectors at a combiner box	5	5.36	2

The maintenance plan derived from the MINPL and the MCDA method are presented in Figure 3. Additionally, at Table 15 includes the detailed maintenance cost of: a) the optimal solution, provided by the MINLP model, b) the selected solution, provided by the MCDA method and c) the plan of the base model. At this iteration the optimal solution of MINLP model and the selected solution of MCDA method coincides in terms or the prioritization, but the selected team differs. The team's selection at MINLP solution is stochastic, considering that both teams are available and none of them has previously undertake any maintenance activity. Despite, the selection of *p*2 team in MCDA method is based on the high level of personnel expertise. Considering this the final selected maintenance plan is based on the MCDA tool.

Detailed information about the working hours of personnel is provided in Table 15. Since the selection of team is the only difference between MINLP and MCDA, the maintenance cost remains the same. However, when it comes to the base model, the two faults are assigned to both teams. So, the increased cost is due to the higher fuel expenses and personnel's salary.

Based on the cost of the solution, and considering the ability of the MCDA tool to deal with qualitative variables, the selected solution derives from the MCDA method. This is due to higher level of personnel expertise. The information about the repayment time of the systems and the daily working hours according to the selected plan are presented in Table 16 and Table 17 respectively.

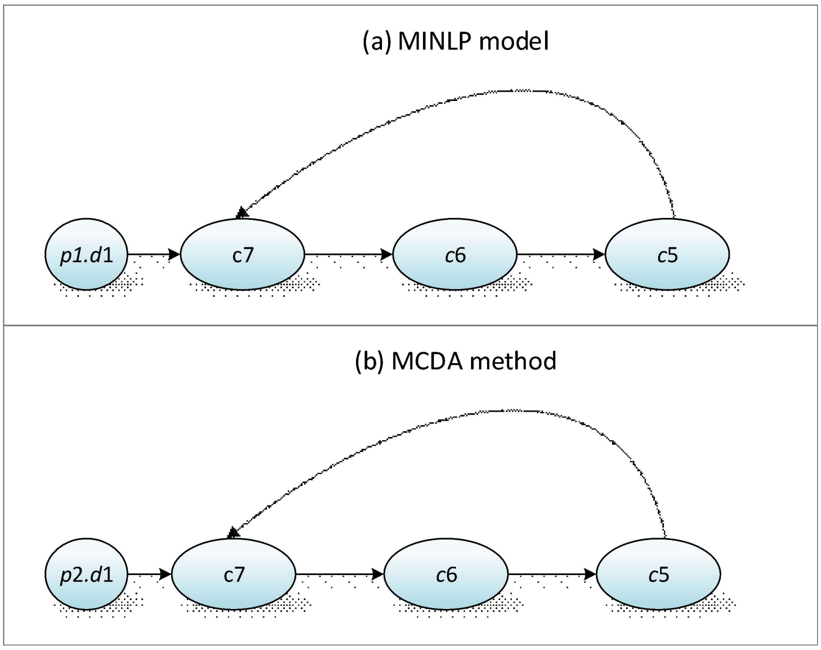

Figure 3. Test_case#1 Iterration#1: maintenance plan.

Table 15. Test_case#1 Iteration#1: Detailed cost.

PV system	MINLP model	MCDA method	Base model
Maintenance plan	*p*1.*d*1: *c*7->c6->c5	*p*2.*d*1: *c*7->c6->c5	*p*2.*d*1: *c*7->c6 *p*1.*d*1: *c*7->c5
Energy losses (€)	29.04	29.04	24.07
Salary (€)	42.93	42.93	53.87
Fuel cost (€)	6.552	6.55	13.1
Total	78.52	78.52	91.04

Table 16. Test_case#1 Iteration#1: Repairment information

	c6	*c5*
Start maintenance	9:30	11:30
End maintenance	11:15	14:30

Table 17. Test_case#1 Iteration#1: Daily working hours.

	d1	*d2*
*p*1	-	-
*p*2	5.361	-

5.1.2 Iteration#2

At the second iteration (Iteration#2) the model is executed regarding the tickets referring to systems *c*1 and *c*5 (Table 18). In this case the solution of the MINLP model, the selected MCDA alternative and the solution of the base model coincides, as it is presented in Figure 4. Additionally, the cost for each category, i.e., energy losses, salary and fuel cost, are included in Table 19.

Table 18. Test_case#1 Iteration#1: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_9	*c*1	26/2/2021 17:32	Polluted air filter - derating	4	2.5	1
Erago_7	*c*5	26/2/2021 17:42	Main switch open and does not reclose again	1	12.5	3

Table 19. Test_case#1 Iteration#2: Detailed cost.

PV system	MINLP model	MCDA method	Base model
Maintenance plan	*p*1.*d*1: *c*7 ->c1 *p*2.*d*1: *c*7 ->c5	*p*1.*d*1: *c*7 ->c1 *p*2.*d*1: *c*7 ->c5	*p*1.*d*1: *c*7 ->c1 *p*2.*d*1: *c*7 ->c5
Energy losses (€)	1.19	1.19	1.19
Salary (€)	54.13	54.13	54.13
Fuel cost (€)	8.06	8.06	8.06
Total (€)	63.39	63.39	63.39

The detailed information about the start time and the end time of the maintenance procedures is presented in Table 20.

Table 20. Test_case#1 Iteration#2: Repairment information.

	*c*1	*c*5
Start maintenance	17:45	19:45
End maintenance	19:30	22:00

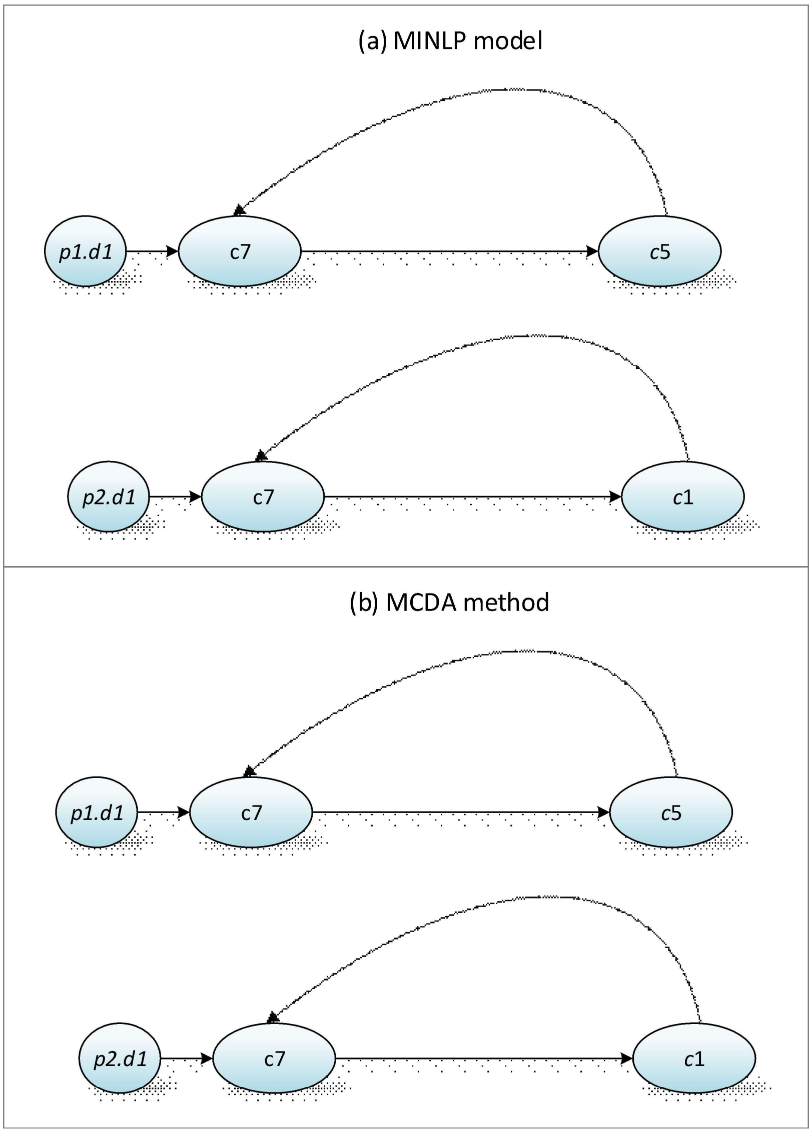

Figure 4. Test_case#1 Iterration#2: Maintenance plan.

Additionally, in Table 21 the daily working hours of the personnel is presented. Considering that team *p*2 has also repaired the previous tickets that opened within the same day, the working time of previous iteration also included.

Table 21. Test_case#1 Iteration#2: Daily working hours.

	d1	*d2*
*p*1	4.4	-
*p*2	7.727	-

5.1.3 Iteration#3

Iteration#3 is executed at 27/2 considering the faults detected at *c*1, *c*4 and *c*6, as presented in Table 22. At this iteration the optimal solution of MINLP model and the alternative with the highest ranking number selected by the MCDA method differs, as demonstrated in Figure 6. Specifically, although the MINLP model indicates that all maintenance activities should be executed within the same day, the MCDA alternative propose to complete the repairment of system located in *c*6 the next day. This decision is based on the followings:

1. The level of fault severity at *c*6 is low.
2. The repairment of all systems within the same day has as a result the teams to work overtime, as presented in Table 24.

Although the MCDA method considers the daily working hours of personnel, it does not take into account the cost of personnel salary and lead to higher salary cost. This is clear in Table 23, where the cost of the solutions is presented. Considering the aforementioned, the final solution is selected based on the MINLP model. The information about the repairment time of the systems is included in Table 25.

Table 22. Test_case#1 Iteration#3: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_6	*c*6	27/2/2021 10:03	Fan failure and overheating	4	2.5	1
Eragro_5	*c*4	27/2/2021 10:04	Switch failure/damage	4	12.5	3
Eragro_9	*c*1	27/2/2021 10:15	Switch failure/damage	4	12.5	3

Table 23. Test_case#1 Iteration#3: Detailed cost.

PV system	MINLP model (Final selection)	MCDA method	Base model
Maintenance plan	*p*1.*d*1: *c*7 ->c1 *p*2.*d*1: *c*7 ->c4->c6	*p*1.*d*1: *c*7 ->c1 *p*2.*d*1: *c*7 ->c4 *p*2.*d*2: *c*7 ->c6	*p*1.*d*1: *c*7 ->c6-> c1 *p*2.*d*1: *c*7 ->c4
Energy losses (€)	101.19	101.5	116.49
Salary (€)	119.04	121.6	122.19
Fuel cost (€)	16.6	20.59	19.73
Total (€)	236.83	243.69	258.41

Table 24. Test_case#1 Iteration#3: Daily working hours.

	d1	*d2*
*p*1	4.4	-
*p*2	10.78	-

Table 25. Test_case#1 Iteration#3: repairment information.

	c1	*c4*	*c6*
Start maintenance	10:15	10:15	15:15
End maintenance	14:30	15:00	22:00

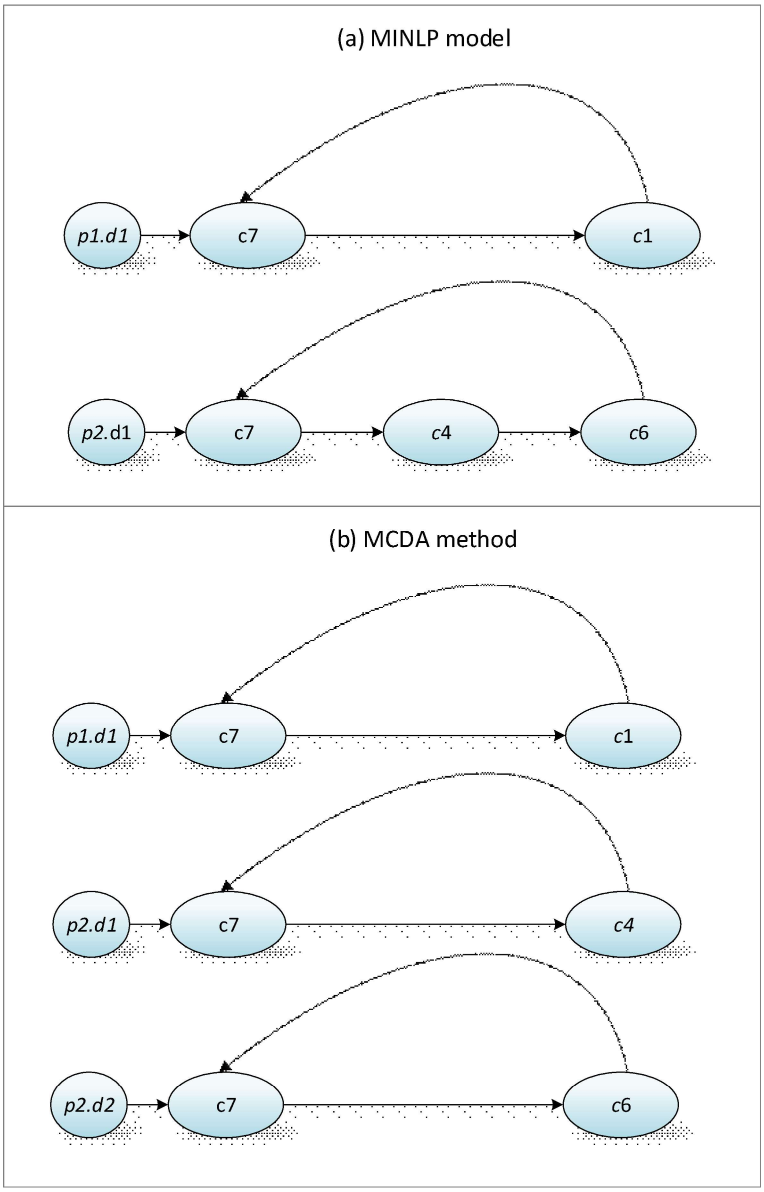

Figure 5: Test_case#1 Iterration#3: Maintenance plan

5.2 Test_case#2

5.2.1 Iteration#1

At the first iteration, the model has to handle two tickets referring to system located in *c*6 and *c*5. The faults are included in Table 26. Additionally, Table 27 presents the cost of the optimal solution, the selected alternative based on MCDA and the maintenance plan according to the base model. Considering the required maintenance time for both tickets, the faults cannot be restored by one team within the same day so the MINLP model as well as the MCDA method indicate that the repairment of each system should be assigned to each team, while the team's selection for each repairment coincides. This is also in compliance with the base model. Considering these, there is no difference between the maintenance cost of the integrated model's method and the maintenance plan of the base model. Finally, the detailed information about the total daily working hours as well as the start and end time of the maintenance activities are presented in Tables 28 and 29, respectively.

Table 26. Test_case#2 Iteration#1: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_6	c6	15/5/2021 17:17	Switch failure/damage	4	12.5	3
Eragro_7	c5	15/5/2021 17:27	Fan failure and overheating	4	2.5	1

Table 27. Test_case#2 Iteration#1: Detailed cost.

PV system	MINLP model (Final selection)	MCDA method	Base model
Maintenance plan	*p*1.*d*1: *c*7 ->c6 *p*2.*d*1: *c*7 ->c5	*p*1.*d*1: *c*7 ->c6 *p*2.*d*1: *c*7 ->c5	*p*1.*d*1: *c*7 ->c6 *p*2.*d*1: *c*7 ->c5
Energy losses (€)	5.48	5.48	5.48
Salary (€)	85.87	85.87	85.87
Fuel cost (€)	13.1	13.1	13.1
Total (€)	104.45	104.45	104.45

Table 28. Test_case#2 Iteration#1: Daily working hours.

	d1	*d2*
*p*1	5.37	-
*p*2	5.37	-

Table 29. Test_case#2 Iteration#1: Repairment information.

	c5	*c6*
Start maintenance	17:30	17:30

End maintenance	22:15	22:15

5.2.2 Iteration#2

The tickets at the second iteration are presented in Table 30, while the cost of the MINLP model, the selected MCDA solution and the solution of the base case are included in Table 31. Both the total cost of the optimal plan derived from the MINLP model and the selected plan of the MCDA method is the same and according to the maintenance schedule the repairment of both systems are scheduled for the next day. Yet for the system's repairment, the solution with the highest-ranking number of the MCDA indicates that the maintenance activities should be completed from team *p*2 considering the higher level of expertise. On the other side, at the base case the maintenance of system located in *c*1 is executed within the same day. This has as a result the increment of both salary and fuel cost.

According to these, the final decision of the integrated model derives from MCDA method. The details about the total working hours of personnel as well as the start and end repairment time of the systems are included in Table 32 and Table 33, respectively.

Table 30. Test_case#2 Iteration#2: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_9	c1	15/5/2021 18:46	Main switch open and does not reclose again	1	12.5	3
Girayhan_3	c2	15/5/2021 18:59	Switch failure/damage	4	12.5	3

Table 31. Test_case#2 Iteration#2: Detailed cost.

PV system	MINLP model	MCDA method (Final selection)	Base model
Maintenance plan	*p*1.*d*2: *c*7 ->c1->*c*2	*p*2.*d*2: *c*7 ->c1->*c*2	*p*1.*d*2: *c*7 ->c1 *p*2.*d*2: *c*7 -> *c*2
Energy losses (€)	0.76	0.76	0.76
Salary (€)	43.2	43.2	46.4
Fuel cost (€)	1.51	1.51	3.02
Total (€)	46.22	46.22	50.18

Table 32. Test_case#2 Iteration#2: Daily working hours.

	d1	*d2*
*p*1	5.37	5.4
*p*2	5.37	-

Table 33. Test_case#2 Iteration#2: Repairment information.

	*c*1	*c*2
Start maintenance	00:00	01:30
End maintenance	01:15	05:30

5.2.3 Iteration#3

Since at the next execution of the model the systems at the first iteration have not been repaired yet, at this iteration the tickets of the previous one (Ieration#2) have been also considered. Specifically, the new tickets refer to systems *c*3 and *c*4 However, the tickets for systems *c*1 and *c*2 are also included, as it is presented in Table 34.

Table 34. Test_case#2 Iteration#3: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_9	c1	15/5/2021 18:46	Main switch open and does not reclose again	1	12.5	3
Girayhan_3	c2	15/5/2021 18:59	Switch failure/damage	4	12.5	3
Eragro_8	c3	15/5/2021 19:15	Polluted air filter - derating	4	2.5	1
Erago_5	c4	15/5/2021 19:23	Main switch open and does not reclose again	1	12.5	3

At this iteration the maintenance cost of the base model and the selected MCDA solution coincides, as it presented in Table 35. The main difference is detected at the maintenance prioritization of *c*1 and *c2* as well as the team's selection the systems' repairment. This is based on the fact that at the base model the team's selection is stochastic.

The final decision of the maintenance plan is based on the lower total cost provided by the MINLP model. Although, this solution has the highest cost in terms of energy losses, the deviation is negligible, and the solution provides the lowest cost of personnel salary. Table 36 provides information about the total working hours of personnel per day, while Table 37 includes the start time and end time of the maintenance activities.

Table 35. Test_case#3: Iteration#2: Detailed cost.

PV system	MINLP model (Final selection)	MCDA method	Base model
Maintenance plan	*p*1.*d2*: *c7* ->c1->*c2*->*c*4 *p*1.*d*2: *c7*->*c*3	*p*2.*d*1: *c*6 ->c4 *p*1.*d*2: c7->c3 *p*1.*d*2: *c7*->*c*1->*c*2	*p*2.*d*1: *c*6 ->c4 *p*2.*d*2: c7->c1->c2 *p*1.*d*2: *c7*->*c*3

Energy losses (€)	0.66	0.14	0.14
Salary (€)	92.8	94.27	94.27
Fuel cost (€)	13.31	13.32	13.32
Total (€)	106.77	107.73	107.73

Table 36. Test_case#2 Iteration#3: Daily working hours.

	d1	*d2*
*p*1	5.37	5.4
*p*2	5.37	-

Table 37. Test_case#2 Iteration#3: repairment information.

	c1	*c2*
Start maintenance	00:00	01:30
End maintenance	01:15	05:30

5.3 Test_case#3

5.3.1 Iteration#1

At the present iteration the model handles the tickets of systems *c*5 and *c*6. The detailed information of the faults are included in Table 38. Both MINLP and MCDA model proposes the same maintenance plan. In terms of system prioritization. Specifically, considering the high severity level of the fault at the system *c*5 its repairment is prioritized. When it comes to the selection of team, the selected solution with the highest priority number indicates that team *p*2 should undertake the repairment, taking into account the higher level of personnel expertise.

On the other hand, at base model, since both teams are available, the maintenance activities are assigned to each team. This results in decrement of energy losses, which is negligible compared to the energy losses of the MINLP and MCDA method, but also in increment of salary and fuel cost. The cost of each maintenance plan is presented in Table 38.

Finally, in Table 39 and Table 40 the daily working hours and the information about the time of repairment activities are included.

Table 38. Test_case#3 Iteration#1: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_6	c5	17/6/2020 13:01	Main switch open and does not reclose again	1	12.5	3
Eragro_7	c6	17/6/2020 13:10	Fan failure and overheating	4	2.5	1

Table 39. Test_case#3 Iteration#1: Detailed cost.

PV system	MINLP model	MCDA method (Final selection)	Base model
Maintenance plan	*p1.d1: c7* ->c5->*c6*	*p2.d1: c7* ->c5->*c6*	*p2.d1: c7* ->*c6* *p2.d1: c7* ->*c5*
Energy losses (€)	25.06	25.06	24.63
Salary (€)	50.93	50.93	61.86
Fuel cost (€)	6.55	6.55	13.14
Total (€)	82.84	82.84	99.63

Table 40. Test_case#3 Iteration#1: Daily working hours.

	d1	*d2*
p1	-	-
p2	6.37	-

Table 41. Test_case#3 Iteration#1: Repairment information.

	c5	*c6*
Start maintenance	13:15	15:15
End maintenance	15:00	19:15

5.3.2 Iteration#2

At the second iteration of the test case, two tickets open referring to systems *c*1 and *c*2. Both tickets have the same severity level and require the same time to restore the system's normal operation, as presented in Table 42. In this case, the solution provided by the MINLP model results in lower salary and fuel cost compared to the selected solution of MCDA, as presented in Table 43. However, the energy losses are increased. Based on these, the MCDA model provides a lower total cost compared to MINLP model, although the deviation between the cost of the two techniques is not extensively higher. The total cost of the base model also coincides to the cost of the selected MCDA solution. However, the selection of the personnel team is stochastic.

Table 42. Test_case#3 Iteration#2: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Eragro_9	c1	17/6/2020 17:17	Switch failure/damage	4	12.5	3
Girayhan_3	c2	17/6/2020 17:24	Switch failure/damage	4	12.5	3

Table 43. Test_case#3 Iteration#2: Detailed cost.

PV system	MINLP model	MCDA method	Base model

		(Final selection)	
Maintenance plan	*p2.d2*: *c7* ->c2->c1	*p1.d1*: *c7* ->c1 *p2.d2*: *c7* ->c2	*p2.d1*: *c7* ->*c1* *p2.d1*: *c7* ->c2
Energy losses (€)	12.13	8.15	8.15
Salary (€)	67.84	70.4	70.4
Fuel cost (€)	1.51	3.02	3.02
Total (€)	82.84	81.57	81.57

In Table 44 and Table 45, the daily working hours as well as the time of repairment in terms of the final selected solution are presented.

Table 44. Test_case#3 Iteration#2: Daily working hours.

	d1	*d2*
*p*1	4.4	-
*p*2	6.37	4.4

Table 45. Test_case#3 Iteration#2: Repairment information.

	*c*1	*c*2
Start maintenance	17:15	00:00
End maintenance	21:00	05:45

5.4 Test_case#4

5.4.1 Iteration#1

At the present iteration three tickets referring to systems *c*4, *c*1 and *c*6 open. Detailed information about the faults is presented in Table 46. Considering the optimal solution provided by the MINLP model and the selected solution of the MCDA method, the prioritization of the systems' repairment differs and the total cost of the MILP model is lower. Additionally, the maintenance cost of the base model is the same as the optimal plan derived by the MINLP model, as Table 47 presents.

In this case, the MILP solution is selected. The working hours of personnel as well as the time of repairment activities are presented in Table 48 and Table 49.

Table 46. Test_case#4 Iteration#1: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Erago_5	c4	23/9/2020 9:38	Fan failure and overheating	4	2.5	1
Eragro_9	c1	23/9/2020 9:41	Main switch open and does not reclose again	1	12.5	3

Eragro_6	c6	23/9/2020 9:41	Two Broken/Burned Connectors	3	3.36	2

Table 47. Test_case#4: Iteration#1: Detailed cost.

PV system	MINLP model (Final selection)	MCDA method (Final selection)	Base model
Maintenance plan	*p1.d1: c7 ->c6* *p2.d1: c7->c1->c4*	*p1.d1: c7 ->c4* *p2.d1: c7->c1->c6*	*p1.d1: c7 ->c1* *p2.d1: c7->c6->c4*
Energy losses (€)	35.68	39.53	35.68
Salary (€)	87.73	87.73	87.73
Fuel cost (€)	19.86	19.73	19.86
Total (€)	143.27	146.99	143.27

Table 48. Test_case#4 Iteration#1: Daily working hours.

	d1	*d2*
p1	4.37	-
p2	6.6	-

Table 49. Test_case#4 Iteration#1: repairment information.

	c1	*c4*	*c6*
Start maintenance	11:00	9:45	9:45
End maintenance	15:45	10:45	13:30

5.4.2 Iteration#2

At the second iteration of the test case 4, a new ticket opens for system *c4*. However, since the repairment of system *c5* has not started yet, for the formulation of the maintenance schedule, the ticket for system *c4* is also included as presented in Table 50.

Table 50. Test_case#4 Iteration#1: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Erago_5	c4	23/9/2020 9:38	Fan failure and overheating	4	2.5	1
Eragro_7	c5	23/9/2020 9:47	Polluted air filter - derating	4	2.5	1

The schedules of both MINLP model and MCDA method are the same. Additionally, the maintenance plan of the base model coincides with the aforementioned. So, at the present iteration the integrated model cannot achieve lower cost for the maintenance procedures. Detailed information about the maintenance cost, the total daily working hours and the time of systems' repairment are provided in Table 51, Table 52 and Table 53.

Table 51. Test_case#4: Iteration#1: Detailed cost.

PV system	MINLP model (Final selection)	MCDA method (Final selection)	Base model
Maintenance plan	*p*1.*d*1: *c*6 ->*c*5 *p*2.*d*1: *c*1->*c*4	*p*1.*d*1: *c*6 ->*c*5 *p*2.*d*1: *c*1->*c*4	*p*1.*d*1: *c*6 ->*c*5 *p*2.*d*1: *c*1->*c*4
Energy losses (€)	22.56	22.56	22.56
Salary (€)	83.74	83.74	83.74
Fuel cost (€)	15.83	15.83	15.83
Total (€)	109.24	109.24	109.24

Table 52. Test_case#2 Iteration#3: Daily working hours.

	d1	*d2*
*p*1	8.32	-
*p*2	9.6	-

Table 53. Test_case#2 Iteration#3: repairment information.

	c4	*c5*
Start maintenance	11:00	13:30
End maintenance	15:45	17:30

5.4.3 Iteration#3

At the last iteration of the present test case, the repairment of system *c*5 has not started yet. So, along with the new ticket, the ticket of *c*5 is also considered (Table 54). As Table 55 indicates, the lower maintenance cost is provided by the MCDA method, while the cost of the MINLP model and the base model coincides. This is due to the fact that the MINLP model takes into account not only the maintenance cost but also the severity level of faults for the minimization of the objective function. However, the integrated model achieves in total can achieve cost minimization based on the MCDA method.

Table 54. Test_case#4 Iteration#1: Tickets information.

PV system	System/Location code	Ticket opens	Type of fault	Repairment time	Losses (%)	Fault Severity
Girayhan_3	c2	23/9/2020 12:22	Main switch open and does not reclose again	1	12.5	3
Eragro_7	c5	23/9/2020	Polluted air	4	2.5	1

	9:47	filter - derating

Table 55. Test_case#4: Iteration#1: Detailed cost.

PV system	MINLP model	MCDA method (Final selection)	Base model
Maintenance plan	*p*1.*d*1: *c*6 ->*c*2->*c*5	*p*1.*d*1: *c*6 ->*c*5 *p*2.*d*2: *c*7->*c*2	*p*1.*d*1: *c*6 ->*c*2 *p*2.*d*2: *c*7->*c*3 *p*1.*d*2: *c*7->*c*5
Energy losses (€)	34.48	45.80	34.48
Salary (€)	63.79	52.91	63.79
Fuel cost (€)	9.61	4.79	9.61
Total (€)	107.88	103.62	107.88

The daily working hours and the maintenance time in terms of the final selection are presented in Table 56 and Table 57, respectively.

Table 56. Test_case#2 Iteration#3: Daily working hours.

	d1	*d2*
*p*1	8.37	1.40
*p*2	9.6	-

Table 57. Test_case#2 Iteration#3: repairment information.

	*c*2	*c*5
Start maintenance	00:00	13:30
End maintenance	01:12	17:30

6 TECHNOECONOMIC ANALYSIS

6.1 Annual cashflow

The assessment of the annual cashflows is performed considering the cash inflows and the cash outflows. For the particular problem, the cash outflows refer to the annual maintenance cost of the systems' repairment, while the cash inflows are the profit of the annual yield energy of the total systems.

6.1.1 Annual cash outflows

In Table 58 the total maintenance cost of the integrated model and the base model for each iteration of the previous test cases is presented.

Table 58. Maintenance cost of examined scenario.

Test Case	Iteration	Integrated model	Base model	Cost reduction

		(€)	(€)	(€)
Test_Case#1	Iteration#1	78.52	91.04	12.52
	Iteration#2	63.39	63.39	0.00
	Iteration#3	236.83	258.41	21.58
Test_Case#2	Iteration#1	104.45	104.45	0.00
	Iteration#2	46.22	50.18	3.96
	Iteration#3	106.77	107.73	0.96
Test_Case#3	Iteration#1	82.84	99.63	16.79
	Iteration#2	81.57	81.57	0.00
Test_Case#4	Iteration#1	143.27	143.27	0.00
	Iteration#2	109.24	109.24	0.00
	Iteration#3	103.62	107.88	4.26
Total		**1156.72**	**1216.79**	**60.07**

The number of tickets opening per day for each test case of the examined scenario (4-6 tickets) is a valid number, considering that a maintenance agency in charge for 40 systems with total nominal capacity of 32 MWp, handles 1.1 ticket per day, i.e., 401 tickets per year. Additionally, for the formulation of the test cases we utilized five days of the whole year and the total number of tickets is 23. So, in average, the model deals with 4.6 tickets per day, i.e., 1679 tickets per year. If we assume that there is a linear dependency between the number of tickets and the total nominal capacity, at the examined scenario the maintenance agency is in charge for PV systems with total nominal capacity 133.8 MW. In Table 59 the detailed information about the examined scenario is presented.

Table 59. Maintenance agency details for the examined scenario.

Examined scenario	
Installed capacity	133.8 MW
Tickets per day	4.6
Tickets per year	1679

The total annual cash outflows, with and without the deployment of the integrated model, are presented in Table 60. The assessment of the annual outflows is based on the assumption that there is a linear dependency between the maintenance cost and the number of tickets per year.

Table 60. Annual outflows with and without the deployment of the Integrated model.

	Annual outflows
Integrated model	84,440.56
Base model	88,825.67
Cost saving	4,385.11

6.1.2 Annual cash inflows

Based on the project's data, the total yield energy of six systems with 6MWp total installed capacity, at 2020, is 11 GWh. Taking into account that at the examined scenario the total installed capacity 133.8 MWp, the annual energy yield is 58.668 GWh. At Table 61 the yield energy and the annual inflows of the project's data and the examined scenario are presented. For the assessment of the income the energy price has been set equal to 0.08 €/kWh.

Table 61. Yield energy and cash inflows.

	Yield energy (GWh)	Cash inflows (€)
Project's data (6 MWp)	11.000	880,020.82
Test case (133.8 MWp)	234.67	18,773,777

6.2 Net Present Value

For the economic evaluation of the integrated model, the Net Present Value (NPV) method is used. More specifically, the NPV is the value of all future cashflows, i.e., difference between cash inflows and cash outflows, discounted to their present value. The future cashflows can be discounted to their present value as:

$$NPV = M_0 + \frac{M_1}{(1+r)^1} + \frac{M_2}{(1+r)^2} + \ldots + \frac{M_n}{(1+r)^n} = \sum_{t=0}^{t=n} \frac{M_t}{(1+r)^t} \quad (3)$$

For the evaluation of the NPR of the two cases, i.e., with and without the deployment of the integrated model, the discounting rate has been set equal to 4%, while the analysis refers to the next 20 years. At Table 62 and Figure 6, the NPV is presented for the two cases, is presented. The deviation between them is 63,980.18 €, which is a considerable amount of money considering a period of twenty years.

Table 62. NPV of the integrated and the base model.

Model	NPV (€)
Integrated model	272,683,525.7
Base model	272,619,545.5

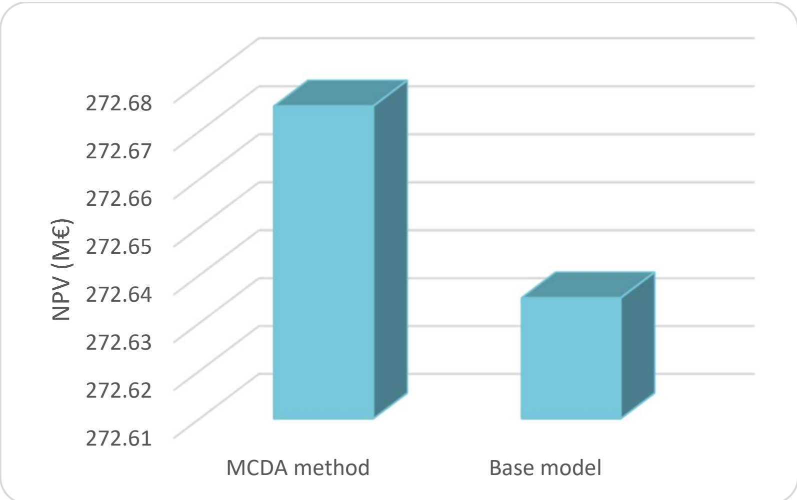

Figure 6. NPV of the integrated and the base model.

7 Conclusions

At the present Deliverable 3.5, the technoeconomic assessment of the integrated tool, consisting of the MINLP model and the MCDA method, is presented. The analysis has been performed for a period of twenty years and the results have been compared to the base model, i.e., the usual actions a maintenance agency follows for the repairment of faulty systems. For the assessment the NPV method has been utilized. The results highlight that the deployment of the integrated model can lead to significant cost savings over the examined time period.

8 References

[1] K. Lepenioti *et al.*, "Prescriptive analytics: Literature review and research challenges," *International Journal of Information Management,* 50, 2020, pp. 57-70.