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Infrastructure Asset Management of Urban Water Systems

Helena Alegre and Sérgio T. Coelho

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1. Introduction

Urban water systems are the most valuable part of the public infrastructure worldwide, and utilities and municipalities are entrusted with the responsibility of managing and expanding them for current and future generations. Infrastructures inexorably age and degrade, while society places increasing demands for levels of service, risk management and sustainability.

As many systems reach high levels of deferred maintenance and rehabilitation (ASCE, 2009), the combined replacement value of such infrastructures is overwhelming, demanding judicious spending and efficient planning.

Infrastructure asset management (IAM) of urban water infrastructures is the set of processes that utilities need to have in place in order to ensure that infrastructure performance corresponds to service targets over time, that risks are adequately managed, and that the corresponding costs, in a lifetime cost perspective, are as low as possible.

IAM methods partially differ from those applicable to managing other types of assets. One of the reasons is the fact that such infrastructures have indefinite lives, in order to satisfy the permanent needs of a specific public service. Infrastructures are not replaceable as a whole, only piecemeal. Consequently, in a mature infrastructure, all phases of assets lifetime coexist. Additionally, in network-based infrastructures, it is frequently not feasible to allocate levels of service to individual components because there is a dominant system behavior (e.g. symptoms and their causes often occur at different locations).

IAM is increasingly becoming a key topic in the move towards compliance with performance requirements in water supply and wastewater systems. Sustainable management of these systems should respond to the need for:

- Promoting adequate levels of service and strengthening long-term service reliability;

- Improving the sustainable use of water and energy;

- Managing service risk, taking into account users' needs and risk acceptance;

- Extending service life of existing assets instead of building new, when feasible;

- Upholding and phasing in climate change adaptations;

- Improving investment and operational efficiency in the organization;

- Justifying investment priorities in a clear, straightforward and accountable manner.

2. Overview of current knowledge and practice

Given its origin in the financial sector, where the economic approach is prevalent, the first significant developments in the field of infrastructure asset management were led by accountants and economists. In the late 1980s, the South Australia Public Accountants Committee published a series of eight reports alerting all Australian governments for the need to seriously consider the management of their infrastructure if deterioration of valuable public services were to be avoided (Burns *et al.*, 1999). Following these reports, Prof. Penny Burns, at the University of Adelaide (Australia), played an crucial role in bringing to attention the importance of the subject and formalizing key concepts and principles (e.g., Burns, 1990; Burns *et al.*, 1999). Australian leadership in this field endures to the present day, through both industry practice and initiatives by organizations such as the Institute of Public Works Engineering Australia (IPWEA, www.ipea.org.au), the National Asset Management Steering Group (NAMS, www.nams.au.com), the Australian National Audit Office (ANAO, www.anao.gov.au), the Asset Management Quarterly International (AMQI, www.am-qi.com), ACORN Inc. (www.acorninc.org) and the Water Services Association Australia (WSAA, www.wsaa.asn.au).

The Australian and New Zealand AM school is synthesized in the International Infrastructure Management Manual, revised and updated periodically (current edition: IIMM, 2011), which addresses different types of public infrastructures and promotes the Total Asset Management Process.

IAM has equally seen significant advances in many other countries, such as in the US (e.g. Clark *et al.* 2010; US EPA, 2012), the UK (e.g. IAM/BSI, 2008; UKWIR, 2003) and Portugal (Alegre and Covas, 2010; Coelho and Vitorino, 2011; Alegre *et al.*, 2011). From a practical standpoint, very good examples of leading-edge utility practice can be found in Asia (e.g., Singapore PUB), and in Central and Northern Europe, such as in the Netherlands (e.g. PWN - North Holland), Germany (e.g. Munich, Berlin), Norway (e.g. Oslo) or Sweden (e.g. Stockholm, Malmo).

IAM has also registered scientific developments, particularly with regard to algorithms and tools aiming at supporting pipe rehabilitation prioritization and decision-making. Whole-life costing (e.g. Skipworth *et al.*, 2002), as well as life time assessment and failure forecasting, are

among the most researched topics (e.g., Sægrov ed., 2005; Sægrov ed., 2006; Malm *et al.*, 2012; Renaud *et al.*, 2011). From 2005, the biannual LESAM (Leading-Edge Strategic Asset Management) conferences of the International Water Association have clearly demonstrated the increasing interest and recognition of this field of knowledge (e.g. Alegre and Almeida ed., 2009).

Effective decision-making requires a comprehensive approach that ensures the desired performance at an acceptable risk level, taking into consideration the costs of building, operating, maintaining and disposing capital assets over their life cycles. Brown and Humphrey (2005) summarize these concepts by defining IAM as "the art of balancing performance, cost and risk in the long-term".

IAM is most often approached based on partial views: e.g., for business managers and accountants, IAM means financial planning and the control of business risk exposure (Harlow and Young, 2001); for water engineers, IAM is focused on network analysis and design, master planning, construction, optimal operation and hydraulic reliability (Alegre and Almeida ed., 2009); for asset maintenance managers, the infrastructure is mostly an inventory of individual assets and IAM tends to be the sum of asset-by-asset plans, established based on condition and criticality assessment; for many elected officials, since water infrastructures are mostly buried, low visibility assets, IAM tends to be driven by service coverage, quality and affordability in the short run. Common misconceptions include reducing IAM to a one-size-fits-all set of principles and solutions, mistaking it for a piece of software, substituting it for engineering technology, or believing that it can be altogether outsourced. In practical terms, many existing implementations tend to be biased by one or several of these perspectives.

3. IAM as an integrated approach

To avoid the shortcomings inherent to these partial views, integrated IAM approaches are required, driven by the need to provide adequate levels of service and a sustainable service in the long-term.

Integrated IAM may be implemented in many different forms. Even for a specific utility and a given external context, different approaches may be successfully implemented. However, there are some basic principles commonly accepted in the current leading literature, practice and standardization (Hughes, 2002; INGENIUM and IPWEA, 2011; Sægrov ed., 2005; Sægrov ed., 2006; Sneesby, 2010).

An integrated methodology is presented that approaches IAM as a management process, based on PDCA principles and requiring full alignment between the strategic objectives and targets, and the actual priorities and actions implemented, embedding the key requirements of the forthcoming ISO 55000/55001/55002 standards on asset management (ISO, 2012a, 2012b, 2012c). The approach expressly takes into account that a networked infrastructure cannot be dealt with in the same way as other collections of physical assets: it has a dominant system behavior (i.e., individual assets are not independent from one another), and as a whole it does not have a finite life – it cannot be replaced in its entirety, only piecemeal (Burns *et al.*, 1999). The methodology allows for the assessment and comparison of interven-

tion alternatives from the performance, cost and risk perspectives over the analysis horizon(s), taking into account the objectives and targets defined (Alegre and Covas, 2010; Almeida and Cardoso, 2010). In summary, the objective of an integrated approach is to assist water utilities in answering the following questions:

- Who are we at present, and what service do we deliver?

- What do we own in terms of infrastructures?

- Where do we want to be in the long-term?

- How do we get there?

The cube shown in Fig. 1 symbolizes an integrated IAM approach. It advocates that IAM must be addressed at different planning decisional levels: a strategic level, driven by corporate and long-term views and aimed at establishing and communicating strategic priorities to staff and citizens; a tactical level, where the intermediate managers in charge of the infrastructures need to select what the best medium-term intervention solutions are; and an operational level, where the short-term actions are planned and implemented. It also draws attention to the need for standardized procedures to assess intervention alternatives in terms of performance, risk and cost, over the analysis period. The other relevant message is that IAM requires three main pillars of competence: business management, engineering and information.
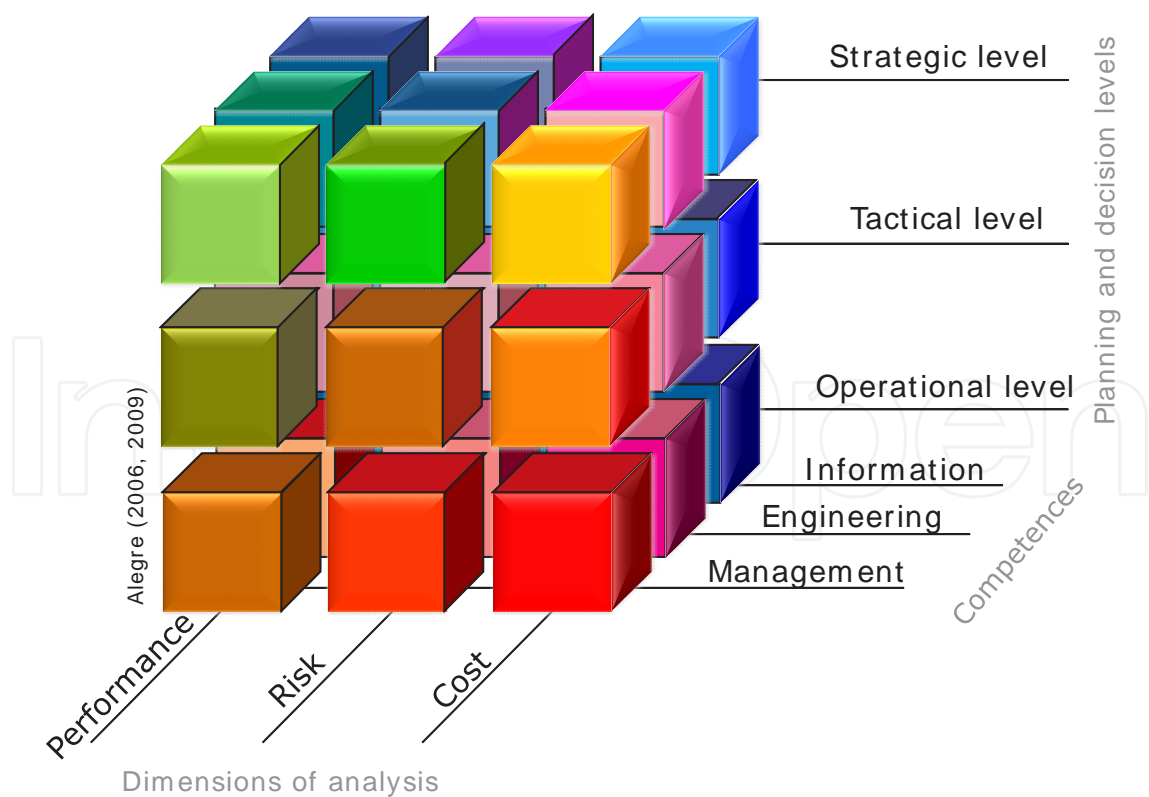
Figure 1. General IAM approach

At each level of management and planning – strategic, tactical and operational – a structured loop (Fig. 2) comprises the following stages: (i) definition of objectives and targets; (ii) diagnosis; (iii) plan production, including the identification, comparison and selection of alternative solutions; (iv) plan implementation; and (v) monitoring and review. Most utilities already have several elements of this process in place. What is often missing is a review mechanism – a way to measure compliance with set goals – as well as an effective alignment between the different management levels.

Figure 2. The planning process at each planning level

Setting up objectives, assessment criteria, metrics and targets is a crucial stage in order to set up clear directions of action, as well as accountability of results through timely review, within a given time frame (short, medium or long-term) (ISO 24510:2007, 24511:2007, 24512:2007). These metrics and targets are an essential basis for establishing the diagnosis, prioritizing intervention solutions and monitoring the results.

The process cascades through the decisional levels within the organization's management structure. The global approach is based on plan-do-check-act (PDCA) principles aiming at the continuous improvement of the IAM process. The key notions in this process are alignment among the decisional levels and their actors; bottom-up feedback; and involvement and empowerment of the entire organization, from the CEO to the asset operators, in order to promote leadership, co-ordination, collaboration, corporate culture acceptance, motivation, commitment and corporate know-how.

4. From whole-life costing to long-term analysis of indefinite life systems

Comparing intervention alternatives from the financial stand point requires that all relevant costs and revenues incurred during the asset life be taken into account. The costs in particular include such items as design and building costs, operating costs, maintenance costs, associated financing costs, depreciation, and disposal costs. Most of the reference literature on asset management recommends a whole-life costing approach (also known as life-cycle ap-

proach). However, this is not directly applicable to urban water infrastructures and other networked infrastructures that have indefinite lives and behave as systems, not as mere collections of components with independent functionality.

As argued by Burns *et al.* (1999), infrastructure assets are defined functionally as assets that are not replaced as a whole but rather are renewed piecemeal through the replacement of individual components, whilst maintaining the overall function of the system. As a whole, infrastructure system assets have indefinite lives. Conversely, economic lives can only be assigned to the individual components of an infrastructure system.

However, intervention decisions cannot be made based exclusively on the analysis of each individual asset. Individual assets cannot deliver a service by themselves, but only as part of a system or subsystem. The causes of malfunctions are often located away from where the symptoms emerge. Levels of service cannot be allocated to individual assets, for most of the infrastructure's components. Intervention alternatives, aimed at producing the desire defect, tend to imply jointly modifying a combination of assets, which display different remaining lives, values, condition, etc..

These two key features – the indefinite life of the infrastructure as a whole, and its system behavior – make the classical life-cycle approach effectively unsuitable to IAM. The objective is to ensure that the service provided meets the targets over time, keeping the risk in acceptable levels and minimizing the overall costs from a long run viewpoint.

How long is "long-term"? Long enough that interventions are given time to reach their infrastructural maturity, all the lifecycle stages of the most relevant assets are included in a meaningful way, and the investments under consideration are rewarded by their accrued benefits; but not so long into the future as to unreasonably limit the significance of the assumptions made for the scenarios considered, such as demand or land use projections.

5. Performance, risk and cost

5.1. Performance assessment

As previously mentioned, IAM aims at ensuring that, in a long-term perspective, service performance is kept adequate, risks incurred are acceptable and the corresponding costs are as low as feasible. Assessing performance, risk and cost is therefore key to effective IAM.

Performance may translate by either the efficiency or the effectiveness of the service. Performance assessment is a widespread activity used in economics, business, sports and many other walks of life in general, in order to compare and score entities and individuals and take management or other decisions (Alegre *et al*., 2000, Matos *et al*., 2003, Alegre *et al*. 2006, Cabrera &Pardo, 2008, Sjovold *et al*. eds., 2008, ISO 24510, ISO 24511, ISO 24512).

Assessment is defined as a "process, or result of this process, that compares a specified subject matter to relevant references" (ISO 24500).Performance assessment is therefore any approach that allows for the evaluation of the efficiency or the effectiveness of a process or

activity through the production of performance measures. Performance measures are the specific parameters that are used to inform the assessment. The principal categories of performance measures include (Sjovold *et al*. eds., 2008):

- Performance indicators, which are quantitative efficiency or effectiveness measures for the activity of a utility. A performance indicator consists of a value (resulting from the evaluation of the "processing rule") expressed in specific units, and a confidence grade which indicates the quality of the data represented by the indicator. Performance Indicators are typically expressed as ratios between variables; these may be commensurate (e.g. %) or non-commensurate (e.g. \$/m3). The information provided by a performance indicator is the result of a comparison (to a target value, previous values of the same indicator, or values of the same indicator from other undertakings) (Alegre *et al*. 2006; ISO 24500, Sjovold *et al*. eds., 2008).

- Performance indices, which are standardised and commensurable measures, may result from the combination of more disaggregated performance measures (e.g. weighted average of performance indicators) or from analysis tools (e.g. simulation models, statistical tools, cost efficiency methods). Sometimes they aim at aggregating several perspectives into in a single measure (Alegre, 2008, Sjovold *et al*. eds., 2008).Differently from the performance indicators, they contain a judgment in itself, intrinsic to the standardization process (e.g. 0 – no function; 1 – minimum acceptable; 2 – good; 3 – excellent).

- Performance levels, which are performance measures of a qualitative nature, expressed in discrete categories (e.g. excellent, good, fair, poor). In general they are adopted when the use of quantitative measures is not appropriate (e.g. evaluation of customer satisfaction by means of surveys) (Alegre, 2008, Sjovold *et al*. eds., 2008).

Performance indicators may be converted into performance indices through the application of a performance function, or into performance levels when they are compared with reference levels, in order to support interpretation or multi-criteria analyses. Such transformations may be particularly useful in the graphical representation of a set of performance indicators.

5.2. Risk assessment

Risk analysis may address an organization in its entirety, a system or sub-systems (aggregated or lumped analysis), or individual system components(component or discrete analysis). Risk assessment may be carried out in many different ways, and is often (though not always) quantifiable: for instance, if the probability of failure of every pipe in a network is known, as well as its consequence, expressed in terms of the ensuing reduced service (unmet demand), the total risk of not supplying the users may be expressed as the expected value of the annual unmet demand (Vitorino *et al*., 2012).

Risk analysis is a vast field of expertise where several mainstream frameworks have been developed for infrastructure-based problems, such as fault-tree analysis or the approaches centered on risk matrices (Almeida *et al*., 2010). The latter is one of the most versatile and structured formalisms available when approaching the range of (quantifiable or unquantifi-

able) risks that are faced by urban utilities, and is based on a thorough analysis of risk consequences and on the categorization into both probability and consequence classes.

Probability classes can be defined by different probability intervals that may be derived, typically, from linear, exponential or logarithmic functions. The selection of probability classes is done by the decision maker; the criteria are not only depending on the type of problem but also on the range of possibilities acceptable to the decision maker, thus related to her perception of risk. Probability and probability classes are assigned to each individual component of the system when dealing with a component-based analysis or to an area/ sector when the analysis is focused on an area with specific and known risk features.

Independently of the type of failures that may take place, they can result in a range of potential consequences not only to the water infrastructure and services but also to other infrastructures. Moreover, consequences can also include socio-economic disruptions and environmental impacts. Therefore, when assessing the risk associated with a specific event, several consequence dimensions should be taken into consideration (Table 1).

Dimension	Type of variables to express relative value in each class
Health and safety	number and severity of injuries number and severity of people affected by disease number of people affected permanently (mortality and disability)
Financial	monetary value; should be a function of the size of utility e.g. annual operating budget (AOB)
Service continuity	Duration of service interruption (availability and compliance with minimum standards); differentiation of type of client affected can be used (residential, hospital, firefighting)
Environmental impacts	Severity e.g. expressed as expected time for recovery (long-term "> y years"; mid-term "x to y years"; short-term "w to v months"; rapid recovery "less than w months") Extent (e.g. dimension of area, water quality index, volume or duration of event) Vulnerability (e.g. protected areas, abstraction areas of influence for water supply)
Functional impact on the system	Various performance measures (e.g. population/clients not supplied for a T $>D_{interruption}$; client.hours without supply); thresholds can be associated with legal requirements
Reputation and image	number of complaints; number of times the name of the utility appears in the media, …
Business continuity	damage to materials, service capacity, available human resources to maintain system function and recovery time (e.g. % capacity affected.hours)
Project development	effect on deviation of objectives (e.g. scope, schedule, budget)

Table 1. Dimensions of consequence (adapted from Almeida *et al*., 2011)

Although other classes of consequences may be adopted, a typical classification might look like this: 1 – insignificant; 2 – low; 3 – moderate; 4 – high; 5 – severe.

The way in which probability and consequence are combined reflects the degree of cautiousness of the analyst, which may vary. Fig. 3 shows a moderate risk perception matrix. A risk matrix should have at least three risk levels (low, medium and high risks) that are to be associated with the acceptance levels of risk: Low or acceptable risk (green); Medium or tolerable risk (yellow); and High or unacceptable risk (red)(Almeida *et al.*, 2010).

		Consequence				
		1	2	3	4	5
Probability	5	green	yellow	red	red	red
	4	green	yellow	yellow	red	red
	3	green	green	yellow	yellow	red
	2	green	green	green	yellow	yellow
	1	green	green	green	green	green

Figure 3. Risk matrixadopting a moderate risk perception

5.3. Cost assessment

Cost assessment is the other fundamental axis of analysis for comparing and selecting intervention alternatives in an IAM framework. All relevant costs and revenues items that take place during the analysis horizon and which differ from the *status quo*, should be accounted for, for any of the intervention alternatives considered.

The inclusion in the analysis of cost items that are common in nature and value to all alternatives is optional, as they will not have an effect on the comparison but may be useful in informing it. However, if quantifying the actual net present value or internal rate of return of a financial project is important to the exercise, then all the relevant costs and revenues must be included. In practice, it is often the case that rehabilitation interventions do not affect revenues, and mainly have an effect on system performance, on system risk(by affecting system reliability) and on capital and operational costs (e.g., repair costs, complaint management, regulatory or contractual service compliance failure).

In general and simplified terms, the main cost items include:

• Investment costs, expressed as a given amount at a given point in time, and with a given depreciation period (if not linear, a depreciation function must be known as well).

- Operational costs, normally organized in three classes: (i) Cost of goods sold; (ii) Supplies & external services; (iii) personnel; operational costs are expressed as annual values, over the analysis period.

- Revenues, either through lump sums occurring at specific points in time (e.g. public subsidies), or distributed over the analysis period (e.g. revenues from tariffs). Revenues are also expressed by their annual value over the analysis period.

Whenever relevant, the costs of planning and designing new assets, as well as disposal costs of assets that reach the end of their service lives, should be included.

Since the end of the analysis horizon does not coincide in general with the end of the service life of most assets, the residual value of all assets at the end of the analysis period must be considered.

Cost-benefit analysis may include not only direct costs and revenues, as described above, but also indirect (i.e., those that are direct costs for a third party) and intangible costs and benefits. However, practice shows that utilities often do not feel comfortable in expressing certain such costs in monetary terms (e.g., increasing public health risk because the water quality does not meet the targets). An option that is recommended by some approaches (Alegre *et al.*, 2011) and successfully implemented in a good number of utilities is to express indirect and costs as performance or risk metrics, and include only direct costs in the cost axis of the analysis.

6. Strategic, tactical and operational planning

Strategic planning needs to be grounded on the utility's vision and mission. It should be built for the entire organization, and it aims at establishing the global and long-term corporate directions.

The first stage is the definition by top management of clear objectives, assessment criteria, metrics to assess them, and finally, targets for every metric. Realistic objectives and targets require proficient knowledge of the context. In general, this is provided by the monitoring and feedback procedures in place. If a utility is preparing a strategic plan for the first time, setting up objectives requires taking into account the available context information, even if not structured and accurate.

The second stage is diagnosis, consisting of an analysis of external context (global and stakeholder-specific) and of the internal context (both organizational and infrastructure), anchored in the objectives and targets established. The context evaluation should be carried out through to the planning horizon. SWOT (strengths-weaknesses-opportunities-threats) analysis is a suitable way to express the results of this stage.

The third stage is the formulation, comparison and selection of strategies that lead to meeting the targets, given the diagnosis. The results should be expressed in a document, the stra-

tegic plan, a document that should be synthetic, clear, and effectively disseminated to all relevant internal and external stakeholders.

The implementation of the strategic plan is ensured by a suitable chain of management, where the tactical and operational planners and decision makers play key roles. Implementation should be monitored periodically (in general, annually). Strategic plans should be kept up to date, so that global and long-term directions are known and clear to the entire organization at all times. This may require reviewing and updating every 1/3 to 1/5 of the plan's horizon.

Tactical planning and decision-making should be founded on the strategies and on the strategic objectives and targets. The aim of tactical planning is to define what are the intervention alternatives to implement in the medium term (typically 3 to 5 years). IAM tactical planning is not restricted to infrastructural solutions, as it should also consider the interventions related to operations and maintenance and to other non-infrastructural solutions. Managing the infrastructure has close interdependencies with the management of other assets: human resources, information assets, financial assets, intangible assets. The IAM plan needs to address the non-infrastructural solutions that are critical for meeting the targets and are related to these other types on assets, e.g., investing in a better work orders data system.

The key stages of tactical planning are similar to those described for strategic planning. The objectives, metrics and targets need to be coherent and aligned with the strategic level. Metrics should address all three dimensions of performance, risk and cost.

The diagnosis should be carried out based on the metrics selected, for the present situation and for the planning horizon. Due to the system behavior of the water infrastructures, there is the need to adopt a progressive system-based screening progress, aimed at identifying the most problematic areas. In general, the water systems under analysis should be divided into sub-systems, and the metrics assessed for each of them. The most problematic are captured and analyzed in more detail. For those that do not display significant overall problems, there is the need to confirm that they do not have relevant localized problems. If they do, these localized areas need to be retained as well for detailed analysis. This screening process leads to the identification of priority areas of intervention. For these, the diagnosis needs to be more detailed in order for the causes of the problems to be properly understood. The screening process may not apply to non-infrastructural interventions affecting the entire organization (e.g. organizational changes, IT and information system upgrades).

The next stage is actually producing the plan, and is one of the most work-intensive as it encompasses the demanding engineering processes involved in identifying and developing feasible intervention alternatives for each of the subsystems, and the assessment of their responses over the analysis horizon for the metrics selected. For each subsystem, the intervention alternatives need to be compared, and that alternative which best balances the set of metrics for the chosen objectives, over the long-term, will be selected. The set of best interventions alternatives, compatible with the financial resources that can be mobilized and

with the planning horizon, will be included in the tactical plan. The plan must make allowance for the resources needed to implement it.

The detailed diagnosis and the design and analysis of infrastructural and operational intervention alternatives are not trivial tasks and often require the use of sophisticated modeling tools. This is where the more advanced research efforts have been centered, such as mentioned in section 2 (e.g. Skipworth *et al.*, 2002; Sægrov ed., 2005; Sægrov ed., 2006; Malm *et al.*, 2012; Renaud *et al.*, 2011; Alegre and Almeida ed., 2009).

The last stages of tactical planning are the implementation, monitoring and periodic review of the plan. Implementation is materialized via operational management. Monitoring and reviewing are critical for the continuous improvement process. It is recommended that the tactical plan defines their modes, responsibilities and periodicity. Operational IAM planning aims at implementing the interventions selected in the tactical level.

7. Long-term balanced design - carrying urban water systems into the future

As explained before, the performance of individual components is only relevant inasmuch as it contributes to system performance. Some components will have more impact on the system than others, and the behavior of such systems is usually quite complex, giving rise in the last decades to a whole field of expertise devoted to developing and using network analysis models, among the most advanced and useful tools in engineering.

From the viewpoint of infrastructure asset management, the notions of "system design", "preventive maintenance" and "system rehabilitation" should be seen fundamentally as part of the same long-term balanced design process.

Even in those parts of the world where service coverage has reached its effective limit, and designing new systems or system extensions appears to be a thing of the past, it must be realized that design skills and experience are just as needed in carrying present-day systems into the future as they once were in creating the first outlines.

Essentially, investing in a system over a period of time should maximize the performance-risk-cost balance while transforming the system into its ideal for the next 20 or 30 years: that which best serves the strategic objectives defined for the infrastructure as a whole, as explained previously.

If at a strategic IAM level it is common to try to balance conflicting objectives (e.g., improving the environmental sustainability and reducing costs to ensure economic sustainability), at the tactical and operational level, which must be aligned with the former, that is also the nature of the problem: e.g., water supply reliability is commonly achieved through pipeline redundancy, which often causes reduced flow velocities and potentiates water quality issues.

On the other hand, analyzing over long periods of time must account for what is usually a changing context: societal values and expectations evolve; regulations become more demanding; technologies improve; urban areas progress; the climate and the environment fluctuate and change; natural resources become scarcer.

The current emphasis on water-energy efficiency is driven by most of the above factors of change. However, old paradigms are broadly accepted without being questioned. For instance, drinking water networks are still designed in most developed countries to respond to fire flows. Is this the most rational approach? In the Netherlands, for instance, this paradigm is changing. Smaller diameter networks are not only less expensive but also generally behave better in terms of water quality. Firefighting is ensured from a basic trunk main grid. If paradigm shifts occur, rehabilitation interventions need to take them into account.

The fact that most water systems are far from ideal today is a consequence of a growth process that has been forced to react to that changing context over the decades. Most mature systems today are not exactly what they would be if we were to start with a clean slate. Yet, it is common to see preventive maintenance or rehabilitation strategies centered on replacing the pipes with a higher risk of failure with new pipes of the same size. Would it not make sense to try to project the best possible system for a given time horizon – 20, 30 years – and use those very same opportunities of intervention to make the present day system gradually morph into that better design?

The fact is that there are many cases when the water networks are adequately and efficiently designed and operated, meeting the hydraulic, water quality and energy targets for the present and for the expected future demands. In these cases, the key driver for rehabilitation is indeed the risk of pipe failure, usually assessed through the combination of failure probability and component importance (in terms of the consequence its failure). Much of the leading-edge theory and practice is tailored for these situations, where the like-for-like replacement strategy fits well.

In classical terms, infrastructures used to be seen as living through a sequence of stages, from the initial design, through constructing new (or extending), operating, maintaining and rehabilitating or replacing by new again. This is indeed the typical AM approach for other types of physical assets. In mature infrastructures, however, all these stages co-exist, and designing new, extending, maintaining or rehabilitating are fundamentally parts of the same process.

The IAM framework introduced in sections 3 to 6induces essentially one approach to the problem, illustrated in Fig. 4 in very simple terms. IAM planning starts from an existing infrastructure and aims at optimizing its behavior over the analysis period, enabling a progressive improvement of the infrastructure condition and functional response. In well-maintained mature infrastructures, this requires that the fair value at the end of the planning horizon is not lower than the initial value.
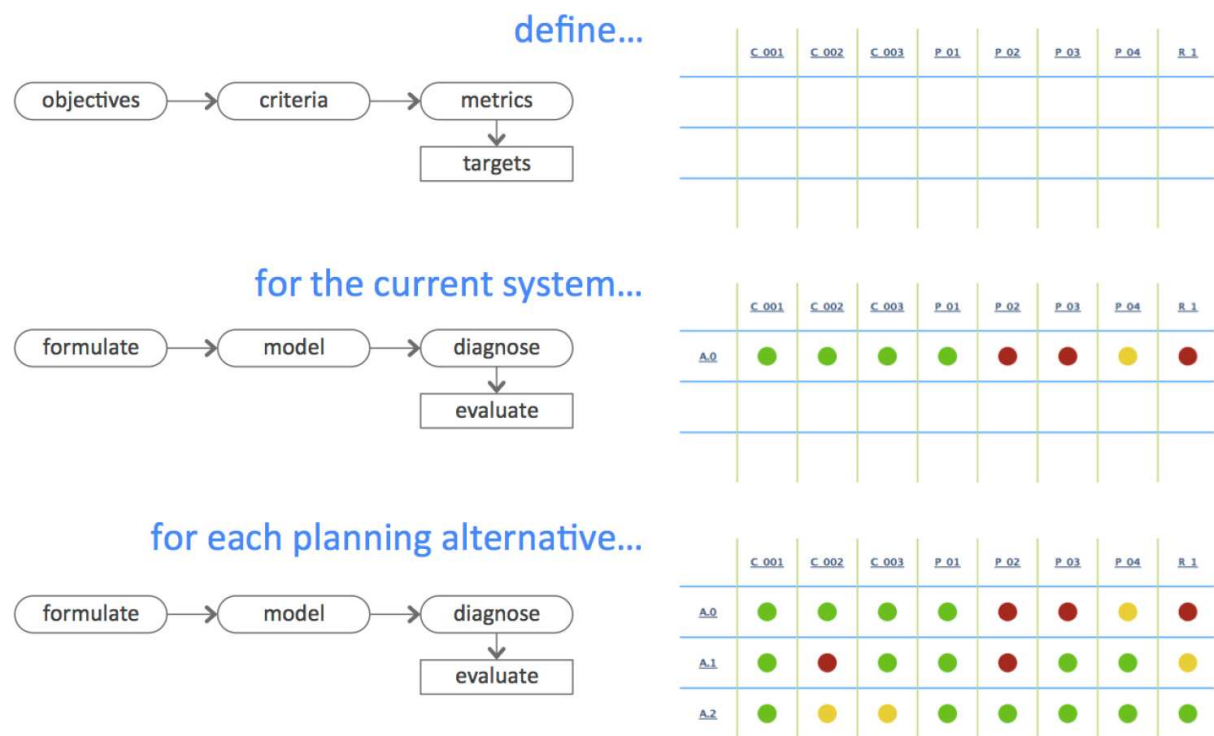
Figure 4. The long-term balanced design planning process

The drawing board on the right-hand side is initially marked out by the green vertical lines, representing the metrics for the criteria chosen to drive the analysis. A thorough diagnosis and assessment of the current system according to those metrics is carried out (represented by the first blue horizontal at the top).

The planning board is then successively populated with the best available planning alternatives (represented by the subsequent blue lines). The intersections represent the assessment of each planning alternative for each metric. The purpose of the process is to fill out the table to the extent possible.

8. Examples from the industry

8.1. Strategic planning in a midsize utility

The vast majority of water utilities in the world serve populations of less than 100 000. Most midsize utilities have room for significant improvement in terms of infrastructure asset management. This specific example arises from Portugal, where the water services regulator enforces a national system for quality of service assessment, and concerns a midsize utility in a developed urban area (more detail can be found in Marques *et al.*, 2012). Service coverage is no longer an issue, but the assets are aging, and the service is not as financially and environmentally efficient as desirable. Quality of service, transparency in investment prioritization and environmental sustainability are the key IAM drivers for the managers.

The utility adopted the objectives and assessment criteria of the regulatory system, as they were deemed adequate for their own internal strategic purposes. Operating exclusively as a retail services utility, they selected the applicable metrics and targets from the regulatory system (Table 2). Each metric is clearly defined, with units, definition, assessment rule and specification of the input variables.

Taking these objectives into account, a SWOT analysis was carried out (Table 3).

Objectives and criteria	Metrics
1. Adequacy of the service provided	
1.1 Service accessibility	Physical accessibility of the service (WS, WW)
	*Economical accessibility of the service (WS, WW)
1.2. Quality of service provided to users	*Service interruptions (WS)
	*Quality of supplied water (WS)
	*Reply to written suggestions and complaints (WS, WW)
	*Flooding occurrences (WW)
2. Sustainability of the service provision	
2.1. Economic sustainability	*Cost coverage ratio (WS, WW)
	Connection to the system (WS, WW)
	*Non-revenue water (WS)
2.2. Infrastructural sustainability	*Adequacy of treatment capacity (WS)
	*Mains rehabilitation (WS)
	*Mains failures (WS)
	*Sewerage rehabilitation (WW)
	*Sewer collapses (WW)
2.3. Physical productivity of human resources	*Adequacy of human resources (WS, WW)
3. Environmental sustainability	
3.1. Efficiency of use of environmental resources	*Energy efficiency of pumping installations (WS, WW)
3.2. Efficiency in pollution prevention	Sludge disposal from the treatment plants (WS, WW)
	*Adequate collected wastewater disposal (WW)
	* Emergency overflow discharges control (WW)
	Wastewater quality tests carried out (WW)
	Compliance with discharge parameters (WW)

WS: water supply services; WW: wastewater services; *adopted by the utility to assess the strategic objectives.

Table 2. Objectives, assessment criteria and metrics of the Portuguese regulatory system

STRENGTHS	WEAKNESSES
- Good information systems on the water supply infrastructures	- Insufficient information systems on wastewater infrastructures
- Sufficient information to assess the water supply systems condition and performance	- Financial restrictions
	- Inadequate tariffs
- Strong competence of human resources	- Poor structural infrastructure condition
- Relation between information systems and work orders	- Poor functional infrastructure performance
	- Insufficient historical records
	- Inadequate quality of data

OPPORTUNITIES	THREATS
- Equipment and technologies available to support IAM	- Portuguese legislation and regulation by ERSAR* (increase in costs)
- Portuguese regulation by ERSAR *	- Political uncertainties
- Portuguese legislation related with IAM	- Economic crisis and financial restrictions
- Incentives for sustainable use of energy	- Demographic development uncertainties
	- Illegal cross connections in wastewater systems

* ERSAR: the water and waste services regulator in Portugal

Table 3. SWOT analysis summary

The SWOT analysis results led to the establishment of strategies. For drinking water, the key selected strategies were *Controlwater losses* and *Promote proactive rehabilitation practices*, whereas for wastewater the strategies established were *Reduce untreated wastewater discharges* and *Reduce cross connections and infiltration/inflow in wastewater systems*. The common strategies of both types of services were *Improve infrastructure information systems* and *Increase system reliability*.

8.2. Tactical planning in a midsize utility

Let us put ourselves now in the position of a middle manager of the same utility, in charge of infrastructure planning and rehabilitation for the water supply system. Let us take as an example the strategic objective *Improve the efficiency of use of environmental resources (water and energy)*, as listed in (see criterion 3.1). The utility's networks display undesirable failure rates (pipe breaks) and the energy bill for pumping is higher than would appear reasonable; the network has unflattering water losses and localized pressure problems during peak consumption hours remain.

- How would we act?

- How would we prove that our decisions are effectively addressing the strategic objective?

- How would we quantify the impact of our decisions and of subsequent actions?

In traditional AM practice, we would probably start by gathering an updated and reliable inventory of the existing assets and by compiling as many reliable records as possible of their condition and failure history. We would try to identify the locations where there are pressure problems, and we would also look at pump efficiency and energy consumption. We would probably try to assess the relative importance of each asset. Combining these types of information, we would prioritize interventions within our budget constraints.

This would contribute to answering the first question. What could be done about the other two? Fixing pumps and replacing some pipes will undoubtedly contribute to saving water and energy. But would that maximize the utility of the investment made? A discerning board might be less than satisfied; and the third question would still remain unanswered. They might ask some additional questions:

- Have we satisfactorily dealt with the hydraulic problems? Were we able to allocate levels of service to each individual asset when dealing with pressures and water losses?

- How did we select the sizes and materials of the new pipes?

- Did we assume that the existing network's configurations (e.g., layout and diameters of networks, location and characteristics of storage tanks and pumping stations) are adequate from the energy point of view?

These are the types of issues that a good IAM approach should aim to tackle in a structured, aligned and transparent way. As a basis for tactical planning, this utility took the strategic directions previously defined: objectives, targets and strategies. The following tactical IAM objectives were set:

- Increase system reliability in normal and contingency conditions (see criterion 1.2, Table 2);

- Ensure economic sustainability (see criterion 2.1, Table 2);

- Ensure the infrastructural sustainability of the system (see criterion 2.2, Table 2);

- Decrease water losses (see criterion 3.1, Table 2).

At a first stage of tactical planning, the network was evaluated coarsely in its main subdivisions: trunk main system and supply subsystems (DMAs, or District Metering Areas). The prioritisation of DMAs with higher intervention needs was based on the assessment of the selected metrics for all DMAs, not only for the current situation, but also by assessing the response of the existing systems to the predicted evolution of external factors (e.g., demands, regulation, funding opportunities, economics).

DMA 542 was in this high priority group, since it failed to comply with most tactical targets. It supplies a stable and heterogeneous urban area, comprising new and old residential buildings, schools, shops and some commercial areas. It supplies approximately 10,000 people (4,388 contracts) with a network of approximately 12.5 km of total pipe length, 40% of which in asbestos cement and the remainder in more recent plastic materials. Water is supplied by gravity from a service tank at elevation 185 m, and the lowest ground elevation is 107 m.

The tactical plan was designed for a 5-year planning horizon (2011-2016). Any envisaged interventions will have to be scheduled over this period. However, the evaluation was carried out over a 20-year analysis horizon in order to ensure that the interventions planned are the best compromise both in the medium-and in the long-term (Alegre *et al.*, 2011). The available investment budget for this DMA allows for the replacement of approximately 1 km of pipeline per year, for 5 years. Reference assessment timesteps were considered at years 0, 1, 2, 3, 4, 5, 10, 15 and 20 (i.e., 2011 to 2031).

Since this example involves only alternatives related to physical intervention in the infrastructure, compliance with the above-mentioned tactical IAM objectives was assessed through the following performance, risk and cost metrics:

- **Inv**: *investment cost*, measured through the net present value at year 0 of the investments made during the 5-year plan.

- **IVI**: *infrastructure value index (IVI*, the ratio between the current value and the replacement value of the infrastructure (Alegre and Covas, 2010); it should ideally be close to 0.5.

- **P_{min}**: *minimum pressure under normal operation index*, measuring compliance with the minimum pressure requirements at the demand locations.

- **P_{min}***: *minimum pressure under contingency conditions index*, measuring compliance with the minimum pressure requirements at the demand locations when the normal supply source point to this DMA fails and an alternative entry point is activated.

- **AC**: *percentage of total pipe length in asbestos cement*; although this metric may seem unconventional as a performance indicator, it was selected as a proxy for system resilience, reliability and ease of maintenance (or the lack thereof), given the poor track record of the aging asbestos cement pipes in this utility.

- **RL**: *real losses per connection*, as defined in the IWA performance indicator system (Alegre *et al.*, 2006).

- **UnmetQ**: *risk of service interruption*. This reduced service metric is given by the expected value of unmet demand over 1-year period. The risk of service interruption associated to a specific pipe depends on the likelihood of its failure and on its consequence on the actual service. This risk is calculated for each pipe as a combination of failure probability and component importance.

The values of the metrics were further divided into 3 ranges (good, fair and poor) according to the thresholds set by the utility, based on the experience of their key staff (Table 4).

The diagnosis of the situation at year 0 using the assessment metrics and associated reference values pointed to the following problems:

- *Reliability of the system:* insufficient pressure in normal conditions at some locations; high pipe failure rates; low system resilience in contingency operation conditions.

- *Infrastructural sustainability:* poor condition (high failure rates) of asbestos cement pipes.

- *Water losses:* high leakage levels.

	Good (green)	Fair (yellow)	Poor (red)
Inv (cost units)	[0, 350[	[350, 450[	[450, ∞[
IVI (-)	]0.45, 0.55[	[0.30, 0.45[; [0.55, 0.70[	[0, 0.30]; [0.70, 1]
Pmin (-)	[3, 2[	[2, 1[	[1, 0]
Pmin* (-)	[3, 2[	[2, 1[	[1, 0]
AC (%)	[0, 9[	[9, 15[	[15, 100]
RL (l connection^{-1} day^{-1})	[0, 100[	[100, 150[	[150, ∞[
UnmetQ (m^3/year)	[0, 20[	[20, 30[	[30, 100]

Table 4. Multi-criteria reference values

Several system-driven solutions and like-for-like replacement solutions, within the available budget, were analysed (Marques *et al.*, 2011) and designed to solve or mitigate the problems identified in the diagnosis, both in-house and through external consultants. The final set of alternative solutions were summarized as follows (including retaining the *status quo*):

- **Alternative A0** (*status quo*, or base case): corresponds to keeping the existing network as it is, and retaining the current reactive capital maintenance policy (which in the present case was based on repairs after break only).

- **Alternative A1** (*like-for-like replacement*): an IAM project consisting of a prioritized list of pipes to be replaced by the same-diameter HDPE pipes. The prioritized list was developed externally to the AWARE-P software, following a like-for-like replacement strategy, using pipe failure and consequence analysis (as in FAIL/CIMP) and an ELECTRE TRI decisional method, and taking into consideration 3rd-party coordination.

- **Alternative A2** (*system-driven solution*): an IAM project based on an *ideal* redesign for the network, as if it were built from scratch for the present-day context – significantly different from the actual current network, which was designed and constructed from the 1940s onwards. This ideal redesign, heavily backed by network modelling, driven by performance and risk assessments, is viewed by the utility as a future target reference, to be gradually reached by incrementally changing individual pipes as they are replaced, and by making some key layout modifications. It addresses the same pipes targeted in A1, but replaces them with new pipes of optimal diameter (often smaller, as the original network has overcapacity in places); in Year 5, a new 625 m-long pipeline connecting to a neighbouring DMA is introduced in order to improve reliability of supply in emergency situations.

The assessment of the three alternatives was carried out for the 5-year planning horizon and for a 20-year analysis horizon.Table 5 illustrates the results of the selected metrics for the three alternatives at Year 5. Fig. 5shows snapshots of the 3D view of results, with time, assessment metrics, and alternatives depicted respectively along the left, right and vertical axes. The majority of the assessment metrics are constant after year 5 (with the exception of IVI and UnmetQ), due to the adoption of a constant demand scenario (this is a very stable resi-

dential area),and to having assumed negligible growth of O&M costs. In this case, the comparison and selection of alternatives can be based on the assessment for Year 5.

Alternatives	Assessment metrics						
	Inv (c.u.)	IVI (-)	Pmin(-)	Pmin * (-)	AC (%)	RL (l conn⁻¹ day⁻¹)	UnmetQ (m³/year)
A0	0	0.47	2.88	0.00	37.2	116	36
A1	274	0.73	2.88	0.00	1.5	52	22
A4	350	0.70	2.99	2.99	8.5	54	18

Table 5. Case study: results obtained from the evaluation of three alternatives at year 5

(a) All 3 alternatives

(b) Alternative

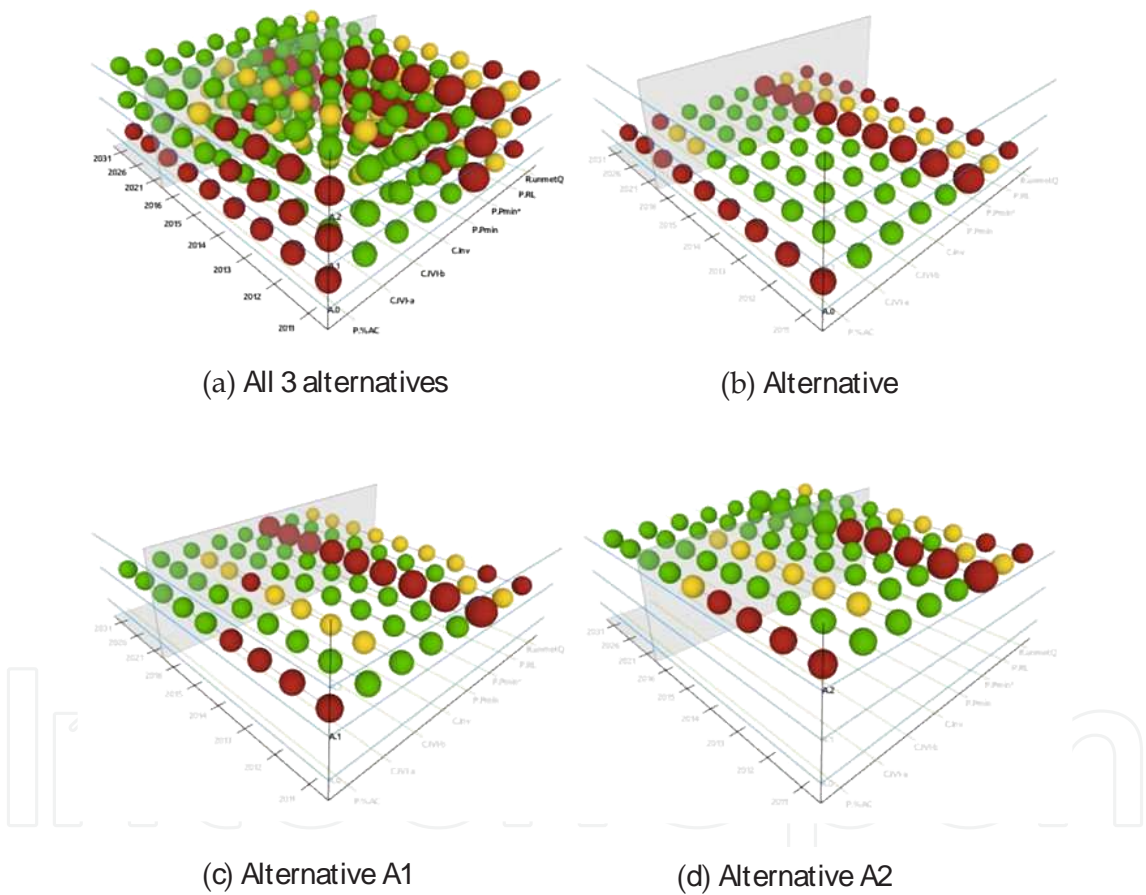(c) Alternative A1

(d) Alternative A2

Figure 5. Metric results expressed as a 3D *cube*; left axis: time; right axis: metrics; vertical axis: alternatives.

Experience shows that it is often less costly simply to repair pipes and pay for the water lost in leakage than to invest in the rehabilitation of the system. This was confirmed here by looking at alternative A0 at year 5. However, for the remainder of the analysis period (yrs. 6-20) the problems identified in the diagnosis become increasingly evident, through poorer network reliability and moderate water losses that tend to intensify due to normal wear.

The results for A1 show that it is generally better than A0 is terms of infrastructural sustainability, water losses and risk (IVI, AC and UnmetQ). Investment is of course higher than in A0, but within the available budget. However, A1 perpetuates the design deficiencies inherent to the existing system (A0).

Alternative A2 aims at realistically and progressively bring the existing network to a configuration closer to the ideal. Its resilience is improved when compared to A0 and A1, as it reinforces the options for supplying the network from an alternative supply point. Investment costs are higher than for A1 (350 vs. 274cost units). The percentage of asbestos cement pipes is also significantly reduced (to 8.5%, from 37% for A0). This alternative displays the best all-round long-term balance of performance, risk and cost, as expressed by metrics that reflect the tactical objectives, in full alignment with the utility's strategic objectives.

8.3. Benefits of using a structured IAM approach in the example utility

The adoption of a structured IAM approach in the utility illustrated by this example provided proficient answers to all the questions initially formulated:

- Using a coherent and aligned system of objectives, metrics and metrics enables the IAM manager to show that the decisions are effectively addressing the strategic objectives, and to quantify their impact.

- The hydraulic problems were duly taken into account by splitting the whole system into subsystems and analysing in more detail, including in hydraulic terms, the most problematic ones.

- The selection of sizes and materials for the new pipes was driven by the ability of the existing network in meeting current and future needs and in minimizing energy consumption.

9. Concluding remarks

Infrastructure asset management of urban water infrastructures will be increasingly critical in the coming decades. In industrialized countries, particularly those affected by World War II, the heavy investments in new systems carried out in the 1950's, 1960's and 1970's are aging fast, partly due to inadequate or deferred capital maintenance. This places an additional demand for efficiency in planning for the future. In developing regions, the shortage of financial and technical resources further add to the need for their well-judged, efficient use in a long-term perspective.

With the current lack of planning and capital maintenance, the services that are taken for granted in many societies are placed into an increased risk of failure, at least from the viewpoint of the levels of service currently provided.

Regardless of their size, complexity and level of maturity or development, water utilities need to implement structured IAM approaches that may ensure the sustainable manage-

ment of their systems. There are some key recommendations to be taken into account when implementing an IAM program:

- IAM is all about people – successful implementation requires:

- IAM is not implemented overnight. It is an incremental, step by step process that must be kept as simple as possible with a long-term view. The structured approach recommended in this chapter aims at identifying intervention priorities, including new organizational procedures, data management and decision making processes.

- Reliable data are the foundation of successful IAM. Before investing on new data collection, it is vital to get the most out of the existing data, through proficient recycling, quality control, analysis and interpretation.

- As superfluous as the statement may seem, IAM is not solved or even set in motion by acquiring a software application.

- IAM is an internal process in a utility. Although external expert advice is valuable, it should be seen as a contribution to an internally driven effort, e.g., in capacity building or to sort out specific technical issues problems, such as when engineering consultancy is brought in to develop and advise on infrastructural alternatives to solve given issues. IAM should not be outsourced.

- Water utilities have many common problems and difficulties. Sharingthem, and any solutions, among peers has always proved to be enriching, effective and highly motivational.

- Make it happen – start today!

Author details

Helena Alegre and Sérgio T. Coelho

LNEC - National Civil Engineering Laboratory, Lisbon, Portugal

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