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Trusting your expert gut in wastewater network renewal planning

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ABSTRACT: *The principles of asset management are well understood by our industry experts, but when it comes to their application the waters are murky. Wastewater network asset managers are left to apply their own expert judgements to determine when and where their capital renewal millions should be spent. Trusting the expert gut is a good thing and can lead to high quality decision making if done right.*

In this paper I present my master's thesis research examining "Intuitive Decision Making for Wastewater Pipe Networks".

The levels of service and performance of our wastewater networks are not just technical but also impact the economic, environmental, social and political systems in our communities. This makes their optimised management highly complex. The greater the complexity the more we must rely on the intuitive judgements of industry experts.

To capture this phenomenon, I've created and tested an industry survey to model the typical risk-based decision making process. The survey results capture the intuitive insights of over 40 industry experts and document the collective importance of the various factors considered during the wastewater network renewal planning process.

Beyond showcasing the premise and results of the thesis, my hope is that this topic encourages insight of how we might continue to acknowledge and harness expert intuition for effective infrastructure decision making.

KEYWORDS: urban infrastructure, wastewater networks, asset management, decision making, documenting expert intuition, industry survey, significance weightings.

1 Introduction

Urban infrastructure demands significant attention and financial commitment from local governments in New Zealand and around the globe [1]. Councils face many challenges in their responsibility to maintain and expand infrastructure networks, subject to aging and degradation, in an environment of increasing public expectation for levels of service, sustainability and management of risks.

In the case of the Christchurch earthquake rebuild, approximately $2 billion was required to rebuild the city's horizontal infrastructure, of which the largest portion was associated with the wastewater network [2]. The high cost to the public for wastewater infrastructure reinforces the importance and relevance of research targeted at informing and improving the effectiveness of asset management decision making in this area.

The principles of integrated asset management are well understood and implemented in our country. New Zealand and Australian local governments have led the way through the development and publication of the International Infrastructure Management Manual (IIMM) which promotes a Total Asset Management Process [3]. The IIMM forms an important benchmark for integrated asset management systems around the world and is regularly referenced in recent academic papers. The strength of the IIMM is the focus on developing integrated organisational strategies and having a decision making process that is aligned with the overall plan and takes into account all of the various stakeholders.

There are numerous standards, guidelines, computational models and support tools that assist the development of integrated asset management frameworks by describing the decision making process from a rational perspective as described by van Riel, Langeveld et al. [4]. For example, capital expenditure strategies may focus on the “hard” network data such as pipe size, age, material, and perhaps camera footage from inside the pipes. Reliance on this “hard” data for decision making is problematic due to the complexity of wastewater networks and uncertainty regarding the relationships between data, performance and causality. Poor data quality is another reason to be wary of deterministic decisions based on “hard” data.

In contrast to the numerous support tools using “hard” data, little formal guidance is available on how to appropriate operational deficiencies into the decision process [4]. And potentially more significant, is the omission of formal methods of including intangible factors such as political, economic, environmental and social influences. It is often these intangible influences that have the greatest bearing on capital expenditure for wastewater networks.

A next step in wastewater asset management, perhaps, is to provide decision makers guidance for practically implementing a process of weighing up intangible and often competing influences to make transparent and robust decisions.

Investment decisions for wastewater networks are complex and take into account a broad system of influences. The wide range of influences supports the idea that wastewater networks are complex and deterministic decisions based on “hard” data alone are not appropriate. Instead, decisions require the use of “intuition” to weigh up the various factors in order to make a best fit decision so that investment and construction actions can proceed. Good intuitive decisions rely on the relevant knowledge and experience of the decision maker(s) and as Elms and Brown [5] explain, also on quality decision making processes that reflect the complexity of the system. Current research and guidance for intuitive decision making is not well developed, thereby leaving local governments in New Zealand potentially exposed to unmitigated risks of bad decisions.

This study addresses the problem by investigating intuitive decision making processes and developing a new methodology to quantify and document decision data. The new methodology provides a formal tool to assist wastewater asset managers appropriate the intuitive nature of their decisions. The new methodology could be adopted by industry organisations to enhance the long term quality of wastewater network asset management and other strategic infrastructure decisions.

2 Intuitive decision making

2.1 What’s so complex about wastewater networks?

With the goal of enhancing the decision making process, there is an important step to identify the complexity of the chosen system. A complex system is a special class of system and has a number of identifiable characteristics.

Simon’s [6] description of complex systems is used widely among many disciplines as a definition: “we can regard a system as complex if it can be analysed into many components having relatively many relations among them, so that the behaviour of each component depends on the behaviour of others”.

The non-linear relationships within a complex system is another important identifier.

The major challenges in predicting wastewater network system outcomes can be grouped into the following categories:

Socio technical

The influences are a mix of the technical (pipe attributes, hydraulics, loading demands etc.) and social (financial impacts, stakeholders, public safety, environmental protection, political interests and regulation).

Network complexity

There is an important connectedness where each individual element is part of the wider system and there is an inherent interdependence. As pipe networks grow in size and number, the complexity of the connectedness also grows.

Unknown causality

Causation is the “cause and effect” relationship where a network performance state can be shown to be the result of a particular characteristic. Due to the complexity of the network there is a high degree of uncertainty as to what characteristics caused a particular issue of failure.

Missing data

Local Governments struggle with asset data that is either altogether missing, incomplete or unreliable. This issue is confounded by the nature of wastewater networks being buried underground assets, effectively invisible. This data issue is a barrier to the prediction of outcomes using calculative models.

2.2 Why intuition?

Nobel Prize winning seminal psychology researcher Daniel Kahneman describes the two distinct modes of thinking, adopting the terms widely used by psychologists in this field: System 1 and System 2 [7].

System 1 operates automatically and quickly, with little effort and without the requirement of voluntary concentration. This mode of thinking draws on our relevant experience, knowledge and "gut", and is fundamentally important for intuitive decision making.

System 2 allocates attention to the effortful mental activities that demand it, including complex computations. These operations are trace mathematical and logical solutions to the question or task at hand. This mode of thinking is relied upon heavily when adopting rational decision making processes.

The field of engineering, and subsequently much of the asset management discipline, has a practical outlook and could be viewed as the application of science and mathematics to provide some societal need. It follows that these scientific and mathematic fundamentals require that engineers rely heavily upon the System 2 mode of thinking and rational decision making. Rational decision making serves appropriately when problems are well defined and can be broken down or well approximated to form a series of factors and relationships where the mathematical System 2 approach can be applied.

However, the case for System 1 thinking is increasingly relevant where problems or decision making systems grow increasingly large, complex and less well understood and System 2 thinking is less able to find appropriate solutions.

Indeed, the complexities of wastewater network asset management decision making provide a fertile setting for the application of System 1 intuitive thinking to thrive.

2.3 Intuitive pitfalls

As much as is it appropriate to use expert intuition when considering complex decision systems, it is also appropriate to understand the associated pitfalls.

Transparency

There is a transparency issue as decision makers use their own expert knowledge to jump from A to E in a decision without necessarily being able to articulate or document the skipped calculations of B, C and D.

Bias

We all carry unconscious bias, and these are manifested in many ways within intuitive decision making to undermine the accuracy of our decisions. Bias can appear in a multitude of ways; anchoring, confirmation bias, groupthink, information bias, loss aversion and many more.

Institutional knowledge

Network knowledge is gained through experience and some of our best expert staff have been around for some time gathering their exquisite insights. However, demographic change is real and an impact of our aging society is the very real risk of losing intuitive decision expertise held as institutional knowledge by staff approaching retirement.

2.4 Infrastructure decisions

Given that intuition forms a vital role in decision making systems for wastewater network asset management, and is subject to various pitfalls, it is important that effort is applied to enhance the quality of this decision making. This points to the practical focus of this thesis to develop a new methodology to document intuition within the wastewater network context. By documenting the intuitive decision process, the door is opened for more transparency, elimination of cognitive bias and the capture of institutional knowledge.

In 2017 the New Zealand Minister of Local Government commissioned a review of three waters infrastructure services. The review is ongoing but initial findings in November 2017 [8] concluded a number of statements eerily in tune with the statements and aims of this thesis research:

Variable asset management practices, and a lack of good asset information, are affecting the performance of three waters infrastructure/services

Transparency and accountability are relatively light for an essential service

There are capability and capacity challenges, particularly for smaller councils and small drinking water suppliers

Improving the quality of intuitive decision making through effective documentation could prove to be a significant step towards addressing these ministerial concerns above.

The following chapters describe the developed methodology for documenting intuition, the collected results and conclusions drawn about how the intuitive decision process can benefit.

3 Industry survey to document intuition

3.1 The decision system model

The developed method is based on creating a decision model where the various relevant factors can be applied in combination based on their levels of importance. An industry survey allows the weighting of importance, or "significance" to be determined from answers collected from wastewater network experts.

The decision system model is based on those factors identified in the van Riel, Langeveld et al. 2015 study and those factors derived from New Zealand case studies. The framed question is: "which pipe should I replace/repair".

The decision system model is broad and includes components from the various socio-technical spheres:

- Systemic improvement
- Economic impact
- Environmental impact
- Political impact
- Ease of management
- Network performance

It would be a major undertaking to attempt to extract and document expert intuition across all of these spheres. Choosing just one category to explore in greater detail and develop survey questions around was the most attractive option. The option was taken to focus on gathering survey input data relating to just one of the overarching categories: **Network Performance**. Focussing the survey on this single category provides proof of concept of how the survey could then be further developed for other categories and the entire decision tree eventually stitched together to represent the whole system.

In order to represent the sphere of network performance, further breakdown of the decision tree is required. The sub-tree used to determine network performance has been developed around a risk-based approach taking into account the most likely failure modes. The five factors of greatest failure concern within the sub-tree of network performance are shown in Figure 1 below with examples of the expanded tree.

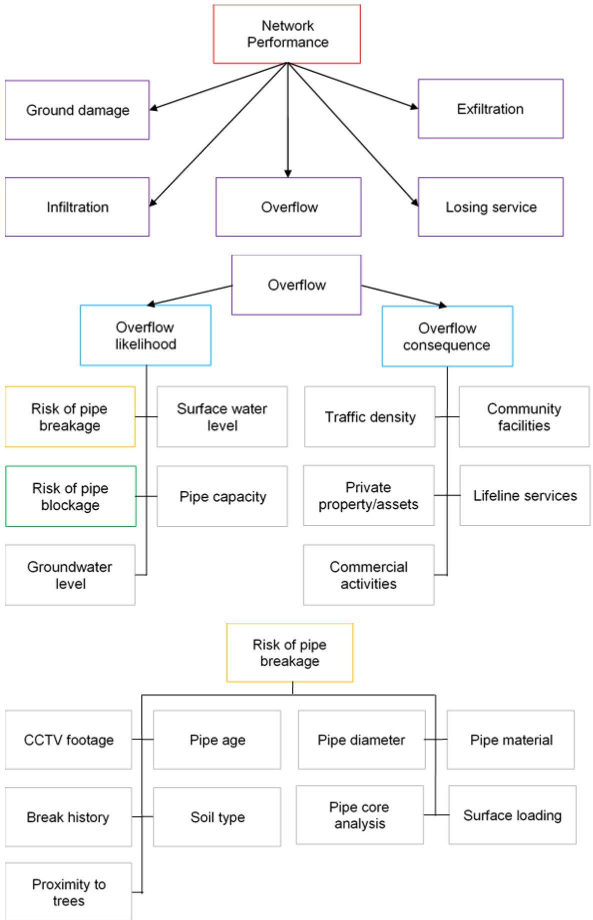

Figure 1: Examples from the decision tree

3.2 Quantitative assessment

For each of the factors laid out in the figure above, prioritised decisions can be derived by looking at the various factor scores and significance weightings.

Factor score

In this approach a factor score of 5 is bad and a factor score of 1 is good. "Bad" is also synonymous with high risk and "good" synonymous with low risk.

Example of typical user defined 1 – 5 factors scores are presented in Table 1 below for the factors beneath the "Risk of Pipe Breakage" in the decision tree. The classification of 1 - 5 scores is subjective and can be set in such a way that supports the decision analysis that the asset manager is trying to perform.

Table 1: Factor score examples

Factor	Factor score = 1, Good (i.e. low risk)	Factor score = 5, Bad (i.e. high risk)
CCTV footage	No defects, good pipe condition	Multiple significant pipe defects showing poor pipe condition
Pipe age	New pipe with >75% of expected remaining useful life left	Old pipe with <5% of expected remaining useful life left
Pipe diameter	Small pipe diameter (<150 mm) with a low impact to overall network performance in a failure event	Large pipe diameter (>450 mm) with a high impact to overall network performance in a failure event
Pipe material	Modern plastic material with flexibility	Brittle pipe material with vulnerability to deterioration
Break history	No break history	>3 breaks within the last 5 year period
Blockage history	No blockage history	>5 blockages within the last 5 year period
Soil type	Firm well drained soil	Soft ground conditions, liquefiable soil, corrosive soil
Pipe grade	Steeper than minimum gradients for tractive force gravity pipeline design	Flatter than minimum gradients for tractive force gravity pipeline design
Pipe dips	No pipe dips	Has pipe dips greater than 100% of pipe diameter
Proximity to trees	>25 m from trees	<5 m from trees

Significance weighting

The decision tree has been laid out in a way that the significance of the various factors and subfactors can be determined from the expert intuitive inputs. This is collected using the industry survey and forms the basis for the significance weighting.

The survey frames the questions from the perspective of a wastewater network asset manager who is tasked with the situation of having to determine which pipes in their network to repair or replace. The weightings are made qualitative by using the Likert scale in Table 2 below.

Table 2: Likert-type scale

Likert Scale	**Score**
Extremely significant	5
Very significant	4
Moderately significant	3
Slightly significant	2
Not at all significant	1

Derived impact score

The derived impact score is calculated by multiplying the factor score and the significance weighting.

Figure 2 below provides an example of how three sub factors contribute to the score of the decision tree level above.

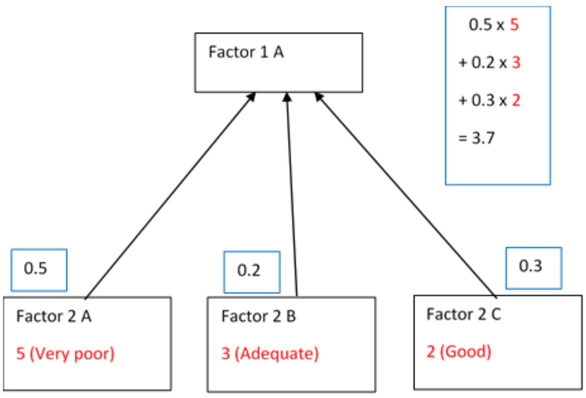

Figure 2: Deriving scores from the tree

So the derived score for Factor 1A based on the significance weighting (from industry expert intuition) and factor score (from network data or knowledge) is 3.7. Applying this to the wastewater network assets, it might represent a scenario where a particular pipe asset has a pipe breakage score (Factor 1 A) of 3.7 based on having a very poor CCTV footage score

(Factor 2 A), adequate pipe age score (Factor 2 B), and have a good pipe diameter score (Factor 2 C).

3.3 Survey questions

For each question the participants were required to rank (using the Likert Scale) each of the sub-factors for that particular question within the decision tree model. Table 3 shows the question topics covered.

Table 3: Survey question topics

Q1	Likelihood of pipe breakage
Q2	Likelihood of pipe blockage
Q3	Likelihood of ground damage
Q4	Consequence of ground damage
Q5	Likelihood of infiltration
Q6	Consequence of infiltration
Q7	Likelihood of overflows
Q8	Consequence of overflows
Q9	Likelihood of losing customer service
Q10	Consequence of losing customer service
Q11	Likelihood of ground damage caused by exfiltration
Q12	Consequence of ground damage caused by exfiltration
Q13	Overall performance of pipes in the network

Survey participation

The survey was distributed online using the Qualtrics online survey software. A request to participate in the survey was sent to Water New Zealand and the Institute of Public Works Engineers of Australasia. Direct requests were also sent to a number of Councils and engineering consultancies. It was requested that participants be experienced in wastewater network renewal decisions or investigations. Beyond being in an organisation that received the survey invite, the survey participants were self-selecting The survey was taken by 43 participants between 7 February 2017 and 27 February 2017.

4 Results

Figure 3 shows an example of the results from one of the industry survey questions.

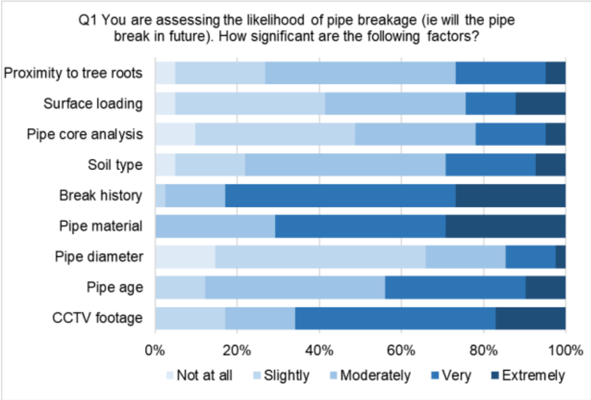

Figure 3: Example survey result

Typically the significance scores from the experts were in the 3 – 4 range. This sort of data can be uniquely analysed using a method known as Top 2 Box. The Top 2 Box calculation is useful survey methods such as the Likert scale and calculates the percentage of all results on the 1 – 5 scale that were reported as 4 or 5, that is, *Very Significant* or *Extremely Significant*. The Top 2 Box results are shown in Table 4 as a percentage of responses that were 4 or 5.

Table 3: Top 2 Box scores

Q'n ID	Factor	Top 2 Box
10	Lifeline services impact (eg hospital or evacuation links)	100%
13	Overflow	97%
2	Blockage history	93%
5	Groundwater level	89%
13	Losing customer service	89%
10	Commercial service impact	86%
9	Pipe blockage	86%
1	Break history	83%
12	Lifeline services at the pipe location (eg hospital or evacuation links)	81%
2	Pipe dips	79%
3	Pipe breakage	79%
5	Pipe breakage	78%
6	Pipe capacity	78%
7	Pipe capacity	78%
7	Pipe blockage	78%
8	Lifeline services (eg hospital or evacuation links) at the pipe location	78%
4	Lifeline services (eg hospital or evacuation	76%

	links) at the pipe location	
9	Pipe breakage	75%
10	Community service impact	75%
11	Pipe breakage	75%
1	Pipe material	71%
4	Traffic density at the pipe location	70%
8	Commercial activities at the pipe location	69%
9	Pipe capacity	67%
12	Commercial activities at the pipe location	67%
8	Community facilities at the pipe location	67%
1	CCTV footage	66%
3	Soil type	66%
2	CCTV footage	64%
2	Proximity to tree roots	64%
2	Pipe grade	64%
12	Community facilities at the pipe location	64%
4	Commercial activities at the pipe location	62%
10	Residential service impact	58%
11	Soil type	58%
13	Infiltration	56%
11	Ground slope	56%
3	Groundwater level	55%
6	Treatment costs (eg additional cost of putting the infiltrated groundwater through the wastewater treatment plant)	53%
6	Conveyance costs (eg additional cost of pumping the infiltrated groundwater)	50%
12	Traffic density at the pipe location	50%
8	Private property/assets at the pipe location	50%
5	Soil type	49%
4	Community facilities at the pipe location	49%
12	Private property/assets at the pipe location	47%
1	Pipe age	44%
4	Private property/assets at the pipe location	43%
11	Pipe blockage	42%
2	Break history	41%
7	Pipe breakage	39%
11	Groundwater level	39%
13	Exfiltration	36%
13	Ground damage	33%
7	Surface water level	33%
2	Pipe diameter	33%
7	Groundwater level	31%
1	Soil type	29%
8	Traffic density at the pipe location	28%
1	Proximity to tree roots	27%
3	Pipe blockage	26%
1	Surface loading	24%
2	Pipe material	23%
1	Pipe core analysis	22%
9	Surface water level	19%
1	Pipe diameter	15%
2	Pipe age	10%
9	Groundwater level	8%
2	Soil type	0%

These results provide the input for the significance weighting for each of the factors. Further analysis was done to determine how much of an influence each factor has on the overall network performance score. This was conducted by creating a model where each factor score is combined with its significance weighting (from the industry survey results) and connected together using the format of the overarching decision tree.

Unsurprisingly, those factors appearing near the top of the decision tree had more of an impact on the overall network performance compared with those that appear as sub factors at lower levels of the tree. Table 4 below shows the impact of each factor by raking them according to how sensitive the overall network performance score is to a change in each individual factor score. The top three factors in each tier level are highlighted.

Table 4: Overal impact on network performance

Tier	Factor	Sensitivity
T3	Overflow	2.65
T3	Losing customer service	2.38
T3	Infiltration	1.54

T3	Exfiltration	1.23
T3	Ground damage	1.19
T2	Pipe capacity	1.49
T2	Pipe blockage	1.48
T2	Pipe breakage	1.37
T2	Lifeline services (eg hospital or evacuation links) at the pipe location	1.27
T2	Commercial activities at the pipe location	1.22
T2	Lifeline services impact (eg hospital or evacuation links)	1.20
T2	Community facilities at the pipe location	1.20
T2	Groundwater level	1.18
T2	Commercial service impact	1.16
T2	Community service impact	1.12
T2	Private property/assets at the pipe location	1.12
T2	Soil type	1.11
T2	Residential service impact	1.08
T2	Surface water level	1.07
T2	Traffic density at the pipe location	1.07
T2	Treatment costs (eg additional cost of putting the infiltrated groundwater through the wastewater treatment plant)	1.06
T2	Conveyance costs (eg additional cost of pumping the infiltrated groundwater)	1.05
T2	Ground slope	1.02
T1	Break history	1.17
T1	CCTV footage	1.16
T1	Blockage history	1.16
T1	Pipe dips	1.12
T1	Pipe material	1.11
T1	Proximity to trees	1.09
T1	Pipe grade	1.08
T1	Pipe age	1.04
T1	Pipe diameter	1.03
T1	Surface loading	1.01
T1	Pipe core analysis	1.01

5 Conclusions

Several observations are possible when looking at the industry survey results and considering how this method of documenting intuition might be further applied.

5.1 Limitations

Similar significance scores from the raw data

Two thirds of the results had mean significance scores between 3.00 and 4.00 which resulted in small variations between recorded factors. The survey content was constructed using factors identified as relevant to wastewater network asset management in previous literature, therefor it was unlikely that respondents would give a score of 1 “Not at all Significant”. This leaves only four realistic choices from 2 – 5 which would have contributed to these tight range of responses.

Assumption that factors should be combined in a linear way

Each tier of the decision tree is made up of the combined weighted scores of the subfactors beneath it. This model provides analysis using the assumption of a linear relationship between factors and sub factors. An alternative method would need to be applied if modelling a non-linear relationship. The chosen decision tree format is highly influential

The results are tied to the specific decision tree chosen

Firstly, the choice of which factors are included within the decision model and which are not has a bearing.

Secondly, the number of factors that appear at each level of the tree is an important factor.

Thirdly, the decision of the tier level that each factor or sub factor is located in has an impact on that factor’s overall significance impact.

Fourthly and lastly, the number of tiers chosen in total will have an impact.

The four points above suggest that the greater the level of complexity in the decision tree, the more influence the tree itself has on the overall result and application. Consequently, a simple tree with few tiers and few sub factors is likely to work best if the aim is to apply the surveyed expert weightings with the least level of potential distortion.

Intuition is also needed to set the factor scores

The method numerically represents the significance weightings of the numerous factors based on expert judgements. However, the application of the decision model requires these to be combined with the factor scores from 1 (very good) to 5 (very poor), which are also subjective, to make an overall assessment.

5.2 Benefits

Provides prioritisation scores

The method does indeed provide prioritisation scores once the significance weights are combined with the factor scores. The method is adapted from existing techniques and theories and provides a workable solution. Having quantitative prioritisation scores documented adds immediate value to the improvement of intuitive decision making over time.

Identification of the factors to include or not include in decision making

Looking at the Top 2 Box results provides a clear indication of which factors are deemed significant or not significant for this renewal prioritisation decision. These observations can be used to refine and simplify the decision tree model to only use the highest scoring factors.

Targeted data collection

The significance weightings also show us which are the most important factors to concentrate on for data collection.

Targeted effort for setting 1 to 5 factor score categories and thresholds

Similar logic also applies to the task of setting the 1 to 5 factor score thresholds. The knowledge of which factors are most significant can help to hone the effort applied when coming up with the 1 to 5 factor score categories and thresholds.

Qualitative decision making and prioritisation

It may be that a purely numeric representation of the decision tree is beyond what the asset manager is capable of at a given point in time but nevertheless the significance weightings could still be referred to in their intuitive process where a qualitative high/med/low significance is used without necessarily attempting to calculate final prioritisation scores.

Testing the decision tree structure and hierarchy

The process of completing the survey and applying the method provides a chance to analyse the results and then go back and challenge what was originally assumed as the appropriate decision tree.

Can be applied across a network

Once set up, the method can be applied at scale allowing the computational benefit of process repetition. The significance weights are assessed at a network level and are therefore appropriate to be applied wholesale across the network.

Provides a documentation trail

The documentation allows auditing of the decision quality and also gives a starting point for refining the method over time to facilitate continuous improvement.

Links individual factors with ultimate decision outcome

For each factor it is possible to see which other factors are influenced by it and also to see how those factors ultimately affect the decision outcome.

Used as a shortlist

It may be that the asset manager wishes to retain the autonomy of the ultimate decision making, and even in this case the method provides assistance. This method could be used to shortlist pipes as candidates for action still allowing room for the asset manager to apply their own expert intuition at the end of the process.

6 Acknowledgements

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