

Moving from One Site to Multi-Site Vulnerability Studies: Decision Analysis for Trade-off Between Risks and Benefits

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Abstract

This paper provides a vulnerability study for a gas production site. Decision tree analysis is implemented to provide risk-informed decisions on the maintenance strategies to minimize the unavailability and downtime costs. In this context, the decision analysis assesses the impact on the availability of the plant after having decided to buy some spare parts to mitigate the criticality of some equipment. This will help the decision makers to make an optimal decision before spending their budget on buying the spare parts while they can reliably forecast a maximized availability. The decision analysis also will move from one site approach to the multi-site vulnerability studies. Result concludes a recommendation for the company on deciding the optimum maintenance strategies and provides a list of required spare parts to be bought in advance to reduce the associated risks and costs.

Keyword: Decision Analysis; Maintenance Decision; Risk; Vulnerability.

Introduction

The ultimate task for an engineer is to establish a consistent decision basis for planning, design, manufacturing, construction, operation and management of engineering facilities such that the overall life cycle benefit of the facilities is maximized [1]. In this context, international companies that sell their products and assure the availability of their systems want to minimize the downtime and maximize the availability [2, 3, 4]. They must decide on the optimal maintenance strategies to keep their system operational while the safety and reliability besides the resilience are crucially considered [5]. There must be an optimal trade-off between achieving the best maintenance strategy with the minimized cost and the system reliability with maximized safety [6]. The challenging issue in making optimized decisions is that usually the realistic results of the decision taken is observed after the decision is, actually, taken and implemented on the industrial system [7]. Therefore, a framework that reliably predict the outcome of the decision that will be taken is very promising [8].

Decision analysis, or applied decision theory, was first developed by Raffia and Schlaifer [9] to apply the theory of decision making in uncertain environments, developed by the work of great 18th centuries scientists

namely Bernoulli, Bayes, and Laplace, on real-world applications enabling the decision makers apply what she/he is asked for on a system that is provided with uncertain information [10]. Nowadays, the decision theory is applied on different fields of study like engineering [11, 12, 13], medical science [14] to business and economics [15]. Recent advancements of decision analysis in engineering field is on its application on structural health monitoring [16, 17] and sensor placement and scheduling [18, 19, 20]

In this work, we will show an application of decision analysis on the maintenance of a chemical plant that produces industrial gas. The case study presented is about the maintenance decisions in the plants and raises the question on the maintenance strategies to decide on the best action in order to decrease company's risk of operational failures. These failures may result in safety concerns, prolonged downtime (availability), or repeated trips (reliability). It is aimed at establishing recommendations (maintenance, spare parts) for each of the components. These recommendations will define when and why it is convenient to buy spare components

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in advance, considering the failure risk of the plants, the recovery time and the cost of spare and unavailability.

To answer these questions, a risk model is developed. The decision analysis method [21] is used for this purpose. Decision trees are drawn for each subcomponents of the plant, and the expected value of each maintenance strategy are calculated. The decision analysis is performed in two approaches of one site and multi-site plant. In multi-site approach the expected values are computed considering that a fraction of production of failed plant can be replaced by another plant’s product. Based on these results, maintenance recommendations are provided to the company.

This paper is organized as follows:

At section 2, decision tree analysis is provided. The decision tree analysis for one site and multi-site approach and maintenance recommendations are discussed with details in this section. Section 3 provides the concluding remarks.

Decision Tree Analysis

Decision trees are special types of event trees which are used as a decision support tool to apply the framework of decision theory to provide a theoretical and figurative way for risk analysis and maintenance decisions [22]. A decision tree is a model of decisions scenarios along with all associated possible consequences, costs and utilities [23]. This tree has a structure like a flowchart in which each node represents a possible action, each branch represents the outcome of that action and each leaf represents a label (i.e. decision taken after considering all the actions). Visualizations that are provided by the decision trees greatly enhance the set of potential actions/decisions and their associated consequences in a unified traceable manner. In the decision tree analysis, the consequences of each possible action are defined in monetary terms (utility) [24]. Optimal decision is then identified as the decision with the maximum expected value of that utility function. The utility function expresses the decision-maker’s preferences with reference to the consequences. A real case study of utilizing decision tree will be discussed as follows:

In this work, we apply the decision tree analysis on real case study of an international company which makes gas compression plants all over the world and guarantees its plants availability. Therefore, it is important to make risk-informed decisions on the maintenance strategies that minimize the unavailability and downtime costs.

The case study is a site composed of two plants which is scratched in the following scheme at Fig. 1.

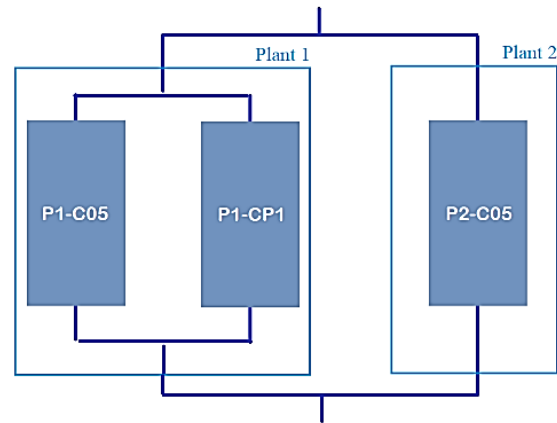


Fig.1. Scheme of the two plants, P1 and P2. P1 has two compressors C05 and CP1 in parallel, while P2 has one compressor C05. P2C05 can work instead of P1C05.

There are two plants Plant 1 and Plant 2 (called P1 and P2 respectively). P1 is composed of two different compressors C05 and CP1 in parallel compressing two different products. P2 is composed of just one compressor, the same as P1, the C05 compressor. In case of any accident and unavailability, P2-C05 can produce instead of P1-C05. Unavailability of P1 costs 10 K€/day while unavailability of P2 costs 6 K€/day. Every compressor consists of several subcomponents all working in series. In detail, C05 and CP1 have 27 subcomponents. We assume the subcomponents to be different in the case of the two compressors, due to different type of product.

The details of the probability of failure, unavailability, repair time, and the cost of the spares for each subcomponent are provided at Tables 1 to 3. There are four qualitative levels defined for the failure probability of each subcomponent (Not Significant (NS), Low, Medium, High). The time of unavailability of the plant in case of failure of any subcomponent is related to the type of the subcomponent failed and the availability of the spares. For example, if breaker of the C05 compressor fails, the unavailability of plant P1 is 45 days in case there is no spares available. However, if the spares are already available, the unavailability of the plant 1 is just 8 hours that we call this unavailability of the repair time. If any other components of P1 fails, the unavailability of P1 is different from that of breaker and is specific for that failed subcomponent where their specific details can be read from Tables 1 to 3.

Table 1. Subcomponents of plant P1-C05 (detailed properties)

Main Equipment	Subcomponent	Probability of Failure	Unavailability	Spare price (k€)	Repair Time
Breaker	Breaker	Low	1,5 months	21	8 hours
	Protection relay	Low	1 month	6	8 hours
Motor 10MW	Stator	Low	2 months	360	1 week
	Rotor	Low	2 months	240	1 week

Main Equipment	Subcomponent	Probability of Failure	Unavailability	Spare price (k€)	Repair Time
	Bearing	Medium	3 weeks	24	1 week
	Exchanger	NS	2 weeks	78	2 days
Coupling	-	Low	20 months	48	1 week
Gearbox	Bull Gear	Low	20 months	210	2 weeks
	Pignon-Shaft	Low	20 months	108	2 weeks
Rotor	Impeller	Low	20 months	42	2 weeks
	Bearing	Low	2 months	24	5 days
	Labyrinths', Seals	Low	2 weeks	15	2 weeks
Exchanger	Tube bundle	High	2 weeks	36	3 days
	Shell	Low	NS	48	3 days
IGV	Servomotor	Medium	1 week	9	4 hours
	Nozzle	NS	3 weeks	18	2 days
Check-Valve	-	Medium	1 week	3	1 days
Anti-surge	Valve	NS	3 weeks	6	6 hours
	Servomotor	Medium	1 week	6	6 hours
	Solenoid	Low	8h	0.6	3 hours
	Transmitter	Low	8h	0.6	3 hours
Vent Valve	-	Medium	2 weeks	7.2	6 hours
PLC	-	Low	2 weeks	9	6 hours
Oil circuit	Oil pump trained	Medium	1 month	6	6 hours
	Oil pump auxiliary	NS	1 week	9	6 hours
	Exchanger	NS	1 weeks	9	8 hours
	Oil filter	Low	NS	2.4	2 hours

Table 2. Subcomponents of plant P1-CP1 (detailed properties)

Main Equipment	Subcomponent	Probability of Failure	Unavailability	Spare price (k€)	Repair Time
Breaker	Breaker	Low	1,5 months	52.5	8 hours
	Protection relay	Low	1 month	15	8 hours
Motor 20MW	Stator	Low	2 months	900	1 week
	Rotor	Low	2 months	600	1 week
	Bearing	Medium	3 weeks	60	1 week
	Exchanger	NS	2 weeks	195	2 days
Coupling	-	Low	20 months	120	1 week
Gearbox	Bull Gear	Low	20 months	525	2 weeks
	Pignon-Shaft	Low	20 months	270	2 weeks
Rotor	Impeller	Low	20 months	105	2 weeks
	Bearing	Low	2 months	60	5 days
	labyrinths', Seals	Low	2 weeks	37.5	2 weeks
Exchanger	Tube bundle	High	2 weeks	90	3 days
	Shell	Low	NS	120	3 days
IGV	Servomotor	Medium	1 week	22.5	4 hours
	Nozzle	NS	3 weeks	45	2 days
Check-Valve	-	Medium	1 week	7.5	1 days

Main Equipment	Subcomponent	Probability of Failure	Unavailability	Spare price (k€)	Repair Time
Anti-surge	Valve	NS	3 weeks	15	6 hours
	Servomotor	Medium	1 week	15	6 hours
	Solenoid	Low	8h	1.5	3 hours
	Transmitter	Low	8h	1.5	3 hours
Vent Valve	-	Medium	2 weeks	18	6 hours
PLC	-	Low	2 weeks	22.5	6 hours
Oil circuit	Oil pump trained	Medium	1 month	15	6 hours
	Oil pump auxiliary	NS	1 week	22.5	6 hours
	Exchanger	NS	1 weeks	22.5	8 hours
	Oil filter	Low	NS	6	2 hours

Table 3. Subcomponents of plant P2-C05 (detailed properties)

Main Equipment	Subcomponent	Probability of Failure	Unavailability	Spare price (k€)	Repair Time
Breaker	Breaker	Low	1,5 months	35	8 hours
	Protection relay	Low	1 month	10	8 hours
Motor 20MW	Stator	Low	2 months	600	1 week
	Rotor	Low	2 months	400	1 week
	Bearing	Medium	3 weeks	40	1 week
	Exchanger	NS	2 weeks	130	2 days
Coupling	-	Low	20 months	80	1 week
Gearbox	Bull Gear	Low	20 months	350	2 weeks
	Pignon-Shaft	Low	20 months	180	2 weeks
Rotor	Impeller	Low	20 months	70	2 weeks
	Bearing	Low	2 months	40	5 days
	labyrinths', Seals	Low	2 weeks	25	2 weeks
Exchanger	Tube bundle	High	2 weeks	60	3 days
	Shell	Low	NS	80	3 days
IGV	Servomotor	Medium	1 week	15	4 hours
	Nozzle	NS	3 weeks	30	2 days
Check-Valve	-	Medium	1 week	5	1 days
Anti-surge	Valve	NS	3 weeks	10	6 hours
	Servomotor	Medium	1 week	10	6 hours
	Solenoid	Low	8h	1	3 hours
	Transmitter	Low	8h	1	3 hours
Vent Valve	-	Medium	2 weeks	12	6 hours
PLC	-	Low	2 weeks	15	6 hours
Oil circuit	Oil pump trained	Medium	1 month	10	6 hours
	Oil pump auxiliary	NS	1 week	15	6 hours
	Exchanger	NS	1 weeks	15	8 hours
	Oil filter	Low	NS	4	2 hours

There is the above-mentioned information available in the uncertain environment. The company wants to get risk-informed recommendations to decide

to buy which spare parts to reduce the unavailability of the plant. The decision tree provides a useful tool for the company to decide in a rational way being informed of the risks and benefits of each action. Therefore, to give reliable information to the decision maker to buy or not to buy each specific subcomponent, a decision tree will be drawn for each of 3*27 subcomponents integrating the unavailability and repair cost with its associated failure probability to give him/her an expected value of taking each action in monetary terms. This utility value will give a comparison tool for the decision maker to choose the most profitable action.

The decision analysis is performed based on two different approaches. In the first approach that is called one site approach, a decision tree is drawn for each subcomponent failure and the unavailability of the plant imposed by failure is compared to the no failure event in two different strategies of buying and not buying the spare parts. The expected values derived from the decision tree will help the decision maker to find the convenient strategy for that subcomponent. The second approach is called the multi-site approach in which the unavailability of P1-C05 compressor can be replaced by a fraction with the P2-C05 compressor. These approaches are described in the following sections.

One Site Approach

The failure probability of each subcomponent is defined qualitatively. First, a quantitative value is dedicated to each of them. The quantitative value of the probability of failure is derived from the frequentist definition of probability [25] where the probability of failure of a component in its lifetime comes from the number of failures experienced from past operational experience. As an example, assuming there is enough data of the past operational experience for a specific component, when in a sample of 10000 components working at the same operational stress, 1 failure has occurred during that components standard lifetime, the probability of failure is resulted to be equal to 0.0001. This quantity is assumed as the value of the probability of failure for NS qualitative category. Similarly, we assume that the Low probability of a component corresponds to a probability of failure equal to 0.01, Medium probability to 0.03, and finally High probability to 0.1. In addition, we know the compressor P1-C05 is producing the 60% of the capacity, so we assume that its cost of unavailability is equal to 0.6*10 K€/day, while the cost of unavailability of P1-CP1 is 0.4*10 K€/day.

The example decision tree of Fig. 2 is for the breaker subcomponent of the breaker equipment of plant P1-C05 with the properties indicated at the second row of Table 1. There are two actions available for the company. First, is to buy the spare and second is to do nothing. Each action has its own consequences in terms of cost (namely the cost of the spare part or the cost unavailability if a failure occurs). There are also two probable outcomes

after the action is decided which is the failure or no-failure of the component. For example, for breaker subcomponent of P1-C05, the probability of failure (P_f) equals to 3%. The spare cost is 21K€. The unavailability of the plant in case of no spare is 45 days with the cost equal to 45*6K€, and the repair time is 8 hours with the cost equal to 8/24*6K€. There are 4 possible scenarios:

1. The action is to do nothing, and the subcomponent fails. This means that to take the plant back to operation, the total cost is to pay for the unavailability of the plant in 45 days (45*6K€) plus the spare part.
2. The action is to do nothing, and the subcomponent does not fail. This is the ideal scenario in which the cost is zero.
3. The action is to buy the spare, and the subcomponent fails. This means that to take the plant back to operation, the total cost is to pay for the unavailability of the plant (i.e. the repair time) in 8 hours (8/24*6K€) plus the spare part (spare part cost was paid before the failure occurred).
4. The action is to buy the spare, and the subcomponent does not fail. In this case, only the spare part cost is paid.

These four scenarios are schemed at the decision tree of Fig. 2, where the values beside each scenario's end state (i.e. the red triangle) is its consequent cost and scenario's number is drawn inside the triangle.

First, to find the expected loss of each scenario, the cost of scenario is multiplied by its associated probability. Therefore, the expected loss of each scenario is calculated as follows:

1. $S_1 = \text{expected loss for scenario 1} = 291 \times 0.03$
2. $S_2 = \text{expected loss for scenario 2} = 0$
3. $S_3 = \text{expected loss for scenario 3} = 23 \times 0.03$
4. $S_4 = \text{expected loss for scenario 4} = 21 \times 0.97$

Then the expected loss of each action is calculated as the summation of its relevant scenarios. If the action is to do nothing, there are two probable scenarios of failure and no failure (scenarios 1 and 2). Therefore, the expected loss is equal to summation of expected loss for failure (S_1) plus the expected loss for no failure (S_2), making the expected loss of doing nothing (A_1) equal to:

$$\bullet \quad A_1 = S_1 + S_2 = 8.73$$

Similarly, the expected loss of the action "buy spares" (A_2) equals to the summation of expected losses of scenarios 3 and 4

$$\bullet \quad A_2 = S_3 + S_4 = 21.06$$

Comparing these expected losses associated with each action (A_1 and A_2), it is concluded that the action of do nothing (A_1) has lower expected loss than buying spare (A_2). Therefore, the rational decision here is to do nothing

for the breaker since it minimizes the loss and in other word maximizes the benefit.

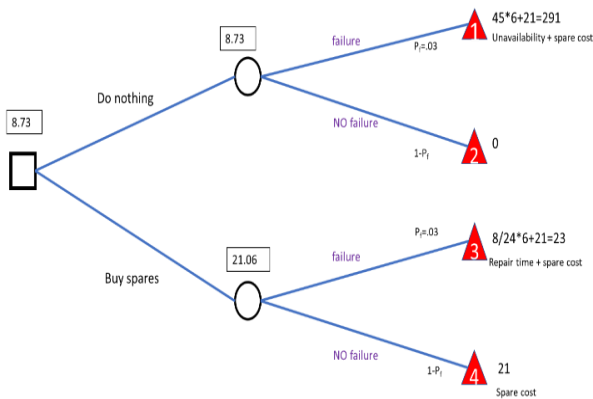


Fig.2. Decision tree of each subcomponent of each compressor. The compressors are considered as independent. The negative sign for costs is omitted.

Similarly, the decision tree of Fig. 2. were drawn for every subcomponent of each compressor to decide whether it is profitable to buy the spare parts or not. Thanks to the 27×3 decision trees drawn for all the subcomponents shown in Tables1 to 3, the expected losses of doing nothing and buying the spares are calculated for all of them. The rational decisions are deducted. Those subcomponents that need the spares to be bought in advance, based on the decision tree analyses, are listed in Table 4.

Table 4. Sub-Components that need buying spares

Subcomponent	Expected loss for doing nothing	Expected loss for Buying spares	Delta
ImpellerP1C05	109.26	44.52	64.74
CouplingP1C05	109.44	49.26	60.18
ImpellerP2C05	110.1	72.52	37.58
CouplingP2C05	110.4	81.26	29.14
Oil pump trainedP1C05	9.3	6.075	3.225
Pignon-ShaftP1C05	111.24	110.52	0.72

The results of Table 4 shows that out of 81 subcomponents of 3 plants, it is rational to buy the spares for the 6 listed subcomponents. The Ranking of the difference among the expected losses of subcomponents are also provided with the Delta value, the greater delta is the greater value of buying spare. Based on this ranking and in case of limited budget, the company can choose which subcomponents to buy first with the greater delta value.

Multi-site Approach

Since plant 1 is composed of two compressors, its availability is more important than plant 2 in terms of the product value. Moreover, plant 1 and 2share the same compressors (C05) in two different sites. Same subcomponents are also shared by both P1C05 and P2C05

and the unavailability cost of P1C05 and P2C05 is the same. Therefore, we consider the case where there is the possibility to make P2-C05 work instead of P1-C05 in case of P1-C05 unavailability.

The idea is to suppose that a percentage t of the production of P1-C05 can be assigned to P2-C05 in case of emergency. This enables the plant 1 to maintain production and cause a decrease of the cost of unavailability of P1 to (1-t) *6 K€/day, assuming that P2 is not full capacity.

The decision tree of Fig. 3 describes the process, considering both P1-C05 and P2-C05. In total 27 decision trees will be drawn for all subcomponents of P1-C05.It worth mentioning that this approach is focused on keeping plant 1 operational and the operation of plant 2 will be sacrificed for plant 1. Two forms of probability of failure is used in this approach: First, the probability of the failure of the subcomponents of P1-C05 which is similar to the on-site approach and is derived from Table 1 (denoted as failure or its complements NO failure in Fig. 3). Second, the probability of the operation (reliability) of plant 2 (denoted as P2 works in Fig. 3) depends on the operation of all its subcomponents and is derived from Equation 1:

$$R_2 = \prod_{i=1}^{27} (1 - p_i) \tag{1}$$

Where p_i is the probability of failure of each subcomponent of plant 2 derived from Table 3. This means that for plant 2 to be operational, all its 27 subcomponents should be operational.

At the other hand, the failure probability of P2-C05 is simply the complement of R_2 (denoted as P2 does not work in Fig. 3) which is equal to the equation:

$$P_{f2} = 1 - R_2 \tag{2}$$

We assume the probability of simultaneous failure for same subcomponents of P2-C05 and P1-C05 is zero. The costs are only computed in terms of P1; thus, we are not computing the cost of repairing P2.

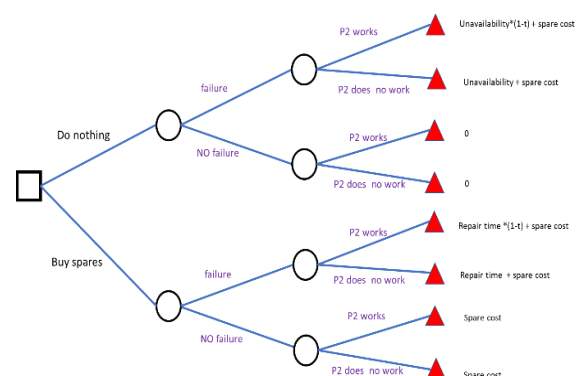


Fig. 3. Multiple Plants decision tree for P1-C05. Computing the cost of P1 since P2-C05 can partially work instead of P1C05.

For each subcomponent of P1-C05 the decision tree can be drawn with this logic that if the subcomponent fails, the unavailability of P1-C05 is not 100% and a

fraction t of its unavailability can be compensated by using the products of plant 2 as shown in Fig. 3.

For every subcomponent, we can plot the estimated expected loss of the action “do nothing” in terms of percentage of production added to P2-C05 in case of P1-C05 failure. Fig. 4 depicts this for the “Coupling” sub equipment of P1-C05. When $t=0$, the expected loss is equal to the one site approach where its values can be referred from Table 4. We can see in this figure that when t increases the expected loss of do nothing” decreases, and therefore, there is no need to buy the spares.

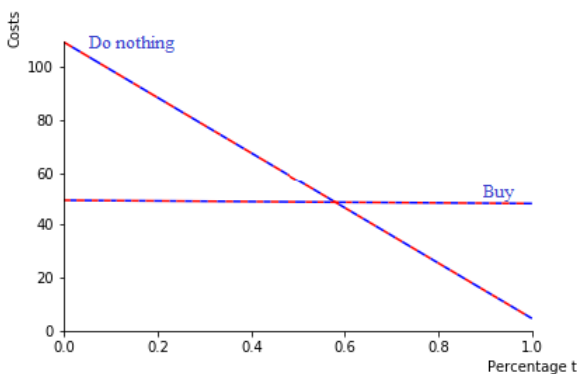


Fig. 4. Subcomponent Coupling of P1-C05 Compressor. Expected value if spare is bought in advance or not.

For three levels of t , namely 0.2, 0.5, and 0.8, The decision trees are computed for each subcomponent of P1-C05, and the expected losses of two strategies of buying spares and doing nothing are calculated for the three mentioned t values. Under these assumptions, it always better not to buy subcomponents when $t=0.8$, buy two subcomponents when $t=0.5$, and buy three subcomponents when $t=0.2$. Table 5 summarizes the results.

Table 5. Subcomponents that need buying spares

$t=0.2$	$t=0.5$	$t=0.8$
ImpellerP1C05	ImpellerP1C05	-
CouplingP1C05	CouplingP1C05	-
Oil pump trainedP1C05	-	-

Results show that when the t percentage increases, there is no need to buy the spares since the unavailability is better compensated by the plant 2 operation. However, when t is lower, there are more subcomponents needed to be bought.

Conclusion

In this research, using the decision analysis, a simple vulnerability analysis of the gas production site is conducted. The decision trees are computed for two approaches of one site and multi-site. Recommendation

lists for the subcomponents that their spares should be bought are provided both for the one site and multi-site approach. It is concluded that the subcomponent Impeller and Coupling are the most vulnerable subcomponents and their failure impose high risk and cost to the system. In the multi-site approach, it is concluded that when the fraction of production replacement by the other plant increase, the need for buying spare reduces. Utilizing a fraction of P2 compressor’s production when P1 fails can help saving money in terms of unavailability of P1-C05. The framework proposed in this work is a sophisticated approach while it is feasibly applicable to the industry and can be applied on real case studies of industrial systems to give them risk informed decisions on maintenance strategy while reliably capturing a good prediction on their systems availability.

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