Setting Targets In An Asset Management Performance Measurement Framework

Green, D; Masschelein, S; Hodkiewicz, Melinda; Schoenmaker, Rob; Muruvan, S

Publication date
2016

Document Version
Accepted author manuscript

Published in
Proceedings of 2016 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE 2016) 2016 World Congress on Engineering Asset Management (WCEAM2016)

Proceedings of 2016 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE 2016)
2016 World Congress on Engineering Asset Management (WCEAM2016)
July 25-28, 2016, Jiuzhaigou, Sichuan, China

QR2MSE2016 & WCEMA2016-DRAFT

Setting Targets In An Asset Management Performance Measurement Framework

Daniel Green[1], Stijn Masschelein[2], Melinda Hodkiewicz[3*], Rob Schoenmaker[4], Sugandree Muruvan[1]

1. Water Corporation, Perth, Australia
2. Business School, University of Western Australia, Perth
3. School of Mechanical and Chemical Engineering, University of Western Australia, Perth
4. Faculty of Civil Engineering and Geosciences, Delft University of Technology, Netherlands

[*] Corresponding Author: melinda.hodkiewicz@uwa.edu.au

ABSTRACT

All asset-intensive organisations have some sort of asset performance targets in place. How legitimate are these targets? Are they achievable given the resources and span of the control of the manager responsible? Are they fair? Is it clear how targets for asset performance measures should be set?

Drawing on performance measurement literature and current practice, we identify factors to be considered in setting targets for asset performance metrics. The resulting framework comprises four steps: 1) the identification of factors influencing the performance metric, 2) the identification of interventions within the control of the asset manager that could influence the metric, 3) data collection and statistical analysis to identify the influence of these interventions, 4) simulation of future performance of the metric to establish targets or ranges of acceptable performance.

The framework is illustrated using an asset performance metric, pipe blockages, for asset managers of regional waste water assets. Findings are: 1) target setting involves a deep understanding of what influences the metric, and this requires data collection, cleaning and validation, as well as liaison with experts, 2) the importance of establishing how the metric can be influenced by factors beyond the immediate control of the asset manager, this affects its legitimacy, and 3) the opportunity presented by simulation to provide target ranges appropriate for the variability in many asset performance metrics. The absence of expected relationships raises questions about the appropriateness of the metric, the effectiveness of the work and/or the data quality.

Asset managers should be careful setting targets to asset performance measures. The process developed in this paper can be used to inform target setting activities.

KEYWORDS: Asset Management, Performance Management, Performance Indicators, Target Setting

1 BACKGROUND/INTRODUCTION

Decision making in asset intensive organisations should be based on the organisational goals these organisations want to achieve, which calls for the development of an asset planning performance framework. In this framework the line of sight from organisational goals via asset management goals drilling down to asset related goals becomes visible. Several authors [like 1, 2] have suggested the Balanced Scorecard (BSC) [3] as a basis for performance measurement to integrate asset performance and corporate objectives. The new ISO asset management standard refers to this as the 'alignment of objectives' [4].

The organisational and asset related goals need targets. Because without specific targets, it still remains unclear what the organisation is aiming for. After the translation of organisational goals into objectives and performance measures and targets, performance information can be used to drive decision and link actions to meeting the targets [5]. The ISO asset management standard refers to this as the need for periodic performance evaluation [6, Clause 9]. A target can be defined as the level of performance that the organisation aims to achieve for a particular activity in or over a stipulated period [Based on 7]. Or stated more simply: a target is the intended level of performance. Targets can relate to any kind of performance measure, like input, process, tasks or output. Turning measurement into management targets make it possible to estimate if the organisation is able to meet its targets, considering the available resources (organizational, physical and monetary) [8].

Then the following question becomes relevant: How to set the targets? The existing literature mainly focuses on target setting from a *demand* point of view. Describing the target setting process usually starts with identifying the customer or stakeholder expectations [8-10]. But what about the *supply* point of view? Is it clear what the asset manager really can do to influence the results of the performance measures? If so, what exactly can the asset manager do? And to what degree does that influence the performance measure? This paper focuses on the target setting from a *supply* point of view and how to set targets that are fair, achievable and do not block ambition?

The paper is organised as follows: The literature review examines previous work on performance measurement systems in relation to target setting and especially the fairness or legitimacy of the performance measure and target. This is followed by a section on the approach used and a description of the case study. The results of the regression modelling and simulation are followed by a discussion section reflecting on this work and its outcomes.

2 LITERATURE REVIEW

2.1 Functions of performance measurement

Performance measurement (PM) can have several functions as shown in Figure 1. One of the functions of performance measurement is creating transparency. Through PM organisations can show what their products and associated costs (external) are and use the measurements for learning and improving (internal). The effects or impact of these functions of PM on the one that is being measured are limited, whereas PM used for sanctioning (like cutting budgets or penalties) has a great impact on the one that is being measured.

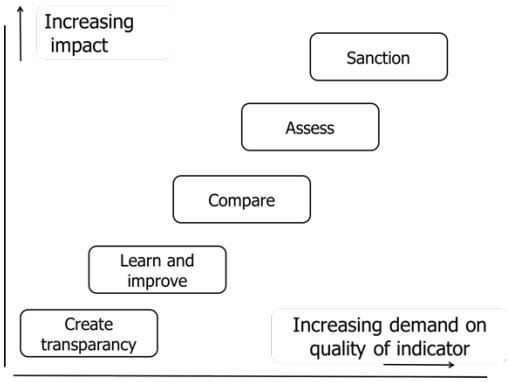

Figure 1 Functions of performance measurement [based on 11, 12]

PM that includes assessment (of goal achievement) and sanctioning requires a high quality of performance indicators because comparison, assessment and sanctioning have an increasing impact (not only financial) on the one that is measured. PM literature clearly shows that the higher the impact of PM, the lower the effectiveness: the *Law of Decreasing Effectiveness* [11]. PM then becomes an incentive for strategic behaviour, like shirking, gaming the numbers and will lead to unintended consequences [13], [14]. This is illustrated by 'after a while you start doing things to get a good score instead of doing the right things' [15], which may lead to scoring good on performance measures but leading to suboptimal performance overall.

PM with sub-optimal indicators or sub-optimal targets will lead to a lack of ambition [16] or will block innovation. E.g., suboptimal PI's in sewer management lead to: 'encourage adoption of less sustainable techniques or solutions' [17].

2.2 Quality of performance indicators

Extensive literature is available about the quality of individual indicators [18-20]. Often lists of criteria are given leading up to 20 (conflicting) criteria. More generally speaking PI's have to comply with three criteria [21]:

- *Validity and reliability:* the indicator has to be measurable and has to measure what it is intended to measure, again and again
- *Functionality:* the indicator has to be relevant, the indicator has to contribute to the overarching objectives
- *Legitimacy:* The indicator has to be accepted, e.g., the one that is being measured has to be able to influence the results of the indicator

In this paper on target setting we focus on *legitimacy*. A legitimate PI is a PI that is accepted by (in this case) the asset manager. Aspects of a legitimate PI with a legitimate target are:

- *Achievable*: the depending on degree to which AM can the influence the results of the performance measure with available (financial) resources
- *Clarity, unambiguity* of the PI or target and it is clear for the AM how to meet the target
- *Level of involvement* of the AM in designing the PI and setting the target.

Reduced legitimacy is an incentive for strategic behaviour and the PI is considered unfair by the asset manager [11].

2.3 Target setting - Supply point of view

Looking at target setting from a supply point of view reveals that there are several constraints that have to be taken into account. Marsden and Bonsall [22] mention legal, contractual, resources (financial) limitations. The report *Target-Setting Methods and Data Management to Support Performance-Based Resource Allocation by Transportation Agencies* [9] lists conditions as span of control, financial resources, time frame, technical resources and organisational structure. If we link these conditions to the general criterion of *legitimacy* – or fairness of the PI and target – then the question arises: What is the span of control of the asset manager? Do the efforts of the asset manager influence the indicators? To be able to answer that question we need to know what influence the PI. Technical knowledge is required, for example in the case of sewer blockages (our case study) we need to know what causes these blockages. Marlow et al. [23] give a description of possible influences of sewer blockages. Another important factor is the possible temporal mismatch or time delay between action and measurability of the effect. The effects of maintenance interventions will not always occur in the same measurement reporting period of the indicator.

A final aspect that plays an important role is that many asset management organisations have geographically distributed assets (e.g., rail, roads, sewer and drinking water systems). As a consequence, they have divided their organisations into regions. PI's originating at a regional level are (bottom-up) aggregated to a single indicator at a central level (national, state-wide). Reporting at a central level will disguise detail of performance of individual regions – good performance, bad performance – and regional characteristics: metropolitan, rural, outback. The same goes for central (top-down) target setting. It may be that central target is not fair for the individual regions because of region-specific conditions or factors that influence the metric.

A last aspect about target setting is that targets should be challenging to avoid lack of ambition. A careful balance between achievability and challenge should be sought after. There are several methods to identify the achievability of the targets [22]: model-based; extrapolation; evidence-led judgement and aspirational. In this paper we will use the extrapolation of historical data.

3 METHOD

The first step in the work is to select a case study and a suitable performance metric within the company collaborating on this research. Following this the process

involves four steps: 1) the identification of factors influencing the performance metric, 2) the identification of interventions within the control of the asset manager that could influence the metric, 3) data collection and statistical analysis to identify the influence of these factors and maintenance interventions, 4) simulation of future performance of the metric to establish targets or ranges of acceptable performance. These are described in more detail below.

3.1 Case study

The selected case study is based on the Asset Management branch of the Water Corporation, a State Government-owned and regulated water utility. They are the principal supplier of water, waste water and drainage services to hundreds of thousands of homes and businesses. They have just under 3000 employees and manage a 2014 asset base with a replacement value of over A$30 billion. Functional assets exist in six operational areas across 2.6 million km2 – North West, Mid-West, Goldfields and Agricultural, South-West, Great-Southern and Perth regions. Each operational area is run by a regional or alliance manager.

Gravity sewers were selected as the asset of interest and the wastewater blockages per 100km as the performance measure. This measure was chosen given the political, environmental and social risks associated with wastewater. These risks were being reviewed at the Water Corporation at the time of decision. Currently performance across the state is assessed against a statewide target. This statewide target is set by the Regulator but the Water Corporation is able to propose and justify alternate values as part of their regulatory submission. The work explores the potential to replace the statewide target with region-specific targets to enable cross-region comparisons. However processes are needed to set targets for regions with different operating and historical contexts.

Factors affecting wastewater blockages have been considered by previous researchers [23-27]. These factors can be classed into groups based on pipe attributes (e.g. length), terrestrial location (e.g. soil type and tree proximity), geographical location (e.g. effect of climate) and usage conditions (broadly what and how much is being put through the pipes). The factors considered in this analysis are pipe type, age, network length, population density and rainfall as well as a number of cost factors, capital investment, preventative maintenance expenditure, corrective maintenance expenditure.

3.2 Data collection and statistical analysis

The approach consisted of collating blockage performance data from a sample of 8 regions from all across Western Australia – Australind (AU), Carnarvon (CA), Eaton (EA), Esperance (ES), Exmouth (EX), Kambalda (KB), Karratha (KA) and Laverton (LA). The purpose of the sample set was to obtain data for a range of operating environments each with different network lengths, level of investment, pipe types, ages, weather patterns and population density.

Exploratory analysis was performed through boxplots of the spread of performance from year to year and from region to region. Data irregularities such as missing years of weather data were identified and cleansed. The exploratory analysis showed unresolvable incomparability of the cost data across the geographic regions and inconsistent allocation of costs to different cost categories. Therefore, the cost data are excluded from the regression model.

To see the sensitivity in variables from region to region generalised linear regressions were used. In order for regions of different sizes to be compared, the variables were scaled by network length when necessary. Prior knowledge and the exploratory analysis narrowed the number of variables in the regressions. Blockages per 100 km are modelled as a normal distribution N(μ, σ) where

$$\begin{aligned} log(\mu) = \beta_0 + \ & \beta_1 \%VC + \beta_2 \%PVC + \beta_3 Age \\ & + \beta_4 Population\ Density \\ & + \beta_5 (Max\ Rain - Mean\ Rain) \end{aligned}$$

The interaction variables in the regression are a combination of pipe type, age, population and rainfall. The purpose of these terms was to see if some variables working together function more profoundly than by themselves. Statistical significance, coefficient magnitude and standard errors were assessed when running the regressions.

3.3 Simulation and validation

The coefficients (β's) from the linear regressions were then simulated 1000 times for every region and for every year with the 'arm' package [28] for 'R' [29]. The simulated coefficients were drawn assuming a normal distribution with mean $\hat{\beta}$ and standard deviation $\sigma(\hat{\beta})$ from the generalised linear regression. The simulated coefficients were then combined with the actual data to produce 1000 predicted blockages (ŷ's) for every location year. The ŷ values were then accumulated into histograms. The histograms of the predicted blockages represent the prediction distribution of blockages per 100km. The actual performance in that year was overlaid on the histograms to provide comparison between actual and predicted performance.

The simulation model was validated by imitating the procedure of setting a target in the future. Variable estimations were made for 2013 and simulations were run on past 2005-2012 data to predict the number of blockages in 2013. Through observation, the prediction histograms were then compared to the actual performance in 2013.

4 RESULTS

4.1 Data description

We describe the variation in the blockages per 100km over regions and over time in Figure 2. For the selected regions, blockages do not show a trend nor does the

variation within years show a distinct pattern. In contrast, the regions differ significantly in both the level and the variation of blockages per 100km. These plots indicate that the Water Corporation cannot treat all regions the same with respect to wastewater blockages.

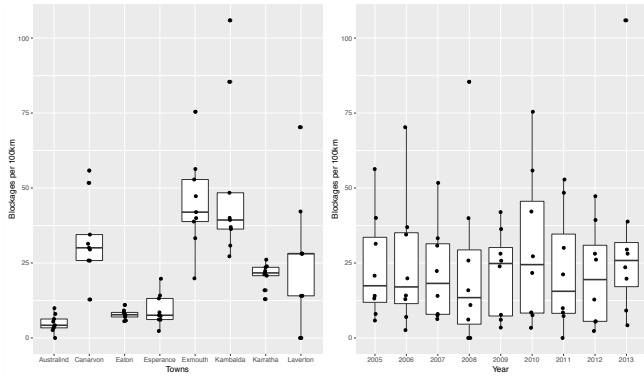

Figure 2: The boxplots visualise the variation across regions and time in the blockages per km.

4.2 Regression model

We present the results for the regression for the full dataset and for the dataset without the year 2013 in Table 1. The latter regression is further used to predict 2013 out of sample. The table reports the coefficient estimate and the standard error for the estimate between brackets. The table shows that the regression results do not differ meaningfully across both samples which confirms that most of the variation in the number of blockages is between the the regions and not over different years.

	Full sample	Restricted sample
Intercept	3.08***	3.05***
	(0.13)	(0.10)
PVC (as proportion)	-2.86*	-3.18*
	(1.55)	(1.88)
AC (as proportion)	-1.50	-1.88
	(1.10)	(1.24)
Population density (100/km)	0.14	0.11
	(0.39)	(0.43)
Age (decades)	0.22	0.12
	(0.25)	(0.26)
Excess Rainfall (100ml)	0.04	0.02
	(0.12)	(0.15)

Table 1: The table presents the regression coefficient estimates (and standard errors) for the regression results. The full sample results are based on data from 2005-2013 while the restricted sample results are based on data from 2005-2012.

****, **, * Indicates a significant effect at the 0.01, 0.05,0.10 level.*

The most important driver of the number of blockages is the pipe type in the region's network. All things equal, regions with 10% more PVC compared to vitrified clay pipes are expected to have 27%[3] less wastewater blockages and regions with 10% more asbestos cement pipes are expected to have 17% less wastewater blockages. Most explanatory variables are not significant at traditional significance levels however the coefficients have the expected sign in that increases in population density, age of the network, and excess rainfall are associated with more blockages. More specifically, an increase of 100 habitants/km of the network is associated with an 11% increase in blockages. A ten-year increase in the network's age is associated 13% more blockage and 100ml more rainfall than the average is associated with 2% more blockages.

4.3 Simulation results

Based on the restricted model, we can mimic the work of a supervising manager at the start of the year 2013. The manager develops a model with the 2005-2012 dataset as given in Table 1. To simulate the distribution of the potential number of blockages in each region in 2013, the manager also needs to set values for the explanatory variables in 2013. For the Rain variable, we take the median difference in maximum and minimum rainfall in the past 8 year for each region. We assume that the proportion of PVC and VC does not change from 2012. The age is adjusted with one extra year. To predict the distribution of the number of blockages per 100km for each region, we run 1000 simulations for each region. Figure 3 shows the simulations and the actual number of blockages in 2013 where predictions for negative blockages are transformed to 0 blockages/100km.

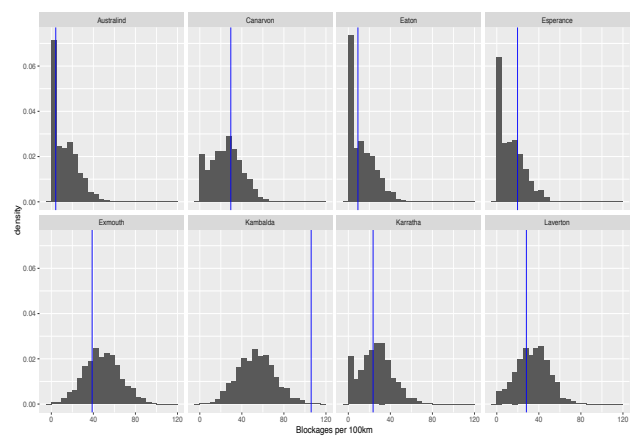

Figure 3: The figure presents the predicted distribution of the number of blockages per 100km in 2013 based on the 2005-2012 data.

The simulations have a number of attractive features. We can see that the distribution is markedly different across the eight regions. Some regions are predicted to

[3] The calculation is based on the restricted sample results. A 10% increase in PVC has a -3.18 x .10 effect on the log scale. We can transform this to a multiplicative $e^{-.318} = .73$ effect on the natural scale of blockages per km.

have more wastewater blockages than others in expectation. Some regions have more uncertainty in their predictions. The predictions match the actual number of blockages in blue reasonably well. Even Kambalda, which is clearly an extreme case, is still within the possibilities according to the model.

The simulation adequately captures the variation between the geographical areas even in the absence of cost data. The availability of reliable cost data could be used to further reduce uncertainty in the estimates.

The predictions in the figure are contingent on our choices for the explanatory variables in the regression. The advantage of our approach is that the simulation can be repeated (1) with different values for the explanatory variables to test the sensitivity of the predictions to different assumptions and (2) with multiple values for each explanatory values. The latter approach would reflect the uncertainty about for instance the weather or population growth at the start of the year 2013. The predictions would likely be more spread out to reflect this uncertainty

4.4 Setting a target

The aforementioned manager can use the simulations to set different targets for the regions. Due to the flexibility of the simulation approach, the manager can employ multiple methods to set those targets. We illustrate one possibility, appropriate to the specific setting of the Water Corporation. Assume that the Water Corporation wants to achieve a state-wide target of 30 wastewater blockages per 100km and that the eight regions are representative of the entire state of Western Australia. The state-wide number of blockages can easily be calculated as the weighted average of the regions' number of blockages with the network length as the weights.

We can set region specific targets according to the following process. First, we calculate the state-wide number of blockages per 100km for the 1000 simulations. The average state-wide blockages per 100 km is 20.9 and the median is 21. The state-wide performance measure is above 30 in 7.8% of the simulations. In other words, the simulations signal that the state-wide target of 30 is easy to achieve but it is not impossible to exceed it. We can now set the target as follows. We give every simulation run a weight according to how close the state-wide target is to 30, for instance the reciprocal of the absolute difference between the simulated state-wide performance and 30. For every region, we can calculate the weighted average over all simulations as the target. The intuition behind this methodology is that we give more weight to simulation runs that simulate state-wide performance close to 30. In the case of the Water Corporation, the targets would be set as in Table 2. Again, our methodology allows to us to make a distinction between different regions.

Australind	Carnarvon	Eaton	Esperance
18	31	14	21

Exmouth	Kambalda	Karratha	Laverton
57	53	37	36

Table 2: This table shows the targets for each region that correspond to a state-wide target of 30 blockages per 100km.

4.5 Performance evaluation

Lastly, we demonstrate how our methodology can be used to evaluate the performance of each region at the end of 2013 when the actual number of blockages is known. The supervising manager can of course directly compare the actual performance to the target in Table 2. However, a more sophisticated analysis is also possible. We can calculate a model based performance score for each region as how likely the region could have performed below its actual number of blockages. This performance score can be interpreted in the same way as the number of blockages. The best performing region is ranked as "1" and the higher the number, the worse the performance relative to the other regions.

	Model	Rank Model	Actual	Rank Actual
Australind	0.34	2	4	1
Carnarvon	0.62	6	29	6
Eaton	0.46	5	9	2
Esperance	0.71	7	20	3
Exmouth	0.28	1	39	7
Kambalda	0.99	8	106	8
Karratha	0.43	4	24	4
Laverton	0.36	3	28	5

Table 3: The table presents the model based performance score and the actual number of blockages per 100km for each region in 2013. Both measures can be interpreted in the same way. A higher score means worse performance. However, since the model based score is derived from a probability and is bounded between 0 and 1, it cannot be compared directly to the actual score. Therefore, we also report the rank of each region according to both performance measures is also represented in the table.

The model based performance score and actual score are given in Table 3 together with each region's rank based on both measures. Since the model based score is bound between 0 and 1, the ranks are reported to enable easy comparison between both methodologies of evaluating the geographical areas.

The results of this exercise show the value from our model based approach is not identifying the extremely good or bad performers such as Kambalda but to better distinguish the performance of areas whose actual performance is closer together. For instance, Exmouth with a high number of blockages (39 per 100km) is seen as the best performer according to our model. This illustrates how our model based approach takes into account the specific circumstances of Exmouth and rates its performance above the performance of for instance Australind with only 4 blockages per 100km.

6 CONCLUSION

Asset managers should be careful setting targets to asset performance measures. In this paper a framework is proposed and tested using an asset performance metric, pipe blockages, for asset managers of regional waste water assets. Statistical analysis is performed on pipe blockage data from 8 regions. Each region has quite different pipe network characteristics such as network length, age, pipe types, weather patterns and population and as a result differing annual pipe blockage rates. The challenge of determining an appropriate target for each region based on a common and transparent approach is met through the use of linear regression modelling and simulation. The process would allow the Water Corporation to develop site specific targets that take into account their network characteristics and their past performance. It would also allow investment decisions on preventative maintenance and/or renewals projects to be better targeted.

Other findings are as follows. Target setting involves a deep understanding of what influences the metric, and this requires data collection, cleaning and validation, as well as liaison with experts. It is important to establish how the metric can be influenced by factors beyond the immediate control of the asset manager, this affects its legitimacy. The target is based on what the other regions would have done given the same values for pipe type, population density, and rainfall. This approach attenuates the effect of a region performing badly for a number of years and as a result getting easier targets which would happen if you base the targets entirely on past performance from a single region.

The process can also be used to determine if a relationship exists between asset management activities such as preventative maintenance work and the pipe blockage metric. The absence of expected relationships raises questions about the appropriateness of the metric, the effectiveness of the work and/or the data quality.

The process produces targets that are fair, legitimate, and achievable given the resources and span of the control of the manager responsible. The process is also transparent so it is clear how the target values are determined.

REFERENCES

[1] Parida, A., *Asset Performance Assessment*, in *Asset Management - The State of the Art in Europe from a Life Cycle Perspective*, T. van der Lei, P.M. Herder, and Y. Wynia, Editors. 2012, Springer: Dordrecht.

[2] Tsang, A.H.C., A.K.S. Jardine, and H. Kolodny, *Measuring maintenacne performance in a holistic approach.* International Journal of Operations & Production Management, 1999. **19**(7): p. 691-715.

[3] Kaplan, R.S. and D.P. Norton, *The Balanced Scorecard: translating strategy into action* 1996, Boston, MA: Harvard Business School Press.

[4] ISO, *ISO 55000 Asset management — Overview, principles and terminology*. 2014, ISO: Geneva, Switzerland.

[5] Moynihan, D.P., *The Dynamics of Performance Management : Constructiing Information and Reform*. 2008, Washington, D.C.: Georgetwon University Press.

[6] ISO, *ISO 55001 Asset management — Management Systems - Requirements*. 2014, ISO: Geneva, Switzerland.

[7] National Audit Office, *Measuring the Performance of Government Departments*, N.A. Office, Editor. 2001, National Audit Office: London.

[8] Franceschini, F., M. Galetto, and D. Maisano, *Management by Measurement - Designing Key Indicators and Performance Measurement Systems*. 2007, Berlin: Springer.

[9] NCHRP, *Target-Setting Methods and Data Management to Support Performance-Based Resource Allocation by Transportation Agencies*. 2010, Transportation Research Board: Washington, D.C.

[10] NAMS Group, *International Infrastructure Management Manual*. 4th ed. 2011, Thames, New Zealand: National Asset Management Steering Group

[11] de Bruijn, J.A., *Managing performance in the public sector*. 2007, Utrecht: Routledge. 122.

[12] van Dooren, W., *Performance Measurement in the Flemish Public Sector: A Supply and Demand Approach*, in *Faculteit Sociale Wetenschappen*. 2006, K.U.Leuven: Leuven.

[13] Pidd, M., *Perversity in public service performance measurement.* International Journal of Productivity and Performance Management, 2005. **54**(5/6): p. 482-493.

[14] Smith, P., *On the unintended consequences of publishing performance data in the public sector.* International Journal of Public Administration, 1995. **18**(2): p. 277-310.

[15] Schoenmaker, R., *De ingeslagen weg (The chosen way)*. 2011, Delft University of Technology: Delft.

[16] Milgrom, P.R. and J. Roberts, *Economics, organization, and management*. 1992, Englewood Cliffs, N.J.: Prentice-Hall. xvii, 621 p.

[17] Ashley, R. and P. Hopkinson, *Sewer systems and performance indicators - into the 21st century.* Urban Water, 2002. **2002**(4): p. 123-135.

[18] Franco-Santos, M., et al., *Towards a definition of a business performance measurement system.* International Journal of Operations and Production Management, 2007. **27**(8): p. 784-801.

[19] Neely, A., et al., *Designing performance measures: a structured approach.* International

Journal of Operations & Production Management, 1997. **17**(11): p. 1131 - 1152.

[20] Bouckaert, G. and T. Auwers, *Prestaties meten in de overheid*. 1999, Brugge: die Keure.

[21] Bouckaert, G., *Measurement and meaningful management.* Public Productivity and Management Review, 1993. **12**(1): p. 31-43.

[22] Marsden, G. and P. Bonsall, *Understanding the role of performance targets in transport policy.* Transport Policy, 2006. **13**(3): p. 191-203.

[23] Marlow, D.R., et al., *Sewer Performance Reporting: Factors That Influence Blockages.* Journal of Infrastructure Systems, 2011. **2011**(17): p. 42-51.

[24] Arthur, S., H. Crow, and L. Pedezert, *Understanding blockage formation in combined sewer networks.* Water Management, 2008. **161**: p. 215-221.

[25] Jin, Y. and A. Mukherjee, *Modeling blockage failures in sewer systems to support maintenance decision making.* Journal of performance of Constructed Facilities, 2010. **24**(6): p. 622-633.

[26] Rodríguez, J.P., et al., *A database and model to support proactive management of sediment-related sewer blockages.* Water research, 2012. **46**(15): p. 4571-4586.

[27] Ugarelli, R., et al., *Statistical analysis and definition of blockages-prediction formulae for the wastewater network of Oslo by evolutionary computing.* Water Science and Technology, 2009. **59**(8): p. 1457-1470.

[28] Gelman, A. and Y.-S. Su, *arm: Data Analysis Using Regression and Multilevel/Hierarchical Models. R package version 1.8-6.* 2015.

[29] R Core Team, *R: A language and environment for statistical computing.*, ed. R.F.f.S. Computing. 2015, Vienna, Austria.: R Foundation for Statistical Computing.