Developing asset management indicators and visualisation of information to improve long-term planning tools for water supply systems

Pedro Nogueira Fernandes Aguiar Costa

Master's Dissertation

Supervisor: Prof. Ana Camanho
Co-Supervisor: Prof. Nuno Marques de Almeida

U. PORTO

FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Master in Mechanical Engineering

2021-06-28

Abstract

All companies have limited capital available to make investments in their infrastructures. Consequently, investments must be as wise as possible to ensure proper assets' functioning with a manageable risk level. This will enable the obtainment of high service levels at the lowest possible cost. The cost, performance and risk dimensions can be quantified through multiple financial and operational indicators. An established indicator that reflects the cost and risk dimensions and is already in use within the water sector in Portugal is the Infrastructure Value Index (IVI).

The present dissertation proposes an enhanced approach to calculate the IVI indicator, that allows the decision-makers to correctly compare the various assets condition and estimate the impact that future investments will have on the condition of the assets and the overall system. It discusses a revised formulation for the IVI and illustrates its application with an empirical case study consisting of water infrastructures managed by the Portuguese Company Águas do Douro e Paiva (AdDP). The study includes two infrastructures with different characteristics to test the feasibility and adaptability of the new formulation of the IVI indicator. The objective of this study is to discuss possible improvements to the methodology used to assess the condition of infrastructures and make the indicator relevant for the capital investment planning of infrastructure assets.

The methodology created details the condition of the assets that consitute the infrastrucuture and uses this information to calculate the IVI. However, information on adequately unbundled assets cannot always be obtained. Thus, an approach where the indicator is calculated with more aggregated data is tested and extended to the remaining infrastructures of AdDP's Lever North subsystem. The accuracy of this alternative is compared with the methodology first developed.

The information has value if it can be easily transmitted. Data organization and visualization are pertinent subjects in asset management that should be treated with due importance. An adequate information system facilitates communication between the various departments of an organisation. Therefore, an information system is proposed according to AdDP's reality, from which Dashboards will be created to facilitate communication with employees.

Resumo

Todas as empresas têm um capital limitado disponível para fazer investimentos nas suas infraestruturas. Consequentemente, os investimentos devem ser o mais prudentes possível para assegurar o funcionamento adequado dos ativos com um nível de risco controlável. Isto permitirá a obtenção de elevados níveis de serviço ao mais baixo custo possível. As dimensões de custo, desempenho e risco podem ser quantificadas através de múltiplos indicadores financeiros e operacionais. Um dos indicadores estabelecidos que reflete as dimensões de custo e risco e que já está a ser utilizado no sector da água em Portugal é o Índice de Valor da Infraestrutura (IVI).

A presente dissertação propõe uma abordagem melhorada para calcular o indicador IVI, que permite aos decisores comparar corretamente a condição dos vários ativos e estimar o impacto que os investimentos futuros terão na condição dos ativos e no sistema global. A presente tese discute uma formulação revista para o IVI e ilustra a sua aplicação com um estudo de caso empírico constituído por infraestruturas de água geridas pela Empresa Portuguesa Águas do Douro e Paiva (AdDP). O estudo inclui duas infraestruturas com características diferentes para testar a viabilidade e adaptabilidade da nova formulação do indicador IVI. O objetivo deste estudo é discutir possíveis melhorias na metodologia utilizada para avaliar o estado das infraestruturas, e tornar o indicador relevante para o planeamento do investimento de capital dos ativos das infraestruturas.

A metodologia criada detalha a condição dos ativos que constituem a infraestrutura e utiliza esta informação para calcular o IVI. No entanto, nem sempre é possível obter informações sobre os ativos adequadamente desagregados. Assim, é testada uma abordagem em que o indicador é calculado com dados mais agregados e alargado às restantes infraestruturas do subsistema Lever Norte da AdDP. A precisão desta alternativa é comparada com a metodologia inicialmente desenvolvida.

A informação tem valor se puder ser facilmente transmitida. A organização e visualização dos dados são assuntos pertinentes na gestão de ativos que devem ser tratados com a devida importância. Um sistema de informação adequado facilita a comunicação entre os vários departamentos de uma organização. Por conseguinte, é proposto um sistema de informação de acordo com a realidade da AdDP, a partir do qual serão criados *dashboards* para facilitar a comunicação com os funcionários.

Acknowledgements

First of all, I would like to thank AdDP, which opened the doors for me to carry out the dissertation that finishes this stage of my academic journey. An organization with competent professionals who were always available to help so that this dissertation could be done with the best conditions.

I thank Engineer Gabriel for all the *know-how* that he was always willing to share, for his availability, and for trusting me to carry out this project as challenging as rewarding. I also thank Professor Nuno Almeida for all the theoretical contributions provided in this very current subject that is asset management. To Engineers João Ferreira, Alberto Afonso, and Lígia Ramos for the brevity with which they answered all the technical questions related to the organization infrastructures. Thanks to Engineer João Vieira for his help in developing the work done and for always being available to help when needed.

To Professor Ana Camanho, thank you for the supervision and constant availability, for the knowledge transmitted, and for proposing me challenges that were a premiere for me.

A special thanks to my friends who stayed with me on this journey. Thank you for accompanying me on endless days in the library, in the lectures after sleepless nights, and for your patience because sometimes I can be a bit tedious. Thank you because, without you, this stage of my life would still be happening but not in the special way it was.

And last and most importantly to my parents. Thank you for always taking care of me and giving me the best education possible. Thank you for the pride in me that you insist on showing, and that gives me the strength to always give the best of myself to meet your expectations. Thank you for always believing in me and making me the person I am today.

"Minds are like parachutes, they only function when they are open."

James Dewar

Contents

Acronyms and Symbols

BI	Business Intelligence
IA	Information Asset
IAM	Infrastructure Asset Management
IVI	Infrastructure Value Index
KPI	Key Performance Indicator
PS	Pumping Station
REF	Report and Evaluation Form
RR	Reservoir
WTP	Water Treatment Plant

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction

Water is the source of life. Around 70% of the human body's cells contain water, so preserving water resources is preserving our existence. Since water is an essential good, its affordability must be guaranteed to every individual. Therefore, water supply services for the population are of fundamental importance for the proper functioning of society. Like in many other countries, the firms responsible for the water supply in Portugal operate in a monopolistic context. The firm's objective is to distribute water and it is from this that the need to regulate this sector arises. If the water sector were not regulated, the lack of competition might lead water utilities to provide low-quality services with no attention to the environmental issues, with excessive focus on profits. Thus, it is clear that the need to regulate the sector is central to ensuring consumers' high service levels and access to an essential good. The demands of the regulator have been increasing over the years. Ensuring access to good water quality is not enough. The organizations responsible for water supply, in addition to good service levels, must ensure economic, financial, social, and environmental sustainability. One of the ways to guarantee this sustainability is to ensure that companies comply with a series of key performance indicators that reflect these dimensions (D'Inverno et al. (2021)).

Water utilities need a huge number of assets to keep their treatment and distribution network running. The available capital is often not sufficient to meet all investment needs as they arise. Thus, the deferral of critical investment and the subsequent decay of the infrastructure condition may compromise the level of service established by the regulator. There is evidence that worldwide the integrity of urban water infrastructures is at risk with the constant deferral of necessary rehabilitation and maintenance works (e.g. AWWA (2017); CSA (2014)). Portugal is not different; the national panorama lacks rehabilitation in the infrastructure of water supply systems (MAOTE, 2014). As a result, the autorities responsible responsible for the sector's administration are currently facing challenges to ensure the long-term sustainability of urban water services. Asset management tools can contribute to this purpose by obtaining the needed information to make the best decisions to ensure this sustainability.

The asset management function is to use assets to generate value and achieve organizations' objectives. Thus, any organization subject to recurrent and extensive capital investments, needs to have a strong asset management team. Asset management supports the realization and production of value by balancing the financial, environmental, and social costs, risk and service quality associated with assets. The benefits of a solid asset management department can include: improved financial performance, informed investment decisions, risk management, improved service delivery, improved sustainability of the organization, among others (Hastings (2021)).

Throughout this thesis, concepts of asset management in a real business context are addressed. The company where this dissertation is carried out is the Portuguese water distribution company Águas do Douro e Paiva (AdDP).

Águas do Douro e Paiva, S.A., like any company in the water supply sector, is a regulated company with many assets requiring constant and significant investments, making its careful management essential. Because it is a capital-intensive sector, it is necessary to have all the relevant information to make the best decisions when prioritizing investments. To make the best decisions, a trade-off between the dimensions "Risk", "Cost" and "Performance" becomes essential (Alegre (2010)). AdDP's Asset Management department already balance these dimensions through multiple financial and operational indicators. An established indicator that reflects the "Risk" and "Cost" dimensions and is already in use within the water sector in Portugal is the Infrastructure Value Index (IVI).

The Infrastructure Value Index (IVI) has proven to be an effective tool to support long-term planning, in particular by facilitating the ability to communicate and to create awareness of the condition of the infrastructures (Alegre et al., 2014). Although organizations have already started using this indicator, its calculation depends on subjective information, as its components can be interpreted differently. This dissertation contributes to the literature on asset management by proposing a different approach to the estimation of the Infrastructure Value Index (IVI) aligned with companies' practices and financial/accounting procedures.

1.2 AdDP

AdDP's mission is to manage the upstream water supply system, ensuring efficiency, reliability, quality of service, product safety, and respect for the highest social and environmental values (AdDP, 2017).

The public water supply services are classified in bulk or upstream and distribution or downstream systems, depending on the type of activity the managing entity performs. In the water supply service case, upstream systems consist of a set of components upstream of the distribution network, connecting the water medium to the downstream system. In turn, downstream systems are composed of municipals that enable the water supply service to be provided to consumers. AdDP can be referred to as a bulk system or an upstream system.

On 01 February 2017, the Decree-Law 16/2017 established the latter concession for the bulk water system managed by AdDP, with the social purpose of exploring and managing the system of southern Greater Porto, involving the current number of 20 municipalities, for 20 years. It is noteworthy to remind that the system had been originally created in 1995, defined in the first AdDP concession's contract, for 30 years. Its previous design comprised 18 municipalities of the Porto region. After a merging process, in 2015, with other companies, in the north of Portugal, creating a bulk system to the whole north of Portugal, managed by Águas do Norte, S.A., the current structure of AdDP resulted from the scission of such larger system. The following 20 municipalities that now integrate the system cover an area of 2,715 km^2 with 1,7 million inhabitants: Amarante, Arouca, Baião, Castelo de Paiva, Cinfães, Espinho, Felgueiras, Gondomar, Lousada, Maia, Matosinhos, Oliveira de Azeméis, Ovar, Paços de Ferreira, Paredes, Porto, Santa Maria da Feira, São João da Madeira, Valongo and Vila Nova de Gaia. Besides enjoying the service, these municipalities are also shareholders and own 49% of the company. The remaining 51% of the share capital is owned by Águas de Portugal, SGPS, S. A. (AdP), a state Group of Enterprises that integrates several companies along the country. AdDP's system also supplies water to part of the population of two additional client municipalities – Vale de Cambra and Penafiel – which are not shareholders. The multi-municipal bulk system comprises the catchment, treatment, and supply of water, for the 22 municipalities, which are then responsible for the water delivery to citizens through their municipal distribution water networks (AdDP, 2000).

This dissertation takes place within the Asset Management and Engineering department, responsible for managing the life cycle of the infrastructures and coordinating and controlling the company's investment plan. It is also responsible for the execution, coordination, and supervision of studies, projects, and contracts. Regarding the management of the infrastructure's life cycle, there is a need to revise the methods used to calculate and compare the condition of the group's various assets.

Noteworthily, in 2019, an Asset Management system was implemented by AdDP and certified by ISO 55001 standard, joining the other certified systems implemented by the company in the past, namely under ISO 9001, ISO 14001, ISO 50001 and OHSAS 18001 standard, as well as SA 8000.

1.3 Project

The availability of information necessary for asset management, such as an articulation between financial and operational indicators, is fundamental. This articulation allows the integration of life cycle costs and potential failure costs (not timely execution of replacement or rehabilitation investment) in the decision-making about investments to be made (financial risk). Therefore, AdDP must define economic measures used in decision-making regarding water supply infrastructural assets investments.

Hence, this project aims to study and apply an indicator, the Infrastructure Value Index (IVI), that reflect the reality of the condition of the infrastructures and formulates a recommendation to forecast future values as a function of the foreseen investments. This forecast makes this indicator valuable and an adequate measure to define infrastructure sustainability criteria.

IVI is a recent and still little used indicator presented by the Portuguese water supply regulator in Alegre (2008), and this work intends to contribute to its improvement. The IVI is presented as a tool that allows the analysis of infrastructure conditions and helps the decision-making regarding capital investments.

It is explained below the execution plan followed in this dissertation work.

A literature review was conducted on the indicator variables and what reformulation alternatives already exist for the indicator improvement. Then the formulation presented in Covas (2018) for obtaining the variables was reformulated under any business reality. An extension of the indicator forecast for future years as a function of capital investments is carried out through a proposed change to the formulation.

The methodology was created and then put into practice in two pilot cases study in a water supply system infrastructure of Águas do Douro e Paiva (AdDP) and then extended and tested its viability in infrastructures with different characteristics. The whole process involved operational and financial teams to collect the information needed on the parts of the infrastructure and discuss whether the results obtained with the methodology reflect the reality of the infrastructure. The work was always done in close collaboration with several teams in the company, taking into account the multidimensional nature of the indicator.

The presentation of the information is made through Dashboards, created according to the indicator calculated. To this end, a database with all the infrastructures information understudy was built, and a relational model was developed to characterize this information.

1.4 Dissertation structure

This thesis begins by addressing the concept of asset management and the impact that this area of engineering can have on organizations in Chapter 2. This chapter also presents the strategic balance that asset management has to make between the dimensions "Cost", "Performance", and "Risk". This chapter will additionally present the best practices for constructing Dashboards and the importance of having well-defined information assets that can serve as a means to transmit information.

In Chapter 3, the standard structure of a water supply system will be presented. This chapter will further present the AdDP water supply system where the IVI formulation was tested. The various departments of the company will be presented, and in particular, the department where the study was conducted. The project will also be framed to understand its necessity. A water supply system is a capital-intensive sector, so asset management is an area of particular importance here. In the first instance, this dissertation will abord this concept.

The development of a methodology for calculating the IVI indicator will be presented to a pilot case, the Jovim Pumping Station Unit. Moreover, this approach will be extended, to confirm its feasibility, to another unit - Lever Upstream Abstraction, which involves a two-catchments water intake followed by a water pumping station. Both these infrastructures are located at Lever Compound, which also embodies a Water Treatment Plant. This dissertation intends to be an added value for the organization and the scientific community. Thus, it is proposed to publish a scientific paper on this case study, and this paper is presented in Chapter 4.

The methodology created details the condition of the assets that constitute the infrastructure. However, information on adequately unbundled assets cannot always be obtained, namely when Asset Management Systems have been implemented recently. This work's approach started at a more aggregated level, upon utility's information available, and then deepened the data to identify costs and condition state of the main assets of the infrastructures studied. In Chapter 5, the feasibility of working at the infrastructure condition level rather than at the asset level will be addressed. The information obtained has to be easily transmitted. Therefore, in chapter 6, Dashboards will be presented, which were created for employees (experts) to be questioned about their validation of assets' current situation, thus validating the methodology. These Dashboards are made based on an information system created, under the company needs, with information taken from company documents.

Finally, in the Chapter 7 an overview of the work is done and a reflection regarding the outcomes of the project and the contributions of the dissertation to the scientific field of Asset Management. Possible future works are also covered here, both potential scientific and business contributions.

Chapter 2

Theoretical Background

This chapter covers the fundamentals of Asset Management. It covers subjects such as Asset and Asset Management definitions and the most commonly used strategies in Asset Management. It also covers the importance of having a reliable database to store asset information and developing good visualization tools to support Asset Management.

2.1 Definition of Assets

The assets that companies own are both tangible (equipment, infrastructure, computers, etc.) and intangible, such as financial, human capital, and information (Evans and Price (2020)). All types of assets are important to ensure the smooth running of an organization. It is necessary the same effort to manage all kinds of assets.

The primary focus of this thesis is on tangible assets. The entire methodology created aims to address and develop good management practices for this assets. The type of assets under study are infrastructures that have a high financial value and require significant investments. Thus, the need to use tools that assist the decision-making process for investments in such assets becomes evident. However, intangible assets, such as information, are also managed since they serve to obtain and visualize information related to tangible assets.

A tangible asset can be defined from a financial perspective as an asset with a finite monetary value and a physical form. Tangible assets can be transacted for some economic value through the liquidity of different markets. Tangible assets are the opposite of intangible assets, which have a theorized value rather than a transactional exchange value. (Kenton, 2020).

A suggestion of the life stages of an tangible asset is presented in the scheme 2.1. It is shown in cyclical form because when one asset is deactivated, another will have to replace so that the system continues to do the proper function (ERSAR (2020)).

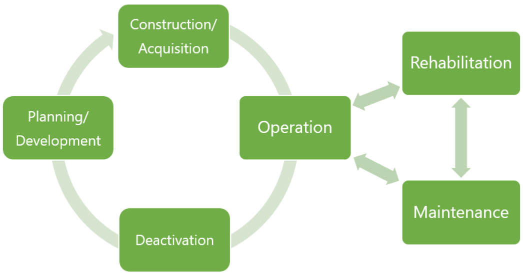


Figure 2.1: Life stages of an asset (adapted from ERSAR (2020))

When there is a need to acquire an asset, it is necessary to determine and meet the requirements to integrate it into the system. Thus, developing an asset management plan that defines policies for performance monitoring and asset maintenance in the planning phase is necessary. The maintenance teams should use tools to evaluate the assets condition, to plan maintenance actions. Top management needs information to help make decisions on investments. That should be decided according to the condition of the assets and the risk of service failure, but also the value the organization can extract from its assets (minimizing costs during each asset's life-cycle). In brief, such decisions address costs, risk and performance.

During the construction phase, it is necessary to monitor the project to ensure quality control and that the specifications defined in the planning are met.

Most companies have their assets in full utilization. Therefore, the best methodologies to ensure good condition and extended use of assets at reasonable costs must be followed.

When the useful technical life of an asset ends, its deactivation follows. The useful technical life is understood to be the period after installation during which the asset fulfills its intended function. Associated with the deactivation of an asset are numerous implications - economic, environmental, legal, etc. - that cannot be forgotten. The destination of the deactivated asset should also be considered. Whether it is dismantled or used for another purpose, decommissioning presents costs and eventually revenues (Azevedo, 2019).

2.2 Asset management and the water sector

Asset Management is a comprehensive concept that approaches several areas. Its focus is to use assets to generate value and achieve the goals of an organization. Thus, it is entirely the responsibility of each entity to define what that value is. To determine the type of assets and the goals to be achieved is necessary to consider aspects such as the nature of the organization, the operational context, the financial limitations, and the organization's needs.

There are a vast number of accepted definitions for asset management. One that is considered to be quite comprehensive is the definition of the Department of Water and Environment Affairs of South Africa. It states that Infrastructure asset management (IAM) is an integrated decision-making process, planning, and control over the acquisition, use, safeguarding, and disposal of assets to maximize their service delivery potential and benefits and to minimize their related risks and costs over their entire life (Bhagwan (2012)).

Therefore, Asset Management is the name given to monitoring the life cycle of assets and achieving a strategic balance in economic, social, and environmental terms. The management team's job is to identify the critical assets and which investment are the best given the available capital.

Organizations with this area well developed have a competitive advantage, achieving better financial performance, more assertive and conscious decision making, and improvements in the service provided.

With this concept in mind, it becomes clear that Asset Management is a complex process that involves all the company's departments. It is then essential to articulate all parties to make the necessary information available and as complete as possible. Therefore, a correct asset management strategy can be outlined and executed.

As already mentioned, the water supply sector is a capital-intensive sector, where investments are continuously made, even when no expansion of company infrastructure is planned or when expansion of the demand is not expected (some times even under decreasing demand prediction). Investment in specific infrastructures at the expense of others, in most cases, are irreversible decision. Thus, the best decision-making tools for capital realizations must be used so that decisions are founded and that they reflect the best investment alternative, considering the means available to the company.

Asset Management in the water supply sector arises from a need to overcome current challenges. Available resources are scarce, and there is a growing demand from society (customers and the regulatory authority) for better public services relative to water tariffs and planned investments. There is also the need to safeguard the operating state of the assets and have intervention policies in emergencies resulting from equipment failure.

2.3 Asset Management Strategy

As stated before, Asset Management needs to find a balance between the dimensions "Performance", "Risk", and "Cost" of assets. The way this relationship is made depends on each company or department under analysis. There is not one correct alternative but a wide range of possible options, and all of them viable. Companies must choose the one that best suits each situation. Figure 2.2 presents two alternatives that try to describe two ways to manage a similar situation. For the same levels of performance required, the company can choose to increase the capital it is willing to spend to decrease the risk or invest less capital but accepting to deal with higher risk levels. There are, however, limits of acceptability for the risk, performance, and cost dimensions that the decision-maker must set according to external or internal requirements.

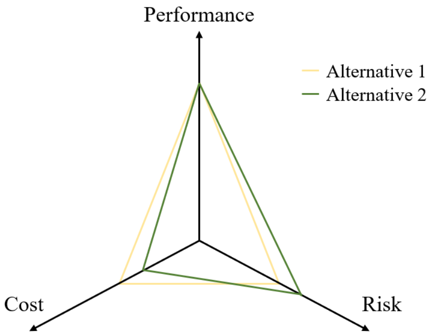


Figure 2.2: Balance between "Performance", "Risk" and "Cost" (adapted from Alegre (2010))

The "Performance" of a system depends on the evaluation measures defined in each company. In the case of a water supply system, performance is translated by the quality of service provided. This level of service is translated by indicators such as physical and economic accessibility of the sector, supply failures, and environmental impact. Water quality has to be assured and be within the parameters set by the regulator. However, ensuring a flawless service is difficult since the cost-benefit ratio of investing more capital in quality of service is not linear (figure 2.3). The capital required to increase service levels follows an exponential function. This means that a large amount of capital is necessary for small increases in service quality above certain thresholds. Society would not be satisfied with the increases in water rates that this slight increase in service quality involves.

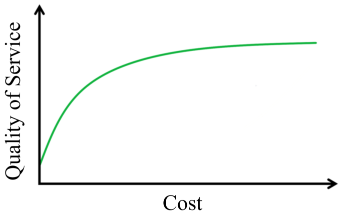


Figure 2.3: Balance between the quality of service and cost (adapted from Bhagwan (2012))

The "Risk" assessment is made by multiplying the probability of occurrence by the respective consequences. This relationship can be checked by looking at the matrix of Figure 2.4. The figure shows three zones in different colors. The green zone is low risk, the yellow zone medium risk, and the red one high risk. The limits displayed are only a representation since these must be defined within each company.

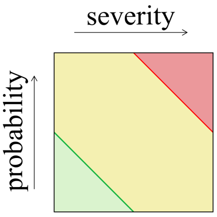


Figure 2.4: Risk Matrix (adapted from Alegre (2010))

The "Cost" analysis should include investments, operation and maintenance interventions during the period analyzed, and decommissioning costs at the end of the assets' useful life. Risk and cost are linked since a minimum cost cannot be desired without accounting for risk. By not investing enough in well-functioning equipment, increasing the risk of failure, misleading savings are being made. In the case of water supply systems, asset downtime leads to costs, such as emergency interventions and production stoppages (water that is no longer billed).

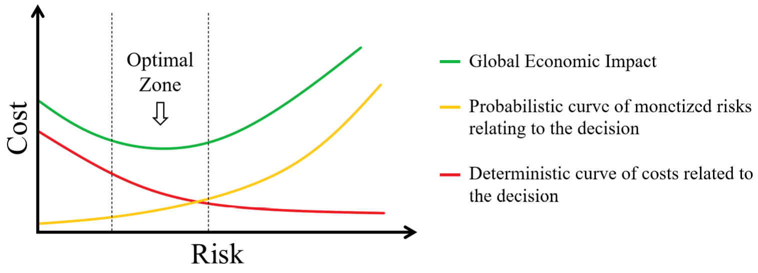


Figure 2.5: The risk/cost trade-off applied to operating assets (adapted from Azevedo (2019))

The overall economic impact is what must be accounted for. Thus, an effort must be made for good planning of the investment strategy. Asset Management plans its activities at operational, tactical, and strategic levels (Alegre (2010)). These levels of planning contribute to the balance of the three dimensions presented in 2.2.

Strategic plans cover the entire organization and set the overall goals. The main objective is to sustain and strengthen the management processes by setting objectives and targets to be achieved. Planning is usually promoted by the organization's management and is done for a long time horizon, from 10 to 20 years.

Tactical plans are more focused on specific subsystems. In order to achieve the objectives established strategically, tactical plans are developed, which determine rehabilitation interventions in the various infrastructures. The challenge here is to set priorities for action, i.e., which area of the infrastructure capital is best used. Commonly, tactical planning is advocated for medium terms, from three to five years.

The operational plan is more specific and localized in scope. Here, the processes and procedures to be executed to achieve the strategic and tactical objectives of the organization are defined. These action plans are developed for short periods of one to two years.

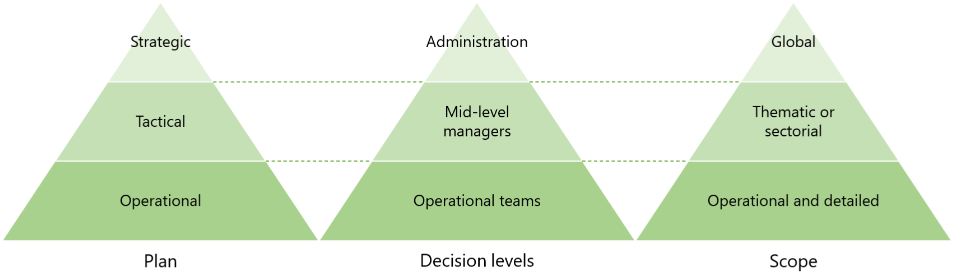


Figure 2.6: Planning Strategies (adapted from Alegre (2010))

Financial planning is part of all the plans discussed above and is an integral part of the asset management functions. Asset management tries to balance financial and non-financial objectives, managing performance, risks, and costs during the total life cycle of the assets.

From a financial perspective, asset management deals with capital investments (CapEx) and current annual costs (OpEx), where the sum of the two is called TotEx. Long-term planning (strategic and in some cases tactical planning) includes capacity planning, asset life cycle planning, capital investment planning, and long-term financial planning, while short-term planning (operational planning) includes budgets and operational planning (Hastings (2021)).

Capital investment planning is the capital investments defined by the organization (Hastings (2021)). These investments are typically planned over a time horizon of 5 to 10 years. The types of capital investments that companies can execute are:

i: acquisition, creation or expansion of an asset, which may emerge from the need to upgrade service levels, technological advances or increased demand;

ii: renovation or rehabilitation of assets already in use, resulting from preventive or corrective policies to increase service levels and asset lifetimes;

iii: investments in assets with the sole purpose of providing the company with financial returns or a future opportunity value.

Every department, financial or non-financial, must provide the team responsible for making capital investment decisions with pertinent information. The type of information that is important to consider includes technological advances, future demand and trends, costs at any stage of the asset life cycle, obsolescence, age, condition states, and associated risks.

As the available capital is limited, there is always a balance between operating costs and capital investments. Capital investments such as asset renewal (CapEx) can translate into reduced maintenance costs (OpEx). Similarly, an increase in the capital spent on better maintenance can extend the life of assets, deferring capital investments. OpEx and CapEx planning should be done so that the minimum life cycle cost of the asset is achieved.

2.4 Dashboards importance and good construction practices

Organizations recognize that intangible assets, such as information, are not treated with the same rigor as other assets. Careless management of information leads to significant risks and foregone revenue, avoidable cost, unrealized profit, lost productivity, and sub-optimal staff morale (Evans and Price (2020)).

As stated by Rasmussen et al. (2009) more and more companies are flooded with data. Information should be handled appropriately and used in a way that conveys value to the company. For managers to make the best possible decisions quickly, it is essential to transform data into structured information that is easily understood and supports analysis.

Asset management is about having the right asset, in the right place, at the right time, to support the mission of the organization. For this to happen, it is essential to develop tools, like Dashboards, that monitor, access, and analyze critical indicators for asset management (Norman (2014)).

Dashboards integrate and synthesize two critical dimensions within any company, performance management and business intelligence (BI). BI represents the tools and systems that play a vital role in the strategic planning process of a corporation, allowing the integration of applications, databases, software, and hardware essential to users and enabling the analysis of information to optimize decision-making (Harrison et al. (2015)).

Effective deployment of dashboards within an organization can dramatically reduce the need for financial and operational reports. For a dashboard to be effective, it must be well constructed to quickly and correctly transmit information (Few, 2006). The fundamental challenge of dashboard design is the need to squeeze a lot of information into a small amount of space, resulting in an effortlessly and immediately understandable display. The best way to get an efficient Dashboard is to (Few, 2006):

Not to Exceed the Boundaries of a Single Screen: The dashboard should try to have all information about a subject on a single screen without having to scroll or switch between screens. For a subject, having all the information in view on a single screen makes it easier to connect the various information displayed.

Give Context to Information: Measures of what is happening in a business rarely translate into valuable data if they are not accompanied by good support. A context is needed for the information.

Present Only the Necessary Information: The information presented should be enough for the user to understand the context generally and quickly.

Choose Efficient Measures:. A measure is efficient if it is the one that most clearly and efficiently communicates the meaning that the dashboard viewer should discern.

Choose Appropriate Display Media: Choosing a non-ideal display media is the most common mistake. For instance, using a graph when a table of numbers would work better, and vice versa, is a frequent mistake.

Choose an Appropriate Display Media Variety: It is usually associated with the previous point. Vary the display media shouldn't occur just because there is the afraid that those viewing the dashboard will get bored. If the best method to present the information is to use only graphs, then these are the ones that should be used.

Use a Well Designed Display Media: The display media chosen may be the best fit, but it must be constructed with rigor to be understood quickly.

Encode Quantitative Data Accurately: The information can give the wrong impression even though the values it presents are correct. For example, in the image 2.7 there is an impression that example B is less than half as large as A when in reality, the Y-axis starts at 50 and not at 0.

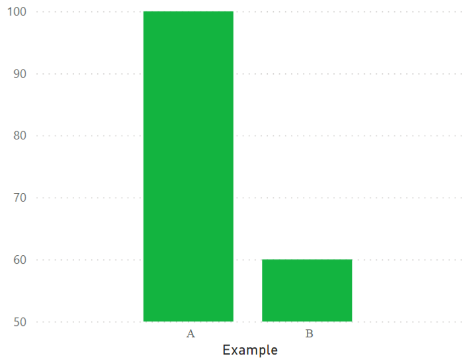


Figure 2.7: Encoding Quantitative Data Inaccurately Example (adapted from Few (2006))

Have a Good Data Arrangement: Often there is a lot of information to view despite the limited space available for it. Therefore, the data needs to be organized as well as possible.

Highlight Important Data Effectively: The most important information should be captured right away. It must be organized so that it is the first thing that catches the user's attention.

Use Only the Decoration Needed: Excessive decoration should be avoided as much as possible so as not to confuse the user. What should be on a dashboard is only the necessary information.

Have a Good Color Choise: Color choices should be made thoughtfully, with an understanding of how the human perceive color and the significance of color differences. Some colors are hot (red) and demand our attention, while others are cooler (blue) and less visible.

Design an Attractive Visual Display: Unappealing dashboards do not capture the user's attention.

Through Dashboards, the information obtained from the asset management work can be aggregated and efficiently transmitted to the decision-making entities, since well-built Dashboards allow: communicating and planning strategies; monitoring and oversight; have a comprehensive view of the organization; analyze possible problem root causes; integrate data from multiple sources; reduce costs and redundancies advancing organizational and asset management maturity (Norman (2014)).

Chapter 3

Case study

3.1 Water supply system

The United Nations outlined in 2015 17 life-changing goals, known as Sustainable Development Goals (SDGs). The sixth goal is to provide "Clean Water and Sanitation" to everyone by 2030. The services provided by the water treatment and suply sector are recognized as essential public services

The sector is divided into two subsectors: the water services subsector and the urban waste management subsector. The water services subsector provides two types of service: the public water supply service and the urban wastewater sanitation service. AdDP, the organization where this study is carried out, provides public water supply services and is a bulk system, as referred before.

The infrastructures that compose a bulk water supply system are abstractions, water treatment plants (WTP), pumping stations (PS), reservoirs (RR), and pipes (Covas (2018)). And the way the connection between these infrastructures is made is shown in the figure 3.1.

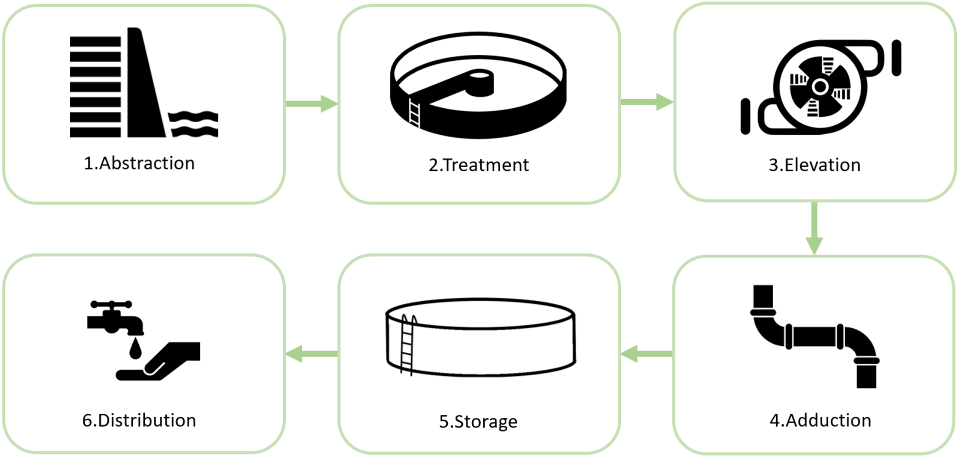


Figure 3.1: Water supply system (adapted from ERSAR (2020))

Raw (untreated) water is extracted from nature through abstraction. Water abstraction can be surface, groundwater an sub-alluvial.

Surface abstractions take water from reservoirs, rivers, or lakes. The flows extracted with this type of abstraction are higher than those of groundwater. However, they have worse quality, which usually require more treatment. Reservoir abstraction tends to be by a tower, well, or flotation, while river abstraction tends to be by tower or well. Underground abstractions collect water in artesian wells. The sub-alluvial abstractions consist of a collector well with radial drains built-in various directions, located on one or more levels of varying length depending on the direction. Usually, these wells are built using hydraulic driving into alluvial aquifers with high transmissibility and hydraulic connection to surface water bodies (Mendonça (2018)).

After being abstracted, the raw water goes to the water treatment plants (WTP). Here, impurities and components harmful to health are eliminated. The type of treatment used in the WTP depends on the state of the water. Thus, the worse the water condition, the more intensive and complex the treatments applied will be.

The purpose of the pumping station is to provide pressure energy to the water to reach higher points of the network (often, reservoirs) through lifting pipes.

Reservoirs in water supply systems can serve several purposes. They can serve as an intermediate means of regulating fluctuations in consumption to abstraction. They can store water for use in emergencies, such as fire or abstraction interruption. They can serve as pressure reservoirs to balance pressures during pumping periods.

Pipelines are classified into three groups: intake pipelines, distribution pipelines, and connection branches. The intake pipelines are part of the upstream systems, and their function is to transport water to the reservoirs or the distribution source. This stage is referred to as adduction. The distribution pipelines and the connection branches concern the low-level systems.

3.2 The Águas do Douro e Paiva company

AdDP's functions cover the collection, treatment, and supply of water for public consumption, which must be carried out regularly, continuously, and efficiently.

3.2.1 Operational structure of the company

The AdDP water production and supply system is divided into three operational and geographical units: Lever, Vale do Sousa and Baixo Tâmega.

The Lever subsystem is divided in two subsystems, the North and the South. The North supplies Porto, Matosinhos, Maia, Gondomar, Valongo and part of the municipality of Paredes. The South supplies Vila Nova de Gaia, Espinho, Santa Maria da Feira, Oliveira de Azeméis, São João da Madeira, Ovar, Arouca and part of the municipality of Vale de Cambra.

This dissertation is focused on the Lever North subsystem. The global AdDP system is represented in figure 3.2. Plotted in green is represented Lever North subsystem.

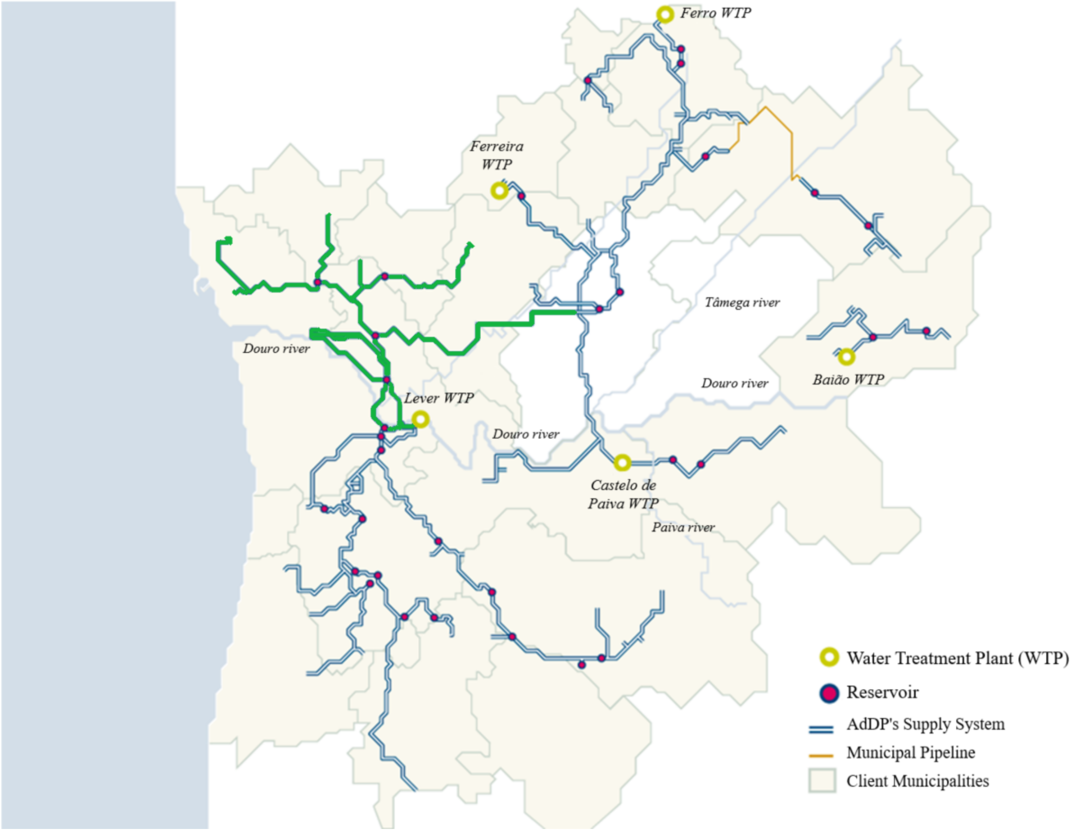


Figure 3.2: AdDP's Supply System (adapted from Águas de Douro e Paiva (2017))

The type of infrastructures that make up the Lever North subsystem are pumping stations, pipelines, abstractions, a water treatment plant, and reservoirs.

There are five pumping stations (PS) located in Jovim, Feiteira, Ramalde, Vale Ferreiros and Lever. Jovim PS has the particularity of being identified as two different infrastructures since it comprises two buildings built in different years (two separate Pumping Stations, in fact, the old and the new one).

The subsystem is composed of 125 km of pipelines with different diameters which make the connection between Lagoa, Jovim, Lever, Nova Sintra, Ramalde, Cabanas, Pedrouços, Freixieiro, Nogueira, Xistos, Formiga, Vale Ferreiros, Monte Pedro, Feiteira, Rebordosa and Galegos.

In Lever subsystem, the primary source of water is the Douro River through three abstractions located in the Lever complex: the Lever WTP Surface Abstraction, the Lever Upstream Sub-alluvial Abstraction and the Lever Downstream Sub-alluvial Abstraction. The water is then treated at the Lever WTP.

The two Sub-alluvial Abstractions, which date from the 80s, were built on sand existing in the place and are composed of two wells. The Lever Sub-alluvial wells don't have the typical construction methodology presented in chapter 3.1.. The wells were built at the same time as the dam nearby, in open space. After the more than 40 m concrete wells were made, a sand layer of around 30 m was laid on the bottom, to become the river bad when the river returned to its course, when the dam construction would be finished.

There is only one water treatment plant, and it is located in Lever. This infrastructure treats all the water that is delivered to Lever North. Thus, it treats the water from sub-surface abstractions that do not require any treatment besides disinfection and the water from superficial abstractions that have harmful properties and need to be treated appropriately.

Finally, there are six reservoirs, and these are located in Lagoa, Jovim, Ramalde, Pedrouços, and Monte Pedro.

3.2.2 Organisational structure of the company

The organizational structure of the company is represented in the organogram of Figure 3.3.

This project was conducted within the Asset Management and Engineering department, which reports directly to the Board of Directors.

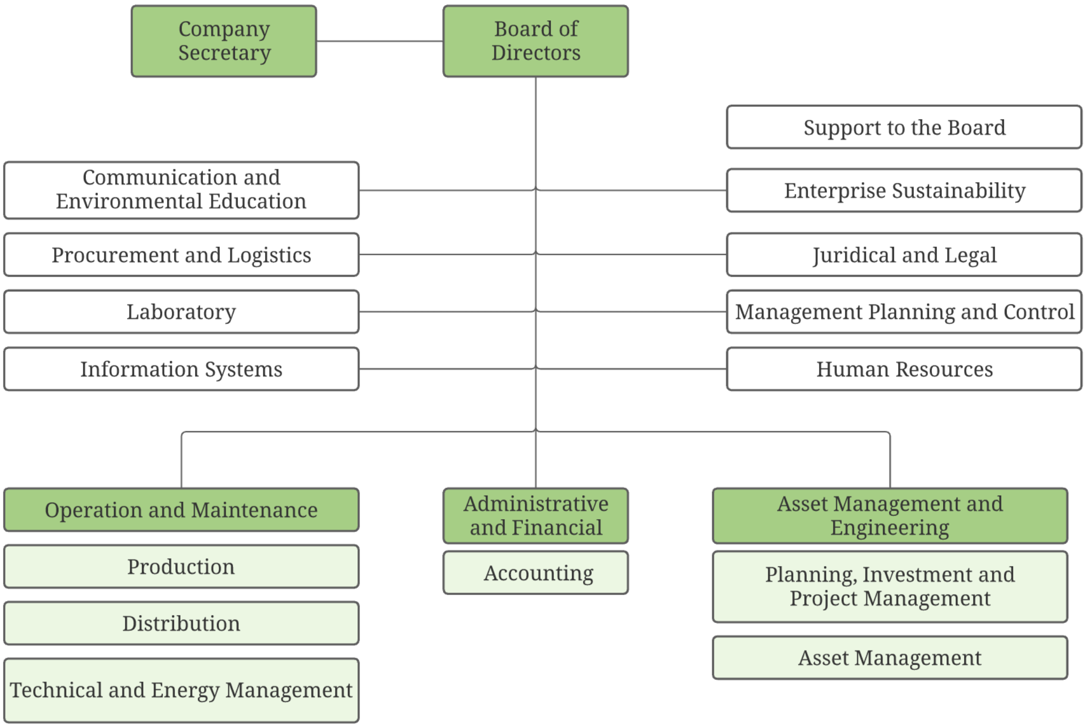


Figure 3.3: Company Ornogram

3.2.3 Asset Management and Engineering Department

The Asset Management and Engineering Department is divided into four groups areas - Asset Management, Planning, Geographical Information System, and Projects and Construction Works - and the way they relate to each other is evidenced in Figure 3.4. Asset management is the group area where the present study is carried out.

The asset management area is responsible for: inventorying assets, managing the assets' register and creating codifications for assets; managing the life cycle of assets, assessing condition, monitoring, and managing risk; planning future interventions in the short, medium, and long-term asset management plan.

Planning is responsible for planning and controlling investments. Its function is to compile the investment data that defines the objective, costs, and expected deadlines and manage the studies, projects, and construction works.

Projects and construction work mainly develop project management activities, namely contracting external services for the design phase, contracting and overseeing the construction work, getting licenses and authorizations, purchasing land, beginning and closing the construction work, and various construction monitoring activities.

Finally, the Geographical Information Systems (GIS) supervises surveying and design teams for works and projects, coordinates topographic and cadastral surveys, approves final designs and organizes their archives, and uploads all of this data to the WebSIG platform.

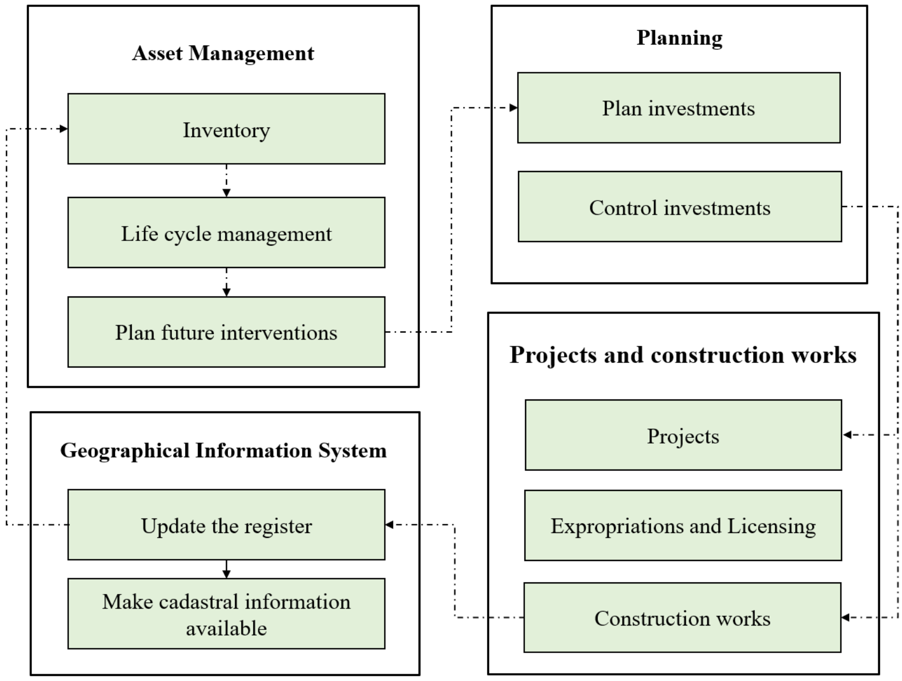


Figure 3.4: Asset Management and Engineering Department

3.3 Information about the company's assets and infrastructures

The Asset Management and Engineering Department information regarding assets and infrastructures is stored through the Maintenance Management System software (AQUAMAN) and Report and Evaluation Forms (REF).

A location code is associated with each asset. Locations are created in SAP Plant Maintenance (SAP PM). SAP PM is a software product that manages all maintenance activities in an organization. Plant Maintenance module consists of key activities to include inspection, notifications, corrective and preventive maintenance, repairs, and other measures to maintain an ideal technical system.

With the locations created, these are later replicated in AQUAMAN, allowing the management of the assets.

The REF is composed of two parts:

- the general description of the asset and the main results of the inspection carried out, with a record of the main findings of the inspection, as well as proposals for action;
- the asset evaluation sheet that attributes a score according to the global evaluation of its performance in Performance, State or Condition, and Safety.

3.4 Project context in the company

This document aims to present and apply an indicator that translates the current state of infrastructures and supports long-term investments, the Infrastructure Value Index (IVI). The indicator is discussed, and suggestions for improvement are presented.

This study arises from the needs felt by two areas of the GAE department: Asset Management and Planning.

Asset Management should use indicators to track the life cycle of the assets and their respective states of condition. The IVI is a simple-to-understand indicator that addresses these issues well. Its relevance to address these subjects has been perceived in the company, so it has been calculated in the past. However, the formulation used does not translate in the best way the reality of the infrastructures, hence the need to be restructured.

Planning has to apply a set of indicators/tools that contribute to adequate, transparent, and well-founded decision-making regarding investments. However, is experiencing difficulties obtaining them, either due to lack of time or information. The IVI is pertinent because besides being an indicator that allows the infrastructure condition to be monitored, it also enables investments to be substantiated.

Chapter 4

Discussing improvements to an indicator-based approach for the capital investment planning of infrastructure assets

This chapter proposes a different methodology to the one currently in vigor to calculate the IVI, proposed by Covas (2018). The planned changes are in determining the current infrastructure condition and the influence that planned future capital investments might have on the infrastructure condition. This chapter is based on the content of an Extended Abstract submitted to the 5th International Conference on Water Economics, Statistics, and Finance, to be held in Porto, 22-24 September 2021.

4.1 Introduction

Asset Management is a holistic concept that is transversal to several areas. It is focused on the use of assets to generate value and achieve the goals of the organization. The concept of value should be defined by each firm, according to its mission. Therefore, asset management must consider the nature of the organization, the operational context, the financial limitations, and the organization's needs to define the goals to be achieved and the means required to maximize the value obtained from the assets.

There are a vast number of accepted definitions for asset management. One that is considered to be quite comprehensive is the definition of the Department of Water and Environment Affairs of South Africa's which states that Infrastructure Asset Management (IAM) is an integrated process of decision-making, planning, and control over the acquisition, use, safeguarding and disposal of assets to maximize their service delivery potential and benefits, and to minimize their related risks and costs over their entire life (Bhagwan, 2012).

Organizations with well-developed asset management procedures may gain competitive advantages, as this enables the achievement of better financial performance, more assertive decision-making, and improvements in quality of services. Overall, asset management may enhance organizations' efficiency and sustainability.

Asset management is essential in the water supply and sanitation sector, given its intensive capital nature. High investments have to be continuously performed by the utilities of the sector, often involving irreversible decisions. Consequently, investments must be as wise as possible so that the proper functioning of assets and high service levels can be achieved at a manageable risk level and the lowest possible cost. This involves designing strategies in a context of informed decision-making that requires integrating asset management approaches into planning and management processes to generate benefits both for service users and stakeholders.

To achieve the best execution of these strategies, a trade-off between the dimensions 'Risk', 'Cost' and 'Performance' becomes essential. These dimensions are quantified through multiple financial and operational indicators. This article contributes to the literature on asset management by proposing a different approach to establish an indicator that reflects the "Risk" and "Cost" dimensions. This indicator, called the Infrastructure Value Index (IVI), is already in use within the water sector in Portugal, and is aligned with companies practices and financial/accounting procedures.

The IVI has been explored in various R&D and industry projects in the water sector. It has been recognized as an effective tool that supports long-term investment planning. It is calculated as the ratio of the current value of an infrastructure to its replacement cost. The current value of an infrastructure is its market value in the present condition. The replacement cost is the current price that has to be paid for a modern alternative to the infrastructure under study.

Conceptually, the IVI is a powerful tool because it translates pertinent information in a simple way. It allows the decision-makers to correctly compare the various assets condition and estimate the impact that future investments will have on the condition of the assets and the overall system.

The IVI indicator was first introduced by Alegre (2008) and was subject to improvements by Alegre et al. (2014). Although organizations have already started using this indicator, its calculation depends on subjective information, as its components can be interpreted in different ways. More recently, Vieira et al. (2020a) presented a methodology to forecast the evolution of the IVI in future years as a function of planned capital investments. This approach makes the indicator valuable in a company context and allows it to be embedded proactively in the capital investment planning process.

Although the IVI is mostly used in the water supply and sanitation sector, this paper aims to present a tool that can be extended to other industries, making this indicator truly impactful in asset management. For example, Salvado et al. (2020) have adapted and tested this methodology for managing large building-assets portfolios.

This chapter aims to build upon previous efforts and test a new approach for long-term investment planning focused on the annual capital expenditure and asset deactivation. Relatively to earlier studies, the novel contributions of this chapter is the development of a methodology where the useful life of the assets is adjusted to their age and current condition. This is an advancement in comparison with the common practice of using only the state of condition to determine the current value of the asset. Another contribution is a more objective approach to the long-term IVI calculation proposed by Vieira et al. (2020b). This improvement is centred on simplifying the formula first presented, reducing the number of subjective variables, mitigating the associated error. The methodology developed was applied in a Portuguese water supply company. A dashboard was also constructed to enable the visualization of the information obtained. The new methodology was developed in cooperation with sompany collaborators, to ensure the inclusion of enterprise knowledge and proper validation of the results obtained.

4.2 Capital investment planning for infrastructure/asset management

This section describes the approach proposed for the calculation of the IVI in a system and how companies and the regulator are currently using it.

4.2.1 Traditional IVI formulation

As stated in the introduction, the IVI is the quotient between the Infrastructure Current Value and the Infrastructure Replacement Cost:

$$\text{Infrastructure Value Index}(\%) = \frac{\text{Infrastructure Current Value}}{\text{Infraestructure Replacement Cost}} \tag{4.1}$$

The Infrastructure Current Value (ICV_t) estimates how much the company would profit from decommissioning and selling the assets that comprise the infrastructure after disposal costs have been accounted for (equation (4.2)). Note that this value in reality can be negative if the asset is so depreciated that what the company earns with the sale of the assets does not cover the disposal costs (Howard et al., 2015).

$$\text{ICV}_t = \sum_{i=1}^{N} \text{ACV}_{it} \tag{4.2}$$

In expression (4.2), N is the number of assets that compose the infrastructure, ACV_{it} is the asset i $(i = 1,...,N)$ current value in year t, expressed in monetary terms (e.g., in euros).

The Institute of Public Works Engineering Australasia in the Australian Infrastructure Financial Management Manual (Howard et al., 2015) presents the depreciation as a function of the residual useful life to reflect the pattern of consumption of future economic benefits. The residual useful life is the difference between the total technical useful life and the age of the asset in question. The total technical useful life used in this analysis is a national theoretical average.

The depreciation of an asset can then be calculated by the product of its annual depreciation, given by the ratio between its replacement cost and its total technical useful life, and its age. The asset current value is then given by the difference between its replacement cost and its depreciation.

$$\mathrm{ACV}_{it} = cs_{it} - \frac{cs_{it} \times i_{it}}{vu_i} \tag{4.3}$$

In expression (4.3), cs_{it} is the asset i replacement cost in year t expressed in monetary terms (e.g., in euros), i_{it} is the asset i age in year t, and vu_i is the total technical useful life of asset i.

Depreciation can be calculated on an accounting or economic basis. How it is defined whether is used an economic or an accounting approach will depend on how are calculated the variables cs_{it} and vu_i.

The accounting method is static and uses as a reference the beginning of the asset's life. This method divides the acquisition cost by the total technical useful life and obtains a static depreciation associated with each year of the asset's service.

The economic approach is dynamic. That is, it is adjusted every year according to the change in the asset's economic value in that period. The interesting thing in this type of analysis is to know the reality of an infrastructure, taking into account possible obsolescence and its state of condition. Despite the fact that economic depreciation is a better approach, it should be noted that it entails an additional difficulty and is prone to errors, requiring a more significant effort from Asset Management team for a careful and reasoned analysis.

ERSAR suggests using an economic approach since it provides a more accurate estimate of reality. However, in the absence of information to use this method, an accounting approach should be used.

Replacement costs can be calculated in two ways. The first, and less correct, is to use the acquisition cost as the replacement cost. This approach can be used in the absence of better alternatives. The second, and most appropriate according to USEPA (2005), is through the Modern Equivalent Asset (MEA) methodology. This alternative attributes to the replacement cost what the company would have to pay nowadays for an asset that meets the project's specifications. Due to technological advances and currency inflation, which is critical account for, this value is different from the initial acquisition value. Hence it is a more correct alternative than the first (Howard et al. (2015)).

The notions of the current value of an asset, according to the Institute of Public Works Engineering Australasia (equation (4.3)), is under the notions of the current value presented and elaborated upon by the ERSAR's guide (Covas, 2018). In this guide, the current value of an asset is given by its residual useful life multiplied by the estimated annual depreciation.

Through the (4.4) mathematical deduction the approach presented by the Institute results in the asset current value proposed by the ERSAR.

$$
\begin{aligned}
\mathrm{ACV}_{it} &= cs_{it} - \frac{cs_{it} \times i_t}{vu_i} \\
&= cs_{it} - \frac{cs_{it} \times (vu_i - vr_{it})}{vu_i} \\
&= cs_{it} - cs_{it} + \frac{cs_{it} \times vr_{it}}{vu_i} \\
&= \frac{cs_{it} \times vr_{it}}{vu_i}
\end{aligned}
\tag{4.4}
$$

In expression (4.4), vr_{it} is the residual useful life of asset i in year t.

With the equation reached by mathematical deduction it is possible to replace ACV_{it} in the equation (4.2) and arrive at the ERSAR's proposal for ICV_t (equation (4.5)).

$$
\mathrm{ICV}_t = \sum_{i=1}^{N} \left(\frac{cs_{it} \times vr_{it}}{vu_i} \right) \tag{4.5}
$$

The suggested formulation for the IVI in the equation (4.1), at a given period (year t), can be calculated as shown in expression (4.6).

$$
\mathrm{IVI}_t(\%) = \frac{\mathrm{ICV}_t}{\sum_{i=1}^{N} cs_{it}} \tag{4.6}
$$

The value of the IVI index varies between zero and one. A value of zero corresponds to total degradation, and one indicates full preservation of the infrastructure. The expected value of stable infrastructures ranges from 0.4 to 0.6 (Covas, 2018). Values below 0.4 signal that the infrastructures are deteriorated and require significant investments. Values above 0.6 may indicate over-investment in rehabilitation or a recent and non-stabilized infrastructure.

From a computational perspective, the estimation of the IVI index is straightforward. However, it can be challenging to estimate the values of assets' residual useful life, total technical useful life, and replacement cost accurately. The correct determination of these values implies the collaboration of several entities within the organization, including maintenance, operations, and financial departments.

4.2.2 Long term IVI

All the aspects discussed so far present a point estimate for the IVI. However, the relevance of estimating the future value of the indicator in the context of asset management is relevant. It is necessary to predict how the infrastructure condition (IVI) varies with the planned capital investments to make it a more useful indicator for investment decisions.

Once the IVI for the current year has been obtained, its estimation for future years requires comprehensive infrastructure knowledge. Over the years, renovation, replacement, and expansion operations will be carried out on the infrastructure, which should be accounted for. To calculate the IVI on a long-term basis, an approach is proposed in Vieira et al. (2020b) where the expected

CapEx on renovation, replacement, and expansion operations influences the condition of the assets. It is prudent to state that assets or infrastructures subject to high capital investments may see their current condition increase.

The model presented by Vieira et al. (2020b) propose equations for the estimation of the replacement cost, equation (4.7), and for the residual useful life, equation (4.8), of the various assets of each infrastructure, in the future year t.

$$cs_{it} = cs_{i(t-1)} \times (1 - \frac{1}{vu_i}) + \text{CapExRep}_t \times \alpha_{rep} + \text{CapExExp}_t \times \alpha_{exp} + \text{CapExRen}_t \times \alpha_{ren} \tag{4.7}$$

In expression (4.7), CapExRep_t, CapExExp_t, CapExRen_t, are the capital expenditure values, respectively, in investment of renewals, replacements and expansions, at year t, and α_{rep}, α_{exp}, α_{ren} are the coefficients that reflects the impact of a given intervention on the residual useful life.

$$vr_{it} = \beta \times vr_{i(t-1)} + \text{CapExRep}_t \times \alpha_{rep} + \text{CapExExp}_t \times \alpha_{exp} + \text{CapExRen}_t \times \alpha_{ren} \tag{4.8}$$

In expression (4.8), β is the coefficient that translates the level of deactivation of existing assets in replacement interventions, where the replaced assets are deactivated and removed from the existing assets.

In the event of a renewal or replacement, the coefficients α_{rep} and α_{ren} have a positive value that typically ranges between 0.5 and 2. When the intervention contributes fully to the increase of the residual life and is made with assets with the same characteristics as those to be decommissioned, these coefficients will have a value of 1. If the interventions include technological advances and materials with better qualities, the coefficients will be higher than 1. If the interventions are for lower quality assets, the values of the coefficients will be less than 1.

The expansion interventions represented by α_{ren} are easier to determine. If there are expansion interventions that fully contribute to the increase of the useful life of its assets, then this coefficient is equal to 1.

The β is the abatement coefficient ranging from 0 to 1 and gives the deactivation of an asset as a function of the planned replacement in each capital investment. A beta value close to 0 means that the asset understudy will be almost totally dismantled, whereas a beta value close to 1 means that the investment will deactivate the few assets. The coefficient becomes more challenging to obtain when it is far from the limits (near 0.5).

All these coefficients are obtained subjectively since they require engineering judgment and an evaluation of the impact that the interventions will have on the useful life of the infrastructures.

This methodology translates a financial tool based on engineering considerations into the efficiency of the planned interventions.

4.3 An improvement to the IVI calculation

This paper serves to discuss possible changes and additions to the formulation highlighted in chapter 4.2, to make the attainment of the indicator more pragmatic and aligned with the business reality. This discussion culminates with the proposal of a new method for calculating the IVI and extending it to future years.

4.3.1 A new approach to estimate the IVI at time t.

The proposed formulation for calculating the IVI in this paper recurs to the equation (4.6). Where it differs from what is available in the literature is the way the variable ICV_t is calculated. The variables subject to changes in the ICV_t formulation (equation (4.5)) are the assets' estimated residual useful life and the total technical useful life. These variables are adjusted to expresse a more accurate Infrastructure Current Value:

$$\mathrm{ICV}_t = \sum_{i=1}^{N} \left(\frac{cs_{it} \times vra_{it}}{vua_i} \right) \tag{4.9}$$

In expression (4.9), vra_{it} is the asset i adjusted residual useful life, and vua_i is the total adjusted useful life of asset i in year t.

Establishing an residual useful life value by considering a linear depreciation of the asset as a function of age and total technical useful life is easy but leads to inaccurate information. To correctly determine the residual useful life of an asset, it is necessary to account for its state of condition. An asset at the end of its theoretical life that has been subject to good maintenance work and capital investment is still in good condition, consequently increasing the residual useful life. To standardize the classification of the assets' condition (c), the approach proposed by the U.S. EPA (USEPA, 2005) and adapted by Alegre (2008) is used in this study, as shown in Table 4.1.

Table 4.1: Conservation status classification as proposed by the U.S. EPA (Alegre, 2008)

State of Condition (c)	Description	Required rabilitation rate
1	In perfect condition	0%
2	It has minor anomalies	5%
3	Presents anomalies that require significant curative maintenance	10-20%
4	Requires renewal	20-40%
5	Practically unusable asset	>50%

The state of condition varies between 1 and 5 and refers to the degradation of the inherent characteristics of each asset at the date of evaluation. Thus, more degraded assets in need of major rehabilitation interventions will have a lower state of condition, translated by a higher value variable c.

At an international level, there are examples of institutions and entities that use only the state of condition (c) to determine the residual useful life of an asset. As pointed out in Alegre (2008) the U.S. EPA uses a linear relationship between the state of condition and residual useful life.

Another example is that of a simple methodology used by Carollo Engineers Inc. in California (Carollo, 2015), where residual life is given by the expression (4.10).

$$\text{Residual useful life} = (1 - \text{required rehabilitation rate}) \times \text{Original useful life} \tag{4.10}$$

Whilst these approaches may be more accurate than considering a linear depreciation of the asset as a function of age and total technical useful life, using only the infrastructure condition to determine useful lifes seems limiting. It is expected that two infrastructures with very different ages and similar states of condition will have slightly different residual useful lifes. Therefore, the company where the present case study is carried out uses a formulation (equation (4.11), whose graphical representation is presented in figure 4.1) for the residual useful life that accounts for the condition and age of the infrastructure (H2Opt, 2020). The graphical representation was made for a total technical useful life of 60 years to present the concept.

$$vra_{it} = vu_i - (\frac{vu_i}{5} \times c) \times (\frac{i_{it}}{vu_i})^{\frac{1}{c+1}} \quad [years] \tag{4.11}$$

In expression (4.11), c is the condition coefficient ranging from 1 to 5 (USEPA classification shown in the table 4.1).

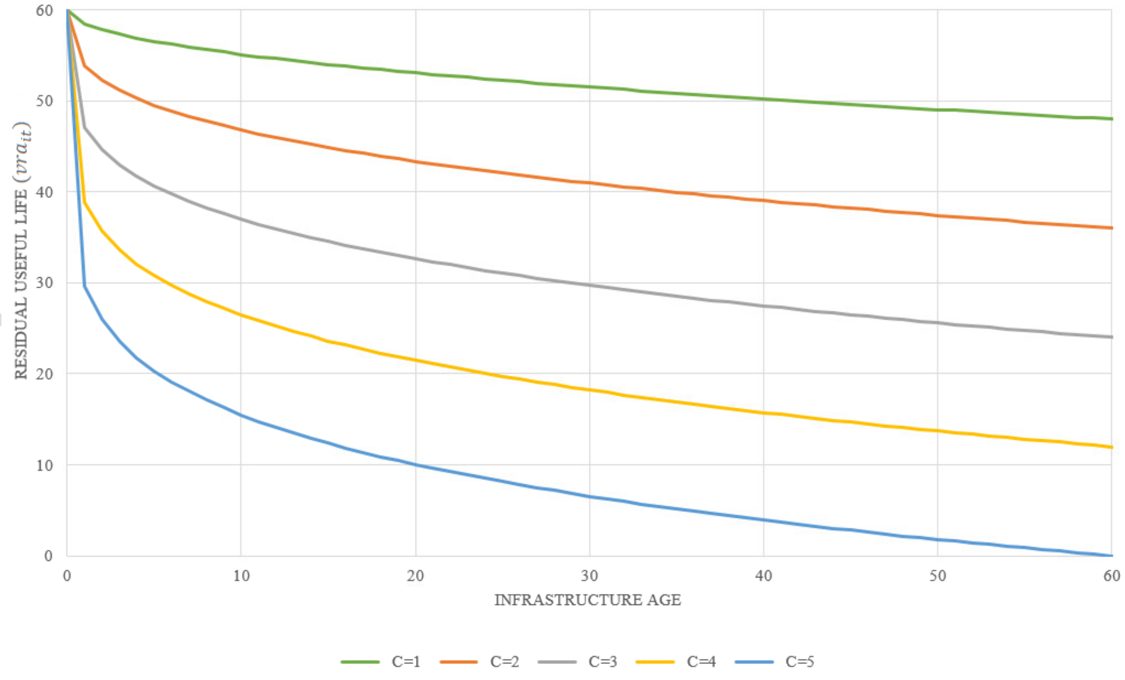


Figure 4.1: Adjusted residual useful life as a function of infrastructure condition

The graphical representation of the equation (4.11) shown in figure 4.1 can also be used to determine vra_{it}. With the condition state of the infrastructure established, the line with the respective color is chosen, and the vra_{it} is determined as a function of the age of the infrastructure.

The proposed methodology is based on the linear variation of the total theoretical useful life with the infrastructure age. It tries to adjust this linear variation, as a function of the condition state and total theoretical useful life, for each condition state, as a function of the age, considering an approximation, in power, inversely proportional to the condition state.

With the determination of the adjusted residual useful life, it no longer makes sense to use the total theoretical useful life, and an adjusted total useful life to the reality of the asset is proposed. This adjusted total useful life will be given by the sum of the infrastructure age and the vra_{it}.

4.3.2 Improvements to long term IVI calculation

The extension of the estimation of the indicator to other future periods was first presented by Vieira et al. (2020b) and is objective of this section to present a correction to this methodology. One inconvenience of the Vieira et al. (2020b) formulation is that it draws on several variables that lack subjective information, such as β, α_{rep}, α_{exp}, and α_{ren}. Another problem is that for some cases, the IVI is greater than 1. An example of such a case is when there is a full replacement of an asset that is not fully depreciated.

Alternatives are proposed for the calculation of the variables vr_{it} and cs_{it} (equations (4.12) and (4.13)) in order to solve these problems.

$$cs_{it} = cs_{i(t-1)} \times (1-\beta) + \mathrm{CapEx}_t \tag{4.12}$$

$$vr_{it} = vu_i \times \frac{cs_{i(t-1)} \times (1-\beta) \times \left(\frac{vr_{i(t-1)}-1}{vu_i}\right) + \mathrm{CapEx}_t}{cs_{it}} \tag{4.13}$$

With the variables vr_{it} and cs_{it} defined and substituting them into equation (4.6) an estimate for future IVIs can be obtained.

The β in this formulation is a percentage rather than a coefficient. Thus, β in the equation (4.13) is the percentage of decommissioning inherent to the various capital investment interventions in renewal, replacement, or expansion. In the formulation presented, instead of having 3 cases of intervention (Renewals, Replacements, and Expansions), there are only 2 (Renewals or Substitutions and Expansions), since in practice, whenever there are renewals, ends up occurring replacements, and decommissions, of assets. What separates the replacements or renewals from the expansions is the β value. When there is a replacement or renewal, the β value corresponds to the percentage of the asset deactivated, and in expansions, the β is automatically 0.

In addition, another approach has been introduced. Whenever an asset or a set of assets is renewed, and it is known the percentage of the assets that have been deactivated, in practice, it is as if it is possible to automatically update the total replacement value of the assets and no longer use the α coefficients. For example, when replacing one-third of an asset, its new replacement cost is two-thirds of its previous replacement cost plus the CapEx planned for that asset.

With this new approach, there is no longer an IVI greater than one since replacement values are revised based on the percentage of the asset replaced and the value of that replacement.

4.4 Case study

This approach to IVI calculation is applied to in the water supply system of Águas do Douro e Paiva (AdDP).

AdDP is a recent company, created on 01 February 2017, with the social purpose of exploring and managing the municipal water supply system of southern Porto for 20 years. The municipalities that integrate this system are 20 and cover 2,715 km^2 with 1.7 million inhabitants.

AdDP comprises a wide range of infrastructures, such as water intakes, pipelines, pumping stations, WTP, and reservoirs. Due to the large size of the company and the fact that it is a capital-intensive sector, the best methodologies to identify the infrastructure condition must be implemented to make informed decisions on where to invest the available capital, hence the interest in undertaking this study. The pertinence of the infrastructure value index is seen by AdDP as one of these decision-making tools. The organization has been presenting an IVI proposal for all the group's infrastructures since 2017.

Until now, AdDP has used the IVI to determine infrastructure conditions in the year under analysis , and the formulation used is the one presented in (4.6).

To determine the replacement cost of the infrastructure, AdDP uses ERSAR Technical Guide 23. In this document, ERSAR proposes replacement values for the different types of infrastructure that make up a water supply system, according to specific characteristics. The Guide divides the infrastructure into two groups - equipment (electro-mechanical) and civil construction - and proposes replacement costs for each one.

The useful lifes of the assets that AdDP considers are 60 years for civil construction and 25 years for equipment. Regarding the residual useful lifes, AdDP subtracts the infrastructure age from the useful theoretical life. The company uses reports that discriminate when the civil construction and equipment groups were built or rehabilitated.

The methodology used so far is not the one that best reflects the reality of the infrastructures since: the infrastructures assets have different ages and total technical useful lifes; the costs presented by ERSAR for each group are based on representative averages of the national panorama, having been developed based on budgets of a broad set of public water supply and urban, and rainwater sanitation contracts carried out in recent years (Covas (2018)); the attribution of residual useful lifes based solely on age, undermining good maintenance policies, is fallacious. The use of indicators that reflect incorrect information brings fewer benefits than not using the indicators at all. Therefore, it is necessary to use a methodology that gets as close as possible to the reality of the infrastructure's condition.

More recently, in 2020, a study was carried out by H20pt to introduce improvements in the methodology used in the IVI formulation. Thus, an equation was formulated for calculating the residual useful life as a function of the asset age and condition. This study represents a relevant improvement since it accounts for maintenance work without disregarding the inevitable deterioration of assets over time. Despite providing a more reliable result, the methodology calculates the IVI by aggregating the assets into equipment and construction, forecasting equal costs, ages, and states of condition for the groups.

A critical point that AdDP is not considering in the IVI formulation is its extension to future years to calculate the influence of investments on the infrastructure condition. This is crucial if the IVI is to be used as an indicator that helps investment planning.

The methodology developed, and presented in this paper, presents a proposal for calculating the IVI that attempts to respond to these limitations.

The proposed methodology is applied to two infrastructures, the Jovim Pumping Station, and the Lever Upstream intake station. However, replicating this approach for the other infrastructures of the group is a proper exercise. Regarding the IVI forecast for future dates, the window chosen for the analysis is five years for the Jovim PS and ten years for the Lever Upstream Abstration into the future because this is the time window in which the CapEx investments are forecasted in AdDP.

The Lever water supply system is divided into two subsystems: the North Lever and South Lever subsystems. The Jovim pumping stations are an integral part of the North Lever subsystem. The water comes directly from the Lever Montante water intake, the final pumping station of the Lever WTP, or through the Lagoa Reservoir.

The older Jovim pumping station (PS1) was integrated into the Multi-municipal system in 1996/97, and a new pumping station (PS2) was built in 1998, enabling the old lift to be also rehabilitated in 1998. Both pumping stations have four electric pump groups and raise the water to Ramalde, each one through its respective pipeline.

PS1 has a lifting capacity of 1,347 l/s and reaches a manometric height of 57.1 m.w.c., while PS2 has a lifting capacity of 2,718 l/s and 56.2 m.w.c..

The Lever Complex Upstream Abstraction dates from the 1980s. It consists of two deep wells where the water is collected by radial drains installed on two levels. After naturally seeping into the bed of the Douro River, the water is sent by gravity to a collecting well about 20 meters deep, from where it will be elevated. A platform equipped with eight pumps is installed over the collecting well. Six of these pumps raise the water to Jovim, and two to the Lever Water Treatment Plant for subsequent treatment.

The pumps responsible for raising the water to the Jovim reservoir can rise to 600 l/s. As regards pumping to the WTP, each pump can lift a variable flow rate of up to 1,500 l/s.

4.4.1 Collection of asset-related data

For the calculation of the IVI, only assets that are directly related to the water supply service are accounted for. Therefore, assets such as office equipment, fire extinguishers, and vehicles are excluded from the analysis.

The asset-related data must be clear, complete, and intuitive. The assets that set the infrastructure must have information about what they are, their function, condition, and installation dates and costs. It is also important to break the assets into their components. It is requested that the condition (c) is defined precisely and with strict judgment since it is directly related to the asset's adjusted residual useful life. This relation is evidenced in the equation (4.11). Determining the condition is the most subjective part of the calculation and, therefore, should be as rigorously and identically calculated as possible for all assets in the company. The parameters used and suggested for estimating this variable are then:

- replacement, renewal and expansion works that have been made during the asset lifetime;
- frequency of maintenance routine work;
- the need for inspection/supervision and operational intervention;
- the availability of the functional unit and the existence of malfunctions that jeopardize its performance;
- the existence of equipment redundancy that ensures uninterrupted operation in case of breakdown or preventive maintenance of one of them.

These are some examples of information that may be needed to define assets conditions. As each case has its particularities, this type of approach may not be ideal for all situations, and companies should use analysis methods that suit their reality.

4.4.2 Breakdown structure

The infrastructures are broken down to a level where it is comfortable to assign values to the variables mentioned in the equation (4.6). The proposed decomposition is based on five levels:

Infrastructure (First level): in the case of a water supply network there are pumping stations, pipelines, reservoirs and abstractions;

Group (Second level): where the infrastructure assets are separated into civil construction, electrical installation and equipment;

Sub-Group (Third level): which function the assets within the group relate to (such as: hydraulic circuit or lifting);

Assets (Fourth level): where there is an effort to organize the components into an item or set of items that have value to the organization (such as: pumping group or electrical boardroom);

Components (Fifth level): parts that make an asset (such as: screws or nuts).

The chosen decomposition is shown in table 4.2. The table only shows information for PS2 and up to the fourth level to make it easier to visualize.

Table 4.2: Breakdown in the first four levels of Jovim PS2

First level	Second level	Third level	Fourth level
PS2 Jovim	Equipment	Production	Generator set
		General support systems	Travelling crane
		Hydraulic circuit	Hydraulic circuit
		Instrumentation, automation, control and measurement	Instrumentation, automation, control and measurement equipment
		Lifting	Pumping group no. 1
			Pumping group no. 2
			Pumping group no. 3
			Pumping group no. 4
			Ventilators
		Hydraulic shock protection	Compressed air system
			ESP Remetal, 35m3 - RSP 3 (EE2) | RAC
		Sampling	Sampling System
	Electrical facilities	Distribution	Electrical boardroom
			Transformer substation
		Safety systems	Security system
	Civil works	Civil Works	Building
			Pipe system

The breakdown of the Lever Upstream Abstraction and Jovim PS1 is made in the same way (Annex A).

Decomposing infrastructures, in most cases, can be a complex and time-consuming task. Information is not always complete and up-to-date, the best way of division may not be intuitive, and an iterative approach may be required. A critical approach and excellent articulation between the various departments of the organization are imperative. The better this division is worked on and cared for, the better the understanding of the infrastructures will be.

The AdDP's infrastrucures are subdivided into five levels according to the information in the database. The first level is already previously defined, which is the infrastructure where the study will be carried out, Jovim PS and Lever Upstream Abstraction. The assets that make up the PS and the Abstraction are then grouped into three categories, Civil works, Equipment, and Electrical facilities, to be under the terminology used by the company and proposed in Vieira et al. (2020b). Getting the decomposition right and selecting the important assets for the water industry is a time-consuming process since it is necessary to know the infrastructure well and critically analyze the database.

4.4.3 Estimation of IVI at time period t

4.4.3.1 Infraestructure Replacement Cost

Regarding the infrastructures replacement costs, it is essential to consider how detailed the technical team can percise the information. It is clear that assigning a replacement cost to the infrastructures is challenging and may not be done with much precision. Therefore, disaggregating the infrastructures in several levels and calculating replacement costs for a given level seems to be the viable alternative. This case study is worked at the asset level, and therefore it is ideal to use data and calculate replacement costs at this level. Nevertheless, data at a more aggregated level can be used when the information at the asset level is missing.

Companies' catalogs are used at this stage, and the technical team is consulted to reach a consensus on costs. This task is made more effortless since forecasting replacement costs for single assets is more straightforward than finding plausible values for replacing the three asset categories or even the station as a whole. PS's asset reports can be used to find the acquisition value of the assets and then account for currency inflation to derive an initial value for the replacement cost. This value is purely theoretical and has to be assessed and confirmed by the technical team, as technological advances may mean different prices from those used when acquiring the assets.

With the assets' replacement cost, it is possible to determine the weights that the different groups of assets (in this case: civil works, electrical installation, and equipment) will have in the total cost of the infrastructure replacement. It is essential to realize that these relative weights are only to have an idea of the distribution since what goes into the IVI formula (equation (4.6)) are the costs of each asset. This distribution is critical to understand if the analysis is by the national panorama.

Different infrastructures are going to have different replacement costs and asset category weights. Infrastructures with different objectives will have different assets. It is to be expected that a PS, where its sole purpose is to lift water to other destinations, has a high weight of equipment category due to the pumping groups. In contrast, due to the wells responsible for collecting the water, an Abstraction has a higher weight of civil works. ERSAR suggests the weights that each group of assets will have in the infrastructure in its technical guide 23 (Covas et al. (2018)). The expected distribution weights for PS's is shown in figure 4.2 and for Abstractions in figure 4.3.

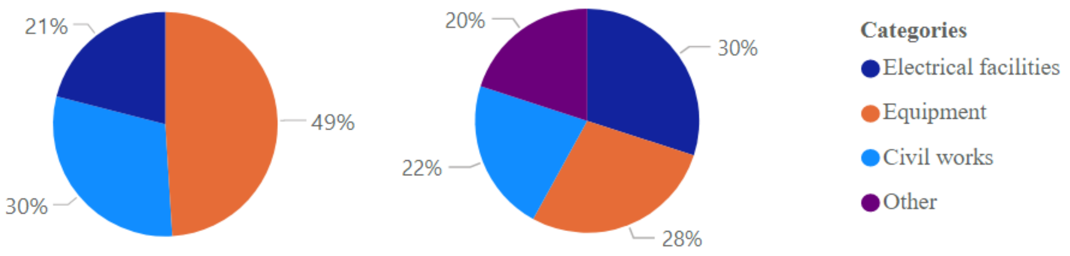


Figure 4.2: Distribution of the PS categories weights by the ERSAR guide (right) and the actual values in AdDP for the Jovim PS (left)

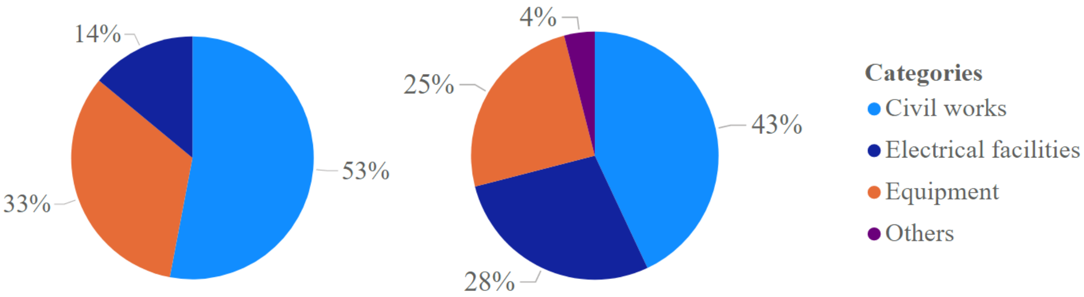


Figure 4.3: Distribution of the superficial abstraction categories weights by the ERSAR guide (right) and the actual values in AdDP for the Lever Upstream Abstraction (left)

It is essential in the end to compare the weights obtained, through research and dialogue with the technical team, with the weights suggested in the ERSAR guide. If the weights are very different, it is advisable to find the cause.

In the Jovim PS, civil construction weights 30% since the station is oversized compared to other stations with the same characteristics. The equipment and electrical installation weight 49% and 21% respectively, which also diverge from the guide values because it is a facility that requires sizeable hydraulic power and consequently large pumping groups.

Regarding the Lever Upstream Upstream, the case also diverges from the values presented in the ERSAR 23 Guide, illustrated in figure 4.3. In this abstraction, the estimated weight of civil construction is 53%, which is larger than the 43% foreseen in the Guide. To understand the discrepancy, it is worth highlighting the assets that are part of the construction category of the Lever Montante abstraction. These assets are two semi-superficial abstractions in the middle of the river, one collecting well, pipes, and the building where the equipment and electrical installations are located.

The abstractions and the well were built due to an opportunity that arose when the river dam was built on the Douro River. The drying of the river was an unavoidable stage in the construction of this abstraction. The capital needed to make this infrastructure today is much more than it was in the past.

Notarising from external needs, the draining of the river is not feasible. The abstraction wells are located in the middle of the river, which has a powerful flow, which would make the costs of drying out exorbitant. The alternative would be to build an embankment with sandy material to serve as a working platform and remove it at the end. In any case, the cost associated with constructing the wells is currently very high and consecutively higher than the national panorama.

The equipment category also has a high relative weight. The Lever Upstream Abstraction raises 90% of the water from the Lever North subsystem. Thus the hydraulic power required is very high and consequently entails a higher replacement cost than electrical installations.

Counting on this abstraction characteristic, the forecasted costs to redo the whole infrastructure are carried out. The weight of each category is then 53% for civil construction, 33% for equipment, and 14% for electrical installations.

The use of the weights for each of the categories (equipment, electrical installations, and civil construction) proposed by ERSAR, being an estimate based on average national costs, will not reflect the reality of each infrastructure. The ERSAR guide should only be used when there are no better alternatives. Since this is not the case, the resulting estimate is suitable and should be used.

4.4.3.2 Residual useful life

The crucial part at this point is determining the condition of the assets that are part of the PS and the Abstraction. Therefore, it is necessary to compare the condition suggested in the REF's with the breakdowns and interventions made over the years and, in case of discrepancies, confront the technical team and arrive at the reason. To determine a useful theoretical life is suggested to use the average useful life in Portugal suggested by ERSAR in Table 4.3

Table 4.3: Assets technical lifespan

Component type	Asset	Technical lifespan (average in Portugal)
Construction	Buildings and Reservoirs	40-50
Pipes	Cast iron and steel	40
	Concrete	60
Equipment	Electric pump groups	20
	Valves	15-20
	Electronic equipment	15
	Control equipment	15

With the condition and the useful theoretical life of the assets defined, it remains to apply the equation (4.11) to get the adjusted residual useful life.

4.5 Results and discussion

4.5.1 Current IVI calculation

The values of the IVI formula, expressed in equation (4.6), can be found in the Appendix B.

The results obtained for the Jovim PS at the current year are shown in the table 4.4.

Table 4.4: Jovim PS total and by category IVI

Category	Current Value	Replacement Cost	IVI
Civil Work	810,281.25	1,290,000.00	0.63
Equipment	989,008.81	2,222,944.44	0.44
Electrical facilities	279,655.91	1,004,000.00	0.28
Total	**2,078,945.97**	**4,516,944.44**	**0.46**

The overall IVI can be formulated according to the equation (4.14).

$$IVI_t(\%) = \frac{\sum_{i=1}^{N} cs_{ct} \times IVI_{ct}}{\sum_{i=1}^{N} cs_{ct}} \tag{4.14}$$

In expression (4.14), N is the number of categories that compose the infrastructure, cs_{ct} is the cost of replacement of the category c $(i = 1,...,N)$ in year t, expressed in monetary terms (e.g., in euros), IVI_{ct} is the IVI value of the category c in year t.

The overall IVI can also be obtained directly by substituting the variables of each asset into the equation (4.6).

The overall IVI is 0.45, and being in the range [0.4,0.6], means that the condition of the infrastructure is in the acceptable range. A closer analysis shows that although everything seems to conform, at first sight, the IVI of the electrical installations is 0.28, which is considerably lower than the acceptable lower limit. As the relative weight of electrical installations is lower than that of construction and equipment, the overall IVI does not have an accentuated drop. To better understand why this value is so low, it is necessary to analyze the IVI of the assets that compose the electrical facility at the third level and see if there is any specific asset pulling the value down or if it is the group as a whole (Annex B). The electrical installation is the same since PS2 was inaugurated. Despite being in good conditions as a result of a good maintenance policy, the total technical useful life of electrical installations is relatively short. This information can mean the need for CapEx investments as soon as possible.

Regarding the Lever Upstream abstraction, the results obtained are shown in table 4.5.

Table 4.5: Lever Upstream Abstraction total and by category IVI

Category	Current Value	Replacement Cost	IVI
Civil Work	2,970,452.74	6,758,637.40	0.44
Equipment	1,806,597.22	5,755,500.00	0.31
Electrical facilities	792,000.00	2,440,000.00	0.32
Total	**5,569,049.96**	**14,954,137.40**	**0.37**

The overall IVI is below the range of acceptable values. A detailed analysis of the categories that make up the infrastructure (Annex B) shows that it is the categories of equipment and electrical facilities that lower the overall value of the IVI.

The assets with the highest weight in the equipment category are the pumping groups. Six of the eight pumping groups that make up the infrastructure were installed in 1987, and although they are operating without significant problems, their advanced age must be taken into account. The difficulty of finding spare parts for these groups is already beginning to show. Thus, even in acceptable conditions, its residual useful life is low since the age of the asset is a variable of the equation (4.11). This consequently translates into a low IVI since the asset's residual life is a variable of the equation (4.6). The two remaining pumping groups, although more recent, are beginning to show decreases in performance. All this translates into an equipment category IVI of 0.31. These considerations can be gauged by examining Appendix B.

The electrical facilities have assets with already advanced age, and several corrective interventions have occurred in the past. The electrical facilities category presents an IVI of 0.32.

Regarding the civil works category, the IVI value is within the acceptable range, with a value of 0.46. Although the abstraction drains require intervention, these infrastructures have a high total technical useful life. Pipes and buildings are in good condition. Although the construction IVI is reasonable, its weight in the global IVI is low, as referred to in chapter 4.3.3..

4.5.2 Long term IVI calculation

The planned capital investments for the two infrastructures are presented in figure 4.4.

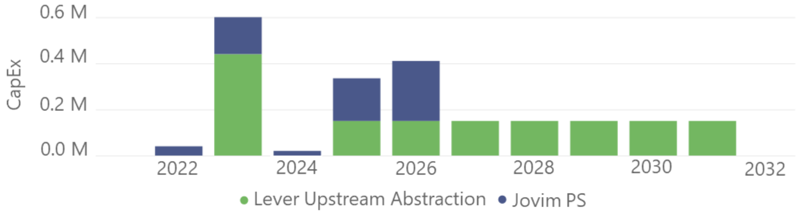


Figure 4.4: Lever Upstream Abstraction and Jovim PS planned CapEx

Regarding the pumping station, the CapEx and the decommissioning percentage inherent to each investment, represented by the β coefficient, are presented in the table 4.6. All components were easily determined with the help of the technical team and the infrastructure REF.

Table 4.6: Jovim PS long-term investments

Year	Asset	Beta	CapEx
2022	Electrical boardroom - PS1	0.15	15,000
	Transformer substation - PS2	0.07	25,000
2023	Ventilators PS2	1	20,000
	Pumping group no.1 PS2	0.15	31,250
	Pumping group no.2 PS2	0.15	31,250
	Pumping group no.3 PS2	0.15	31,250
	Pumping group no.4 PS2	0.15	31,250
	Electrical boardroom - PS2	0.15	15,000
2024	Electrical boardroom - PS2	0.15	20,000
2025	Intrumentation, automation, control and measurement	0.40	60,000
	Pumping group no.1 PS1	0.15	31,250
	Pumping group no.2 PS1	0.15	31,250
	Pumping group no.3 PS1	0.15	31,250
	Pumping group no.4 PS1	0.15	31,250
2026	Pumping group no.4 PS1	0.55	150,000
	Intrumentation, automation, control and measurement	0.40	60.000
	Pumping group no.2 PS1	0.08	25,000
	Pumping group no.3 PS1	0.08	25,000

The overall IVI value, represented in the figure 4.5 chart, varies between 0.45 and 0.4. To reach these values, it is necessary to determine the replacement costs and the residual useful lifes along the future years through the equations (4.12) and (4.13) respectively, where the variables β and CapEx_t are those presented in the table 4.6. Next, an IVI is estimated, through the equation (4.6), for each future year, as a function of the replacement cost and residual useful life. Despite being at the lower limit of the acceptable condition, it is necessary to consider that the electrical installations IVI drops from 0.28 to 0.18, which is not desirable. Although investments are already planned for this group during the period, they are insufficient, making it crucial to discuss the need for more CapEx in electrical installations.

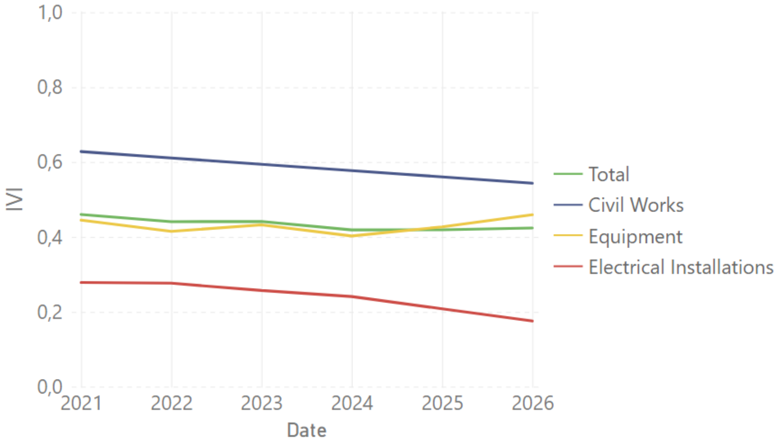


Figure 4.5: Total and by categories Jovim PS IVI forecast

To better understand what is happening in the electrical installation, it is necessary to analyze the group in detail. To do this, it is required to break down the information at the asset level, and this information is presented in the chart of the figure 4.6.

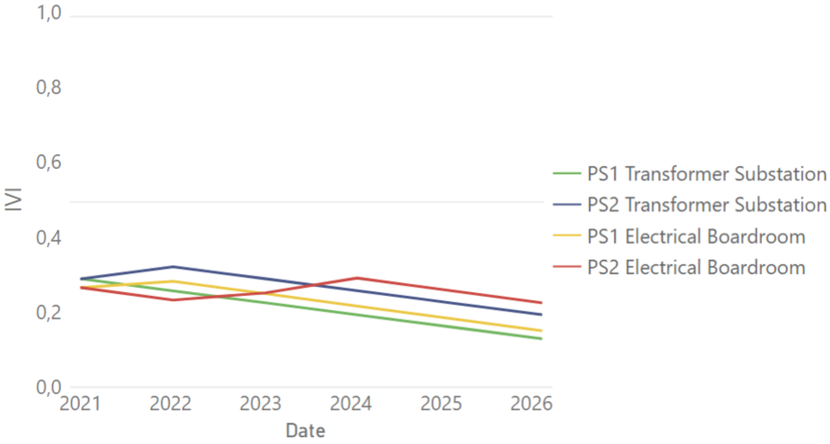


Figure 4.6: Jovim PS Electrical installations IVI forecast

It is noticeable that there is no particular asset undermining the condition of the group. The poor condition is because the group's assets have approximately the same age and the total technical useful life of the electrical installations is less than that of the equipment and construction.

Civil construction will not be subject to investments, the justification being that the building is recent and this category of assets depreciate very slowly. The minimum IVI of 0.54 during the period under analysis corroborates this statement.

The category subject to the most CapEx is equipment. The condition of this group will remain approximately constant over the five years of analysis, varying only between 0.42 and 0.37.

The β and CapEx for the Lever Upstream Abstraction is shown in the table 4.7.

Table 4.7: Lever Upstream Abstraction long-term investments

Year	Asset	Beta	CapEx
2023	Semi Superficial Abstraction no.1	0.15	220,000
	Semi Superficial Abstraction no.2	0.15	220,000
2025	Transformer substation (LPE)	0.75	150,000
2026	Pumping group no.1	0.4	150,000
2027	Pumping group no.2	0.4	150,000
2028	Pumping group no.3	0.4	150,000
2029	Pumping group no.4	0.4	150,000
2030	Pumping group no.5	0.4	150,000
2031	Pumping group no.6	0.4	150,000

The coefficients β for the year 2023 of the Lever Upstream Abstraction present an added difficulty in obtaining. The β is more easily estimated, the more disaggregated the infrastructure is.

By considering the semi-surface abstraction as an asset, there is an aggregation of components with very different total technical useful lifes. This point is easily made when weighing up two elemental components that make up a structure like an abstraction well, the concrete and the paint. The lifetime of concrete is around 100 years, and the paint is about 10. If a paint job is planned for the structure and the "paint job" is considered an asset, it is easy to consider β 1, for that investment. However, suppose the asset is the wall composed of concrete and paint components. In that case, estimating a beta becomes more challenging, and it becomes even more if the asset is the complete abstraction, composed of concrete, paint, drains, reinforcement, etc.

The coefficients obtained for the years 2023 are not error-free. However, any aggregation of components has an associated uncertainty. Any aggregation made will be composed of elements with different total technical useful lifes. The teams must choose an aggregation in which they feel comfortable estimating the variables necessary to determine the IVI with maximum accuracy.

The total IVI and by categories can be analyzed in figure 4.7. The total IVI of the abstraction varies between 0.34 and 0.19. Apart from the fact that the IVI at present is already below the lower acceptable limit (0.4), it tends to worsen until 2032.

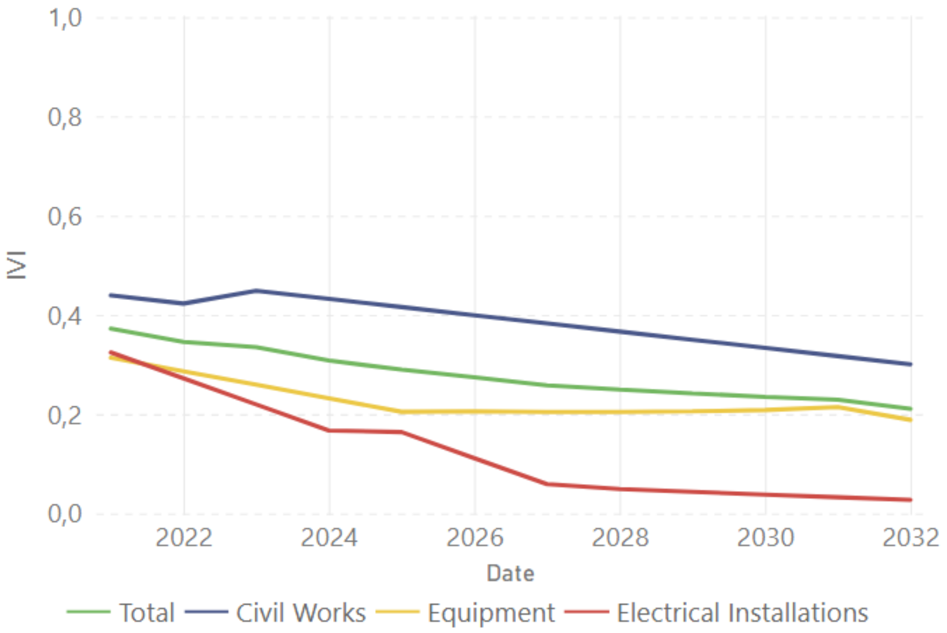


Figure 4.7: Total and by categories Lever Upstream Abstraction IVI forecast

Regarding civil construction, the investment planned for 2023 allows the IVI of this asset category not to drop much until 2032, decreasing only from 0.46 to 0.41. These values are within those foreseen for the proper functioning of the facility and therefore do not translate great alarm. However, 0.41 is already close to the lower acceptable limit and should therefore be reviewed and an investment potentially proposed.

The IVI of the equipment shows a drop from 0.31 to 0.19. Even though pumping groups 1 to 6 have planned rehabilitation for the period under analysis, these are not sufficient investments for the category size, which presents 33% of the weight of the infrastructure.

However, it is in the electrical installations where there are considerable investment shortfalls. The Portuguese average total technical useful life of electrical installations is 15 years. It is expected that the electrical installations, due to their good condition, last longer than the 15 years. This estimate comes from the application of the formulation presented in chapter 4.3.1. However, until 2032 it is foreseen only one investment in one of the category's assets, which makes the group's remaining assets deteriorate almost wholly. The IVI, already low, of 0.32 at present, drops to 0.03 in 2032.

In addition to this indicator helping employees understand in which infrastructure the capital is best used, it also informs which categories need the most investment.

4.5.3 Remarks on the indicator

What makes this indicator impactful is that it requires all teams that deal with assets, such as finance, engineering and operations, to collaborate. The fact that it requires the contribution of all parties means that the results obtained are equally accepted by all the departments involved, and independent areas of the company can use the information it conveys.

Despite being a powerful indicator, it uses subjective information to obtain it. To determine the β coefficient, subjective information from the technical team is used, which may be misleading. It would be interesting to review the methodology to improve this coefficient's accuracy.

The indicator is valuable but has its shortcomings. The β presented translates the level of deactivation that each investment will bring to the respective assets. It means that investments may have significant weights on the asset structure as a whole but translate into a low increase in the residual useful life. For example, when comparing painting the exterior of an abstraction in the river with replacing its drains, having these two interventions similar costs and weights, the estimated IVI, using the formulation created, is identical in both cases. However, the replacement of the drains leads to a more significant increase in the life of the abstraction than the exterior painting. Thus, there is value in a further study of the indicator to address its limitations. A proposal for future research is to study the feasibility of introducing a variable α that quantifies the improvement, function of capital investment, in the residual useful life of an asset through a percentage in the equations (4.13) and (4.12).

Despite the limitations, this study represents a satisfactory result for AdDP for the period under analysis. Interesting future work would be to carry out the same survey for other infrastructures.

4.6 Conclusion

This chapter addresses an indicator already in use by the water supply industry but still relatively recent that can still be worked on.

ERSAR, when presenting the indicator, refers that it is a measure that translates the condition of infrastructure and that it is a suitable measure to define targets regarding infrastructure sustainability criteria (Covas, 2018). The indicator is indeed relevant for determining and planning investments reliably and designate targets. This requires extending the point estimate of the indicator and defining an indicator trend as a function of capital investments.

It is necessary to bring the reality of engineering in infrastructure management closer to the financial approach to investment management, with more rigorous estimates of equipment valuation to be an indicator that is valuable for investment planning.

For decision-making to be taken with the highest rigor, using IVI as a reliable source of information must be guaranteed.

In a single indicator, the proposed methodology allows to have information regarding the present condition of several infrastructures and assets and the effect in the condition of the assets result of CapEx investments. Therefore, despite being difficult to obtain, this is an indicator that is easy to understand and analyze, making it a powerful KPI in its environment. It then allows finance, operations, and engineering teams to be informed of the consequences of decisions made for future investments to make better decisions.

Obtaining a good breakdown of the infrastructure across the four levels, determining the correct state of condition of the assets, and weighting asset values are critical if the IVI intends to give a reasonable value that helps the company rather than hinders it with misleading information.

The case study was carried out on a typical water supply system. It was only possible due to the collaboration of various parts of the company and the existence of credible and organized information. However, it can be extended to other contexts and industries as long as proper precautions are taken.

The investment distribution used is the one proposed by AdDP. The objective of this case study is to verify the consequences in the infrastructure condition through the proposed distribution. However, it would be relevant in a future research to confirm if an increase of the global IVI is possible through a better allocation of capital.

Chapter 5

IVI Extension to the rest of the Lever North System

This chapter extends the IVI calculation to the entire Lever North system, disaggregating the infrastructure into the groups equipment and civil construction only. Equipment in this context refers to all kinds of mechanical equipment and electrical installations.

5.1 IVI aggregated approach

Both the Jovim Pumping Station and the Lever Upstream Abstraction are pilot cases that provide satisfactory results for understanding the condition of the infrastructure in the current year and in future years. However, the business reality is that all the necessary information is not always available to discriminate all the assets and determine the variables needed to reproduce an in-depth study like the one in chapter 4. Besides the inconvenience of the lack of data, the IVI determination has to be done in short periods to be submitted to the regulatory entity. Thus, and only in these cases, it should be preferable to perform the methodology developed without the proper disaggregation.

5.2 Pumping Stations

Excluding the Jovim pumping station, which was already addressed in chapter 4, the stations that are part of Lever Norte, and have not yet been studied, are the Feiteira, Ramalde, Vale Ferreiros, and Lever - Lagoa pumping stations. However, the study for Jovim PS is redone so that in a later section, the comparison between using an aggregated and disaggregated approach is made.

In order to carry out an estimate of the replacement costs for each station, the ERSAR Guide 23 proposes construction cost functions created through the national landscape. The guide provides an online tool that facilitates this calculation. By entering the type of infrastructure and other necessary inputs, the user can obtain a cost estimate. In the case of pumping stations, the inputs are the flow rate and the lifting height. These values are broken down for each station in the company's respective REF's. In addition to the tool giving the total cost of the infrastructure, it also gives a part breakdown of that cost that corresponds to equipment and the part that corresponds to civil construction. The costs presented correspond to updated prices for the year 2016. It is then necessary to update this value for the present 2021. The update relates to currency inflation.

Table 5.1: PS's replacement costs for the year 2021

Designation	Flow rate [l/s]	Height [m w.c.a.]	Total Replacement Cost (2021)	Equipment Replacement Cost	Civil Work Replacement Cost
Jovim PS	4,698	113.3	3,933,115.25€	3,125,002.84€	808,112.41€
Feiteira PS	75	92	331,281.44€	248,083.15€	83,198.30€
Ramalde PS	510	230.6	1,740,179.61€	1,382,635.73€	357,543.89€
Vale Ferreiros PS	538	87.5	729,752.31€	578,579.96€	151,172.35€
Lever - Lagoa PS	3,000	121	5,371,220.27€	4,267,630.72€	1,103,589.55€

From 2016 to 2021, euro inflation was 2.7%, so to update the costs to the current year, add to the 2016 cost 2.7% of the cost of the infrastructure in 2016. This inflation rate was given by the portuguese harmonised index of consumer prices (HICP).

The methodology for calculating the IVI in the current year is the same as the one used previously for the Jovim PS and the Lever Upstream Abstraction. So, in order to use the formulation presented in chapter 4, it becomes necessary to determine condition states, adjusted residual useful lifes, and infrastructures ages. Unlike the case study already performed, a breakdown of the structure down to the asset level will not be carried out. Working on the assets level would be the ideal alternative to have more reliable results. However, due the constraints presented in the beginning of this chapter, as this is only an approach for the company to have a condition overview of the infrastructures, this study will determine condition, age, and adjusted residual useful lifes for the equipment and construction groups. Using REF's and the knowledge of the maintenance team, the age of the groups and the respective states of condition are predicted. The total technical life is taken from the table 4.3. With the variables age, states of condition, and theoretical useful life it is possible to calculate the residual lifes using the equation 4.11. This variables used are presented in table 5.2.

Table 5.2: PS's age, condition and total technical useful life for the year 2021

Designation	Equipment Age	Civil Work Age	Equipment Technical life	Civil Work Technical life	Equipment Condition (c)	Civil Work Condition (c)
Jovim PS	13	22	20	50	1	1
Feiteira PS	15	15	20	50	1.2	2.2
Ramalde PS	8	8	20	50	2.2	1
Vale Ferreiros PS	15	15	20	50	1.6	1.4
Lever - Lagoa PS	19	19	20	50	1.2	1.8

With the adjusted residual useful lifes obtained is possible to determine the adjusted total useful lifes to reality through the sum of the age of the infrastructure with the calculated adjusted residual useful life.

With the adjusted residual useful lifes, the replacement costs presented in table 5.1, and the adjusted total useful life the IVI of the infrastructure with the equation 4.6 can be calculated.

Table 5.3: PS's IVI for the year 2021

Designation	Equipment IVI	Civil Work IVI	Global IVI
Jovim PS	0.57	0.66	0.59
Feiteira PS	0.52	0.7	0.56
Ramalde PS	0.62	0.85	0.67
Vale Ferreiros PS	0.48	0.74	0.54
Lever - Lagoa PS	0.44	0.66	0.49

5.3 Abstractions

The Lever North Water Abstractions are the Lever Upstream Abstraction, and the WTP Lever Superficial Abstraction. The Lever Upstream Abstraction was already studied, so it remains to address the WTP Lever Superficial Abstraction. The calculation methodology would be the same as the one presented in the chapter 5.2. if the ERSAR's online tool had the option to calculate costs for Superficial Abstractions by well. As there is no such possibility, it resorts to the cost proposal in the ERSAR Guide 23, represented in the graphic of the figure 5.1. To determine the costs, it must be first define a flowing power. The equation (5.1) is used for this purpose.

$$\mathrm{Ph} = h \times Q \times g \tag{5.1}$$

In the expression (5.1), h corresponds to the manometric height, measured in m.w.c, Q to the flow, measured in l/s and g to the gravitational acceleration, which is 9.81 m/s_2.

For WTP Lever Superficial Abstraction, the flow rate is 4.420 l/s and the elevation height is 18.7 m w.c.a.

The lift height and the flow rate of the abstraction are taken from the company's REF's, and the flow power can be calculated. Using the cost proposal, graphic of the figure fig:GrafCap, updated replacement costs are determined for the year 2016, and updated to 2021. This costs are presented in table 5.4.

Table 5.4: WTP Lever Superficial Abstraction replacement costs for the year 2021

Designation	Total Replacement Cost (2021)	Equipment Replacement Cost	Civil Work Replacement Cost
WTP Lever Superficial Abstraction	1,195,922.89€	745,501.94€	450,420.95€

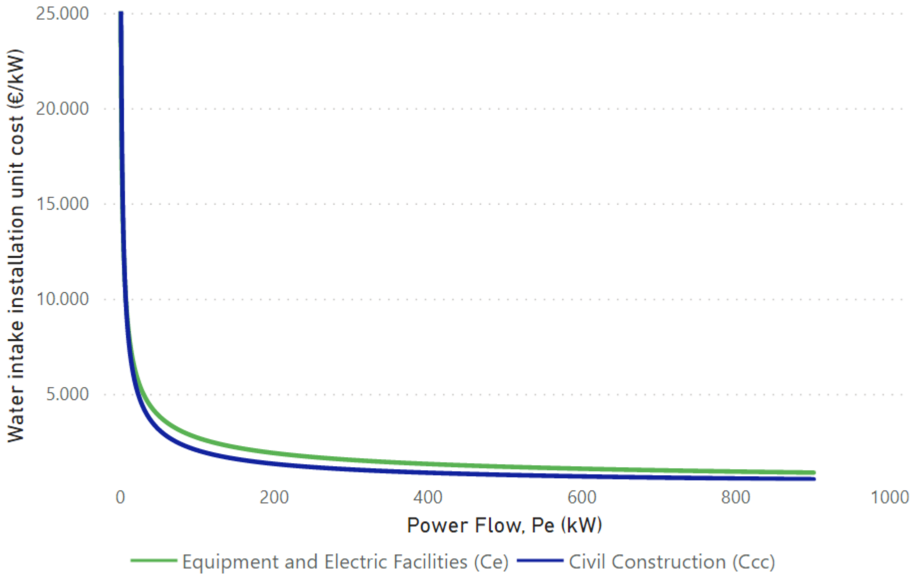


Figure 5.1: Abstraction water intake installation unit cost function of the power flow

The variables age, condition, and total technical useful life are determined in the same way as for the pumping stations and are shown in table 5.5.

Table 5.5: WTP Lever Superficial Abstraction age, condition and total technical useful life for the year 2021

Designation	Equipment Age	Civil Work Age	Equipment Technical life	Civil Work Technical life	Equipment Condition (c)	Civil Work Condition (c)
WTP Lever Superficial Abstraction	12	19	20	50	1.2	1

With all variables defined the formula (4.6) is used to calculate the IVI's for the WTP Lever Surface Abstraction (table 5.6).

Table 5.6: WTP Lever Superficial Abstraction IVI for the year 2021

Designation	Equipment IVI	Civil Work IVI	Global IVI
WTP Lever Superficial Abstraction	0.43	0.68	0.52

5.4 Pipelines

In the sub-system under analysis, the materials used in constructing pipelines are steel, ductile iron, and concrete. The methodology for calculating the IVI is similar to the one that has been used in this chapter. The inputs required to derive replacement costs, using the ERSAR Guide 23, are the material type, diameter, and length of the pipes. The replacement costs and the IVI are easily estimated except for "CE Jovim - Ramalde 0". This pipe is the only one built with concrete material, a material that does not appear in the tool developed by ERSAR. To determine the pipeline cost, it is considered that the viable alternative is its substitution by a steel pipeline. This approximation is because in the ERSAR Guide, the use of steel is considered preferable for pipelines with diameters greater than 1,000 mm, and the pipeline in question has 1,250 mm.

For simplification purposes, only replacement costs and IVI's will be represented (table 5.7). The remaining variables necessary to reproduce the IVI formulation are in the Annex C. For this category of infrastructures, ERSAR only presents a proposal for replacement costs for civil construction. It does not account for equipment because its weight is insignificant.

Table 5.7: Pipelines replacement costs and IVI's for the year 2021

Designation	Replacement Cost (2021)	IVI
CG Lagoa - Jovim	6,827,058.00 €	0.69
CE Lever - Jovim 0	6,017,799.96 €	0.47
CE Lever - Jovim I	6,017,799.96 €	0.53
CG Jovim - Nova Sintra 0	4,186,289.24 €	0.27
CG Jovim - Nova Sintra I	5,684,420.35 €	0.84
CE Jovim - Ramalde 0	2,525,391.97 €	0.49
CE Jovim - Ramalde I	4,835,005.08 €	0.67
CG Ramalde - Cabanas 0	7,072,554.63 €	0.62
CG Cabanas - Pedrouços 0	6,383,586.55 €	0.44
CG Pedrouços - Rotunda AEP	11,338,202.21 €	0.61
CG Rotunda AEP - Freixieiro	2,956,425.93 €	0.73
CG Pedrouços - Nogueira II	4,750,345.37 €	0.75
CG Cabanas - Xistos	1,291,749.30 €	0.73
CG Xistos - Formiga	1,049,244.82 €	0.73
CG Xistos - Vale Ferreiros	671,261.58 €	0.73
CE Vale Ferreiros - Monte Pedro II	580,169.76 €	0.73
CG Monte Pedro - Feiteira	3,004,277.97 €	0.71
CE Feiteira - Rebordosa	228,997.38 €	0.75
CE Ramalde - Galegos	10,434,750.31 €	0.86
CE Lever - Lagoa	6,880,121.53 €	0.7

5.5 Reservoirs

Although a previous study was already conducted by H20pt, where the IVI's of the reservoirs were determined, the study is repeated, updating ages, condition states and inflation. The replacement costs and the IVI's of each reservoir are detailed in the table 5.8

For simplification purposes, only replacement costs and IVI's will be represented. The remaining variables necessary to reproduce the IVI formulation are in the Annex D. For the same reason presented for pipelines, ERSAR does not account for equipment in reservoirs, suggesting only replacement costs for civil construction.

Table 5.8: Reservoirs replacement costs and IVI’s for the year 2021

Designation	Replacement Cost (2021)	IVI
Jovim RR	3,215,211.44 €	0.07
Ramalde RR	1,932,218.34 €	0.34
Pedrouços RR	1,932,218.34 €	0.29
Monte Pedro RR	643,227.56 €	0.42
ETA Lever RAT	2,970,785.44 €	0.57
Lagoa RR	3,381,382.10 €	0.47

5.6 Confrontation between aggregated and disaggregated analysis

To confirm the feasibility of using the more aggregated information, it is interesting to compare the results of the approach for the two situations. To this end, the table 5.9 compares the IVI of the Jovim PS, through both approaches, with the assets aggregated and disaggregated.

Table 5.9: Aggregated and Disaggregated approach for Jovim PS IVI’s calculation

	Replacement Cost (2021)	IVI
Aggregated	3,933,115.25 €	0.59
Disaggregated	4,516,944.44 €	0.46

The difference in replacement cost’s is because the ERSAR 23 guide presents a cost estimate based on national averages, and each infrastructure has its particularities. Thus, an analysis at the asset level, in which replacement costs are discussed according to the characteristics of each installation becomes more precise and more in line with the infrastructure reality. The discrepancy in IVI values comes from the variation in useful lifes and condition states between assets.

The analysis of the pumping station results in the same conclusion each way. The lift station is within the acceptable IVI parameters of [0.4,0.6]. However, there is a considerable difference in the IVI values, which concludes that, whenever possible, the methodology developed at the asset level should be used.

5.7 Final remarks

Working with aggregated assets in the equipment and construction categories, as noted, may be advantageous for situations where it is necessary to present KPI’s information to the regulator in short timeframes. It is also essential to provide the first reflection to the company of what it can expect from the condition status of its infrastructures.

In summary, working with more aggregated data is more straightforward. Still, it can result in inaccurate information, and working with disaggregated information is more labor and time consuming but translates into more accurate information. It is suggested that a balance be struck between the two.

Chapter 6

Organising and Visualising asset management information

This section describes the importance of conveying the information obtained from the various indicators through visual tools.

6.1 Dashboards added value

The creation of Dashboards at AdDP arises from the need for employees to have tools that allow them to question the investment decisions planned for the future. In other words, many times, maintenance teams may have the perception that a particular asset needs more capital investment than another when, this does not reflect the reality. The IVI is an excellent indicator to predict assets' conditions as a result of future investments. Thus, if companies have tools that present the IVI graphically as a function of planned investments, it is easier for them to question the validity of decisions made and iteratively try to reach the most favorable solution.

6.2 Dashboards designed for AdDP

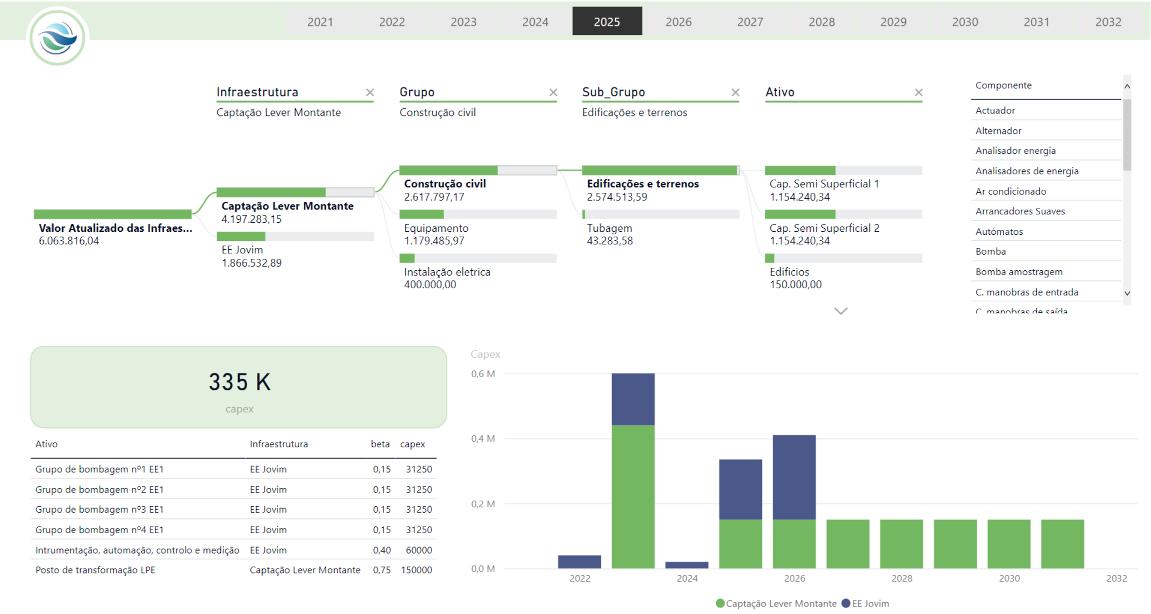
The interfaces represented in the figures 6.1 and 6.3 were created according to the company's needs. This Dashboard is created based on the two case studies explored earlier, the Lever Upstream Abstraction and the Jovim PS. Only these two infrastructures were used since they are the only ones where the IVI for future years was estimated. The elaboration of this Dashboard is made with the visualization tool Power BI.

A decision tree is built in the first interface, where the various infrastructures that make up the water supply network can be broken down into several levels. The decision tree starts with a single node, broken down into possible decompositions, sequentially more detailed. The decomposition levels chosen are infrastructure, group, sub-group, asset, and components. The group comprises asset typologies: equipment, civil construction, and electrical installations. The sub-group corresponds to the object that each asset has in the infrastructure, i.e., an asset "pumping group" belongs to the "lifting" sub-group. The asset, in this context, is an aggregation of reasonable individual components that have similar theoretical lifes and ages and perform a specific task in the system. The breakdown structure presented here is identical to the one proposed in section 4.4.2.

In this first interface, the employees can understand how the value of their infrastructure varies over future years, according to the formula (4.6). The information appears in the interface's decision tree and is filtered by age using the date filter in the top right-hand corner.

At the bottom left, there is a table with information regarding the CapEx value planned for the filtered year and on which assets and infrastructure it is planned. Thus, in this case, it is possible to determine that for the year 2025, a CapEx of 335,000.00 euros is planned. The lower table lists in which assets these investments are planned to be made and the β coefficient that represents the percentage of asset deactivation due to the respective investment.

It is considered essential to have an overview of the planned CapEx investments for all years and all infrastructures. Thus, interface 1 presents a bar chart where this information can be found, at the bottom right. This information is relevant to have an overall notion of the CapEx expected for the total infrastructures in a year, compared to the CapEx expected for a filtered infrastructure, shown in the lower-left corner.

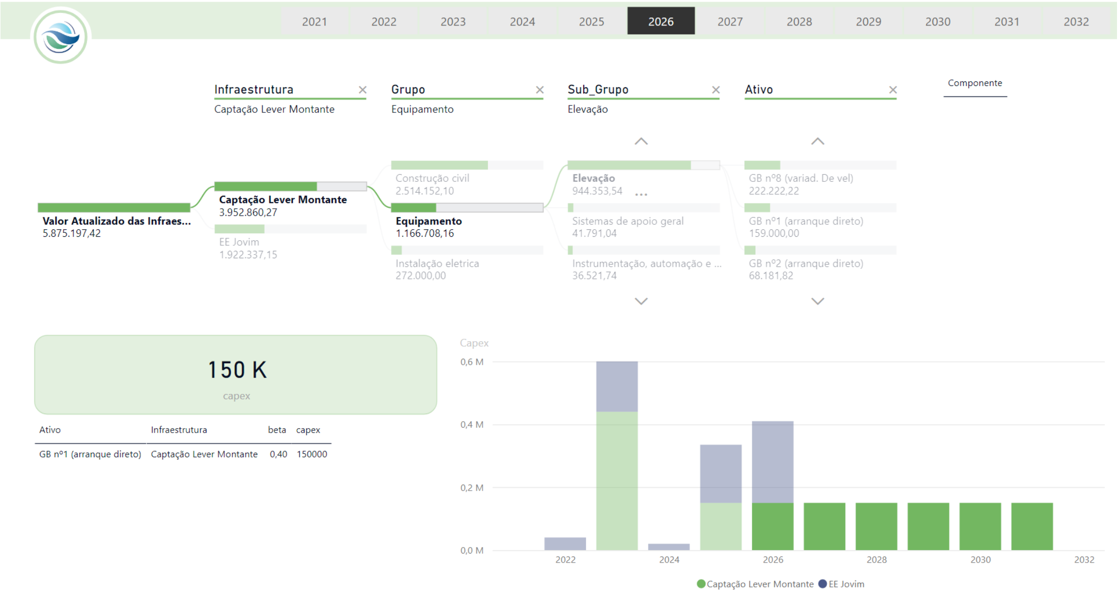


335 K
capex

Ativo	Infraestrutura	beta	capex
Grupo de bombagem nº1 EE1	EE Jovim	0,15	31250
Grupo de bombagem nº2 EE1	EE Jovim	0,15	31250
Grupo de bombagem nº3 EE1	EE Jovim	0,15	31250
Grupo de bombagem nº4 EE1	EE Jovim	0,15	31250
Intrumentação, automação, controlo e medição	EE Jovim	0,40	60000
Posto de transformação LPE	Captação Lever Montante	0,75	150000

Figure 6.1: First Interface

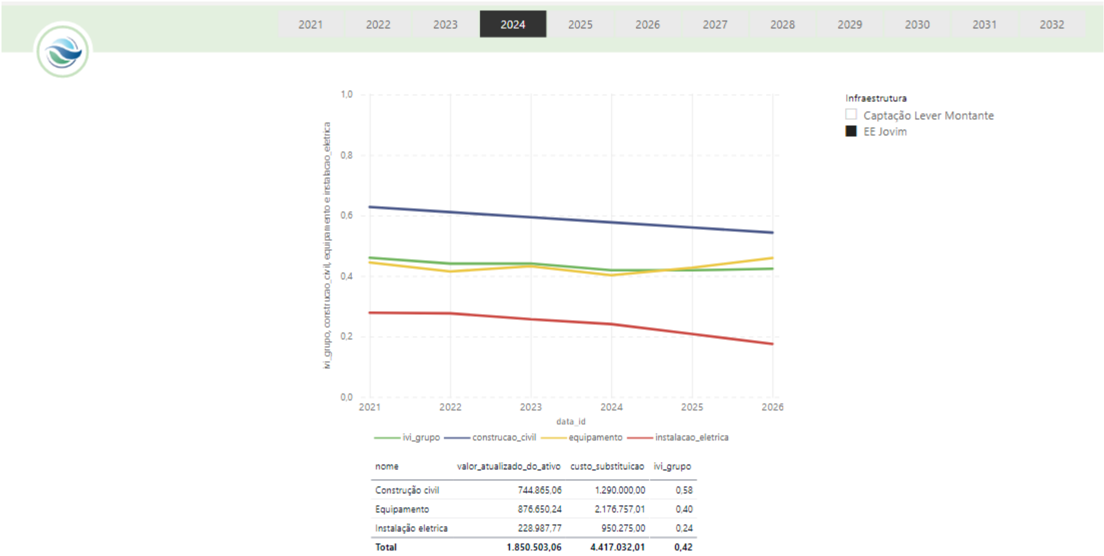
By double-clicking on a decision tree branch, the capital investment planned for that element is shown in the interface, as can be seen in the figure 6.2. By selecting Jovim PS, and then the Equipment Group, the interface updates to the corresponding information. Thus, only the CapEx and β planned for that category and infrastructure for the selected year appear in the lower-left corner. As the bar chart on the bottom right is not filtered by date, the data shows information for that category and infrastructure for the entire years under analysis. Information for other groups and infrastructures is shaded. By analyzing the bar chart, in this example, it is possible to see that all the CapEx planned from 2026 until the end of the years under analysis for Lever Upstream Abstraction is in equipment. It is also possible to observe from the table in the lower-left corner that the CapEx planned for the year under analysis for the filtered infrastructure will be applied in pumping group 1.



Ativo	Infraestrutura	beta	capex
GB nº1 (arranque direto)	Captação Lever Montante	0,40	150000

Figure 6.2: First Interface usage example

The second interface, presented in figure 6.3, allows employees to visualize how IVI performs with the planned investments.



nome	valor_atualizado_do_ativo	custo_substituicao	ivi_grupo
Construção civil	744.865,06	1.290.000,00	0,58
Equipamento	876.650,24	2.176.757,01	0,40
Instalação eletrica	228.987,77	950.275,00	0,24
Total	**1.850.503,06**	**4.417.032,01**	**0,42**

Figure 6.3: Second Interface

The infrastructure to be analyzed can be chosen through the filter created in the checklist.

The lower table translates the current value, the replacement cost, and the IVI of the groups - equipment, civil construction, and electrical installation - of the selected infrastructure. This table is also filtered by date, so the information present relates to the year selected in the filter in the top right corner.

The creation of these Dashboards is based on data modelling.

6.3 Relational Model

Data modeling is an important component in the characterization of these information systems, as stated in Borges et al. (2015). In this phase, the concepts that characterize the problem and how they relate to each other are addressed. Constructing an information system is a process that requires the collaboration of those who are responsible for the development of the project and those who will use it. It becomes particularly interesting to become well acquainted with the processes and correct bad executions of them.

In order to understand how the system created works, it is necessary to understand some data modeling concepts, such as objects, attributes, and classes. An object corresponds to a concept with its individuality and identity. Objects can be concrete or abstract but are always unique. Examples of objects are the AdDP, the Lever Upstream Abstraction, the ISO 55000 standard, or the collaborators of the company. Attributes are dimensions that allow an object to be characterized, such as its name, gender, and age. Classes of objects, or just classes, are the formal characterization of similar objects concerning the situation under study. For example, when considering "Jovim PS" as an infrastructure, making it an object since it has its own identity, the set of AdDP infrastructures can be grouped into the "Infrastructures" class.

Thus, to develop an information system that reflects the reality of the sector under study, six classes were defined - Infrastructure, Group, Sub-Group, Asset, Component, and Register.

The classes - Infrastructure, Group, Sub-Group, Asset, and Component - represent the various levels at which it is possible to disaggregate its infrastructures, and are the same classes presented in the breackdown structure within the chapter 4.4.2.. The only attribute assigned to each of the objects of these classes is its name.

The Register class will consist of the assets and the information about current value, replacement cost, useful lifes, and IVI attributes as a function of CaPex and β's that updates every year. This class arises from the need to separate the physical asset from the information about it updated every year. Thus, the object asset has as attribute the name and translates the individuality of the physical asset, and the object register, which translates the individuality of the information about an asset on a date. The creation of this register class allows for information management and database organization.

The relationship between these classes is represented in the UML diagram of the figure 6.4. The UML presents tables that correspond to the classes created linked by arrows that represent the relationships between classes. The direction of the arrows and the associated numbers represent a varied range of associations. In the present case, the relationships are all one-to-many. For example, the arrow pointing the asset category to the component category, where the number "1" is at the origin and the symbol "*" at the destination, means that an "active" object is composed of several "component" objects, and to a "component" object is associated one and only one "active" object.

Each asset belongs to only one infrastructure and one sub-group typology. Therefore, each sub-group also belongs to a typology of the group equipment, civil construction, and electrical installation. Each asset has a vast number of components. There is only one asset in each register, while an asset may have several registers, proportional to the number of years under study.

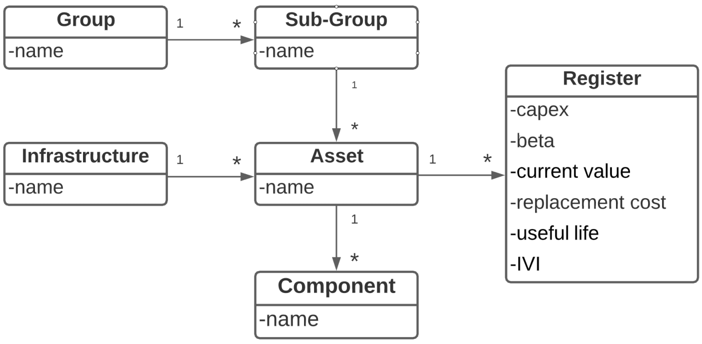


Figure 6.4: UML Diagram

All objects must have an attribute that identifies them and gives them their identity. These attributes are called primary keys. When an object is an attribute of another object, the primary key of the former is used as an attribute and foreign key of the latest.

The table 6.1 represents the generalization of the figure 6.4. In bold, underlined and to the left of the vertical line are the primary keys that refer to each class, Group, Sub-Group, Infrastructure, Asset, Component and Register. The foreign keys present in each class are shown in italics and underlined. Note that the asset class's primary key, asset_id, will be the foreign and primary key of the registry class.

Table 6.1: UML Classes Relationships

infrastructure_id		name					
group_id		name					
subgroup_id		name					
asset_id		name				*subgroup_id*	*infrastructure_id*
component_id		name					*asset_id*
asset_id	**date_id**	replacement_cost	capex	beta	ivi	useful_life	current_value

This model serves as the foundation for database creation, which is done in Excel. Each class originates an Excel sheet, where the variables that constitute this sheet are those presented in the table 6.1. Thus, whenever needed to update information about an object, it is only necessary to do it in Excel. Since the Dashboard created is a tool for visualizing the database created, changing the information in Excel makes it simple to update in Power BI. All that is needed is to press the refresh button in the program (figure 6.5).

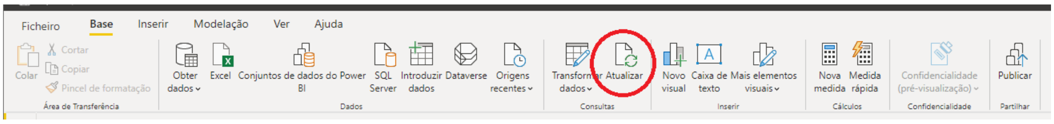


Figure 6.5: Update Categories in Power Bi

6.4 Considerations

The relationships and tables created in the relational model are created for the database. The relational model is created so that the data is stored in the most effective way and without redundant elements. The elements presented in the dashboards are created according to the company's needs so that employees can validate investment decisions. However, the accuracy of the information presented is solely dependent on the inputs provided. Thus, it is necessary to guarantee that the variables introduced in the database translate the reality of the assets.

The visualization and organization of the information obtained by asset management are linked. For dashboards to translate information in the best way, it is necessary to work with a carefully organized database and without redundant information. The management of information in asset management must be treated with due importance since the characteristics of the assets are continuously being updated, either by planned investments, or by breakdowns or accidents, or by depreciation, etc..

Chapter 7

Conclusion

Infrastructure assets, like many other tangible assets, are constantly depreciating. Therefore, capital investments have to be made so that the assets do not break down and the organization's service levels remain acceptable. Therefore, a trade-off between the dimensions 'Risk', 'Cost' and 'Performance' is essential. In order to account for these dimensions, numerous operational and financial indicators have been created. Although there is an enormous range of indicators, each organization has to be selective and choose those that best fit the company's context.

The Infrastructure Value Index (IVI) is an indicator introduced in Alegre (2008), and is a measure that translates the condition of infrastructures and is a suitable measure to define targets regarding infrastructure sustainability criteria (Covas (2018)).

The indicator is indeed relevant for defining and planning investments in a reliable way and define targets. To do so it requires extending the point estimate of the indicator and defining an indicator trend as a function of capital investments.

The IVI is a very comprehensive and easy-to-understand indicator. Despite that, its determination is calculated using subjective information and requires the collaboration of several parties within the organization. To obtain this indicator is used knowledge and information from the financial and operational areas. It becomes clear that although, for now, it is only being used by the Portuguese water distribution and treatment organizations, it translates into pertinent information that can be extended to any industry.

This thesis addresses this indicator and intends to contribute to its exploitation in a water supply system of Águas do Douro e Paiva. It also intends to be a scientific contribution to asset management, as this indicator is recent and should be refined due to its relevance.

This indicator had been explored in a superficial and not very rigorous way in the past by AdDP. However, its relevance was noted, hence the need to reformulate its calculation method.

The methodology created in this thesis allows, in a single indicator, to have information about the current condition of the various infrastructures and the influence that CapEx may have on the condition of assets. For this calculation, each infrastructure is broken down into its various assets, which are treated individually so that the indicator can be calculated with the highest degree of accuracy.

Throughout this dissertation, it is possible to see how the indicator with a disaggregated approach, where each asset is treated individually, can translate different information from an aggregated methodology based on national replacement costs averages. Each infrastructure has its particularities and therefore should be treated as such. An indicator to be useful has to translate correct information, or it will be hindering the decision process rather than helping.

Besides the collaboration of several areas to obtain it, the IVI, to be estimated, requires the company to have a database that translates the reality of the assets. IVI can only be estimated if the assets are well identified, with characteristics obtained accurately such as age, condition, and acquisition costs. Therefore, the company's employees must make an effort to maintain a well-organized database that reflects the business reality. Besides allowing the calculation of the IVI, this organization of information allows the management of information on assets so that other indicators can be created and the asset management area has the tools to do its job. Information is valuable insofar as it can be easily understood and transmitted to employees. There are many ways to visualize information, but it is a good idea to use Dashboards when it comes to operational and financial indicators.

The methodology created is tested in two pilot cases at AdDP company, the Jovim Pumping Station and the Lever Upstream Abstraction. As far as Jovim PS is concerned, the study proved that its overall condition is within the acceptable parameters defined by the regulator but with degraded electrical installations. Regarding Lever Upstream Abstraction, the condition is worse than the acceptable limit, with a notable lack of investment in electrical installations. Besides presenting precarious conditions, the electrical installations in both infrastructures have little planned investment, and deterioration is expected to increase over the years. According to the study conducted, it is possible to assess that besides the distribution of investments not being made most adequately, there is a lack of capital investments in these infrastructures, especially in the abstraction.

Some of the conclusions were unknown to the employees, who, when confronted with the data, realized that the electrical installations and some mechanical equipment were, in fact, worse than they thought, information corroborated by the data asset breakdown records. All these conclusions were drawn because an information system was developed with data on the various infrastructure assets, which served as a basis for constructing dashboards to make the information perceptible. It is not suficient to have a well-calculated and relevant indicator if it is not understandable and efficiently transmitted to the decision makers.

Because of its relevance, it would be interesting in the future to extend the methodology to the rest of the network infrastructures, and analyze the feasibility of the investment plans in the light of the needs.

A more general approach to the indicator was made, extending the IVI to the rest of the group's sub-system infrastructures. The intention was to provide the company with a quick calculation methodology to easily and quickly present the infrastructure's conditions to the regulator. However, there is an increased inaccuracy which corroborates the premise that it is necessary to disaggregate the infrastructure's assets and study them individually so that the overall infrastructure's conditions are as close as possible to reality.

The formulation presented for the IVI calculation is subject to improvement. In fact, for similar weights investments, the methodology does not distinguish those that translate into the useful life increase of the infrastructure. Some information is omitted since it does not account for small interventions that may translate into significant gains in the useful life of the infrastructure. Thus, the formulation is subject to change. A further improvement would be to develop a methodology so that the condition of the assets is defined more homogeneous and rigorous since so far, it is still done subjectively.

The study carried out disaggregates the assets that make up civil works very superficially. The civil works are composed of assets with very different useful lifes, which determines capital investments less precisely. In a future study, it would be interesting to try to disaggregate this category of assets.

In this dissertation, an IVI was estimated for future years as a function of the planned investments. However, an interesting study would be, with the same Capex available, to determine better investment plans. For this exercise, it is necessary to guarantee that the overall IVI of the infrastructures is as high as possible while at the same time ensuring that the asset groups do not reach values that are too low. It is not ideal to have an overall IVI within acceptable parameters if one group is severely degraded.

The IVI provides valuable information by increasing the accuracy of the data it uses. It would be interesting for AdDP to conduct a more in-depth study on the condition of its assets to confirm the values used throughout this dissertation.

Concerning the methodology formulation, there is the possibility to deepen the study and determine costs or capital gains regarding the asset deactivation. The asset's current value, or market value, is already estimated, but decommissioning costs are not.

Bibliography

AdDP (2000). Report & accounts.

AdDP (2017). Vision, mission, and enterprise responsibility policy. `https://www.addp.pt/dados.php?ref=visao-missao-responsabilidade`.

Alegre, H., . C. D. (2010). Technical guide no. 16–gestão patrimonial de infra-estruturas de abastecimento de água - uma abordagem centrada na reabilitação.

Alegre, H. (2008). Water infrastructure asset management. *Research Program, Series «Thesis and Research Programmes», LNEC, Lisbon*.

Alegre, H., Vitorino, D., and Coelho, S. (2014). Infrastructure value index: a powerful modelling tool for combined long-term planning of linear and vertical assets. *Procedia Engineering*, 89:1428–1436.

AWWA (2017). Buried no longer: Confronting america's water infrastructure challenge.

Azevedo, C. (2019). *Asset Management Insights - Phases, Practices, And Value*, page 236. Industrial Press, Inc.

Bhagwan, J. (2012). A compendium of best practices in asset management. *Water Intelligence Online*, 11.

Borges, L., Dias, T., and Cunha, J. (2015). *data modelling in UML (in Portuguese)*, page 171. FCA.

Carollo (2015). Project memorandum 2.4 - condition assessment - final draft, public works integrated master plan - water.

Covas, D. (2018). Technical guide no. 23 – custos de construção de infraestruturas associadas ao ciclo urbano da água .

Covas, D., Cabral, M., Pinheiro, A., Marchionni, V., Antunes, S., Lopes, N., Mamouros, L., and Brôco, N. (2018). Custos de construção de infraestruturas associadas ao ciclo urbano da água - Guia Técnico nº 23. *Lisboa: Entidade Reguladora de Águas e Resíduos*.

CSA (2014). Exploring the issues facing new zealand's water, wastewater and stormwater sector.

D'Inverno, G., Carosi, L., and Romano, G. (2021). Environmental sustainability and service quality beyond economic and financial indicators: A performance evaluation of italian water utilities. *Socio-Economic Planning Sciences*, 75:100852. Decision-Making for Environmental Sustainability.

ERSAR (2020). Relatório anual dos serviços de Águas e resíduos em portugal (2019) volume 1 - caraterização do setor de águas e resíduos. *Entidade Reguladora dos Serviços de Águas e Resíduos*.

Evans, N. and Price, J. (2020). Development of a holistic model for the management of an enterprise's information assets. *International Journal of Information Management*, 54:102193.

Few, S. (2006). *Information Dashboard Design*, page 223. O'Reilly.

H2Opt (2020). Inspeção e avaliação da condição funcional e do risco dos reservatórios da addp.

Harrison, R., Parker, A., Brosas, G., Chiong, R., and Tian, X. (2015). The role of technology in the management and exploitation of internal business intelligence. *Journal of Systems and Information Technology*, 17(3):247–262. Cited By :6.

Hastings, Nicholas Anthony, J. (2021). *ISO 55000 Series Standards*, pages 595–621. Springer International Publishing, Cham.

Howard, J., Dixon, J., and Comrie, J. (2015). Australian infrastructure fnancial management manual (aifmm). *Institute of public works engineering australaisa (IPWEA)*.

Kenton, W. (2020). Tangible asset. `https://www.investopedia.com/terms/t/tangibleasset.asp`.

MAOTE (2014). *Uma Estratégia ao Serviço da População: Serviços de Qualidade a um Preço Sustentável. Vol. 1, Ministry of Environment Spatial Planning and Energy, Portugal (in Portuguese).* PENSAAR 2020.

Mendonça, J. (2018). *Groundwater and Water Supply in Lisbon - The Epal Abstractions (in Portuguese)*, page 221. EPAL.

Norman, A. (2014). Asset management dasboards: A primer. *The Property Professional*, 26(3).

Rasmussen, N., Bansal, M., and Chen, C. (2009). *Business Dashboards: A Visual Catalog for Design and Deployment*. Wiley.

Salvado, F., Marques de Almeida, N., and Álvaro Vale e Azevedo (2020). Future-proofing and monitoring capital investments needs throughout the life cycle of building projects. *Sustainable Cities and Society*, 59:102159.

USEPA (2005). Usepa advanced asset management workshop. `https://19january2017snapshot.epa.gov/sustainable-water-infrastructure/advanced-asset-management-workshop-materials_.html`.

Vieira, J., Almeida, N., Silva, J. G., Castro, C., Lima, B., and Trindade, M. (2020a). Using indicators to deal with uncertainty in the capital renewals planning of an industrial water supply system: Testing the infrastructure value index. engineering assets and public infrastructures in the age of digitalization.

Vieira, J., Cabral, M., Almeida, N., Silva, J. G., and Covas, D. (2020b). Novel methodology for efficiency-based long-term investment planning in water infrastructures. *Structure and Infrastructure Engineering*, 16(12):1654–1668.

Águas de Douro e Paiva (2017). System map (in portuguese). `https://www.addp.pt/dados.php?ref=mapa-sistema`.

Appendix A

Jovim PS1 and Lever Upstream Abstraction infrastructures breakdown

Table A.1: Breakdown in the first four levels of Lever Upstream Abstraction

First level	Second level	Third level	Fourth level
Lever Upstream Abstraction	Equipment	Production	Generator set
		General support systems	Travelling crane
		Instrumentation, automation, control and measurement	Instrumentation, automation, control and measurement equipment
		Hydraulic shock protection	Compressed air system nº1 (2 Compressors for the RACs)
			Compressed air system nº2 (Compressor for the wells)
			AVAC System from the TS LPE
			2 RACs
		Lifting	Pumping Group No.1 (direct start)
			Pumping Group No.2 (direct start)
			Pumping Group No.3 (direct start)
			Pumping Group No.4 (direct start)
			Pumping Group No.5 (direct start)
			Pumping Group No.6 (direct start)
			Pumping Group No.7 (variable speed drive)
			Pumping Group No.8 (variable speed drive)
	Electrical facilities	Distribution	Geral Transformer substation
			LPE Transformer substation
			Power Substation
			Electrical boardroom
	Civil works	Civil Works	Semi Surface Abstraction No. 1
			Semi Surface Abstraction No. 2
			Pipe system
			Building
			Collection Well

Table A.2: Breakdown in the first four levels of Jovim PS1

First level	Second level	Third level	Fourth level
Jovim PS1	Equipment	General support systems	Travelling crane
		Hydraulic circuit	Hydraulic circuit
		Instrumentation, automation, control and measurement	Instrumentation, automation, control and measurement equipment
		Lifting	Pumping group no. 1
			Pumping group no. 2
			Pumping group no. 3
			Pumping group no. 4
			Ventilators
		Hydraulic shock protection	Compressed air system
			ESP 30m3, PN10 - RSP 2 (EE1) | RAC
			ESP 30m3, PN10 - RSP 1 (EE1) | RAC
		Sampling	Sampling System
	Electrical facilities	Distribution	Electrical boardroom
			Transformer substation
		Safety systems	Security system
	Civil works	Civil Works	Building
			Pipe system

Appendix B

Jovim PS and Lever Upstream Abstraction variables for current IVI calculation

Table B.1: Variables for Jovim PS current IVI calculation

Designation	Age	Condition	Theoretical total useful life	Replacement Cost
Edificio EE Jovim	22	1.2	50	645,000.00 €
Tubagem da EE de Jovim	22	1.2	40	645,000.00 €
Sala quadros elétricos - EE1 antiga	22	2.1	15	250,000.00 €
Sala quadros elétricos - EE2 nova	22	1.9	15	250,000.00 €
Posto de transformação EE1 antiga	22	1.7	15	224,000.00 €
Posto de transformação EE2 nova	22	1.6	15	280,000.00 €
Grupo gerador EE2	21	1.5	20	20,000.00 €
Intrumentação, automação, controlo e medição	9	1	15	100,000.00 €
Grupo de bombagem nº1 EE1	19	1.4	20	180,000.00 €
Grupo de bombagem nº2 EE1	19	1.4	20	180,000.00 €
Grupo de bombagem nº3 EE1	19	1.4	20	180,000.00 €
Grupo de bombagem nº4 EE1	19	1.4	20	180,000.00 €
Grupo de bombagem nº1 EE2	21	1.3	20	285,312.39 €
Grupo de bombagem nº2 EE2	21	2.1	20	285,312.39 €
Grupo de bombagem nº3 EE2	21	1.3	20	285,312.39 €
Grupo de bombagem nº4 EE2	21	2.1	20	285,312.39 €
Ventiladores EE1	22	1.7	15	20,000.00 €
Ventiladores EE2	22	1.3	15	20,000.00 €
ESP 30m3, PN10 - RSP 2 (EE1) | RAC	9	1.7	40	56,388.62 €
ESP 30m3, PN10 - RSP 1 (EE1) | RAC	9	1.7	40	56,388.62 €
ESP Remetal, 35 m3 - RSP 3 (EE2) | RAC	9	1.6	40	88,917.66 €

Table B.2: Variables for Lever Upstream Abstraction current IVI calculation

Designation	Age	Condition	Theoretical total useful life	Replacement Cost
Tubagem	34	1	40	100,000.00 €
Edificios	34	1	50	300,000.00 €
Posto de transformação geral	8	3	15	160,000.00 €
Posto de transformação LPE	8	3	15	200,000.00 €
Poço colector	34	4.5	100	316,453.40 €
Instrumentação, automação e controlo	14	2	15	210,000.00 €
Sistema AVAC do PT LPE	14	1	15	55,000.00 €
2 RACs	34	1	50	230,000.00 €
Ponte Rolante	34	1	40	100,000.00 €
Gerador de Emergência- L. Montante	14	2	20	50,000.00 €
Subestação Energia	14	3	15	2,000,000.00 €
Sala de quadros eletricos	14	3	15	80,000.00 €
Sistema Ar. Comprimido nº1 L. Montante (2 Compressor para RACs)	14	1	15	6,500.00 €
Sistema Ar. Comprimido nº2 L. Montante (Compressor para poços)	14	2	15	4,000.00 €
GB nº1 (arranque direto)	34	3	20	600,000.00 €
GB nº2 (arranque direto)	34	2	20	600,000.00 €
GB nº3 (arranque direto)	34	2	20	600,000.00 €
GB nº4 (arranque direto)	34	2	20	600,000.00 €
GB nº5 (arranque direto)	34	2	20	600,000.00 €
GB nº6 (arranque direto)	34	2	20	600,000.00 €
GB nº7 (variad. De vel)	14	2	20	750,000.00 €
GB nº8 (variad. De vel)	14	2	20	750,000.00 €
Cap. Semi Superficial 1	34	4.5	100	3,021,092.00 €
Cap. Semi Superficial 2	34	4.5	100	3,021,092.00 €

Appendix C

Pipelines variables for an aggregated level IVI calculation

Table C.1: Pipelines variables for an aggregated level IVI calculation

Designation	Extension [m]	Diameter [mm]	Material	Age	Theoretical total useful life	Condition
CG Lagoa - Jovim	5,383	1,400	AÇO	13	40	2
CE Lever - Jovim 0	5,914	1,000	FFD	29	40	2
CE Lever - Jovim I	5,914	1,000	FFD	29	40	1
CG Jovim - Nova Sintra 0	10,038	600	FFD	59	40	2
CG Jovim - Nova Sintra I	10,055	900	AÇO	7	40	1
CE Jovim - Ramalde 0	2,584	1,250	BA	41	60	2
CE Jovim - Ramalde I	2,566	1,400	FFD	17	40	1
CG Ramalde - Cabanas 0	4,989	1,200	FFD	17	40	2
CG Cabanas - Pedrouços 0	4,503	1,200	FFD	40	40	1
CG Pedrouços - Rotunda AEP	7,998	1,200	FFD	18	40	2
CG Rotunda AEP - Freixieiro	7,089	600	FFD	11	40	2
CG Pedrouços - Nogueira II	8,761	700	FFD	10	40	2
CG Cabanas - Xistos	1,808	800	FFD	13	40	1
CG Xistos - Formiga	3,401	500	FFD	13	40	1
CG Xistos - Vale Ferreiros	1,238	700	FFD	13	40	1
CE Vale Ferreiros - Monte Pedro II	1,070	700	FFD	13	40	1
CG Monte Pedro - Feiteira	9,738	500	FFD	12	40	2
CE Feiteira - Rebordosa	1,620	300	FFD	12	40	1
CE Ramalde - Galegos	27,239	700	AÇO	6	40	1
CE Lever - Lagoa	3,529	1,800	AÇO	15	40	1

Appendix D

Reservoirs variables for an aggregated level IVI calculation

Table D.1: Reservoirs variables for an aggregated level IVI calculation

Designation	Volume $[m^3]$	Age	Theoretical total useful life	Condition
RR Jovim	33,280	77	50	4
RR Ramalde	20,000	41	50	3
RR Pedrouços	20,000	32	50	4
RR Monte Pedro	3,400	43	50	2
RAT ETA Lever	30,750	20	50	3
RR Lagoa	35,000	19	50	4