Research Article

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Urban Water Infrastructure Asset Management Plan: Case Study

Abstract: The current paper aims the application of the Portuguese infrastructure asset management (IAM) methodology to a case study. The inevitable degradation of urban water infrastructures creates new challenges for water utilities engineers and manager, as they need to decide which components should be rehabilitated to efficiently match the public's demand, while still providing a qualitative and efficient service that doesn't compromise the financial integrity of water utilities.

This methodology is based on a five-step structured sequence - (i) definition of objectives assessment criteria and metrics; (ii) diagnosis; (iii) plan production; (iv) plan implementation; and (v) monitoring and revision – being structured in three distinct levels of planning and decision (*i.e.*, strategic, tactical and operational). The IAM methodology was applied to a sixty-year-old water supply system (WSS) located in Lisbon's metropolitan area, Portugal, mainly focused on steps (i) to (iii) and to the tactical level of planning. Results obtained are discussed and the main conclusions are presented.

Keywords: Infrastructure Asset Management, Performance, Planning, Urban Water Infrastructures

1 Introduction

The post-World War II period was marked by a strong investment in the construction of water supply and waste-water drainage infrastructures. This wave of investment was loosely felt all over Europe, aiming to increase the reduced levels of coverage. Now, more than 60 years have passed, and the inevitable degradation of these infrastructures creates new challenges for water utilities engineers and managers. Degradation is a natural and inevitable process that leads to an increase of operational costs, whilst also jeopardizing the system's reliability and the quality of the service [1]. As such, water utility engineers and managers face the challenge of having to decide which components they should rehabilitate to efficiently match the public's demand, while still providing a qualitative and efficient service that doesn't compromise the financial integrity of water utilities [2].

Infrastructure asset management (IAM) is an integrated and multidisciplinary approach that uses systematic, coordinated activities and practices, allowing water utilities to optimally manage their assets and associated performance, risks and costs over their life-cycle [3]. In essence, IAM is of utmost importance for water utilities to ensure compliance with system performance requirements.

Rehabilitation of water assets is considered by the Portuguese Water and Waste Services Regulator (ERSAR) as a key issue in increasing the efficiency of water utilities. National legislation passed in 2009, effective 2013 (Decree-Law no. 194/2009), requires an IAM system in all water supply services and urban wastewater management services serving 30 000 people and over.

Following this legislation, ERSAR, in conjunction with the Nacional Civil Engineering laboratory (LNEC) and the Instituto Superior Técnico of Lisbon, published two technical guides outlining an integrated IAM methodology for water supply and waste-water drainage systems, as well as a set of supporting technologies. This IAM approach was developed under the AWARE-P project (2009-2011), further developed in the scope of other R&D projects, such as iGPI (2012-2013), INFR5R12 (2013-2014), and, in a very significant way, in the TRUST EU 7th FP project (2011-2014) [4].

This methodology is a broad management process organized into three distinct levels of decision and planning (*i.e.*, strategic, tactical and operational), where each level is composed by a five-step structured sequence (see Figure 1). The three different dimensions (*i.e.*, cost, risk and performance) are incorporated in each level of planning

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Nelson J. G. Carriço: Barreiro School of Technology, Polytechnic Institute of Setúbal, Rua Américo da Silva Marinho, 2839-001 Lavradio, Portugal
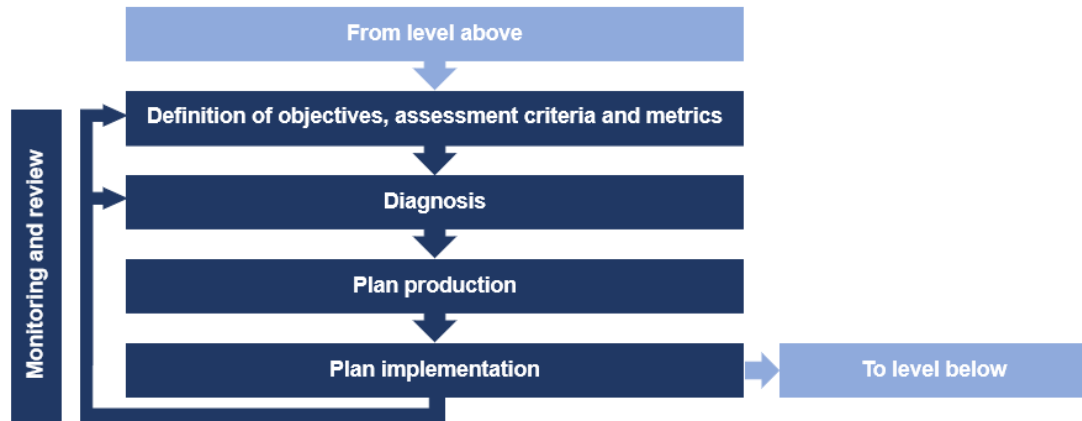
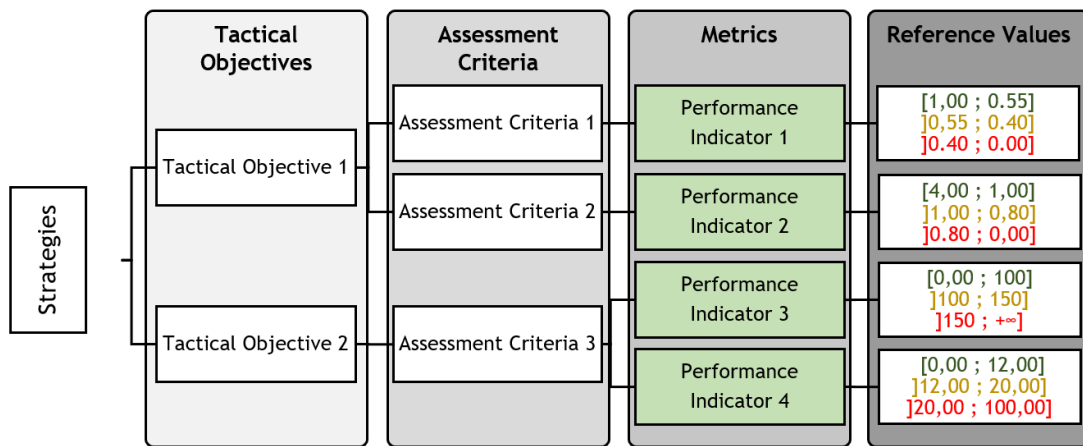**Figure 1:** The AWARE-P's IAM planning process [1].

Figure 2: Definition of tactical objectives, assessment criteria and metrics.

to better support decision-making, particularly at the tactical level. This methodology also aims at goal-driven management, specified in evaluation criteria and metrics, allowing the establishment of targets and monitoring of results [5, 6].

The current paper presents the practical application of the referred IAM methodology, through the development of a tactical plan and applied to a water supply system located in the metropolitan area of Lisbon.

2 Methodology

Although IAM planning should be done the three levels (*i.e.*, strategic, tactical and operational), it is at the tactical level where the strategies that relate to the infrastructure are implemented. Founded on the strategies and on the strategic objectives and targets, the aim of tactical planning is to define what are the intervention alternatives to

implement in the medium term (typically 3 to 5 years) [1]. Nonetheless, IAM tactical planning is not restricted to infrastructural solutions, as it should also consider the interventions related to operations and maintenance and to other non-infrastructural solutions [5, 6].

Tactical planning consists in five steps as depicted in Figure 1. At a first stage, the assessment system is set up, as objectives, assessment criteria and metrics are defined. The tactical objectives are outlined based on the strategies previously defined at the strategic level. This simplifies the process of articulation between levels of planning and guarantees the alignment between the objectives at tactical and strategic level. As depicted in Figure 2, for each of these objectives, assessment criteria and metrics were defined in order to carry out the assessment of its compliance. These assessment criteria are aspects or perspectives through which objective's compliance can be evaluated. Metrics are an essential basis for establishing the diagnosis, prioritizing intervention solutions and monitoring the
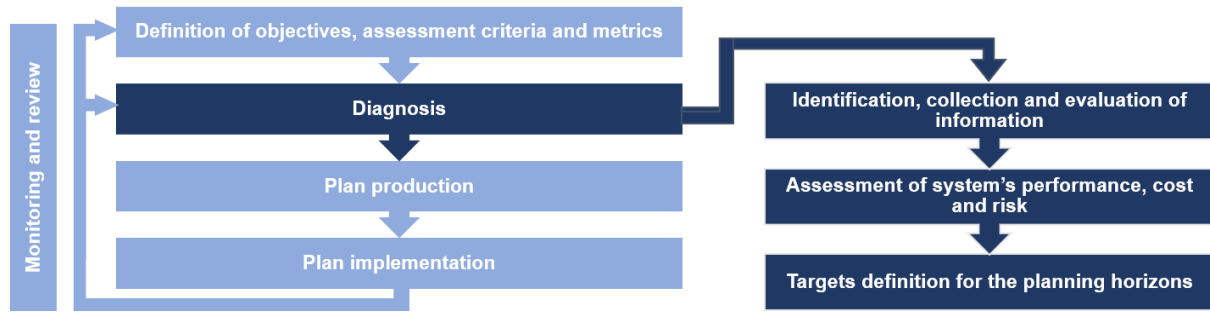
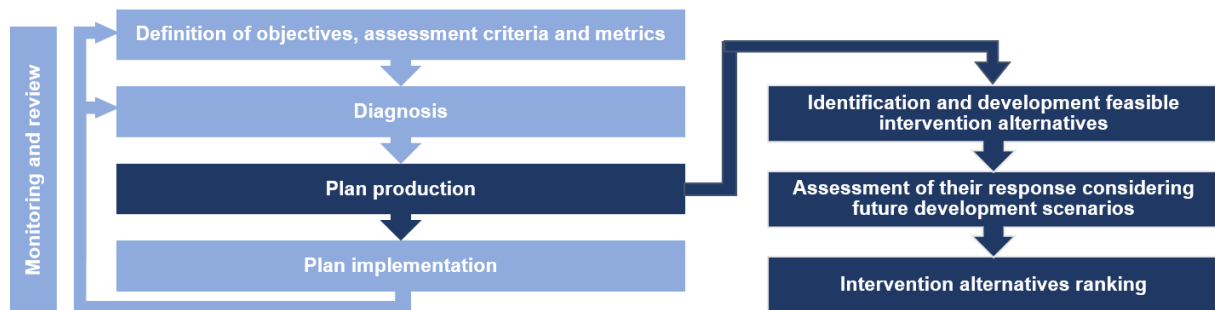**Figure 3:** Stages of tactical diagnosis [4].

Figure 4: Stages of plan production [4].

results as they are specific variables that allow quantitative or qualitative characterization of performance, cost, and risk dimensions [1, 6].

The second step is the tactical diagnosis where dysfunctions that indicate the existence of problems from certain points of view considered relevant are identified, namely, hydraulic, environmental, structural and operational. This step compromises two stages, as depicted in Figure 3: (i) identification, collection and evaluation of information, where the availability and feasibility of the data are evaluated to characterize the system; and (ii) assessment of system's performance, cost and risk, for the reference situation and through comparison between the observed performance and the reference values. Targets for the planning horizons are defined based on the diagnostic result for the reference situation, considering the medium and long-term investment plan defined by the utility (*i.e.*, capacity to intervene, in terms of available resources).

The third step is the plan production and is presented in Figure 4. It is one of the most work-intensive tasks as it encompasses the demanding engineering processes involved in identifying and developing feasible intervention alternatives, as well as the assessment of their response over the analysis horizon for the selected metrics, considering future development scenarios. The diagnosis, design and analysis of infrastructural and operational alter-

natives are not trivial tasks and often require the use of sophisticated modelling tools, such as EPANET [7].

Developed intervention alternatives need to be ranked, which represents a Multiple Criteria Decision Aid (MCDA) problem, to decide the best alternative which ensures the best balance between performance, cost and risk.

The last steps of tactical planning are the implementation, monitoring and periodic review of the plan. Implementation is materialized through development and enactment of operational plans for rehabilitation and expansion. Monitoring allows, through system's assessment, the identification of possible deviations from the established targets and to verify the degree of implementation of each defined action. Necessary corrections are made in the review phase, allowing the process of continuous improvement [5, 6].

3 Case study

3.1 Description

The case study is a sixty-year-old water supply system (WSS) located in Lisbon's metropolitan area, Portugal. The neighbourhood covers an area of 4 square kilometres with a population of about 14,430 inhabitants. As for the build-

ings' typology and functionality, the area is quite hetero-geneous, ranging from single-family dwellings to eleven-story residential buildings as well as a few supermarkets, schools, a cemetery, a central hospital, some shops and in-dustrial plants. The distribution network is about 36 km long, of which 5 km have a transmission function and the remaining 31 km have distribution function, with about 2,180 service connections. The network is of the mixed ty-pology with a combination of both looped and branched portions, as shown in Figure 5.
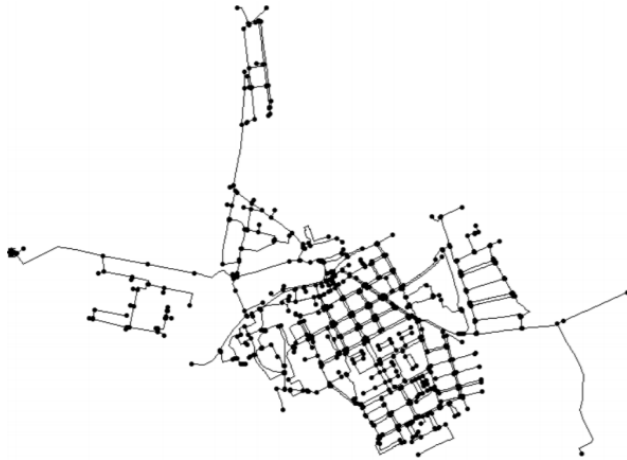

Figure 5: Water supply system's configuration.

Years of reactive interventions have led the network to become aged and deteriorated, with a heterogeneous dis-tribution of the materials, consisting of pipes from the orig-inal system, pipes of network expansions or repairs carried out as a result of ruptures. Most pipes are made of asbestos cement (~63%), PVC (~34%) and HDPE (~3%) with diame-ters varying from 32 to 400 mm.

The case study is located on top of the huge Tagus-Sado aquifer system, the water source of the studied WSS. Groundwater abstraction is made from five wells that oper-ate non-simultaneously.
Then, the water is treated next to the wells through chlo-rine injection. After the treatment, the water is transported to two storage tanks and then raised directly to the distri-bution network through a group of pumps. It is also worth to mention that this WSS is managed by a municipality.

3.2 Tactical objectives, assessment criteria and metrics

As mentioned above, the tactical planning starts with defining the tactical objectives, which should be aligned

with the strategies that were established at the strategic level. The strategic plan that was elaborated by the munic-ipality for the period of 2015-2035 has three strategic objec-tives (SO), such as technical and economical sustainability (SO1), environmental and social sustainability (SO2) and adaptation to users' needs (SO3). Four strategies were de-fined based on these strategic objectives – improve the infrastructure value index (IVI); reduce water and energy losses; improve systems' preventive maintenance and im-prove utility's economical management.

The definition of the tactical objectives was elaborated through direct association of each objective with its respec-tive strategy, resulting in the following tactical objectives (TO): achieve an adequate IVI (TO1), achieve an efficient level of water losses and energy consumption (TO2), pro-mote system's appropriate maintenance (TO3), and ensure utility's economic sustainability (TO4). For each of these objectives, assessment criteria were defined and adapted to system's reality.

To assess the performance and fulfillment of each tac-tical objective, metrics were defined for each of the pre-viously established assessment criteria, based on three different dimensions (*i.e.*, cost, risk and performance). These metrics will be used to perform system's diagnosis, through comparison with the established reference values. Based on the diagnosis results for the reference situation, and considering the medium-term investment plan, tar-gets will be defined for the tactic and strategic horizons.

Figure 6 presents the established metrics and respec-tive reference values, as well as its alignment with the tac-tical objectives and the defined assessment criteria.

Each of the thirteen metrics presented in Figure 3 is explained in a brief and succinct manner.

Performance

Infrastructure value index – IVI (P1). This performance in-dex is given by the ratio between the current value of the in-frastructure and the respective replacement cost. The cur-rent value of the infrastructure was obtained by depreci-ating the value of the assets over the respective years in service. Infrastructure replacement cost was obtained us-ing cost functions [8]. This indicator shows the infrastruc-ture's conservation degree, revealing the need to intervene in a given segment, as well as whether there is excessive or insufficient investment in rehabilitation.

Network Rehabilitation (P2). This performance indica-tor translates the percentage of the network that was re-habilitated in the last year, obtained through work orders' records.
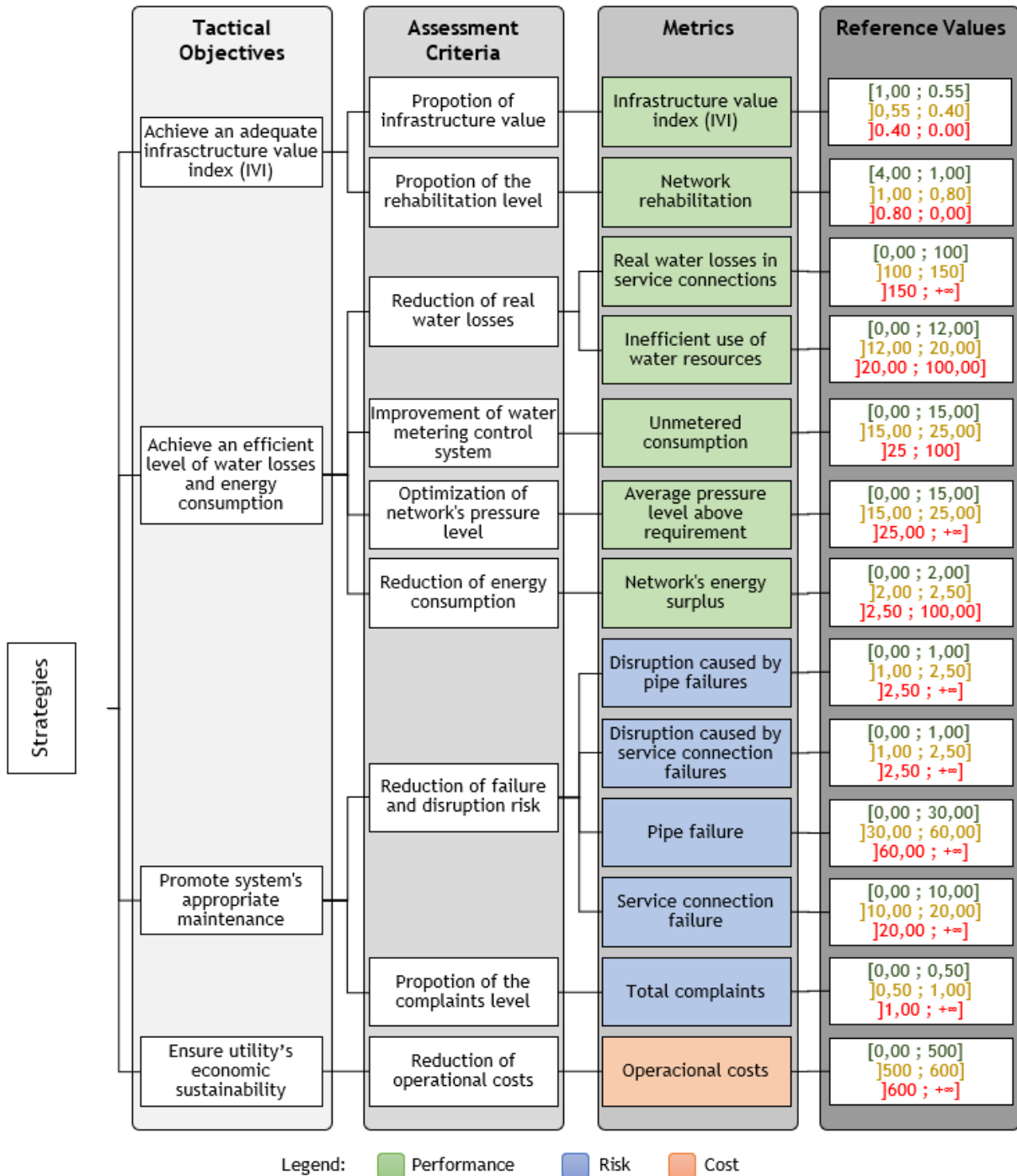
Figure 6: Alignment between tactical objectives, assessment criteria and metrics.

Real water losses in service connections (P3) and Inefficient use of water resources (P4). Real water losses are the physical losses of water from the distribution system up to the point of customer metering, including leakages caused by fissures in pipes and service connections as well as storage tank overflows. These losses inflate water utility's production costs, putting water resources at greater stress, since they represent an amount of water that is extracted, treated and pumped, without, however, being used. The real water losses volume was obtained through the system's water balance, described in ERSAR's technical guide [9] and in accordance with the recommendations of the International Water Association. The P3 indicator is given by the ratio between the real water losses and the to-

tal number of service connections and the P4 indicator is obtained through the ratio between the real water losses and the system input volume.

Unmetered consumption (P5). This metric translates the percentage of water supplied to the system whose consumption is not measured. It is given by the ratio between the unmetered water volume and system's input water volume.

Average pressure level above requirement (P6). This performance index is used to evaluate if the minimum required service pressure is supplied at each service connection, as well as to determine the excessive pressure being supplied to the network. It is obtained by the average of the pressure difference in each service connection and the minimum required service pressure. According to Portuguese legislation, the minimum required service pressure (kPa) is given by 100+40n, N being the number of floors above ground. In the present case study, five floors above ground were considered.

Network's energy surplus (P7). Energy supplied to the network always includes a portion to cover the flow that will be pumped but lost through leaks and breaks. This performance index quantifies the theoretical excess of energy that is supplied to the system and is obtained by the quotient between the total energy supplied to the network and the minimum energy necessary to ensure water supply.

The total energy supplied to the network was obtained through an electric meter installed in the electric pump group. The minimum energy necessary to ensure the supply of water corresponds to the sum of the minimum powers required in each node, in order to satisfy the respective consumption and to comply with minimum pressure requirements [10].

Risk

Disruption caused by pipe failures (R1) and Disruption caused by service connection failures (R2). According to Portuguese legislation, water utilities must ensure continuous water supply to users, which may be interrupted if repairs or replacements in service connections as well as components belonging to the public distribution network are carried out. The disruption's time extension due to pipe failures is calculated with the R1 indicator - it results from the ratio between the disruption's time extension caused by pipe failures and total number of users. R2 indicator calculates the disruption's time extension due to service connection failures. It is given by the ration between the disruption's time extension caused by service connection failures and total number of users.

Pipe failure (R3). This metric quantifies the number of interventions that result from pipe failures. It is given by the ration between the number of interventions caused by pipe failures and the total pipe's length.

Service connection failure (R4). This metric quantifies the number of interventions caused by service connection failures and is given by the ration between the number of interventions caused by service connection failure and the total number service connections.

Total complaints (R5). It is possible to detect certain hydraulic dysfunctions through complaint analysis. The R5 metric is obtained through the ratio between the total number of complaints related to the network's performance and total number of users.

Cost

Operational costs (C1). An inadequate system's performance translates into an increase of the operational costs. The C1 metric is obtained through the ratio between the network's related operational costs (*i.e.*, water treatment, breakdown repair) and the total network's length.

3.3 Tactical diagnosis

As aforementioned, the tactical diagnosis assesses the water supply system in order to identify dysfunctions and problems from different points of view. To do so, the thirteen metrics above-mentioned were computed and compared with the pre-established reference values (See Figure 3). Most of the information needed for metrics calculation was provided by the Municipality. Based on the diagnosis results for the reference situation, and considering the medium-term investment plan, targets were defined for the tactical planning horizon (2022) and the strategic analysis horizon (2035) as presented in Table 1.

Approximately, 58% of the water supply system's pipes were built in 1959, having been, at the date of this article, 58 years in activity. The infrastructural value index revealed an aged network that lacks significant investments in rehabilitation. Additionally, the network's rehabilitation indicator evidenced proactive management, a recent practice that counteracted the reactive management that was practiced by the utility until recently.

The real water losses exhibit a satisfactory result, given the system's age. However, they can be subjected to some reduction.

The unmetered consumption indicator proved to be rather unsatisfactory. Due to the lack of water meters in

Table 1: Obtained results for the reference situation and targets establishment

PI	Designation	Reference Situation (2017)	Targets at planning horizon	
			Tactical (2022)	**Strategic (2035)**
P1	Infrastructure value index-IVI	0,34	0,40	0,45
P2	Network Rehabilitation	1,65	2,00	2,00
P3	Real water losses in service connections	144,76	132,98	100,00
P4	Inefficient use of water resources	15,3	14,43	12,00
P5	Unmetered consumption	28,93	25,26	15,00
P6	Average pressure level above requirement	11,52	11,52	11,52
P7	Network's energy surplus	1,10	1,10	1,10
R1	Disruption caused by pipe failures	1,41	1,30	1,00
R2	Disruption caused by service connection failures	1,08	1,06	1,00
R3	Pipe failure	39,89	37,29	30,00
R4	Service connection failure	31,10	25,55	10,00
R5	Total complaints	0,56	0,54	0,50
C1	Operational costs	505,95	504,38	500,00

green spaces, there's no control or measurement of the water that is used to irrigate these areas.

P6 and P7 indices proved that the network is optimized at the energetic level and there is no need to intervene in this aspect.

R1, R2, R3 and R4 indicators performed poorly. Given the network's age, a significant number of failures in pipes or service connections are expected, as well as its respective disruption time.

R5 and C1 indicators presented satisfactory results, which were very close to the established targets.

3.4 Scenario analysis of water supply demand

A scenario can be defined as a possible trajectory (desirable or undesirable), resulting from a set of factors that are not controlled by the utility, with the potential to influence performance during the period of analysis. The consideration of these scenarios in the analysis makes it possible to deal with the uncertainty about the future concerning water supply demand as well as the configuration and management of the water supply system [1]. The case study integrates a mainly and well established residential area, where no significant development is expected in terms of water consumption. For that reason, scenarios of consumption evolution were not considered.

3.5 Definition of intervention alternatives

Intervention alternatives with the potential to improve the system's performance and achieve the established targets are developed as the evaluation's results for the reference situation are considered.

Since the network is already energetically optimized (*i.e.*, optimal pipe's diameter design considering the minimum energy dissipation rate principle), its rehabilitation will consist on like-for-like replacement, as pipes will be replaced with others of identical cross-section, yet of a more recent material. A possible way to bridge the system's poor performance against unmetered consumption goes by installing meters in its green spaces. Service connections have an average service life of 20 years, well below the 50 years associated to pipes. It is, therefore, necessary to create a service connection rehabilitation plan, whereby 5% are rehabilitated per year. Water meters, when operating beyond their 12 years' service life, start to present mechanical problems that may induce metering errors and, consequently, economic loss. As such, it is necessary to develop and maintain a water meter renewal plan.

Taking these considerations into account, three rehabilitation alternatives were considered:

A_0: The status quo alternative, which corresponds to not perform any rehabilitation interventions in the network whilst maintaining current operations and maintenance reactive practices (no capital investment associated);

Table 2: Assessment of the three alternatives for the tactical and strategic planning horizon

PI	A₀ Planning horizon		A₁ Planning horizon		A₂ Planning horizon		Targets Planning horizon	
	Tactical (2022)	Strategic (2035)	Tactical (2022)	Strategic (2035)	Tactical (2022)	Strategic (2035)	Tactical (2022)	Strategic (2035)
P1	0,31	0,22	0,37	0,44	0,36	0,39	0,40	0,45
P2	0,00	0,00	2,00	2,00	1,50	1,50	2,00	2,00
P3	160,84	226,19	133,01	110,82	138,74	125,68	132,98	100,00
P4	17,00	23,91	14,06	11,71	14,66	13,28	14,43	12,00
P5	32,14	45,20	17,83	14,86	25,09	22,73	25,26	15,00
P6	12,80	18,00	11,52	11,52	11,52	11,52	11,52	11,52
P7	1,22	1,72	1,10	1,10	1,10	1,10	1,10	1,10
R1	1,57	2,20	1,30	1,08	1,35	1,22	1,30	1,00
R2	1,20	1,69	0,99	0,83	1,04	0,94	1,06	1,00
R3	44,32	62,33	36,65	30,54	38,23	34,63	37,29	30,00
R4	34,56	48,59	24,79	12,87	26,79	17,44	25,55	10,00
R5	0,63	0,89	0,52	0,44	0,55	0,49	0,54	0,50
C1	562,17	790,55	464,87	387,34	484,90	439,26	504,38	500,00

A_1: Adoption of an annual rehabilitation rate of 2% for pipes and 5% for service connections, renewal of the water meter park every 12 years and installation of 52 water meters in green spaces during the next 5 years (annual investment of € 135,000);

A_2: Adoption of an annual rehabilitation rate of 1.5% for pipes and 5% for service connections, renewal of the water meter park every 12 years and installation of 52 water meters in green spaces during the next 15 years (annual investment of € 100,000);

3.6 Assessment of intervention alternatives

Taking into consideration the inevitable degradation of infrastructures, the previously defined metrics were computed to assess the intervention alternatives' response over the planning horizons (*i.e.*, 2022 and 2035). Table 2 presents the result of the intervention alternatives assessment for the tactical and strategic planning horizons.

By examining Table 2, it is possible to conclude that the best alternative, as far as performance is concerned, is the A_1 alternative. In this alternative, the clear majority of the targets are reached within the considered planning horizon. A_2 alternative doesn't reach some of the established targets within the considered planning horizon and, as it considers an annual rehabilitation rate of 1.5% for pipes, it acknowledges that some components will exceed their service life and may compromise the system in the long term. Finally, the A_0 alternative features the worst

performance, since no rehabilitation interventions were considered.

3.7 Intervention alternatives ranking

Table 3 presents the intervention alternatives' ranking, done through a simple multicriteria decision analysis method (*i.e.*, weighted sum).

Table 3: Intervention alternatives ranking through multi-criteria decision

Alternative	Ranking	Annual investment
A_1	1	€ 135.000
A_2	2	€ 100.000
A_0	3	0

The annual available budget for rehabilitation interventions is derived from the water supply's revenues, whilst deducting the operational and personnel costs, amortizations and interest as well as energy costs. Approximately, this amounts to € 100,000 per year. Therefore, the A_1 alternative (which ensured the best performance) is vetoed from the analysis since it exceeds the available budget. This budget limitation implies choosing alternative A_2, even though it doesn't allow some targets to be achieved within the considered planning horizon. Additionally, as it considers an annual rehabilitation rate of 1.5% for pipes, it

admits that some components will operate exceeding their expected service lifetime.

4 Conclusions

The current paper presented the practical application of the Portuguese IAM methodology, through the development of a tactical plan, applied to a water supply system.

For this purpose, four tactical objectives were outlined based on the strategies previously defined by the utility at the strategic level. Assessment criteria, metrics and targets were established with the utility's monitoring to evaluate the performance and fulfilment of each tactical objective. As a result, thirteen metrics and targets were defined, embodying three different dimensions (*i.e.*, cost, risk and performance). The diagnosis was carried as metrics were computed and compared with the pre-established reference values. Posteriorly, and based on the diagnosis results, three rehabilitation alternatives were developed and assessed for each different planning horizon. The A1 alternative, which ensured the best performance, was vetoed from the analysis as it exceeded the available budget in 35%. The adopted alternative, A2, complied with the available budget at the expense of some components that will, inevitably, operate while exceeding their expected service lifetime.

In essence, it was concluded that less investment in proactive management could lead to future problems and unforeseen expenses.

References

[1] Carriço, N. (2014). Multi-criteria decision aid methodology for selection and prioritization of rehabilitation interventions in urban water infrastructures (PhD Thesis). Instituto Superior Técnico (IST), Lisbon, Portugal (in Portuguese).

[2] Alegre, H. (2008). Water infrastructure asset management, Research Program, Series «Thesis and Research Programmes», LNEC, Lisbon, ISBN 9789724921341 (in Portuguese).

[3] Alegre, H., Almeida, M.C., Covas, D., Cardoso, M.A., Coelho, S.T. (2011). An integrated approach for infrastructure asset management of urban water systems. In 4th LESAM, Mülheim an der Ruhr, Germany.

[4] Alegre, H., Coelho, S. T., Vitorino, D., Covas, D. (2016). Infrastructure asset management - the TRUST approach and professional tools. Water Sci. Technol. Supply, Vol. 16, no. 4.

[5] Alegre, H., Covas, D. (2010). Infrastructure asset management of water transmission and distribution systems. ERSAR, LNEC and IST, Series ERSAR Technical Guides, Vol. 16, Lisbon, Portugal. ISBN: 978-989-8360-04-5 (in Portuguese).

[6] Almeida, M.C., Cardoso, M.A. (2010). Infrastructure asset management of wastewater and stormwater services. ERSAR and LNEC, Series ERSAR Technical Guides, Vol. 17, Lisbon, Portugal. ISBN: 978-989-8360-05-2 (in Portuguese).

[7] Alegre, H., Coelho, S.T. (2012). Infrastructure Asset Management of Urban Water Systems. In: A. Ostfeld, ed. Water Supply System Analysis. ISBN: 978-953-51-0889-4.

[8] Covas, D., Monteiro, A.J., Teixeira, A.T., Cabeças, A., Barros, C., Figueiredo, D., Pena, J., Mamouros, L., Amado, M. C., Cabral, M., Brôco, N., Lopes, N., Antunes, S., Marchionni, V. (2015). Infrastructure reference costs of the urban water cycle, recovery of solid urban waste and coastal protection (in Portuguese).

[9] Alegre, H., Hirner, W., Baptista, J.M., Parena, R. (2000). Performance indicators for water supply services, 1st edition, Manual of Best Practice Series, IWA Publishing, London, ISBN: 1 900222 272 (160 p.).

[10] Duarte, P., Alegre, H., Covas, D. (2008). Energetic performance assessment in water supply systems. In 13th ENaSB, Covilhã, Portugal (in Portuguese).