Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 89 (2014) 1428 – 1436
Procedia Engineering
www.elsevier.com/locate/procedia

Infrastructure Value Index: A Powerful Modelling Tool for Combined Long-Term Planning of Linear and Vertical Assets

H. Alegre[a,]*, D. Vitorino[b], S. Coelho[a]

[a]National Laboratory for Civil Engineering, Lisbon, (Portugal)
[b]Addition, Lisbon (Portugal)

Abstract

Strategic asset management of urban water infrastructures jointly deals with assets of diverse nature, useful life, cost, age and condition. Service sustainability requires a sound long-term planning, which needs assessing, among other aspects: the value of the infrastructure over time; the need for reinvestments; the impact of long-term re-investment policies. The infrastructure value index (IVI) was proven to be a powerful modelling tool for combined long-term planning of linear and vertical assets. An open-source software enables IVI assessment for both asset-by-asset detailed inventory and for simplified cohort-based infrastructure description. This paper presents the formulation, discusses the underlying assumptions and applicability, and illustrates its use for strategic planning

Peer-review under responsibility of the Organizing Committee of WDSA 2014
Keywords: Long-term planning, asset management, vertical and linear assets, rehabilitation, investment planning

1. Introduction

Strategic asset management (AM) of urban water infrastructures faces the challenge of dealing with assets of very different nature, useful life and cost. Typically, utility managers inherit infrastructures with assets in diverse conditions and stages of their life cycle, some of them linear and buried (e.g., pipe networks), some above ground (e.g., treatment plants, pumping stations, storage structures — in some countries known as *vertical* assets). They are expected to manage their value in order to ensure a service of adequate quality, and make sure that what they pass on to their successors is capable of continuing to do so. Due to the indefinite life of an urban water infrastructure as a whole, a classical life cycle approach is not directly applicable – only to individual assets. Instead, long-term planning is

* Corresponding author. Tel.: +0-351-218443626
E-mail address: halegre@lnec.pt

Peer-review under responsibility of the Organizing Committee of WDSA 2014
doi:10.1016/j.proeng.2014.11.469

needed, embedding the life cycle of the individual assets without losing sight of sustained and sustainable service provision. Both AM of linear assets and of vertical assets have been the focus of R&D, technological evolution and enhanced practices. However, dealing with the indefinite life of the infrastructures and with the integration of linear and vertical assets in a combined and coherent long-term planning approach is still a major challenge — joint consideration of both types of assets is particularly challenging when prioritizing investments or assessing their long-term impacts.

The infrastructure value index (IVI), proposed by Alegre [1] and broadly explored in recent years in various R&D and industry projects (b), [3], [4]), was proven to be a powerful modelling tool for combined long-term planning of linear and vertical assets. IVI is the ratio between the current value of an infrastructure and its replacement cost, and may conceptually be assessed in several different ways, discussed in this paper.

The paper presents the IVI formulation, discusses the underlying assumptions and applicability and illustrates its use for strategic planning. Several alternative ways of assessing IVI are also presented and discussed.

2. Concept and basic formulation

The Infrastructure Value Index, in its essence, is the ratio between the current (fair) value of an infrastructure and the replacement cost on modern equivalent asset basis [1], as stated in (1):

$$\text{Infrastructure Value Index (\%)} = \frac{\text{Infrastructure Current (fair) Value}}{\text{Infrastructure Replacement Cost}} \tag{1}$$

If all assets of a given infrastructure had the same replacement cost and the same useful life, IVI would represent the residual life (%), i.e. [1- (average age/useful life)] %. In a real-life infrastructure, IVI can be seen as a weighted average of the residual lives (%) of the infrastructure components, where the weights are the component replacement costs. IVI is always referred to a date (year), as a snapshot.

The Infrastructure Current Value would be, in a competitive market activity, its market value. In a monopolistic activity, as in urban water services, alternative valuation approaches must be adopted. One possibility might be the use of the accounting value. However, this option is not recommended for multiple reasons, as discussed in 3.1.

The Infrastructure Replacement Cost is the expected cost of a modern equivalent if the infrastructure were built at the year IVI refers to.

IVI can be assessed in many different ways, derived from two main families:

(i) Asset-oriented: Calculation is based on the useful life of each asset, on depreciation curves and on replacement costs for each category of assets;
(ii) Service-oriented: Calculation is based on the performance of functional units of the infrastructure.

An asset-oriented procedure may be adopted for ease of calculation, whenever it is valid to assume that the global design of the existing infrastructure (e.g., network layout, location of tanks, pumping stations and treatment plants) is mostly the same in its modern equivalent. Otherwise, a service-oriented procedure is best preferred.

Whenever an asset-oriented strategy is applied, IVI may be determined considering the individual contribution of each asset (2).

$$IVI(t) = \frac{\sum_{i=1}^{N} \left(rc_{i,t} \cdot rul_{i,t} / eul_i \right)}{\sum_{i=1}^{N} rc_{i,t}} \tag{2}$$

where: t : reference time; $IVI(t)$: Infrastructure Value Index at time t; N : Total number of assets; $rc_{i,t}$: replacement cost of asset i at time t ; $rul_{i,t}$: residual useful life of asset i at time t; eul_i : expected useful life of asset i.

The underlying assumptions of this formulation are that the following variables are known:

- ***Asset replacement costs*** (*rc*) based on reference mean values. Time specific market fluctuations shall be smoothed or eliminated; the use of unit cost functions for each type of asset is recommended (e.g., a unit cost function for small, medium or large diameter pipes base on replaced length; for pumps, a function based on installed power; for sewers, a function based on class of diameter and class of depth);
- ***Residual asset useful lives*** (*rul*). In general, installation date and a linear depreciation are adopted;
- ***Expected asset useful lives*** (*eul*) based on the actual experience and information, and not on the accounting / fiscal depreciation periods.

The quality of reference unit costs, asset condition data and technical useful life predictions is determinant to the quality of IVI results for decision-making. In general, utility managers are able to provide estimates for these variables at an accuracy level that is sufficiently informative to support long term planning. However these underlying assumptions have implications and constraints, as discussed in 3.1.

3. Assessing IVI

3.1. Basic asset-oriented formulation

IVI in a given year can be assessed as follows:

(i) Select a reference year and adopt constant costs;
(ii) Establish unit replacement costs for each cohort of assets; Table 1 shows an example of cost functions for the most current types of assets in water supply systems, extracted from [5] and derived for construction costs in Portugal (reference year: 2013);
(iii) Assess the replacement costs of each asset or cohort of assets, based on the unit function costs and on the corresponding quantities;
(iv) Assess the total Infrastructure Replacement Cost as the sum of every individual value obtained in (iii);
(v) Establish the expected useful lives based on the best rationale available (e.g. Delphi method among operations and maintenance utility professionals);
(vi) Correct (i.e., decrease or increase, regarding the installation age) the current useful life of each asset or cohort, if sound information about condition exists and justifies; corrections may reflect condition / reliability of the asset, but may also reflect technologic or capacity adequacy to the function;
(vii) Assess the value of each asset: multiply its replacement (modern equivalent, whether applied) cost by its residual life (corrected or not); sum for all assets to obtain the Infrastructure Current Value. The use of depreciated accounting asset values is not recommended;
(viii) Assess IVI as the ratio between the values obtained in (vii) and (iv) as stated in (1) and (2).

This approach has the following main underlying assumptions:

a) Water supply and wastewater management and storm water management being monopolistic activities, a market value cannot be adopted for the current value; the revenues generated by an infrastructure do not reflect its condition or reliability; the revenues generated by individual assets of a network system cannot be assessed because the asset cannot provide any service by itself: only as part of the system.
This assumption requires that other forms of asset valuation are adopted. From a financial and fiscal view, the acquisition value and depreciated value matter. The operational view looks at service value. The risk management view tracks insurance value. The easiest way to obtain a current infrastructure value that is meaningful to support long term reinvestment planning is to assess the current value of each asset as a proportion of the replacement cost, based on (1- *expected residual life / expected useful life)*.

Table 1. Examples of cost functions [7]

Asset	Cost Function (in 2013)	Key parameters
Ground	$C_{CW} = 3778.3\ V^{-0.409}$ ($R^2 = 0.6568$)	Total volume, V (m3)
storage tanks	$C_E = 12818\ V^{-0.728}$ ($R^2 = 0.7418$)	
	$C_T = 10713\ V^{-0.510}$ ($R^2 = 0.7448$)	
Elevated	$C_{CW} = 6003\ V^{0.630}$ ($R^2 = 1$), for h = 15 m	Total volume, V (m3)
tanks	$C_{CW} = 14142\ V^{0.511}$ ($R^2 = 1$), for h = 20 m	Tank height, h (m)
	$C_{CW} = 26100\ V^{0.430}$ ($R^2 = 1$), for h = 25 m	
	$C_E = 497.26\ V^{0.875}$ ($R^2 = 0.8913$)	
	$C_T = 5745{,}7\ V^{0.688}$ ($R^2 = 1$), for h = 15 m	
	$C_T = 11896\ V^{0.585}$ ($R^2 = 0.9999$), for h = 20 m	
	$C_T = 20704\ V^{0.509}$ ($R^2 = 0.9998$), for h = 25 m	
Pumping	$C_{CW} = 18444\ P^{-0.607}$ ($R^2 = 0.8768$)	Pump power, P (kW)
stations	$C_E = 38678\ P^{-0.620}$ ($R^2 = 0.8258$)	
	$C_T = 62920\ P^{-0.654}$ ($R^2 = 0.8779$)	
Pipes	$C_{DI} = 53.616\ e^{0.0028\,D}$ ($R^2 = 0.5095$)	Unit cost per m, C (€/m) (2013)
	$C_{HDPE\ NP10} = 0.0008\ D^2 + 0.0156\ D + 20$ ($R^2 = 0.5556$)	Nominal diameter, D (mm)
	$C_{HDPE\ NP16} = 0.0008\ D^2 + 0.3149\ D + 20$ ($R^2 = 0.1508$)	
	$C_{Steel} = 1\ e^{-0.6}\ D^{2.9387}\ 20$ ($R^2 = 0.307$)	
	Unit cost per m.C (€/m (2013)	

Note: Civil works cost, C_{CW} (€/m^3 for tanks and €/kW for pumping stations) (2013); Equipment cost, C_E (€/m^3 for tanks and €/kW for pumping stations) (2013); Total cost, C_T (€/m^3 for tanks and €/kW for pumping stations)

b) In the framework of long-term planning and assessment of IVI, formulation (vii) above is more robust and meaningful than the depreciated accounting values.
Accounting values often do not represent the fair value of an asset, for multiple reasons, such as: (a) It is frequent that the utilities received assets from real estate developers at cost 0. Some utilities integrate this information in their accounting systems at market median costs, but often they are integrated at cost 0. (b) Similar situations may occur whenever there are subsidies to investment; (c) Actual cost is often influenced by time-specific context factors that should be smoothed or eliminated in long-term analysis and planning; (d) Often the accounting system does not have the same level of information disaggregation as asset inventory tailored to assist long-term planning.

c) The value of the infrastructure may be fairly estimated by the sum of the values of its individual assets.
Sometimes the current ideal design of an infrastructure considerably differs from the existing one. If the differences are limited to the replacement of an asset by its modern equivalent, this underlying assumption is valid. Only when there are major differences in the global design, e.g., in the layout of the networks, should an aggregated IVI assessment be adopted instead.

d) Technical useful lives can be provided as input for every type of asset.
The end of life of an asset depends naturally on its adequacy for purpose, which has a significant level of subjectivity to determine. Statistical analysis of past practices is not sufficient to infer on future practices or acceptance criteria. In general, asset failures are repairable, not necessarily defining the end of the asset life. For all these reasons, sophisticated statistical algorithms to assess useful lives are not necessarily more accurate then informed guesses from experienced people. The latter approach has been used in the past implementations of IVI, either using a single value or a range (e.g. 50-60 years).

e) Depreciation of the assets is linear.
Many treatment plants, pump stations and other facilities, equipment and networks present a bath-shaped curve in terms of failure rate: a higher frequency in the first years, due to manufacture or installation defects, a steady period, and a final period where the the asset is rather deteriorated and expected failure rate increases up to an

unacceptable level. This argument is commonly used to justify that linear depreciation may not be adequate to urban water assets. However: (i) a bath curve of failure rate does not necessary lead to a bath curve depreciation rate; (ii) sufficient and reliable data rarely exist to justify the use of a specific non-linear depreciation of the asset; (iii) a clear and transparent simplification is better than a just apparent, not well grounded, sophistication. For these reasons, linear depreciation is recommended, unless specific and well justified reasons exist.

f) Default useful life, i.e., prior to any correction, is given by the difference between the year IVI refers to and the asset installation date; in the case of rehabilitated structures, this may require specific assumptions. Rehabilitation includes replacement, renovation and reinforcement. In the cases of renovation and reinforcement, the reinvestment level may be different from the replacement cost and residual life after renovation may be different from the expected life of a new asset. Whenever relevant, IVI calculation may consider these two situations.

3.2. Basic service-oriented formulation

Existing industry implementations of IVI [6] adopted the asset-oriented approach. Exploratory (unpublished) studies used a service-oriented approach, clearly a field for future research and testing. The basic formulation adopted in these exploratory tests, with promising results, is:

(i) Split the entire system into subsystems with a functional identity (e.g. district metering areas in water distribution systems, drainage sub-catchment basins in wastewater or storm water networks).
(ii) Define / adopt existing corporate assessment system, with service-oriented objectives, assessment criteria and metrics; select the relevant metrics depending on the infrastructure efficiency and effectiveness.
(iii) Standardise each metric for a 0-3 scale (0 – no service; 1: limit between unacceptable and acceptable; 2: limit between acceptable and good; 3 – Excellent).
(iv) All metrics should be relevant and balanced between them but, if necessary, give different relative weights to some metrics.
(v) Assess these metrics for each subsystem; standardise results;
(vi) Assess weighted average, i.e., global level of compliance with the objectives for each subsystems; this is taken as the IVI of that area, for the year data refers to.
(vii) Assess the global IVI using replacement costs of each subsystem as weights. For simplification, proxy variables such as total network length or population served may be adopted.

This approach has the advantage of acknowledging that the value of an infrastructure actually depends on its quality of service (including efficiency and risk considerations). Another advantage is the recognition that useful lives should be an output of service adequacy rather than an input for investment planning. The main disadvantages are the added subjectivity of this process and the non-consideration, in the calculation of the IVI at a certain time, of the expected evolution. If two subsystems have the same current performance, but in one it is likely that the quality of service will decrease in the short term, its IVI should be lower. Further research work is needed to overcome the current disadvantages.

4. Interpretation of IVI results

The IVI of mature, well-maintained infrastructures should be in the vicinity of 50% (40-60%). Higher values point towards one of the following situations:

- Young infrastructures;
- Old infrastructures subject to a recent and significant expansion phase;
- Old infrastructures subject to over-investment in rehabilitation.

Low IVI values translate accumulated lack of capital maintenance.

The investment in new infrastructures tends to be uneven. Reasons are one or a combination of the following:

- Non-linear growth of urbanization;
- Context-dependent access to investment funds, particularly if regional funds are used (e.g. Cohesion Funds in the case of the European Union, or regional or federal funds in many countries around the world).

Fig. 1 represents the evolution of the value of a specific asset. Its maximum value occurs for the installation date and the minimum, 0, for the end of its useful life. The mean asset value is 50 % of the replacement. A linear depreciation is assumed, as discussed in 3.1.

In a mature, well balanced infrastructure, assets of all phases of their life cycles coexist more or less evenly distributed. The global IVI is, according the law of large numbers, a value around 50%.

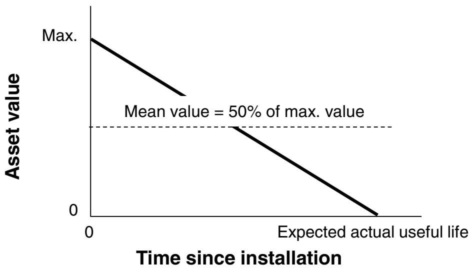


Fig. 1. Evolution of IVI over its useful life.

Given that not all assets of the same type and age are, in practice, at the same time, if the observation period contains several asset life cycles, the IVI will tend to this central value, regardless of its initial value. Whenever investments in new assets occurred in short periods, the need for reinvestments is also concentrated in certain periods of time. Only after several asset cycles the dispersion of re-investment needs occurs naturally. Modelling IVI evolution over time (e.g. 100-150 years) for status quo as well as for diverse investment scenarios provides a useful picture of the long-term impact of today's rehabilitation policies. Furthermore, it helps decision-makers to understand future needs and provides additional sensitiveness to alternative strategies under considerations. Fig. 2 shows the example of an existing infrastructure mostly installed in the late 70's and early 80's. It illustrates the IVI (yellow line) and the reinvestment needs (in pink) if assets were replaced at the end of its expected lives. An expected life of 80 to 100 years was used in the IVI calculations, according to what the utility managers considered realistic.

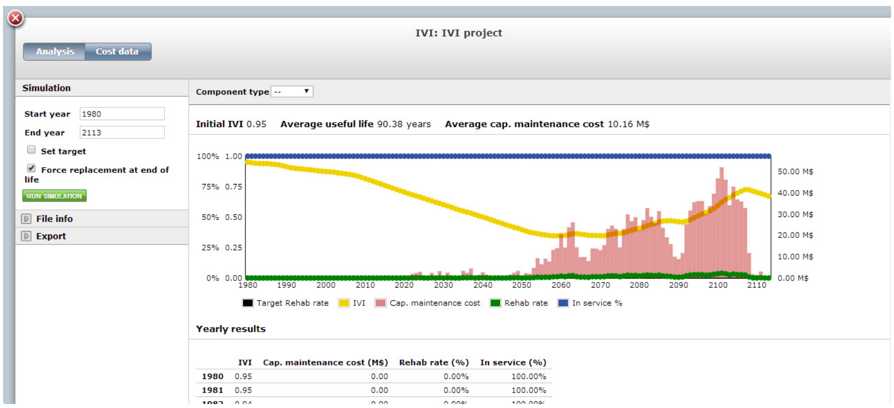
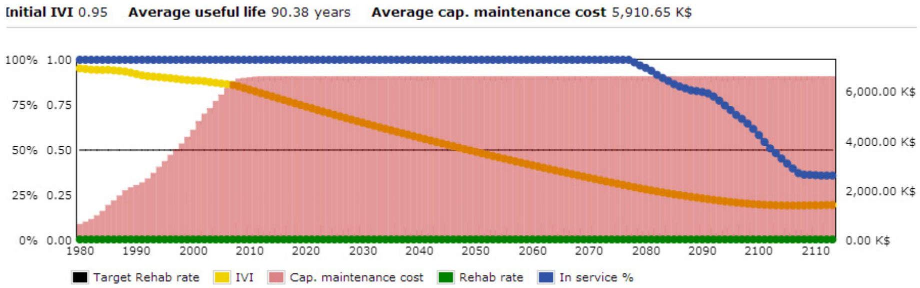


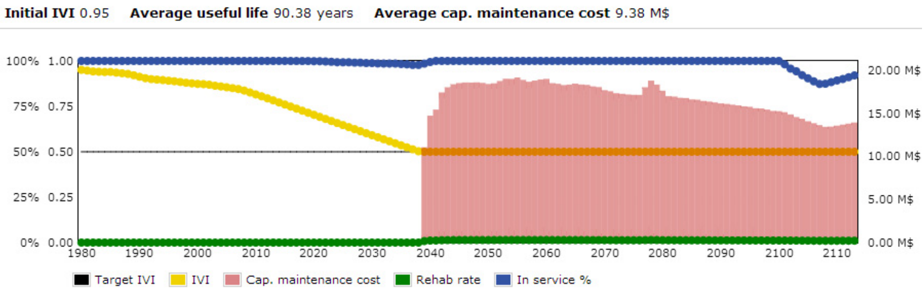
Fig. 2 IVI (yellow line) and reinvestment needs (pink bars) over time – assets replaced at the end of the expected life

IVI with a high value, 95% in 1980 and 77% in 2014, demonstrates the infrastructure's youth; IVI decreases to 35% in 2050's, when the quality of service is likely to already be affected in terms of asset failure frequency. The almost inexistence of reinvestment needs in the first years contrasts with what will happen from 2050 onward. The utility needs to be prepared for these needs, while acting to disperse them. Possible strategies are anticipating some of the interventions or changing the maintenance and renovation procedures (in order to change the expected residual useful life).

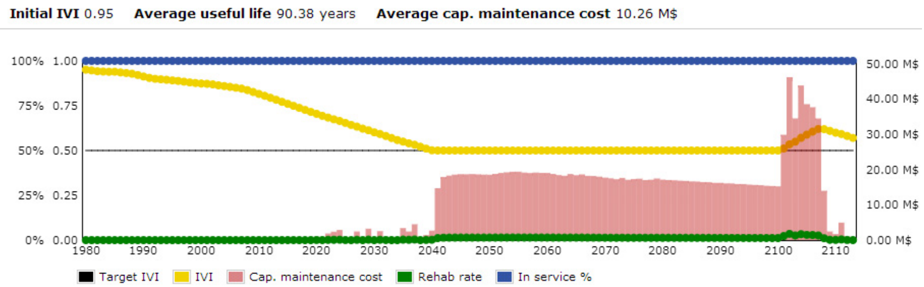
Fig. 3 shows the same infrastructure submitted to three different rehabilitation strategies: a rehabilitation of 0,5% of the replacement value per year (Fig. 3a); (3b) a target value of 50% for the IVI, with (Fig. 3c) and without (Fig. 3b) forcing replacement at the service life.



(a) Strategy: rehabilitation rate = 0,5 % per year



(b) Strategy: IVI ≥ 50 % without automatic replacement at the end of the service life



(c) Strategy: IVI ≥ 50 % with automatic replacement at the end of the service life

Fig. 3 - IVI (yellow line) and reinvestment needs (pink bars) over time - three different reinvestment strategies.

Results show that any strategy that involves replacing an asset before the end of its useful life either leads to assets being operated beyond its service life or to a globally more expensive solution than the operate-to-fail approach. Investment long-term planning requires other considerations than total cost. Service quality, reliability (e.g., service interruptions, disruption to third parties due asset failure), as well as organizational aspects (e.g. uneven distribution of human resources and capital needs) need to be taken into account. For instance, in Fig. a, a rehabilitation rate of

0,5% leads to an abrupt decrease in the percentage of assets in service (blue line) and a steady decrease in IVI.

5. Practical uses of IVI

While IVI, with its recommended assessment formulation, is rather simple, it has the power to integrate complex analyses, providing added value in terms of assessing long term consequences of investment policies and allowing to compare different alternatives. It allows comparing, in a long-term time window, utilities with each other, infrastructures of different nature (e.g., water supply with wastewater or storm water), projects that may have different nature or affect different assets, or different subsets of the systems (e.g., drainage sub basins, DMA).

IVI may be applied in several fields, in order to:

- Support long term re-investment planning, in the framework of strategic asset management;
- Assess the standardised value of an infrastructure in the beginning and at the end of a concession period;
- Set up contractual, regulatory of managerial targets aiming at infrastructure asset;
- Support national or regional rehabilitation policies.

The long-term view of the impact of reinvestment policies helps put into context the consequences of reinvestment savings, and compare less costly solutions (e.g. materials or equipment of lower quality and shorter duration) to solutions requiring a higher initial investment but lower depreciation rates due to longer expected lives.

In the context of enterprise valuation it is normal to check whether the level of investment is of the same order of magnitude of the total asset depreciation, i.e., of the investment in new assets or rehabilitation of existing assets. This situation corresponds to mature companies in a stabilised regimen, where the global value of the assets is in a steady state. However, it does not seem to be a current practice to assess IVI and check whether it is in the vicinity of 50%.

6. Software implementation

Fig. 2, Fig. 3 and Fig. 4 are screenshots from an open-source software implementation ([5], available at www.baseform.org) which enables the assessment of IVI both for asset-by-asset detailed inventory data and for simplified cohort-based infrastructure description, depending on the data available and on the targeted granularity in the results. Any type of physical asset, linear or vertical, can be listed. Modelling features include the specification of rehabilitation rate, annual investment or IVI targets, combined with the possibility of requiring automatic end-of-life replacement. The software requires as input data a list of assets (discretized or grouped by cohorts) with the installation date, estimated useful life range and unit replacement cost.

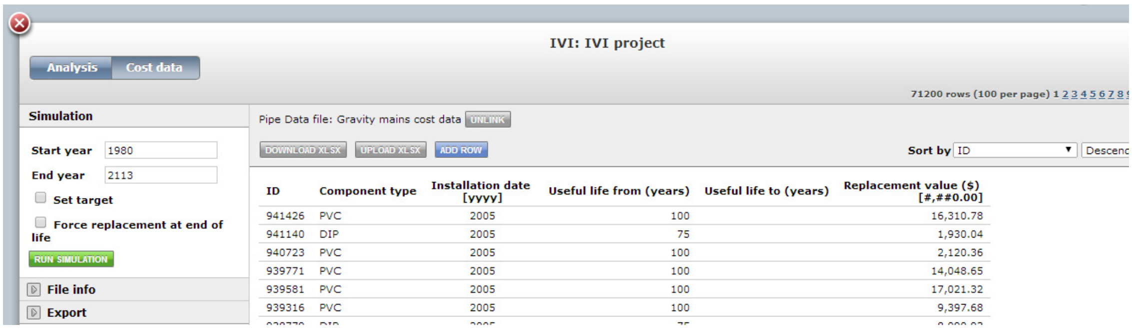


Fig. 4 IVI for two different reinvestment strategies.

7. Conclusions

Statements from utility managers such as “There is one thing I cannot understand with regard to IVI: how could we manage our utility until now without it?" (Marcelo da Velha, Inframoura, Portugal), or "IVI is one of the most common-sense parameters that I think I have ever overlooked." (Steve Sheets, GWRD, USA) illustrate the type of utility feedback about IVI. Apparently obvious, conceptually easy to understand, IVI is proving to be a rather powerful awareness, communication, negotiation and long-term planning tool. The availability of an open-source software implementation that is simple to use and with visual an easy to understand results opens the possibilities for a growing application by utilities. Researchers are encouraged to further develop the approach, particularly with regard to service-oriented procedures.

8. Acknowledgements

The authors acknowledge all participants and sponsors of the projects AWARE-P [2], iGPI [3] and INFR5R12 [4].

References

[1] H. Alegre. Water infrastructure asset management, Research Program, Series «Thesis and Research Programmes», LNEC, Lisbon, ISBN 9789724921341 (in Portuguese) 2008.
[2] www.aware-p.org
[3] www.iniciativagpi.org
[4] www.werf.org/a/k/Search/ResearchProfile.aspx?ReportID=INFR5R12
[5] S.T. Coelho, D. Vitorino, H. Alegre, AWARE-P: a system-based software for urban water IAM planning. 2013 IWA LESAM, Sydney, Australia, (2013).
[6] J. P. Leitão, S.T. Coelho, H. Alegre, M.A. Cardoso, M.S. Silva, P. Ramalho, R. Ribeiro, D. Covas, D. Vitorino, M.C. Almeida, N. Carriço, The iGPI collaborative project: moving IAM from science to industry. 2013 IWA LESAM, Sydney, Australia, 2013.
[7] S. Lopes, D. Covas, N. Lopes, L. Mamouros, N. Brôco, Cost functions for different water supply systems assets: the Portuguese case study. 2013 IWA LESAM, Sydney, Australia, 2013.