Investing in the Future

Long-Term Optimization of Asset Replacement in the Collective Regional Gas Grids of The Netherlands

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Keywords: Asset ageing; Simulation; Optimal replacement policies; Risk management

1. Background

In this paper we discuss the results of a study titled *Long-Term View on Replacement Investments*. This study was conducted under the flag of *Netbeheer Nederland*, the association of Dutch electricity and gas grid companies, by a delegation of experts from all Dutch Distribution Network Operators (DNOs) for gas. In alphabetical order, these are: *Cogas, Delta Netwerkbedrijf (DNWB), Endinet*, *Enexis*, *Intergas*, *Liander*, *Rendo*, *Stedin*, and *Westland Infra*. We refer to Appendix A for an overview of the distribution of the regional gas grids over the DNOs.

The DNOs are public corporations whose shares are owned exclusively by provinces and municipalities. They fulfil an important social task: they are responsible for a safe, reliable, affordable, and sustainable energy supply. An intriguing challenge is the realization of a socially optimal trade-off between these elements; after all, a perfectly safe and reliable grid comes at a prohibitive price. This challenge fits in naturally with the mission statements of the respective DNOs. By way of illustration, Figure 1 shows the triangle used by Enexis to visualize its mission.

Figure 1 Mission triangle

The gas grids of The Netherlands were constructed mainly during a relatively short period in the 1960s, following the discovery of the Slochteren gas field in 1959. A substantial part of the corresponding gas components, or *assets*, is still present today. As a result of ageing of the grid infrastructure, postponement of replacement investments can lead to a deterioration of safety and reliability. At the same time, unnecessarily early replacements will have adverse consequences for the (short-term) affordability for customers. Knowing that the future is uncertain, it is the challenge for and also the craftsmanship of a DNO to replace aged or otherwise vulnerable parts of the grid infrastructure at the right time, in order to achieve the desired future-proof quality of service and low customer costs.

Since the current Dutch regulatory regime does not contain a direct financial stimulus to increase the replacement investments in gas grids, it is paramount that DNOs obtain insight into the effects of planned investments on the future development of company values such as safety, reliability, affordability, as well as sustainability.

2. Aims

In short, the objective of our study is the realization of:

- a collective view on the effects of asset ageing on relevant company values, based on common scenarios;
- insight into common strategies to anticipate these effects.

3. Methods

The following phases were completed:

1. Development of a numerical model that can simulate and provide insight into the effects of ageing and failing assets on company values. The model should contain the collective knowledge of and should be accepted by all DNOs. In addition, the model should provide answers to strategic questions; what asset replacement investments are necessary to fulfil preset targets on company values, and how can an optimal balance between company values be obtained. The model gives the DNOs the opportunity to show the supervisory authorities that they are taking the right measures to achieve the target figures for safety, reliability, and sustainability.

2. Determination of the current structure of the collective Dutch regional gas grids, including an inventory of the current asset populations and age distributions.

3. Determination of the current and estimation of the expected future failure behaviour of assets.

4. Determination and evaluation of common scenarios.

In the remainder of this section we will discuss the first three phases, which correspond to model development and input data collection, in more detail. The final phase, which corresponds to a comparison of the numerical results obtained for the common scenarios agreed on, will be discussed in section 4. We conclude with a summary of the main results of our study and some recommendations for further research.

3.1 Numerical model

In this section we give an outline description of the numerical model that has been developed for the purpose of the study. The study adopts an umbrella approach, in which different types of gas components, hereinafter *asset types*, are combined in one model, which forms an outline representation of the current collective regional gas grids. The central question is what the optimal replacement strategy is for these asset types during the next decades.

Aspects such as future innovations in materials used and changes in net concepts, e.g., substituting gas for heat pumps, are out of scope of the study. For the time being, it was decided to leave implementation risks, in particular the effect that an increase in the level of replacements will most probably lead to an increase in (the probability of) work accidents, out of scope as well. Reconstructions, in which assets are replaced incidentally, are within scope.

The model was programmed and implemented by the first author. Below, we discuss its input, mathematical core and output, respectively. The reference date for collected input data and hence also the start date of the planning horizon is 1 January 2010. In the remainder this date refers to the present.

In short, the model input comprises the following parts: the grid structure, the valuation of company values, the failure behaviour of assets and its effect on company values, and policy constraints. Where applicable, the input has been uniformized to facilitate the aggregation of data from the individual DNOs to a total for The Netherlands.

3.2 Grid structure

The structure of the collective Dutch regional gas grids has been determined by means of a collection of asset types. In total, 26 asset types are distinguished, distributed over 4 asset categories: gas stations, transmission mains (1-8 bar), distribution mains (<1 bar), and service lines. Asset types for mains include varieties of material, such as grey cast iron, steel, respective generations of polyethylene (PE), and polyvinyl chloride (PVC), the latter being the most commonly used material for distribution mains in The Netherlands.

Each asset type has a replacement type. In case an asset of a certain type is renewed, it is replaced by a new specimen of the corresponding replacement type. Appendix B gives a specification of all asset types and corresponding replacement types. Furthermore, each asset type has a current age distribution, obtained by aggregating the age distribution data collected by the individual DNOs. By way of illustration, Figure 2 shows the current age distribution of distribution stations.

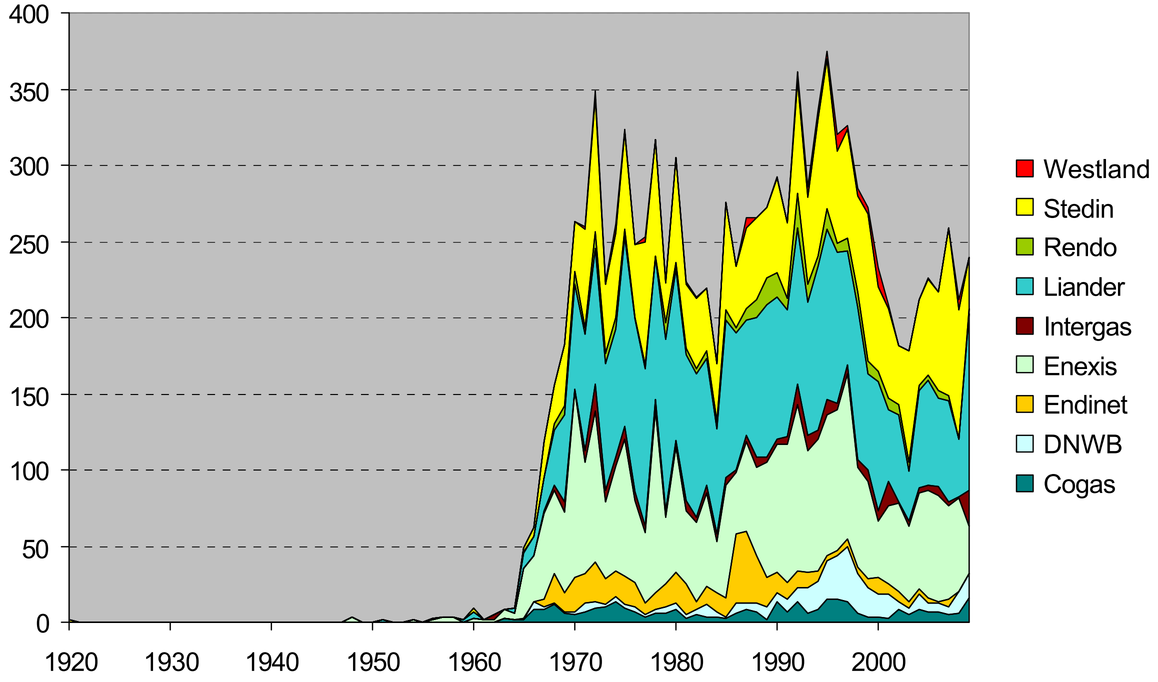

Figure 2 Age distribution of distribution stations

The graph shows the cumulative amounts, per year of construction, of distribution stations that are currently (still) present in the grid. We refer to Appendix B for an overview per asset type of the size and average age of the current asset population of The Netherlands.

3.3 Valuation of company values

In accordance with the international PAS-55 framework, all DNOs have adopted a Risk Based Asset Management (RBAM) system, covering a collection of company values. Our model distinguishes 4 company values: *Safety, Financial, Quality of Supply*, and *Sustainability*. These are mutually weighed by means of a monetary conversion. We consider nominal amounts; effects of inflation are left out of scope. The company value Financial is expressed in euros; it acts as a reference for the other (non-monetary) company values, which we discuss below.

Safety

With respect to safety the model follows the Dutch methodology of the *Safety Indicator Gas* (SIG) [4], developed by the collective DNOs in 2005. The SIG is based on the number of failures on the one hand and the risk per failure on the other. It breaks safety incidents and their severity down to asset types and failure causes. All this data is gathered nationwide since 2005 and comprises a large, ever-growing amount of gas leakages and safety incidents.

The SIG distinguished 6 categories, ranging from *Negligible* to *Catastrophic*, to classify the severity of an incident. The complete classification of incidents according to the SIG is shown in Table 1, which was taken from [4]. Note that the SIG does not only consider bodily harm, but also takes into account incidents with only financial consequences, such as collateral damage in case of an explosion without human presence, or social unrest in case of an evacuation, which is measured in terms of the duration of the evacuation multiplied by the number of stricken customers. In addition, note that the SIG adopts the so-called iceberg theory of Heinrich [1]. The categories are valued on an exponential scale, where for example an accident with injuries with absence is considered 100 times more serious than a dangerous situation and 100 times less serious than an accident with one fatality.

Classification	**Safety**	**Financial**	**Social unrest**
	accidents with bodily harm	**accidents with collateral damage**	**evacuation duration in customer hours**
Negligible	dangerous situation only	< 1k€	< 10
Small	near-accident or first-aid	1k€ - 10k€	10 - 100
Moderate	injury with absence	10k€ - 100k€	100 - 1,000
Considerable	serious injury with absence	100k€ - 1M€	1,000 - 10,000
Serious	one fatality	1M€ - 10M€	10,000 - 100,000
Catastrophic	multiple fatalities	> 10M€	> 100,000

Table 1 Classification of incidents according to the SIG

In its calculations our model considers one so-called *reference event* to represent the overall level of safety, where we have chosen an injury with absence. This refers to the classification *Moderate* in the SIG. In terms of the frequency of occurrence, this reference event is assumed to correspond to 100 dangerous situations and 0,01 accidents with one fatality. For the valuation we use the upper limit of the assigned financial range. This means we value a reference event, or the expected prevention of such an event, at € 100,000.

Quality of Supply

This company value, which is also known as *Reliability*, is expressed in terms of the *System Average Interruption Duration Index* (SAIDI). The SAIDI considers the yearly number of customer minutes lost (CML), which comprises the yearly weighted sum of the durations of interruption of supply times the numbers of stricken customers. The valuation is expressed as €/CML.

For the Dutch gas grids, contrary to the electricity grids, the level of quality of supply is not a key driver. The reason for this is that the current reliability of the Dutch gas grids is very high; the SAIDI is well under 1 minute per year, mainly because of a high degree of redundance due to the fine-mesh structure of the grids. Consequently, the (expected) effects will in advance pale into insignificance compared to the (expected) effects on the other company values, in particular Safety.

Sustainability

The company value Sustainability stimulates reduction of the carbon footprint. In our case this concerns the reduction of methane emissions. This has a substantial impact, since per mass unit methane is 25 times stronger a greenhouse gas than carbon dioxide [3]. By replacing leaking gas pipes by new ones, methane emissions are reduced. In particular, this precipitates the replacement of grey cast iron, which is characterized by substantially higher methane emissions than other materials.

The valuation has been determined as follows. Concerning the contribution to the greenhouse effect, 1 m^3 of CH_4 corresponds to 0.017 tons of CO_2. Based on a long-term trade price of CO_2 certificates of 20 €/ton, this results in a valuation of 0.35 €/m^3 of methane. For comparison, we note that at the time of our study, in 2011, the trade price of natural gas at TTF, the Dutch gas hub, for a 2012 supply contract was around 0.28 €/m^3. Based on a methane content of 80%, this results in the same value of 0.35 €/m^3 of methane.

3.4 Asset failure behaviour

Effects on the company values described above are caused by asset *failures*. Within the context of gas grids these concern primarily gas leakages. Furthermore, station components can fail without causing a gas leakage, but causing an interrupted or uncontrolled gas flow instead. In this section we discuss subsequently the modelled failure behaviour and the expected effects in case of a failure. In the remainder the term “failure” refers to a gas leakage or the otherwise failing of an asset.

Ideally, the decision if and when to replace assets is taken on the basis of as much information as possible, preferring factual observations to assumptions. In our study we have subdivided the determination of the failure behaviour of assets into historical failure behaviour on the one hand and expected future failure behaviour on the other. Although future failing will manifest itself only with the lapse of time, it can be estimated by means of available historical failure data and expert judgement. The model considers *age-dependent* failures, e.g., as a result of corrosion or wear, and *age-independent* failures, e.g., as a result of third party interference, in particular excavation work. Furthermore, failures are considered to be either *fatal* or *non-fatal*. Fatal means the asset is beyond repair and must be replaced correctively; non-fatal means the asset is still repairable.

For each asset type we have defined a failure curve, which incorporates both age-dependent and age-independent failure behaviour, and a fatality curve. For each age the failure curve indicates the failure probability in the next year and the fatality curve indicates the probability that such a failure is fatal. The model is flexible to such an extent that both curves can take arbitrary shapes. Besides simulating the physical failure behaviour of components, the fatality curve can be used to simulate a deficiency of spare parts or knowledge of obsolete components.

Using extensive failure data from uniformized data bases, including the SIG, the failure curves have been constructed and calibrated such that for each asset type distinguished by the model, the number of failures in the coming year as projected by the model is in exact correspondence with the actual, i.e., currently documented, average yearly number of failures. The proportion between age-dependent and age-independent failures was determined by means of failure causes distinguished by the source data bases. We refer to Appendix C for a detailed description of the construction of the failure curves.

3.5 Effects on company values

Asset failures lead to expected adverse effects on the company values. These are described briefly below.

Safety

For each asset type, the expected number of reference events in case of an asset failure has been derived from the SIG and (mandatory) reports of incidents to the Dutch Safety Board. It can be derived from the SIG [5] that the total current effect, over all asset types and DNOs, amounts to approximately 88 reference events per year. This number excludes incidents regarding failures of gasmeters, an asset type which is included in the SIG, but which has been excluded from our study. Including gasmeters, the total current number of reference events amounts to approximately 105. The reason why we have excluded gasmeters from our study is that nearly 95% of the recorded safety hazard is caused by (age-independent) assembly errors.

Financial

Asset failures lead to costs. The expected costs depend on the asset type. Non-fatal failures lead to costs of repair, whereas fatal failures lead irrevocably to corrective replacement costs. Auxiliary services, e.g., hiring a contractor with an excavator, are included in these costs. However, costs associated to environmental damage is considered under Safety.

By replacing assets pre-emptively, age-dependent failures (in particular of obsolete components) can be avoided. These entail preventive replacement costs, which are assumed to be lower than the corrective replacement costs associated with a fatal failure. The expected costs of non-fatal failures and preventive replacements have been determined using index prices and subsequent calculations for real, finished projects. The expected costs of fatal failures have been determined by means of a surcharge on top of the expected preventive replacements costs.

Sustainability

We consider methane emissions from mains and service lines. Based on a methodology already in use to determine the methane emissions from the Dutch gas grid [6], we have determined the average amount, in m^3, of methane emissions per gas leakage, for each of the corresponding asset types. The current total effect, over all asset types and DNOs, is in the order of 12 Mm^3 per year.

3.6 Policy constraints

The model allows for a variety of constraints, which can be used to enforce certain policies. For the purpose of our study we have implemented two constraints in particular. The first concerns minimum and maximum numbers of preventive replacements. These can be specified per year and both per asset type and asset category. Minimum amounts can be used to effectuate replacements commissioned by supervisory authorities, e.g., with respect to mains composed of brittle material. Maximum amounts can be used to model capacity or budget constraints. Moreover, this functionality offers the opportunity to evaluate existing replacement programmes, namely by equating the minimum and maximum amounts, which results in fixed numbers, without room for any optimization.

The second constraint concerns a safety risk tolerance. For each year in the future a maximum expected number of reference events can be specified; the optimization routine will then determine the most favourable replacement strategy that obeys this condition, or indicate that such a strategy does not exist.

3.7 Mathematical core

The model consists of an integral simulation of asset ageing and optimization of the replacement strategy. The model has perfect foresight. This means that for given input it knows what the future wil bring, in the sense that it computes one expected projection of the future. The model has been implemented such that both the input and the output are processed by means of a standardized Excel template. The mathematical core takes care of the interfacing from and to Excel and executes all necessary computations. The optimization problem has been formulated as a Linear Program (LP), which is solved by means of an industrial solver. The objective function is the net present value (NPV) of a weighted sum of expected risk costs and preventive replacement costs. The risk costs consist of failure costs and of monetized safety incidents and methane emissions. The objective function is minimized taking into account any constraints as described above.

To avoid boundary effects, a planning horizon of 100 years is assumed. However, in our discussion of the numerical results we will confine ourselves to the consequences for the next 10 to 50 years. We note that although it was decided not to anticipate a future “end of gas” in our study, this paradigm can be incorporated into the model by reducing the planning horizon accordingly. The NPV calculation is based on a discount factor of 6%, which follows the weighted average cost of capital (WACC) as determined by the Dutch energy regulator for the current regulation period for DNOs for gas [7].

3.8 Model output

The output of the model is presented on the granular level of individual asset types and future years as well as on an overall level. The main focus is on the expected performance with respect to the various company values and on the yearly numbers of replacements.

With respect to safety and sustainability this concerns first of all the expected yearly development of the number of reference events and amount of methane emissions, respectively. With respect to the financial consequences the expected development of the preventive replacement costs and failure costs are presented, as well as the corresponding NPV. In addition to the yearly numbers of replacements, the expected development of the average asset age is presented, both for individual asset types and for the overground grid (containing the stations) and underground grid (containing the mains and service lines).

4. Results

In this section we discuss the numerical results obtained from our model, based on common scenarios collectively agreed on. In this paper we focus on the results for The Netherlands as a whole. Nevertheless, by adjusting the input data of the model, in particular the age distribution of the asset base, the consequences for each of the individual DNOs are readily evaluated.

4.1 Common scenarios

We will focus on 3 of the scenarios considered in the collective study. These are listed in Table 2.

scenario	strategy	safety target
1	Plans issued in 2009	
2	Theoretically optimal	no
3	Theoretically optimal	yes

Table 2 Common scenarios

Scenario 1 is a base scenario, which evaluates the consequences of the replacement plans for the 5-year planning horizon 2010-2014 that were issued by the respective DNOs to the Dutch energy regulator in 2009. Table 3 gives an overview of these plans in terms of the weighted average replacement percentages of the existing populations.

	2010	2011	2012	2013	2014
Transmission mains	0.49%	0.41%	0.39%	0.31%	0.31%
Distribution mains	0.61%	0.66%	0.71%	0.74%	0.77%
Service lines	2.13%	2.33%	2.35%	2.34%	2.43%
Transit stations	2.06%	1.92%	1.92%	1.92%	2.06%
Distribution stations	1.80%	1.81%	1.65%	1.64%	1.64%
Delivery stations	1.15%	1.13%	1.11%	1.11%	1.11%

Table 3 Aggregate replacement plans dated 2009

As part of scenario 1, the percentages for 2014 are considered to be "structural", i.e., they are considered to apply to the further future as well.

Next, scenario 2 considers the theoretically optimal replacement strategy, based on the valuation of company values as previously discussed. Finally, scenario 3 considers the effect, compared to scenario 2, of a safety target. This embodies the strategic objective to maintain the current safety level towards the future. In this scenario the optimal replacement strategy is computed under the explicit condition that each year the expected number of reference events does not exceed 90, which is roughly the current level, as previously discussed.

4.2 Comparison of numerical results

Below we discuss the numerical results obtained for the scenarios described above, focusing on the implication for the level of safety and the level of replacement investments. We note that in each case the numbers and amounts presented concern *expected* values, projected by the model.

4.2.1 Safety

For each of the 3 scenarios, Figure 3 shows the development over the next 50 years of the level of safety, in terms of the yearly number of reference events, as projected by our model.

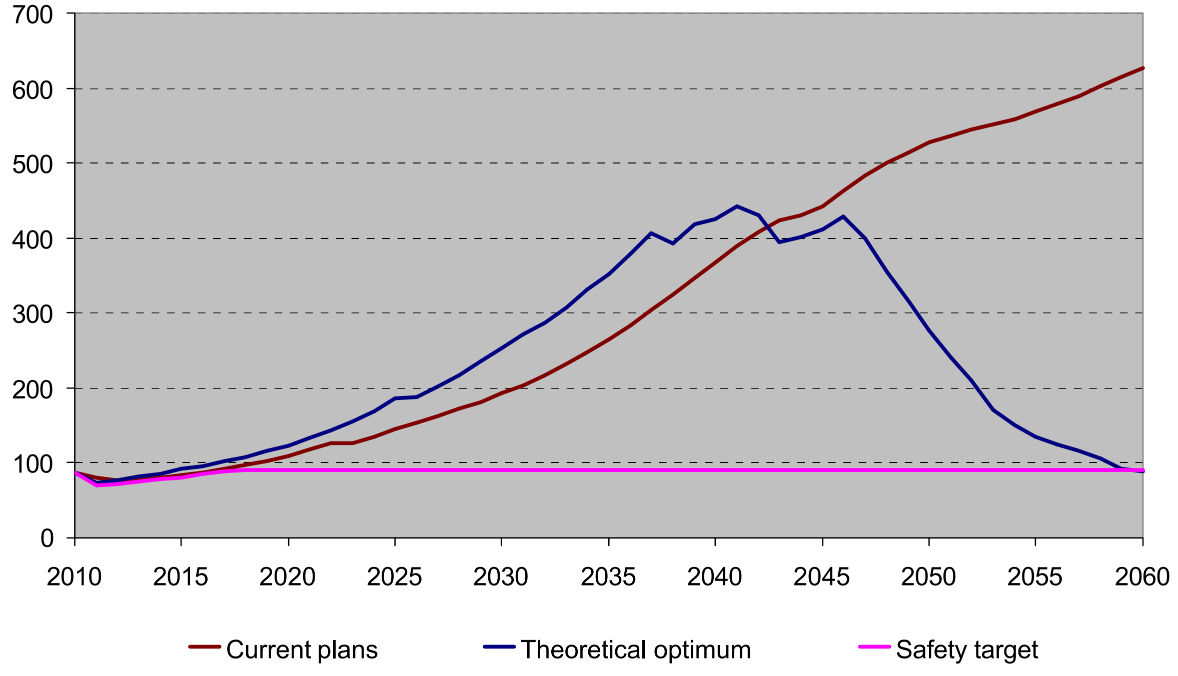

Figure 3 Projected development of the yearly number of reference events

We see from the graph that the current 5-year plans suffice to maintain the current safety level for the planning horizon it was issued for. However, if the plans are prolonged, then the yearly number of reference events will increase steadily. By 2030 the level will have doubled, compared to now. Hence, a structural continuation of the replacement percentages as recorded from the 2009 plans will be insufficient to achieve a long-term continuation, from around 2020 onward, of the current level of safety.

By not imposing any fixed replacement numbers, we enable the model to compute the theoretically optimal replacement strategy. Initially, we see that the resulting development of the yearly number of reference events resembles that of the previous scenario. However, around 2045, the curve ceases to increase; rather, it falls into a sharp decline and, remarkably, even arrives at the current level again around 2060.

Nevertheless, it can be clearly seen that the optimal strategy allows the yearly number of reference events to increase to as much as 5 times the current level. The explanation of this phenomenon must be sought in the valuation of such an event. Apparently, combined with the failure behaviour and age distribution of the grid, this valuation does not outweigh the costs of preventive replacements. The model makes an explicit quantitative assessment to establish an optimal trade-off between safety, sustainability and costs, and in this case this entails the acceptance of a higher number of reference events. Around 2045 the age distribution of the grid has apparently changed to such an extent that the balance in this trade-off has also changed. We can conclude that a valuation of € 100,000 per reference event is insufficient to achieve a long-term continuation of the current level of safety.

By imposing a maximum yearly number of reference events of 90, we can assess the feasibility of the strategic objective to maintain the current safety level towards the future. We can see from the graph that in expectation this is indeed possible. The other side of the coin is that this will inevitably require higher replacement investments. These consequences are discussed below.

4.2.2 Preventive replacement investments

We will now compare the 3 scenarios in terms of the resulting yearly preventive replacement investments and corresponding numbers of replacements over the course of the next 50 years. The projected financial consequences are summarized in Table 4.

	scenario		
50 years	Prolongation of current plans	Theoretical optimum	Safety target
Absolute value (M€)	11,075	17,258	19,803
Average per year (M€)	*222*	*345*	*396*
NPV (M€)	3,651	3,159	6,066

Table 4 Summary of projected replacement investments

Over the course of 50 years we see that the replacement investments corresponding to the theoretically optimal replacement strategy, i.e., scenario 2, are well over 50% higher than those corresponding to the current plans. Interestingly, its NPV is over 10% lower. This indicates that the theoretically optimal strategy defers its replacements further into the future than the current plans. The corresponding average yearly numbers of replacements during the next 10, 20 and 50 years are shown in Table 5, where the values for the next 20 years include the first 10 years and the values for the next 50 years include the first 20 years.

	10 years		20 years		50 years	
Stations	657	1.13%	1218	2.09%	1020	1.75%
Mains (km)	59	0.05%	205	0.17%	2184	1.77%
Service lines	107594	1.75%	93785	1.53%	120305	1.96%

Table 5 Average yearly numbers of replacements; scenario 2

We see that the optimal strategy replaces relatively few mains over the course of the next 20 years, but subsequently makes up for this deferral in the 30 years thereafter. In 2009 the International Gas Union (IGU) [2] stated that: "*Investment in distribution networks will increase, with a greater safety focus on renewal and maintenance of existing networks in mature markets. The estimated annual replacement level of networks will settle at around 1.6 percent of their total length.*" We see that in the long run, the replacement percentages resulting from scenario 2 of our study are much (stations and mains) or somewhat less (service lines) in line with this 1.6%.

Next, we see that maintaining the current safety level in the long run requires an increase in replacement investments of 15%, compared to scenario 2, over the course of the next 50 years. Moreover, the NPV almost doubles. Table 6 shows the corresponding average yearly numbers of replacements during the next 10, 20 and 50 years.

	10 years		20 years		50 years	
Stations	998	1.71%	1469	2.52%	1458	2.51%
Mains (km)	1227	1.00%	2733	2.22%	2326	1.89%
Service lines	132539	2.16%	132085	2.15%	149418	2.43%

Table 6 Average yearly numbers of replacements; scenario 3

Note that the numbers are considerably higher than in scenario 2, in particular with respect to replacements of mains in the next 20 years. In this respect, mains of brittle material, foremost grey cast iron, are of special interest. The DNOs have made agreements with the supervisory authorities concerning the replacement of this material. Figure 4 shows the development of the remaining population, measured in km, of grey cast iron mains, corresponding to the optimal strategy with safety target.

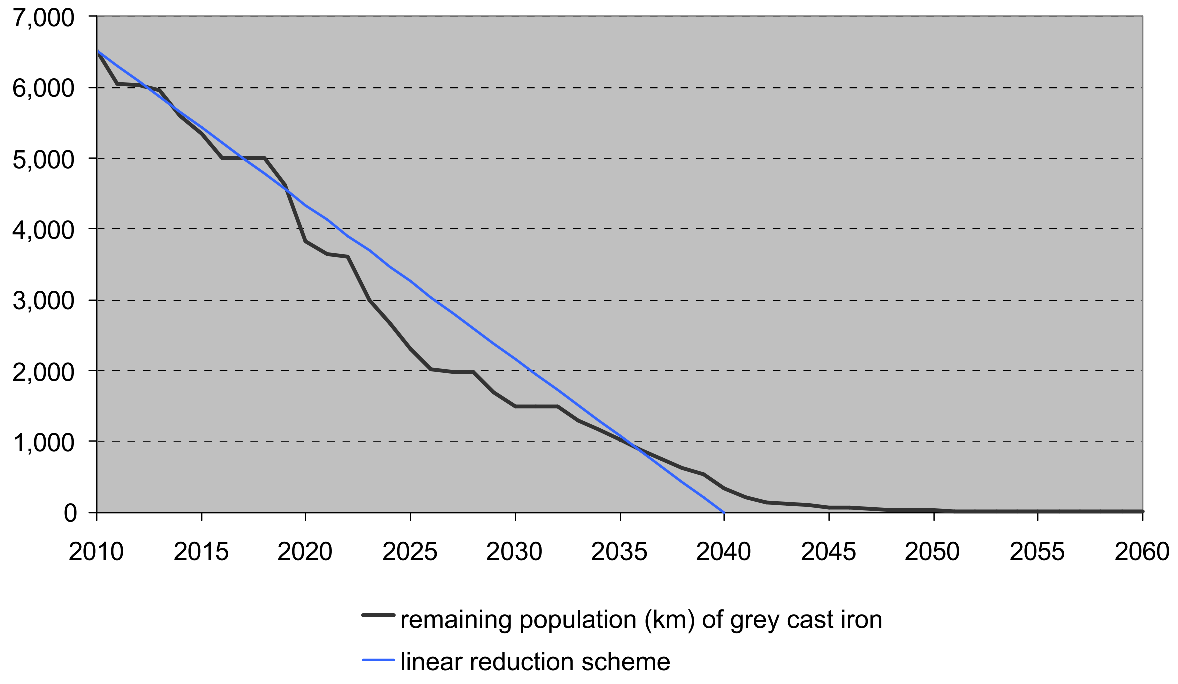

Figure 4 Development of the remaining population of grey cast iron mains; scenario 3

We see that by 2045 practically all grey cast iron will have been replaced, following a fairly regular yearly reduction scheme. The straight line shows a possible execution scheme, replacing 260 km per year. This scheme is in accordance with the plans previously communicated to the supervisor.

One other obsolete asset type we would like to address, is that of service lines that are susceptible to corrosion. Figure 5 illustrates that the amount of time the optimal replacement strategy with safety target uses to part with the remaining population is similar to that used for grey cast iron, namely in the order of 35 years, starting immediately.

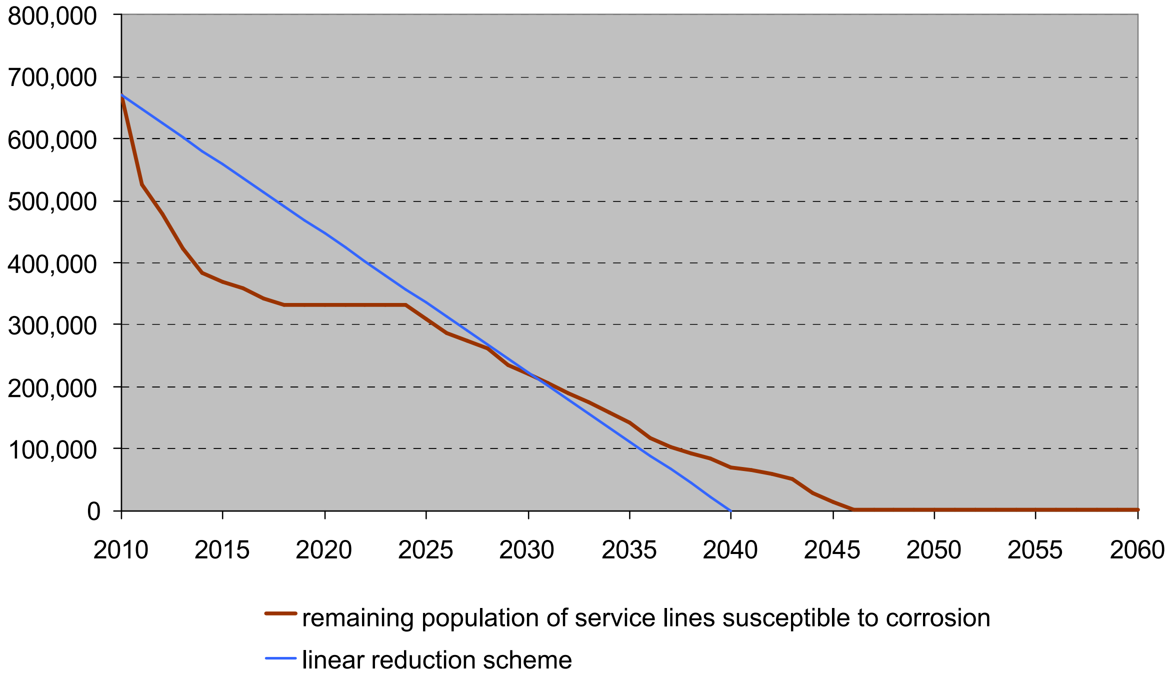

Figure 5 Development of the remaining population of service lines susceptible to corrosion; scenario 3

5. Conclusions

A lot of knowledge concerning the grid structure and failure behaviour of assets was gathered. A common view was created on the effects of asset ageing. A numerical model was developed which predicts future asset failures and their effects, and which calculates the theoretically optimal replacement policy, either with or without safety target.

Numerical results were obtained for both The Netherlands as a whole and the individual DNOs. A simulation based on the existing replacement plans of the respective DNOs shows the effect of a prolongation of the current policy:

- on average about 220 M€ per year worth of preventive replacements for the next 50 years;
- a preservation of the current level of safety for the next 5 to 10 years;
- subsequently, a continual deterioration of the level of safety.

We emphasize that this current policy is based on plans drafted in the past and an extrapolation of these plans into the future. In reality, plans are periodically adapted to new circumstances and insight. In this paper we have provided insight into what plans are required to realize an optimal trade-off between company values, based on the current state of knowledge of asset ageing.

Achieving an optimal trade-off for the next 50 years requires an average annual replacement investment level of about 345 M€, with an NPV of 3.2 bn €. Adversely, this trade-off involves a deterioration of the level of safety. Achieving an optimal trade-off under the condition that the current safety level is maintained in the long run, requires an average annual replacement investment of approximately 400 M€, with an NPV of 6.1 bn €.

Based on the results and scope of our study, we make the following recommendations for further research and consultation:

- Determine at a strategic level which (long-term) safety level the DNOs aim for.
- Determine the willingness and feasibility to increase replacement investments significantly, also in view of additional limitations, including the work force capacity, which is more likely to decrease than increase in the near future. The latter could be a topic for a follow-up study.
- A further intensification of the attention for data quality, since the quantitative results are highly dependent on complete and reliable data.
- A biennial evaluation and recalibration of the study, where model assumptions and estimations are adopted to advancing knowledge.

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Frequently used abbreviations

DNO	Distribution Network Operator
NPV	Net Present Value
SIG	Safety Indicator Gas

Appendix

A. Distribution of regional gas grids in The Netherlands

The distribution of regional gas grids in The Netherlands over the various DNOs for gas is shown in Figure 6. Liander and Endinet are part of the Alliander group of companies. Intergas was acquired by Enexis in 2011 and has been fully integrated as of 2012. The three largest DNOs, i.e., Enexis, Liander and Stedin, each serve close to 30% of the national customer base and collectively own about 85% of the total installed asset base.

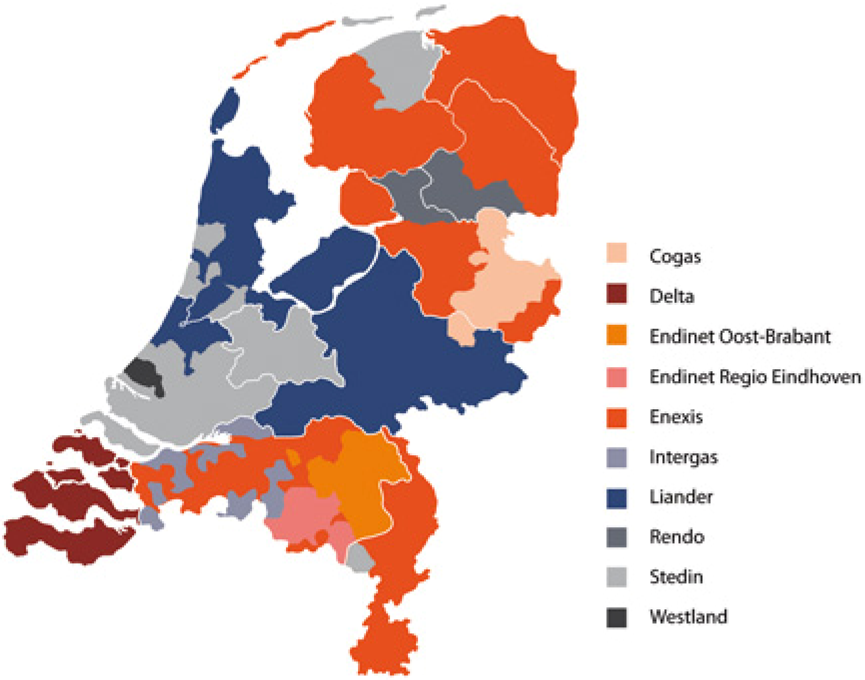

Figure 6 Distribution of regional gas grids in The Netherlands (source: www.microwatt.nl)

B. Specification of asset types

Table 7 shows the asset types distinguished by the model, as well as the corresponding replacement types and main units of measurement. The term "station" refers to the complex of installations, not the building itself. For each asset type, the last two columns of the table show the size and average age, in whole years, of the current asset population of The Netherlands.

number	asset type	replacement	unit	population	average age
	Stations				
1	Transit	1	#	739	22
2	Distribution	2	#	11,044	22
3	Delivery (metered)	3	#	11,469	20
4	Delivery (unmetered)	4	#	34,950	20
	Transmission mains (1 -8 bar)				
5	PE 1st generation 8 bar	7	km	150	38
6	PE 2nd generation 8 bar	7	km	52	25
7	PE 3rd generation 8 bar	7	km	628	6
8	PE 1st generation 1-4 bar	10	km	2,776	40
9	PE 2nd generation 1-4 bar	10	km	2,878	24
10	PE 3rd generation 1-4 bar	10	km	1,380	10
11	Ductile Cast Iron	14	km	880	35
12	Grey Cast Iron or Asbestos Cement	14	km	170	48
13	Steel Bitumen coated (-1972)	14	km	5,695	43
14	Steel PE coated (1972-)	14	km	8,093	24
	Distribution mains (<1 bar)				
15	PE 1st generation	17	km	3,072	39
16	PE 2nd generation	17	km	6,039	22
17	PE 3rd generation	17	km	2,239	9

18	Asbestos Cement	23	km	1,742	42
19	Ductile Cast Iron	23	km	1,180	30
20	Grey Cast Iron	23	km	6,343	47
21	Steel	23	km	5,393	38
22	PVC	23	km	21,492	41
23	PVC HI	23	km	53,139	21
	Service lines				
24	Susceptible to corrosion	26	#	669,665	28
25	Susceptible to subsidence	26	#	77,277	32
26	Other	26	#	5,399,727	21

Table 7 Specification of asset types

C. Failure curve construction

Mains are considered to be composed of individual pipe segments, comparable to service lines, each of which can fail during a year. Similarly, stations are considered as a collection of main components, each of which can fail during a year. For each DNO the average number of main components per station was determined, from which a weighted average was derived.

The yearly failure probability consists of an age-independent part and an age-dependent part. The age-independent part follows from the current failure behaviour. The age-dependent part can be modelled by means of a continuous failure probability distribution. For each asset type we have constructed such a distribution, assuming one basic shape. Using suitably chosen Beta distributions it proved to be feasible for each asset type to bring the number of failures as projected by the model into line with the real number of failures.

The failure probability distributions have been constructed as follows. The Beta distribution has parameters α and β and is defined for ages in the interval [0,1]. For each asset type i this interval has been stretched to $[0,T_{max}(i)]$, where $T_{max}(i)$ is the maximum lifetime assumed for assets of type i. The maximum lifetimes are expert estimations. We have fixed β to 2 and have adjusted α such that the modelled and real numbers of failures are in correspondence. In cases where this proved to be infeasible at first, we slightly re-adjusted $T_{max}(i)$ and then re-adjusted α.

Subsequently, for each asset type the yearly failure probabilities can be derived from the corresponding Beta distribution and age-independent failure probability. Furthermore, for each asset type the cumulative distribution function has been used to model the fatality curve. This means that the probability that a failure is fatal increases gradually with the asset age. By way of illustration, Figure 7 shows the modelled age-dependent failure probability distribution (blue curve) and cumulative probability distribution (pink curve) for ductile cast iron distribution mains, i.e., asset type 19. Both are a function of the asset age.

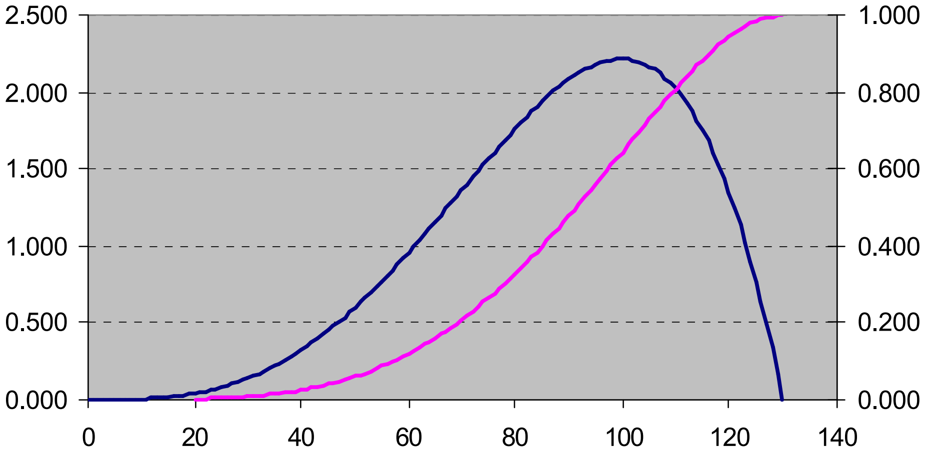

Figure 7 Modelled failure probability distribution of ductile cast iron distribution mains

The distribution for this asset type has been determined based on a basic shape (corresponding to a β of 2), the current yearly number of age-dependent failures, and an estimated maximum lifetime of 130 years. The general choice of a β of 2 results in a curve that starts out flat, to represent the phenomenon that the vast majority of assets has a normal lifetime, typically spanning several decades, during which it remains unscathed from ageing. Only after that time age-dependent failures will start to occur. In case of a Beta curve with a high(er) β, age-dependent failures would already occur in a much earlier stage. The pink curve, the cumulative probability distribution, should be interpreted as follows. In the first 20 years of their lifetime ductile cast iron distribution mains have practically no gas leakages; subsequently, about 5%, half, two thirds and 95% of the mains reaching a lifetime of 50, 90, 100 and 120 years, respectively, will have leaked at least once by then.