PANAMA

PRESCRIPTIVE SOLAR ANALYTICS & ADVANCED WORKFORCE MANAGEMENT

D 6.1

Cost-Benefit Analysis

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Definition of Acronyms

Abbreviation

O&M	**Operation and maintenance**
PV	Photovoltaic
DT	Digital Twin
ART	Active Repairment Time
FIFO	First-in-First-out
CBA	Cost-Benefit Analysis
RxM	Prescriptive maintenance

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

EXECUTIVE SUMMARY

Deliverable 6.1 titled “Cost-Benefit Analysis” includes the cost-benefit analysis of O&M optimization tool as developed and described in Deliverables 3.3 and 3.4. The deliverable consists of two main parts. The first part includes the description of the examined test case. In the second part, the cost-benefit analysis is presented based on the results of the former.

1 Introduction

The European Union has set a goal to become carbon neutral by 2050, with a focus on all areas including energy, transport, financing, and trade [1]. The European Commission has introduced the "REPowerEU Plan" to reduce dependence on fossil fuels, increase the use of renewable energy sources, and lower energy prices over time. The plan aims to raise the capacity of renewable energy sources to 45%, with a specific focus on solar power through the "EU Solar Energy Strategy" [2]. The goal is to have 320 GW of new solar capacity by 2025 and nearly 600 GW by 2030.

As more photovoltaic (PV) systems are installed, the demand for operation and maintenance (O&M) services increases. Investors in PV systems need to guarantee their reliability and profitability over their lifetime, which is why they often hire specialized O&M contractors for maintenance. The scope of the O&M services offered will vary based on the contract, and can include predictive, corrective, and preventive maintenance. Predictive maintenance has gained significant attention over the last years [3]. It refers to the development of accurate fault identification algorithms to minimize the time between fault occurrence and fault detection. Thus, this type of maintenance depends on the system's monitoring and does not require any action from the technicians. In contrast to predictive maintenance, preventive and corrective maintenance involve the technicians' actions. However, the existing predictive and corrective maintenance models aim to improve only the efficiency of individual systems and do not take into account the perspective of the O&M contractor. This includes the availability of technicians and the burden of maintenance activities.

The scheduling of O&M activities is the responsibility of the O&M contractor, but this can become complicated as more PV systems are installed and the number of O&M activities increase. Prioritizing corrective and preventive activities depends on various factors such as weather, the severity of faults, and energy losses. The increasing number of PV systems will put additional pressure on O&M contractors, who will need to handle a larger number of maintenance activities. Statistics from the Solar Bankability project show that over a 2.3-year period, 1,066,536 issues were detected in 772 PV plants with a total installed capacity of 442 kWp.

Given these challenges, it is important for O&M contractors to use advanced methodologies to improve the efficiency of their companies and optimize the scheduling of O&M activities. These methodologies fall under the category of RxM and facilitate the decision-making processes [4]. In terms of PV O&M, the primary decisions to be made are: a) how to allocate human resources and b) the order in which systems should be repaired.

During this project, a RxM tool has been developed in order to optimally schedule the O&M activities and minimize the O&M cost. The implementation of the model is described in deliverables 3.3 "Multicriteria-Decision analysis and results" and 3.4 "Integrated Optimization Tool". The purpose of this deliverable is to present the cost-benefit analysis of the developed O&M optimization tool.

2 Examined test case

The effectiveness of the proposed O&M optimization tool is verified on a test case consisting of twenty random fault scenarios. The main difference among them is the number and types of faults. The following subsections explicitly describe the formulation of the implemented fault scenarios.

2.1 Photovoltaic systems

The scenarios have been developed considering that the O&M company, located in c1, is responsible for 20 PV plants. The locations of the plants are presented in Figure 1. The data of the six PV plants (c2 -c7) have been provided by INSOS side. Still, to test the efficiency of the implemented tool, PV systems c8-c21 are assumed to be located in nearby areas. The coordinates of the PV sites, i.e., longitude and latitude, are included in Table 1. Additionally, the distance and the travelling time between the locations are presented in Table A-1 and Table A-2 of Appendix A, respectively.

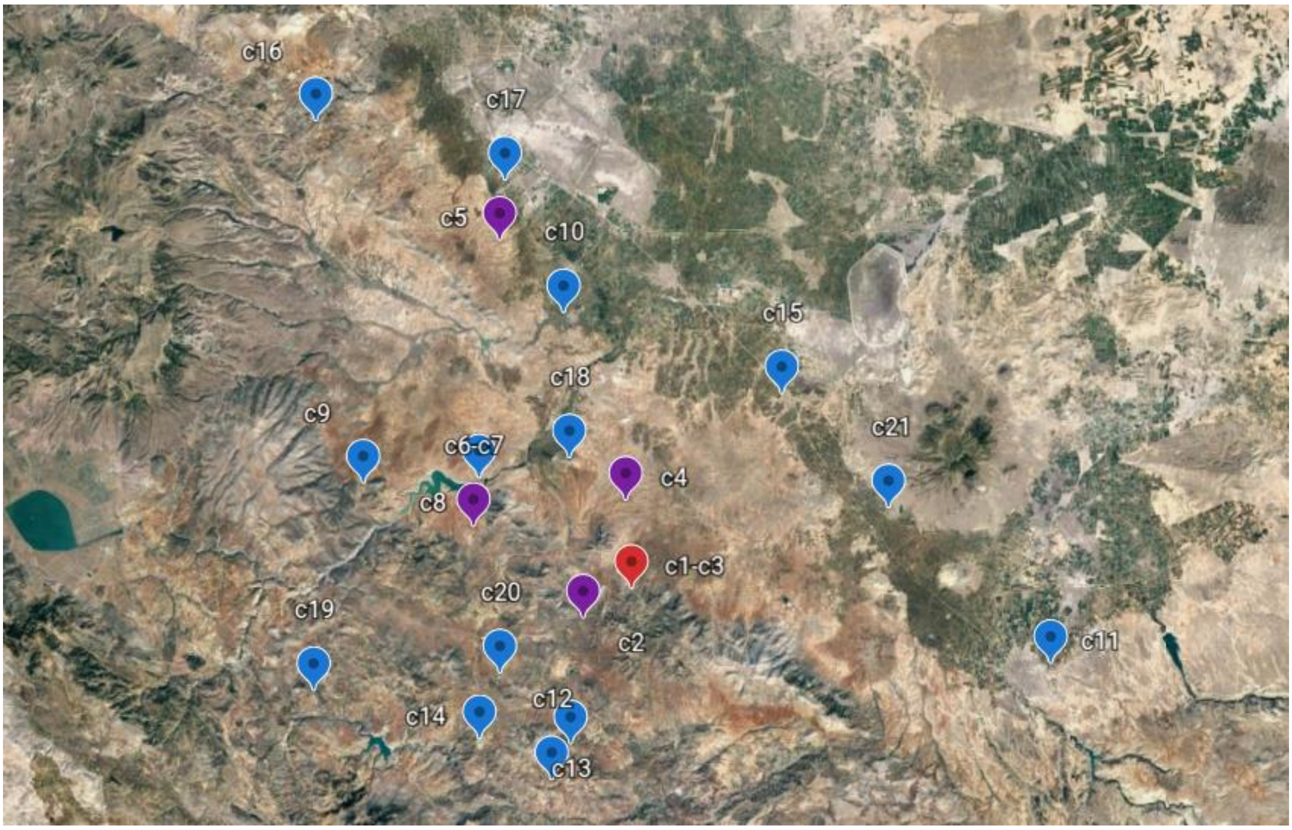


Figure 1. Locations of PV plants.

The installed capacity of each system is 999kW$_p$. However, details about their structure, i.e., number of inverters, strings per inverter, etc., are not available. Therefore, considering the structure of Jupiter, Merkur and Ser systems, we make the following assumptions:

- Each plant consists of 16 inverters
- 12 strings are connected to each inverter
- Each sting comprises of 18 panels

Table 1. Coordinates of PV systems.

PV system	Longitude	Latitude	PV system	Longitude	Latitude
c2	37.34734	32.72938	**c12**	37.17096	33.23273
c3	37.23105	32.67684	**c13**	37.07138	32.63707
c4	37.23105	32.67684	**c14**	37.10808	32.66187
c5	37.34734	32.72938	**c15**	37.10937	32.54779
c6	37.60378	32.57206	**c16**	37.45415	32.92917
c7	37.32117	32.53972	**c17**	37.72698	32.3364
c8	37.32117	32.53972	**c18**	37.65452	32.56837
c9	37.36949	32.54859	**c19**	37.39458	32.64472
c10	37.36369	32.40309	**c20**	37.15626	32.34735
c11	37.53329	32.66036	**c21**	37.17677	32.57403

2.2 Description of faults

During the project, a DT model has been developed able to detect system's anomalies. The DT is able to detect different types of faults, such as sensor and inverter issues. These types of faults are presented in Table 2 and are indexed as F3, F4, F5 and F6. Additionally, based on Solar Bankability project we included faults F1 and F2 for the formulation of scenarios [5]. The ART of faults F1 and F2 is based on the Solar Bankability project [5]. The ART of the rest faults has been defined considering the affected component and results of the Solar Bankability project.

In general, the selected faults refer to different components of the system: a) inverter, b) string and c) sensors. In case of sensor issues the PV power production is not affected. Therefore the losses rate (%) is set equal to zero. The loss rate of faults F1 and F5 is assessed by (1), considering that one of the inverters is out of service. The loss rate of fault F4 is assessed according to (2) considering the affected component and the peak production of the inverter. Finally, the loss rate of F2 is estimated by (3), considering that we have six strings out of service.

Table 2. Types of faults.

Type	Fault	Component	ART (h)	Losses (%)	Source
F1	Switch failure/damage	Inverter	4	6.25	Solar Bankability project
F2	Six broken/burned connectors	String	2.5	3.125	Solar Bankability project
F3	Inverter produces 20% of its Peak production more than the digital twin	Irradiation Sensor	1	0.0	DT
F4	Inverter produces 20% of its peak production less than the digital twin	Inverter	0.5 - 2	1.25	DT
F5	Daily sum(AC production)==0	Inverter	4	6.25	DT
F6	There is no irradiation sensor.	Sensor	2	0.0	DT

$$\text{Loss Rate} = \frac{1}{\text{Number of inverters}} \quad (1)$$

$$\text{Loss Rate} = 0.2 \cdot \frac{1}{\text{Number of inverters}} \quad (2)$$

$$\text{Loss Rate} = \frac{1}{\text{Number of inverters} \times \text{Number of strings}} \quad (3)$$

2.3 Implemented scenarios

The assignment of the faults at each scenario has been implemented based on the uniform distribution. Table 3 includes a brief description of each scenario, i.e., faulty systems and type of faults. The detailed description of the scenarios is provided in Appendix B. From Table 3 it is clear that the number of faults, the type of faults and the faulty systems vary among the scenarios, while the detection time also differs (Appendix B).

Table 3. Short description of the scenarios.

Scenario	Faulty systems	Types of faults
#1	c6, c7, c10, c11, c14, c15, c20, c21	F3, F5, F3, F3, F2, F6, F6, F3
#2	c2, c4, c5, c6, c8, c12, c13, c15	F5, F3, F1, F5, F5, F3, F4, F6
#3	c2, c4, c5, c7, c10, c12, c13, c16, c18	F6, F4, F1, F4, F6, F2, F4, F6
#4	c5, c6, c7, c9, c14, c15	F6, F4, F6, F4, F1, F6
#5	c2, c3, c4, c6, c8, c9, c15, c17, c18, c20	F3, F1, F4, F3, F4, F5, F5, F4, F1, F3
#6	c2, c4, c6, c7, c11, c12, c16, c20, c21	F6, F1, F5, F2, F6, F4, F4, F5, F2
#7	c3, c5, c6, c7, c12, c14, c16, c17, c19	F1, F3, F1, F4, F1, F4, F6, F5, F5
#8	c2, c7, c8, c9, c11, c15, c16, c18, c20	F4, F5, F2, F4, F6, F3, F3, F4, F6
#9	c7, c8, c9, c11, c12, c18, 19, c20, c21	F4, F4, F3, F6, F3, F3, F3, F6, F3, F2
#10	c2, c3, c4, c6, c7, c8, c14, c19	F3, F2, F6, F6, F4, F2, F5, F6
#11	c5, c7, c10, c14, c15, 18, 21	F2, F2, F5, F1, F4, F5, F1
#12	c3, c5, c8, c11, c12, c16, c17, c18, c20	F2, F2, F5, F2, F5, F2, F2, F3, F5
#13	c2, c5, c7, c8, c9, c11, c13, c18	F5, F2, F3, F5, F6, F2, F2, F3
#14	c2, c3, c7, c10, c12, c13, c14, c18	F5, F2, F3, F5, F2, F2, F3, F1
#15	c4, c5, c6, c8, c11, c17, c20, c21	F4, F4, F6, F2, F5, F1, F2, F1
#16	c5, c6, c10, c11, c20, c21	F4, F6, F5, F5, F2, F1
#17	c2, c4, c6, c9, c11, 12, 15, c21	F1, F5, F6, F5, F3, F6, F1, F2
#18	c2, c3, c6, c9, c13, c14, c16, c20, c21	F6, F2, F6, F1, F6, F2, F2, F2, F2
#19	c3, c7, c10, c11, c13, c14, c18	F2, F3, F5, F5, F6, F2, F1
#20	C5, c7, c10, c12, c15, c21	F3, F3, F5, F4, F2

2.4 O&M company

At this examined scenario the O&M company has three teams consisting of two experts each. The main difference between the teams is the level of expertise, as presented in Table 3. Table 3 also includes information about the hourly payment of the personnel. The hourly wage of the experts has been defined according to their expertise. Additionally, considering the overtime hours, the overtime rate has been set equal to 20%.

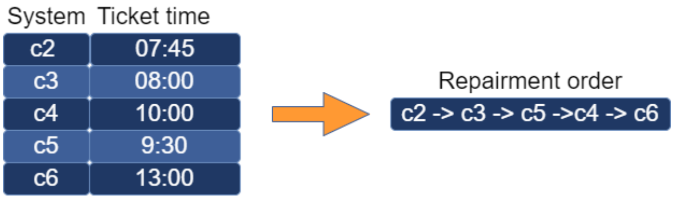
Table 4. Personnel information.

Team index	Expertise	Wage (€/h)	Overtime pay (€/h)
p1	Expert	5.27	6.324
p2	Novice	4.79	5.748
p3	Competent	5.1	6.12

3 FIFO O&M scheme

To compare the efficiency of the proposed O&M tool, a FIFO O&M scheme has been set as the baseline. FIFO is a method of inventory management and cost accounting that assumes that the first items received or produced are the first items to be sold or used. In our case, FIFO O&M scheme is used to define the prioritization of the systems' repairment considering the time the tickets open. The sooner a ticket opens the sooner the repairment is scheduled.

An example of the FIFO process is illustrated in Figure 3. In this example we assume that five faults are detected in systems *c*2, *c*3, *c*4, *c*5 and *c*6 at times 07:45, 08:00, 10:00, 9:35 and 13:00, respectively. Based on the time the ticket opens the repairment order of the systems is defined as *c*2, *c*3, *c*5, *c*4 and *c*6.



System	Ticket time
c2	07:45
c3	08:00
c4	10:00
c5	9:30
c6	13:00

Repairment order

c2 -> c3 -> c5 ->c4 -> c6

Figure 2. Example of FIFO process

The planning of O&M activities takes place at the end of each day and schedules the O&M activities within the next two days. The two-day scheduling period has been selected for this specific test case, meaning that the scheduling period can be adjusted according to the preferences of the O&M company. Additionally, the end of the day depends on the opening hours of the O&M company. At this test case, we assume that the opening hours of the company are between 07:00 – 20:00. The process is presented in Figure 2.

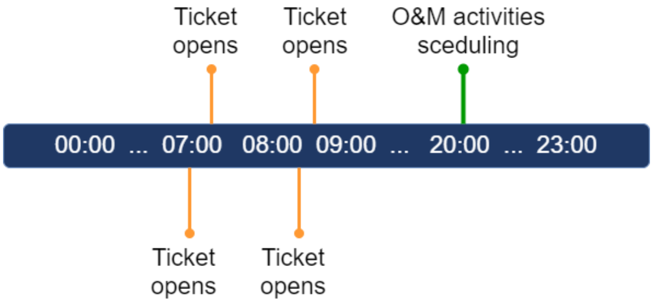


Figure 3. Timeline of O&M activities scheduling.

4 Experimental results

The O&M cost consists of: a) the labor cost, b) the cost of energy losses and c) the fuel cost. Based on the results of the FIFO O&M scheme, the labor cost constitutes the largest part of the total cost on average, i.e., 70% (Figure 3). Therefore, the proper human resources assignment through prescriptive maintenance tool is essential to achieve O&M cost reduction.

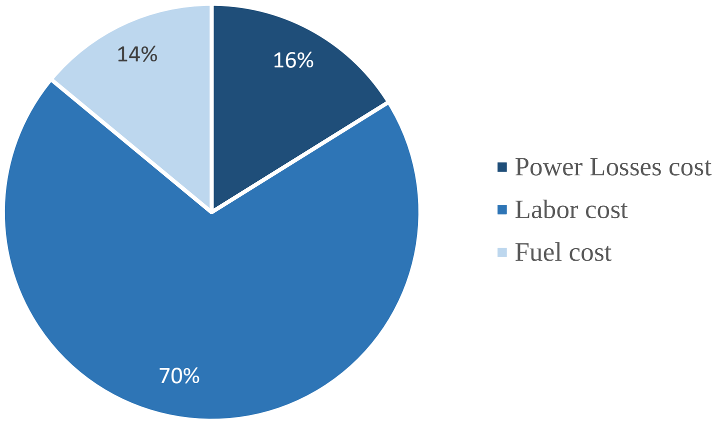


Figure 4. Participation rate of the individual costs.

Figure 5 presents the total O&M cost of the proposed optimization tool and FIFO O&M scheme for all scenarios. Based on Figure 5 it is clear that the proposed O&M optimization tool achieves lower O&M cost in all scenarios compared to the FIFO O&M scheme. The percentage of reduction is presented with the black line and varies between 7.25% and 27.44%.

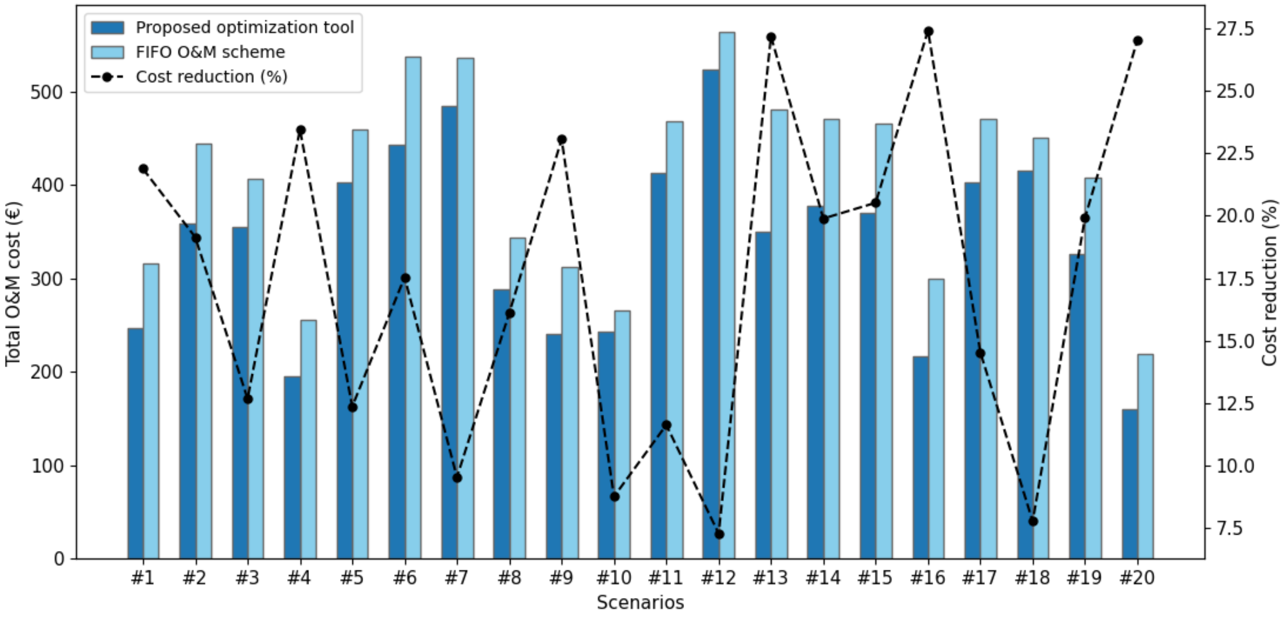


Figure 5. Total O&M cost of the proposed optimization tool and the FIFO O&M scheme.

The individual costs, i.e., energy losses cost, labor cost and fuel cost, are presented in Figures 6, 7 and 8. From Figure 7 we can observe that the proposed optimization tool cannot assure lower energy losses compared to the FIFO O&M scheme. Specifically, for the 60% of the implemented scenarios the cost of the energy losses is higher. On contrary, based on Figure 7 and Figure 8, we can conclude that the labor and the fuel cost decrease with the employment of the proposed optimization tool.

Focusing on the labor cost, which has the highest participation rate at the total O&M cost, the proposed model achieves more than 15% cost reduction at the 70% of the implemented scenarios (Figure 7). Additionally, in scenarios #13, #16 and #20 the cost reduction is higher compared to the rest scenarios, i.e., higher than 25%. This pattern is also observed at the reduction of the fuel cost (Figure 8). On contrary, a slight increment of energy loss cost is observed at scenario #14 and #16 (Figure 6).

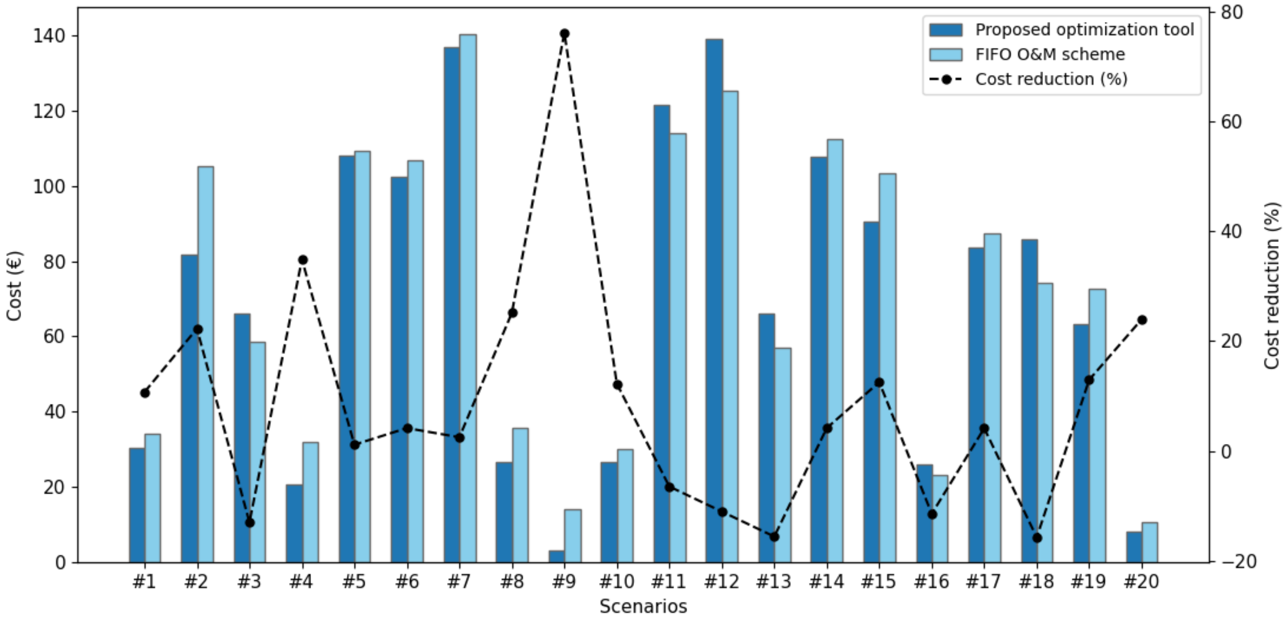


Figure 6. Energy loss cost of the proposed optimization tool and the FIFO O&M scheme.

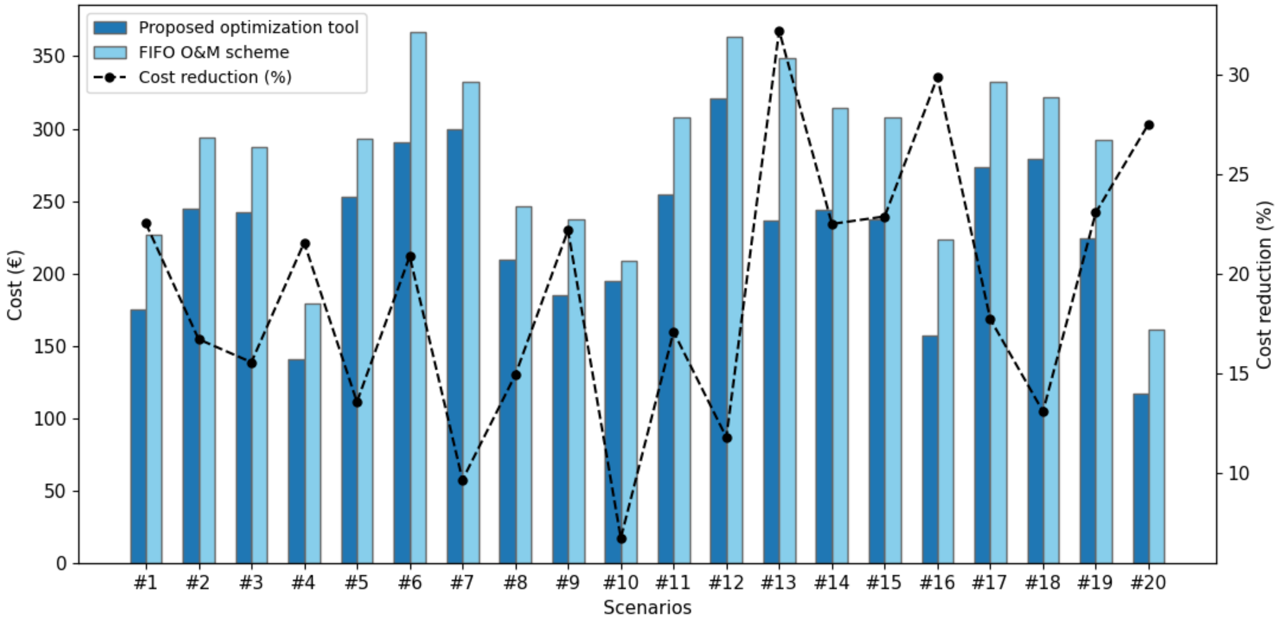


Figure 7. Labor cost of the proposed optimization tool and the FIFO O&M scheme.

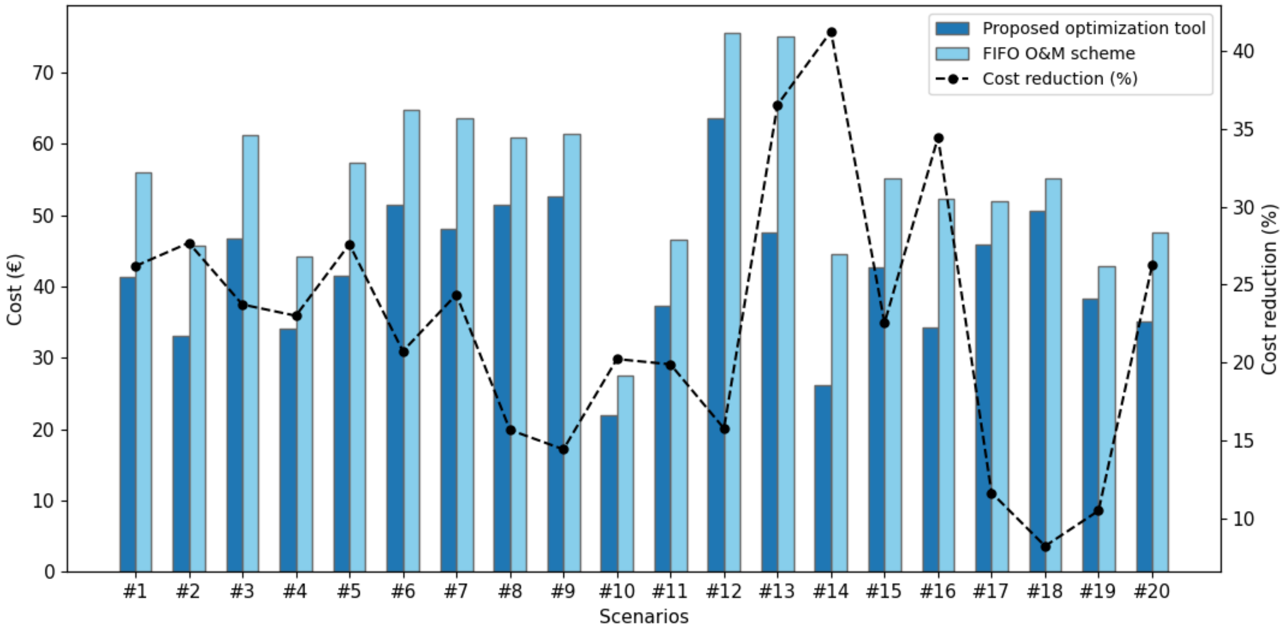


Figure 8. Fuel cost of the proposed optimization tool and the FIFO O&M scheme.

5 Cost-Benefit Analysis

The results of the examined test case highlight that the developed O&M tool can alleviate the O&M cost per 17.15%. Specifically, Table 5 includes the average cost reduction achieved by using the proposed optimization tool in comparison to the FIFO scheme. The results indicate that the optimization tool can lead to a reduction in energy loss costs, although there may be instances where the cost may be higher than the FIFO method. Nevertheless, we can conclude that the employment of the proposed optimization can assure the total cost reduction, considering that the minimum decrement among the implemented scenarios is positive. An average cost decrement is also achieved at fuel, labor and energy loss cost.

Table 5. Information of the scenarios regarding the energy losses cost, the labor cost, the fuel cost and the total cost.

	Average	Min	Max
Energy loss cost	8.68	-15.74	76.15
Labor cost	19.08	6.71	32.19
Fuel cost	22.53	8.22	41.24
Total cost	17.38	7.25	27.44

In general, the proposed optimization tool improves the efficiency of the PV O&M process and can increase the satisfaction of the customers. Specifically, it optimally schedules the O&M actions as derived by the predictive, corrective and preventive models in order to minimize the total O&M cost. The proposed O&M optimization tool provides the ability to O&M contractor to effectively allocate its personnel to different maintenance tasks, based on their level of expertise. This is obvious considering that the model can reduce the labor cost from 6.71% to 32.19% (Table 5). Additionally, the tool takes into account the severity of fault and the economic effect, i.e., cost of energy losses. In this way, the faults that lead to extensive power losses may be prioritized. The developed O&M tool can reduce the total O&M cost by up to 27.44%. Therefore, the satisfaction of the customers will be increased. Afterall, the customers' satisfaction mainly depends on systems profitability and maintenance cost. Considering these, the competitiveness of the O&M company will increase. The O&M contractor will have the ability to provide high-standard O&M services to the customers, by improving the O&M scheduling process.

The costs and the benefits of the employment of the developed O&M optimization tool are presented in Table 6. It should be noted that the only cost that may occur is the requirement of more qualified employees, dedicated to the utilization of the developed prescriptive maintenance tool.

Table 6. Benefits and costs of the developed O&M tool.

Benefits	Description
Facilitating the decision-making process	The scheduling of O&M activities can be extremely difficult procedure when the O&M company has to handle several tickets. Proper scheduling of O&M activities can help to reduce costs associated with energy losses, labor, and fuel. It also helps to improve the availability of resources, such as technicians, and minimize downtime due to maintenance.
Optimal allocation of human resources	The proposed O&M optimization tool provides the ability to O&M contractor to effectively allocate its personnel to different maintenance tasks, based on their level of expertise. This means that the personnel with the most knowledge and experience are assigned to the tasks that require the most skill, while less experienced workers are assigned to simpler tasks.
Increment of the competitiveness of the company	In today's fast-paced and highly competitive business environment, companies need to be flexible and efficient in order to stay ahead of their competitors. By optimizing the O&M scheduling process the O&M company can decrease the O&M cost and increase the profitability of the systems. As consequence the customers' satisfaction is increased by providing high O&M standards.
Costs	**Description**
New employees might be required	The utilization of the proposed prescriptive optimization tool may require more qualified employees with programming skills.

6 Conclusion

At this deliverable we presented a CBA of the developed O&M optimization tool. To test the efficiency of the proposed tool and conduct the CBA, we formulated a test case consisting of twenty different scenarios. The type and number of faults among the scenarios varies. Additionally, a FIFO O&M scheme has been set as a baseline scenario.

Based on the results the proposed O&M tool can reduce the total O&M cost, i.e., labor cost, fuel cost and cost of energy losses, from 7.25% to 27.44%. The proposed O&M tool has the ability to optimally allocate the available human resources, facilitate the decision-making process and increase the competitiveness of the O&M company. Therefore, it can assure not only the viability and profitability of PV systems' investment but also assure the reliability and profitability of the O&M company.

References

[1] (2019). *COMMUNICATION FROM THE COMMISSION The European Green Deal, COM/2019/640 final*.

[2] European Commission, "COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, EU Solar Energy Strategy ", Brussels, 2022.

[3] D. S. Pillai *et al.*, "A comprehensive review on building integrated photovoltaic systems: Emphasis to technological advancements, outdoor testing, and predictive maintenance," *Renew. Sust. Energ. Rev.*, 516, 2022, Article 111946.

[4] K. Lepenioti *et al.*, "Prescriptive analytics: Literature review and research challenges," *Int J Inf Manage*, 50, 2020, pp. 57-70.

[5] *Report on technical risks in PV project development and PV plant operation*. Available: https://cordis.europa.eu/project/id/649997/results. [Accessed: 15 September, 2022].

Appendix A

Table A- 1. Travelling distance (km) between the locations.

	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	c14	c15	c16	c17	c18	c19	c20	c21
c1	0	6.3	6.3	0	52.2	27.3	27.3	28.3	47.5	27.2	53	55.5	32.5	43.1	27.7	75.9	44.3	20	56.9	31	44
c2	6.3	0	0	6.3	52.4	26.4	26.4	42.3	61.7	42.7	52.9	42.3	19.3	29.9	43.2	91.4	59.8	27.9	43.5	17.8	50.2
c3	6.3	0	0	6.3	52.4	26.4	26.4	42.3	61.7	42.7	52.9	42.3	19.3	29.9	43.2	91.4	59.8	27.9	43.5	17.8	50.2
c4	0	6.3	6.3	0	52.2	27.3	27.3	28.3	47.5	27.2	53	55.5	32.5	43.1	27.7	75.9	44.3	20	56.9	31	44
c5	52.2	52.4	52.4	52.2	0	46.2	46.2	36.1	55.3	13.9	81.3	84.8	70.8	72.4	38.6	42	17.1	34.3	86.3	60.3	72.2
c6	27.3	26.4	26.4	27.3	46.2	0	0	8.4	28.5	36.9	79.4	58.5	53.6	46	57.9	67.4	49.9	17.6	40.4	34	70.3
c7	27.3	26.4	26.4	27.3	46.2	0	0	8.4	28.5	36.9	79.4	58.5	53.6	46	57.9	67.4	49.9	17.6	40.4	34	70.3
c8	28.3	42.3	42.3	28.3	36.1	8.4	8.4	0	19.7	29.1	72.9	60.3	55.4	47.9	50.1	58.6	42.1	9.8	40.4	35.8	63.8
c9	47.5	61.7	61.7	47.5	55.3	28.5	28.5	19.7	0	40.1	92.2	79.6	74.8	67.2	71.3	46.9	59.2	29.2	43.5	55.1	83.2
c10	27.2	42.7	42.7	27.2	13.9	36.9	36.9	29.1	40.1	0	70	72.7	59.8	60.3	31.7	52.6	21	22.2	74.2	48.2	61.2
c11	53	52.9	52.9	53	81.3	79.4	79.4	72.9	92.2	70	0	99.3	78.8	89.4	54.7	122	90.3	66.3	103	77.3	28.6
c12	55.5	42.3	42.3	55.5	84.8	58.5	58.5	60.3	79.6	72.7	99.3	0	11.9	12.9	83.2	123	91	58.7	45.5	33.5	90.2
c13	32.5	19.3	19.3	32.5	70.8	53.6	53.6	55.4	74.8	59.8	78.8	11.9	0	43	60.3	108	76.9	54	56.9	22	67.3
c14	43.1	29.9	29.9	43.1	72.4	46	46	47.9	67.2	60.3	89.4	12.9	43	0	70.9	110	78.6	46.4	33.1	21.1	77.9
c15	27.7	43.2	43.2	27.7	38.6	57.9	57.9	50.1	71.3	31.7	54.7	83.2	60.3	70.9	0	73.8	44.5	37.9	84.7	58.7	27.1
c16	75.9	91.4	91.4	75.9	42	67.4	67.4	58.6	46.9	52.6	122	123	108	110	73.8	0	37.4	69.9	124	97.9	110
c17	44.3	59.8	59.8	44.3	17.1	49.9	49.9	42.1	59.2	21	90.3	91	76.9	78.6	44.5	37.4	0	40.7	92.6	66.6	78.2
c18	20	27.9	27.9	20	34.3	17.6	17.6	9.8	29.2	22.2	66.3	58.7	54	46.4	37.9	69.9	40.7	0	59	33	54.2
c19	56.9	43.5	43.5	56.9	86.3	40.4	40.4	40.4	43.5	74.2	103	45.5	56.9	33.1	84.7	124	92.6	59	0	37.2	91.6
c20	31	17.8	17.8	31	60.3	34	34	35.8	55.1	48.2	77.3	33.5	22	21.1	58.7	97.9	66.6	33	37.2	0	65.7
c21	44	50.2	50.2	44	72.2	70.3	70.3	63.8	83.2	61.2	28.6	90.2	67.3	77.9	27.1	110	78.2	54.2	91.6	65.7	0

Table A- 2. Travelling time (h) between the locations.

	c1	**c2**	**c3**	**c4**	**c5**	**c6**	**c7**	**c8**	**c9**	**c10**	**c11**	**c12**	**c13**	**c14**	**c15**	**c16**	**c17**	**c18**	**c19**	**c20**	**c21**
c1	0.000	0.200	0.200	0.000	0.717	0.683	0.683	0.433	0.683	0.333	0.650	0.850	0.467	0.600	0.400	1.100	0.533	0.317	0.750	0.383	0.550
c2	0.200	0.000	0.000	0.200	0.683	0.650	0.650	0.533	0.800	0.567	0.767	0.733	0.333	0.467	0.600	1.300	0.750	0.483	0.567	0.283	0.700
c3	0.200	0.000	0.000	0.200	0.683	0.650	0.650	0.533	0.800	0.567	0.767	0.733	0.333	0.467	0.600	1.300	0.750	0.483	0.567	0.283	0.700
c4	0.000	0.200	0.200	0.000	0.717	0.683	0.683	0.433	0.683	0.333	0.650	0.850	0.467	0.600	0.400	1.100	0.533	0.317	0.750	0.383	0.550
c5	0.717	0.683	0.683	0.717	0.000	0.667	0.667	0.517	0.767	0.283	1.033	1.250	0.933	0.967	0.633	0.917	0.300	0.483	1.033	0.733	0.917
c6	0.683	0.650	0.650	0.683	0.667	0.000	0.000	0.217	0.483	0.533	1.167	1.083	0.833	0.800	0.900	1.183	0.667	0.383	0.633	0.600	1.100
c7	0.683	0.650	0.650	0.683	0.667	0.000	0.000	0.217	0.483	0.533	1.167	1.083	0.833	0.800	0.900	1.183	0.667	0.383	0.633	0.600	1.100
c8	0.433	0.533	0.533	0.433	0.517	0.217	0.217	0.000	0.300	0.383	1.033	0.933	0.733	0.683	0.767	1.100	0.533	0.217	0.650	0.467	0.967
c9	0.683	0.800	0.800	0.683	0.767	0.483	0.483	0.300	0.000	0.567	1.283	1.217	1.000	0.933	0.950	0.867	0.767	0.500	0.833	0.733	1.267
c10	0.333	0.567	0.567	0.333	0.283	0.533	0.533	0.383	0.567	0.000	0.883	1.050	0.767	0.783	0.500	0.850	0.317	0.300	0.867	0.550	0.733
c11	0.650	0.767	0.767	0.650	1.033	1.167	1.167	1.033	1.283	0.883	0.000	1.400	1.017	1.150	0.783	1.667	1.117	0.900	1.250	0.950	0.500
c12	0.850	0.733	0.733	0.850	1.250	1.083	1.083	0.933	1.217	1.050	1.400	0.000	0.417	0.300	1.233	1.867	1.217	0.900	0.900	0.650	1.317
c13	0.467	0.333	0.333	0.467	0.933	0.833	0.833	0.733	1.000	0.767	1.017	0.417	0.000	0.650	0.833	1.533	1.000	0.700	0.750	0.417	0.917
c14	0.600	0.467	0.467	0.600	0.967	0.800	0.800	0.683	0.933	0.783	1.150	0.300	0.650	0.000	0.967	1.500	0.967	0.633	0.650	0.383	1.083
c15	0.400	0.600	0.600	0.400	0.633	0.900	0.900	0.767	0.950	0.500	0.783	1.233	0.833	0.967	0.000	1.183	0.700	0.600	1.033	0.783	0.467
c16	1.100	1.300	1.300	1.100	0.917	1.183	1.183	1.100	0.867	0.850	1.667	1.867	1.533	1.500	1.183	0.000	0.667	1.050	1.583	1.300	1.500
c17	0.533	0.750	0.750	0.533	0.300	0.667	0.667	0.533	0.767	0.317	1.117	1.217	1.000	0.967	0.700	0.667	0.000	0.500	1.067	0.767	1.303
c18	0.317	0.483	0.483	0.317	0.483	0.383	0.383	0.217	0.500	0.300	0.900	0.900	0.700	0.633	0.600	1.050	0.500	0.000	0.750	0.450	0.767
c19	0.750	0.567	0.567	0.750	1.033	0.633	0.633	0.650	0.833	0.867	1.250	0.900	0.750	0.650	1.033	1.583	1.067	0.750	0.000	0.567	1.233
c20	0.383	0.283	0.283	0.383	0.733	0.600	0.600	0.467	0.733	0.550	0.950	0.650	0.417	0.383	0.783	1.300	0.767	0.450	0.567	0.000	0.867
c21	0.550	0.700	0.700	0.550	0.917	1.100	1.100	0.967	1.267	0.733	0.500	1.317	0.917	1.083	0.467	1.500	1.303	0.767	1.233	0.867	0.000

Appendix B

Table B- 1. Fault Scenario #1.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	0	0	0	0	0	0
c4	0	0	0	0	0	0
c5	0	0	0	0	0	0
c6	1	34	1.2	1	0	F3
c7	1	65	4	3	0.0625	F5
c8	0	0	0	0	0	0
c9	0	0	0	0	0	0
c10	1	58	1.2	1	0	F3
c11	1	58	1.2	1	0	F3
c12	0	0	0	0	0	0
c13	0	0	0	0	0	0
c14	1	53	3	3	0.03125	F2
c15	1	74	2.4	1	0	F6
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	0	0	0	0	0	0
c19	0	0	0	0	0	0
c20	1	29	2	1	0	F6
c21	1	73	1.1	1	0	F3

Table B- 2. Fault Scenario #2.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	59	4.8	3	0.0625	F5
c3	0	0	0	0	0	0
c4	1	37	1	1	0	F3
c5	1	36	4.4	3	0.0625	F1
c6	1	80	4.8	3	0.0625	F5
c7	0	0	0	0	0	0
c8	1	49	4.4	3	0.0625	F5
c9	0	0	0	0	0	0
c10	0	0	0	0	0	0
c11	0	0	0	0	0	0
c12	1	59	1.1	1	0	F3
c13	1	61	0.5	2	0.0125	F4
c14	0	0	0	0	0	0
c15	1	31	2.4	1	0	F6
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	0	0	0	0	0	0
c19	0	0	0	0	0	0
c20	0	0	0	0	0	0
c21	0	0	0	0	0	0

Table B- 3. Fault Scenario #3.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	80	2.4	1	0	F6
c3	0	0	0	0	0	0
c4	1	33	0.5	2	0.0125	F4
c5	1	55	4.4	3	0.0625	F1
c6	0	0	0	0	0	0
c7	1	57	0.5	2	0.0125	F4
c8	0	0	0	0	0	0
c9	0	0	0	0	0	0
c10	1	65	2.4	1	0	F6
c11	0	0	0	0	0	0
c12	1	48	2.75	3	0.03125	F2
c13	1	36	4	3	0.0625	F1
c14	0	0	0	0	0	0
c15	0	0	0	0	0	0
c16	1	37	0.5	2	0.0125	F4
c17	0	0	0	0	0	0
c18	1	72	2.4	1	0	F6
c19	0	0	0	0	0	0
c20	0	0	0	0	0	0
c21	0	0	0	0	0	0

Table B- 4. Fault Scenario #4.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	0	0	0	0	0	0
c4	0	0	0	0	0	0
c5	1	60	2.2	1	0	F6
c6	1	71	0.6	2	0.0125	F4
c7	1	55	2	1	0	F6
c8	0	0	0	0	0	0
c9	1	64	0.6	2	0.0125	F4
c10	0	0	0	0	0	0
c11	0	0	0	0	0	0
c12	0	0	0	0	0	0
c13	0	0	0	0	0	0
c14	1	77	4.8	3	0.0625	F1
c15	1	47	2.4	1	0	F6
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	0	0	0	0	0	0
c19	0	0	0	0	0	0
c20	0	0	0	0	0	0
c21	0	0	0	0	0	0

Table B- 5. Fault Scenario #5.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	61	1.2	1	0	F3
c3	1	33	4.4	3	0.0625	F1
c4	1	64	0.5	2	0.0125	F4
c5	0	0	0	0	0	0
c6	1	37	1.2	1	0	F3
c7	0	0	0	0	0	0
c8	1	80	0.55	2	0.0125	F4
c9	1	40	4.8	3	0.0625	F5
c10	0	0	0	0	0	0
c11	0	0	0	0	0	0
c12	0	0	0	0	0	0
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	1	71	4.8	3	0.0625	F5
c16	0	0	0	0	0	0
c17	1	37	0.55	2	0.0125	F4
c18	1	79	4.8	3	0.0625	F1
c19	0	0	0	0	0	0
c20	1	54	1	1	0	F3
c21	0	0	0	0	0	0

Table B- 6. Fault Scenario #6.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	61	1.2	1	0	F3
c3	1	33	4.4	3	0.0625	F1
c4	1	64	0.5	2	0.0125	F4
c5	0	0	0	0	0	0
c6	1	37	1.2	1	0	F3
c7	0	0	0	0	0	0
c8	1	80	0.55	2	0.0125	F4
c9	1	40	4.8	3	0.0625	F5
c10	0	0	0	0	0	0
c11	0	0	0	0	0	0
c12	0	0	0	0	0	0
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	1	71	4.8	3	0.0625	F5
c16	0	0	0	0	0	0
c17	1	37	0.55	2	0.0125	F4
c18	1	79	4.8	3	0.0625	F1
c19	0	0	0	0	0	0
c20	1	54	1	1	0	F3
c21	0	0	0	0	0	0

Table B- 7. Fault Scenario #7.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	1	76	4.4	3	0.0625	F1
c4	0	0	0	0	0	0
c5	1	52	1.1	1	0	F3
c6	1	63	4.8	3	0.0625	F1
c7	1	33	0.5	2	0.0125	F4
c8	0	0	0	0	0	0
c9	0	0	0	0	0	0
c10	0	0	0	0	0	0
c11	0	0	0	0	0	0
c12	1	58	4.4	3	0.0625	F1
c13	0	0	0	0	0	0
c14	1	36	0.6	2	0.0125	F4
c15	0	0	0	0	0	0
c16	1	35	2	1	0	F6
c17	1	34	4.4	3	0.0625	F5
c18	0	0	0	0	0	0
c19	1	41	4.4	3	0.0625	F5
c20	0	0	0	0	0	0
c21	0	0	0	0	0	0

Table B- 8. Fault Scenario #8.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	58	0.6	2	0.0125	F4
c3	0	0	0	0	0	0
c4	0	0	0	0	0	0
c5	0	0	0	0	0	0
c6	0	0	0	0	0	0
c7	1	38	4	3	0.0625	F5
c8	1	52	2.75	3	0.03125	F2
c9	1	53	0.6	2	0.0125	F4
c10	0	0	0	0	0	0
c11	1	47	2.4	1	0	F6
c12	0	0	0	0	0	0
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	1	45	1.2	1	0	F3
c16	1	37	1	1	0	F3
c17	0	0	0	0	0	0
c18	1	63	0.6	2	0.0125	F4
c19	0	0	0	0	0	0
c20	1	74	2	1	0	F6
c21	0	0	0	0	0	0

Table B- 9. Fault Scenario #9.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	0	0	0	0	0	0
c4	0	0	0	0	0	0
c5	0	0	0	0	0	0
c6	0	0	0	0	0	0
c7	1	78	0.5	2	0.0125	F4
c8	1	35	1.1	1	0	F3
c9	1	66	2.4	1	0	F6
c10	0	0	0	0	0	0
c11	1	68	1.2	1	0	F3
c12	1	53	1.1	1	0	F3
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	0	0	0	0	0	0
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	1	58	1.2	1	0	F3
c19	1	77	2.2	1	0	F6
c20	1	52	1	1	0	F3
c21	1	54	2.75	3	0.03125	F2

Table B- 10. Fault Scenario #10.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	35	1.2	1	0	F3
c3	1	29	2.75	3	0.03125	F2
c4	1	55	2	1	0	F6
c5	0	0	0	0	0	0
c6	1	44	2.4	1	0	F6
c7	1	51	0.5	2	0.0125	F4
c8	1	72	2.75	3	0.03125	F2
c9	0	0	0	0	0	0
c10	0	0	0	0	0	0
c11	0	0	0	0	0	0
c12	0	0	0	0	0	0
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	0	0	0	0	0	0
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	0	0	0	0	0	0
c19	1	56	2.2	1	0	F6
c20	1	38	2.5	3	0.03125	F3
c21	0	0	0	0	0	0

Table B- 11. Fault Scenario #11.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	0	0	0	0	0	0
c4	0	0	0	0	0	0
c5	1	75	2.75	3	0.03125	F2
c6	0	0	0	0	0	0
c7	1	57	2.5	3	0.03125	F2
c8	0	0	0	0	0	0
c9	0	0	0	0	0	0
c10	1	63	4.8	3	0.0625	F5
c11	0	0	0	0	0	0
c12	0	0	0	0	0	0
c13	0	0	0	0	0	0
c14	1	67	4.8	3	0.0625	F1
c15	1	30	0.6	2	0.0125	F4
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	1	73	4.8	3	0.0625	F5
c19	0	0	0	0	0	0
c20	0	0	0	0	0	0
c21	1	42	4.4	3	0.0625	F1

Table B- 12. Fault Scenario #12.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	1	79	2.75	3	0.03125	F2
c4	0	0	0	0	0	0
c5	1	50	2.75	3	0.03125	F2
c6	0	0	0	0	0	0
c7	0	0	0	0	0	0
c8	1	57	4.4	3	0.0625	F5
c9	0	0	0	0	0	0
c10	0	0	0	0	0	0
c11	1	63	3	3	0.03125	F2
c12	1	78	4.4	3	0.0625	F5
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	0	0	0	0	0	0
c16	1	40	2.5	3	0.03125	F2
c17	1	35	2.75	3	0.03125	F2
c18	1	57	1.2	1	0	F3
c19	0	29	2.75	3	0.03125	F2
c20	1	33	4	3	0.0625	F5
c21	0	0	0	0	0	0

Table B- 13. Fault Scenario #13.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	57	0.6	2	0.0125	F5
c3	0	45	4.4	3	0.0625	F2
c4	0	0	0	0	0	0
c5	1	45	4.4	3	0.0625	F2
c6	0	0	0	0	0	0
c7	1	69	4	3	0.0625	F3
c8	1	29	2.75	3	0.03125	F5
c9	1	61	3	3	0.03125	F6
c10	0	31	4.8	3	0.0625	F3
c11	1	56	1.2	1	0	0
c12	0	0	0	0	0	0
c13	1	44	0.5	2	0.0125	F2
c14	0	0	0	0	0	0
c15	0	65	3	3	0.03125	F4
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	1	42	3	3	0.03125	F3
c19	0	0	0	0	0	0
c20	0	0	0	0	0	0
c21	0	0	0	0	0	0

Table B- 14. Fault Scenario #14.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	63	4.8	3	0.0625	F5
c3	1	61	2.75	3	0.03125	F2
c4	0	0	0	0	0	0
c5	0	0	0	0	0	0
c6	0	0	0	0	0	0
c7	1	79	1	1	0	0
c8	0	0	0	0	0	0
c9	0	0	0	0	0	0
c10	1	73	4.8	3	0.0625	F5
c11	0	0	0	0	0	0
c12	1	62	2.75	3	0.03125	F2
c13	1	71	2.5	3	0.03125	F2
c14	1	42	1.2	1	0	0
c15	0	0	0	0	0	0
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	1	75	4.8	3	0.0625	F1
c19	0	0	0	0	0	0
c20	0	0	0	0	0	0
c21	0	0	0	0	0	0

Table B- 15. Fault Scenario #15.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	0	0	0	0	0	0
c4	1	52	0.5	2	0.0125	F4
c5	1	41	0.55	2	0.0125	F4
c6	1	30	2.4	1	0	0
c7	0	0	0	0	0	0
c8	1	70	2.75	3	0.03125	F2
c9	0	0	0	0	0	0
c10	0	0	0	0	0	0
c11	1	32	4.8	3	0.0625	F5
c12	0	0	0	0	0	0
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	0	0	0	0	0	0
c16	1	55	2	1	0	0
c17	1	74	4.4	3	0.0625	F1
c18	0	0	0	0	0	0
c19	0	0	0	0	0	0
c20	1	50	2.5	3	0.03125	F2
c21	1	32	4.4	3	0.0625	F1

Table B- 16. Fault Scenario #16.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	0	0	0	0	0	0
c4	0	0	0	2	0	F4
c5	1	54	1.1	2	0	F4
c6	1	51	4.8	1	0.0625	0
c7	0	0	0	0	0	0
c8	0	0	0	3	0	F2
c9	0	0	0	0	0	0
c10	1	43	3	0	0.03125	0
c11	1	74	1.2	3	0	F5
c12	0	0	0	0	0	0
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	0	0	0	0	0	0
c16	0	0	0	1	0	0
c17	0	0	0	3	0	F1
c18	0	0	0	0	0	0
c19	0	0	0	0	0	0
c20	1	41	2.5	3	0.03125	F2
c21	1	58	1.1	3	0	F1

Table B- 17. Fault Scenario #17.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	43	4.8	3	0.0625	F1
c3	0	0	0	0	0	0
c4	1	47	2	1	0	F6
c5	0	0	0	0	0	0
c6	1	40	2.4	1	0	F6
c7	0	0	0	0	0	0
c8	0	0	0	0	0	0
c9	1	51	4.8	3	0.0625	F5
c10	0	0	0	0	0	0
c11	1	61	1.2	1	0	F3
c12	1	66	2.2	1	0	F6
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	1	69	4.8	3	0.0625	F1
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	0	0	0	0	0	0
c19	0	0	0	0	0	0
c20	0	0	0	0	0	0
c21	1	56	2.75	3	0.03125	F2

Table B- 18. Fault Scenario #18.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	1	63	2.4	1	0	0
c3	1	68	2.75	3	0.03125	F2
c4	0	0	0	0	0	0
c5	0	0	0	0	0	0
c6	1	54	2.4	1	0	0
c7	0	0	0	0	0	0
c8	0	0	0	0	0	0
c9	1	48	4.8	3	0.0625	F1
c10	0	0	0	0	0	0
c11	0	0	0	0	0	0
c12	0	0	0	0	0	0
c13	1	31	2	1	0	0
c14	1	67	3	3	0.03125	F2
c15	0	0	0	0	0	0
c16	1	38	2.5	3	0.03125	F2
c17	0	0	0	0	0	0
c18	0	0	0	0	0	0
c19	0	0	0	0	0	0
c20	1	61	2.5	3	0.03125	F2
c21	1	39	2.75	3	0.03125	F2

Table B- 19. Fault Scenario #19.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	1	72	1.1	1	0	F2
c4	0	0	0	0	0	0
c5	0	0	0	0	0	0
c6	0	0	0	0	0	0
c7	1	57	4	3	0.0625	F3
c8	0	0	0	0	0	0
c9	0	0	0	0	0	0
c10	1	73	2.4	1	0	F5
c11	1	46	4.8	3	0.0625	F5
c12	0	0	0	0	0	0
c13	1	37	4	3	0.0625	F6
c14	1	79	3	3	0.03125	F2
c15	0	0	0	0	0	0
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	1	52	2.4	1	0	F1
c19	0	0	0	0	0	0
c20	0	0	0	0	0	0
c21	0	0	0	0	0	0

Table B- 20. Fault Scenario #20.

	Detection	Detection Time	Maintenance Time	Severity of Fault	Loss Rate	Type of Fault
c1	0	0	0	0	0	0
c2	0	0	0	0	0	0
c3	0	0	0	0	0	0
c4	0	0	0	0	0	0
c5	1	57	1.1	1	0	F3
c6	0	0	0	0	0	0
c7	1	72	2.5	3	0.03125	F3
c8	0	0	0	0	0	0
c9	0	0	0	0	0	0
c10	1	32	1.2	1	0	F5
c11	0	0	0	0	0	0
c12	1	48	1.1	1	0	F2
c13	0	0	0	0	0	0
c14	0	0	0	0	0	0
c15	1	38	0.6	2	0.0125	F4
c16	0	0	0	0	0	0
c17	0	0	0	0	0	0
c18	0	0	0	0	0	0
c19	0	0	0	0	0	0
c20	0	0	0	0	0	0
c21	1	73	2.2	1	0	F2