Optimization of replacement times of soft parts in gas pressure control systems

Author:
J.P. Dijks

Study program and institution:
Master Industrial Engineering & Management
Track Production and Logistics Management
Faculty of Behavioural, Management and Social Sciences (BMS)
University of Twente

Colloquium date:
December 18th, 2017

Supervised by:

University of Twente
Dr. M.C. Van der Heijden
Dr. E. Topan

N.V. Nederlandse Gasunie
R.L.J. Oosterhout

Preface

This thesis reports my last assignment in order to obtain the Master's degree Industrial Engineering and Management, track Production and Logistics Management, at the University of Twente. I would like to thank Gasunie for the opportunity to work on the assignment. Also, I want to thank René and Asim for their support during the months at Gasunie, and Matthieu and Engin for supervising me at the University of Twente. Finally, I would like to thank all supervisors and colleagues at Gasunie for all the lessons learned during the research.

The intention of this thesis report is to serve everyone who is interested in either the subject of maintenance optimization or the work I did during my thesis research. I hope you enjoy reading the report.

Peter Dijks
Groningen, 18-12-2017

Management Summary

The main goal of the reported research work was to develop a model to determine the optimal replacement times of certain parts, known as soft parts, of pressure control components at gas delivery stations of Gasunie. These replacement times are based on costs (replacement and failure costs) and availability effects. Availability effects, in this context, refer to the consequences of reaching a low availability level of gas delivery stations. A low availability level results in large costs and low scores on KPI targets. Next to these optimal replacement times, the effects of decreasing the permanent supply disruption levels on costs and availabilities are analysed. Permanent supply disruption is defined as *the impossibility to order all required units at OEMs or other allowed manufacturers.* The permanent supply disruption level is *the ratio of components of a component type that suffer permanent supply disruptions, to the total amount of components of that component type in the installed base of Gasunie.* The permanent supply disruption level could be decreased by either offering extra money to the OEMs to restart the production of the soft parts, or allowing the use of soft parts produced by other manufacturers. In the latter case, these soft parts are called 'replicated soft parts'. According to expert opinions, the main problem in finding alternative manufacturers are the certification issues in gas transport networks. Another option is the temporary use of replicated soft parts. In this case, the temporary use of soft parts is allowed in order to delay the required replacement of the failed obsolete complete component. Then, the obsolete complete component can be replaced somewhere during the year after the failure. This saves costs of launching an emergency installation. When using replicated soft parts only temporarily, less certification issues are expected compared to the permanent use of replicated soft parts. Therefore, also an analysis is reported towards the potential costs savings by allowing temporary use of replicated soft parts, for regulators that suffer permanent supply disruptions of soft parts. Furthermore, an analysis is reported towards the potential costs savings by opportunistic replacement of complete regulators that suffer permanent supply disruptions of soft parts.

For the analyses described in the paragraph above, the use of a discrete event simulation model in Excel VBA was selected. The most important conclusions after these analyses are:

1. The use of opportunistic and preventive age replacement thresholds were selected as most suitable in the case study. This was based on an analysis of the specific characteristics in the case study and a literature research towards determination of optimal replacement times.
2. Optimal preventive replacement time for regulator soft parts is 37 years in combination with an age threshold of 25 years for opportunistic replacement. Using these replacement thresholds for all regulators that do not suffer permanent supply disruptions, Gasunie could save only around 1,067 SC per year in comparison with replacing regulator soft parts only correctively, as is done currently. This costs saving seems very small compared to all extra required planning effort.
3. Sensitivity analyses showed that the potential costs savings are much higher for larger regulator failure costs. For this reason, opportunistic and preventive replacements of regulator soft parts could save costs especially for the GDSs suffering the largest failure costs. However, even if all regulators would suffer failure costs of 3,1 times the estimated average failure costs of regulators, then the optimal age replacement thresholds would lead to relatively low costs savings: only 2,73 SC per year.
4. Opportunistic and preventive replacement of soft parts of monitors and aid and pilot pressure regulators do not save costs.

5. There is a large potential in using replicated soft parts for pressure control components: decreasing the permanent supply disruption level of regulator soft parts from 0,65 to 0,4, leads to a costs saving of around 163,73 SC per year. For monitors and aid and pilot pressure regulators, these amounts are 36,27 and 24,73 SC per year, respectively.
6. Another option is to allow the use of replicated soft parts only for temporarily use after failure of obsolete regulators, in order to delay the required replacement of complete regulators and thereby preventing the required launch of emergency GDSs. This option would save around 60,53 SC per year.
7. In case that for none of the regulator types replicated soft parts will be used, opportunistic replacement of complete obsolete regulators saves costs for Gasunie. Optimal costs savings can be reached by using an opportunistic age threshold of 24 years of the soft parts of the obsolete regulator. The total costs savings per year are around 10 SC.

The listed conclusions of this study can be used by Gasunie to decide about possible replacement strategies of gas pressure control components in gas delivery stations, both for components that suffer permanent supply disruptions and for components that do not suffer these problems. Based on the conclusions, it can be recommended to maintain the use of corrective replacements of soft parts at gas pressure control components. Another recommendation is that the permanent supply disruption level should be decreased for as much as components as possible. If that is not possible, the temporary use of replicated soft parts is the best solution. If that is not possible as well, the obsolete regulators should be replaced at the first opportunity after the soft parts reached the age of 24 years.

Also, this paper reports a detailed context analysis at gas delivery stations of Gasunie. Based on this analysis, a number of recommendations is given to improve the efficiency of the maintenance optimization studies at Gasunie. The most important recommendations are:

1. Further develop a comprehensive list of fundamental basic assumptions of performance-related data of GDSs. The context analysis of this research reported in this paper could be used as input in improving this list.
2. Standardize the design and component types of the GDSs. Standardizing the newly renovated GDSs in one or more of the mentioned factors decreases complexity in both maintenance and maintenance optimization studies.
3. Categorize the installed base of GDSs based on the potential failure costs per GDS, and consider distinct maintenance concepts per group. Exact failure costs could differ per GDS. Because of this difference in failure costs, it might be useful to categorize the GDSs in groups depending on the failure costs per GDS, and study the effect of maintenance activities on total costs for each group.
4. The categorization of GDSs, as mentioned in the third recommendation, could be used for another purpose: the GDSs with the lowest failure costs could be used as test cases for new maintenance concepts.

Table of contents

Figures and tables

Figures

Tables

Dictionary and abbreviations

Dictionary English-Dutch

Aid and pilot pressure regulator	= hulpdruk- en stuurdrukregelaar
Aid pressure regulator	= hulpdrukregelaar
Delivering street	= leverende straat
Diaphragm	= membraan
End blockage	= uitlaatafsluiter
GDS	= gasontvangstation
HTL	= hoofdtransportnetwerk
Industrial GDS	= gasontvangstation leverend aan een of meerdere industrieën
Inlet pressure	= inlaatdruk
Outlet pressure	= uitlaatdruk
Pilot pressure regulator	= stuurdrukregelaar
Regional Network Company	= regionaal net beheerder
RNC GDS	= gasontvangstation leverend aan een regionaal net beheerder
RTL	= regionaal transportnetwerk
Safety blow off	= afblaasveiligheid
Safety shut valve	= afslagveiligheid
Stand-by street	= reservestraat
Start blockage	= inlaatafsluiter

Frequently used abbreviations

C.D.F.	= Cumulative Distribution Function
EGDS	= Emergency Gas Delivery Station
GDS	= Gas Delivery Station
OEM	= Original Equipment Manufacturer
P.D.F.	= Probability Density Function
RMS configuration	= Regulator, Monitor, Safety shut valve configuration
RNC	= Regional Network Company
RSS configuration	= Regulator, Safety shut valve, Safety shut valve configuration

Definitions

Age configuration: combination of values for the four age thresholds T1-T2-T3-T4, with T1(T2) as the age of the regulator (monitor) soft parts after which the first opportunity leads to the opportunity-based replacement of the regulator (monitor) soft parts, and T3(T4) as preventive replacement age for regulator (monitor) soft parts.

Age threshold for opportunistic replacement: the age of component *i* after which the first opportunity leads to an opportunistic replacement of component *i.*

Age threshold for preventive replacement: the age of component *i* to perform a preventive replacement.

Availability effects: the consequences of reaching a low availability level of GDSs. A low availability level results in large costs and low scores on KPI targets, as is explained in Sections 2.4 and 2.7.

Failure effect per failure: the ratio of failures with a specific failure effect to the total number of failures of that unit.

Failure rate: the non-cumulated number of failures of a unit of a specific age divided by the number of units that reached that age. Therefore, the failure rate is equal to:

$$failure\ rate = \frac{\mathrm{f(t)}}{1 - \mathrm{F(t)}}$$

with *f* as number of failed units at age *t* in the population, and *F(t)* as the cumulative number of failed units before age *t* in the population.

GD delivery failure: failure of a particular GDS to deliver the demanded flow of gas to the client.

GDS street: part of the GDS that is able to perform all functions required to deliver the required amount of gas to the outlet of the GDS autonomously.

Inventory availability: the possibility to replace component (parts) that suffer permanent supply disruption. This possibility exists because of available units on stock, undocumented inventories, and creative solutions by technicians to solve failures such as buying these parts at other gas transport companies.

Non-standalone GDS: GDS which function can be taken over by another GDS. The possibility of GDSs to take over the function of another GDS exists because of redundancy in the network of Gasunie. In some cases, the network contains possibilities to deliver gas to clients of a particular GDS via other GDSs. For non-standalone GDSs this possibilities could exist. However, this possibility depends on the capacity and demand at the moment of failure at both the failed and the redundant GDS.

Opportunistic replacement: replacement performed when an opportunity for opportunistic maintenance exists. Opportunities for opportunistic maintenance could be failures or scheduled downtime of another unit in the system.

Opportunity for opportunistic maintenance: the occurrence of a preventive or corrective replacement of any other component type in a GDS street.

Preventive replacement: replacement on a unit performed before the unit is failed, and without the occurrence of an opportunity as is the case for an opportunistic replacement.

Replacement scenario: depending on the failed component part (e.g. soft parts of a component, hard parts of a component, or the encapsulation of the component), replacement of certain part(s) is required. Based on the available spare parts, certain component parts are replaced. There are two extensions of the list of replacement scenarios in the case study: the possible use of emergency equipment, and changes of connected pipes in the GDS streets.

Replicated soft parts: the use of soft parts produced by other manufacturers than the OEM of the component.

Run-to-failure configuration: age configuration with age thresholds higher than the maximum useful lifetime of the components during the simulation period. This configuration represents the concept of performing no opportunistic or preventive replacements. In the Gasunie case, this age configuration is 43-43-73-73, as explained in Section 5.1.

Street: see “GDS street”.

Street delivery failure: failure of a GDS street to deliver gas to the outlet of the GDS.

Permanent supply disruption: the impossibility to order a certain (part of a) component at OEMs or other allowed manufacturers. If the supply of a component type is not disrupted, it can be assumed that there are always components of that component type available at the central warehouse of Gasunie.

Permanent supply disruption level: ratio of components of a certain component type for which the supply is disrupted, to the total number of components of that component type. So, if half of the installed base of e.g. regulators suffers from permanent supply disruptions of its soft parts, then the permanent supply disruption level of soft parts of regulators is 0,5.

Standalone GDS: GDS which function cannot be taken over by another GDS. The possibility of GDSs to take over the function of another GDS, has to do with redundancy in the network of Gasunie. In some cases, the network contains possibilities to deliver gas to clients of a particular GDS via other GDSs. For standalone GDSs, this is not possible.

Transport break: failure to deliver gas to the connected industry or to the gas transport network of the Regional Network Company. A transport break is caused by a GDS delivery failure of a GDS which function cannot be taken over by another GDS at that moment.

Notes for the reader

In order to avoid misunderstandings, the following statements must be made:

- Please note the difference between "availability" (percentage of time that a unit is able to perform its function) and "inventory availability" (the presence of a unit in the stock);
- Please note that a GDS street has nothing to do with a street containing houses. If that is not clear, please read the Section "Definitions" and Section 2.1 carefully;
- References to [1], [2], [3] et cetera are references to internal documents of Gasunie. The intention of these references is to inform Gasunie employees about the sources of information used during this research;
- In this public version of the thesis, all costs are expressed in 'SC' instead of in an existing currency such as Euros, because of confidentiality issues. For the same reason,, the y-axis of the figures showing the failure rates of soft parts, are hidden, as well as the parameters of the failure rate distributions. These are the figures in Section 2.5 and Appendix N. Also, due to confidentiality issues as well, the information in a number of tables and appendices is deleted. In the latter cases, the text before the tables and appendices explain the used method and the type of data that is missing;
- The confidential version of this thesis is saved by Gasunie. If the reader is interested in the hidden information, the confidential thesis might be requested at Gasunie. The contact information of Gasunie can be found at www.gasunie.nl.

1. Introduction

1.1 Introduction

As stated by Nowakowski and Werbińka (2009), most articles in literature regarding optimal replacement times of components are too oversimplified to be useful in practice. Van Horenbeek et al. (2010) mention this gap between academic maintenance optimization models and their application in practice as well. Van Horenbeek et al. (2010) argue that both the existence of this gap and the importance of closing this gap, are already recognized by researchers for years; however, researchers did not succeed to close this gap yet. Dekker et al. (1997), Scarf (1997) and Garg and Deshmukh (2006) give a number of causes of the gap between theory and practice. These include the following causes: the academic models are hard to understand, there is little interest in academic publications by companies, academic models often focus on the wrong type of maintenance, most articles are written for mathematical purposes only, and the focus of researchers is mainly on the development of new optimization models and less on the applicability of these models.

Because of the gap between theoretical and practical relevance, companies could have difficulties in finding an easy to implement model to determine optimal replacement times for their specific context. One of the companies striving to solve this challenge is Gasunie. Major activities of Gasunie are management and maintenance of the gas transport network in The Netherlands. The research described in this paper provides Gasunie more insight in how to use the models and methodologies in literature and practical considerations to develop a model to determine the optimal replacement times of components, based on maintenance costs and availability effects, in a complex situation.

The model will be developed in a case study on pressure control components in GDSs in Gasunies transport network. The decision to use this subject as case study is motivated by the relatively large share of failures caused by these components in the total number of failures at these stations. Also, there are a number of practical complexities that occur specifically at the pressure control components in GDS. These will be explained later.

The main value added to Gasunie by this research is the development of a model to determine the optimal replacement times of (parts of) components, based on costs and availability effects. With this model, it is possible to determine an optimal time to replace these (parts of) components, and the expected costs and expected availabilities belonging to this replacement time. Gasunie, and other organizations, should be able to use (the method to develop) this model for other projects and case studies. The main value added to literature by this research is applying a method to develop an optimal replacement timing model in a complex case study, which could be used as an example in efforts to increase the usefulness of similar models in practice.

1.2 Problem background

The organization where this research is performed is Gasunie. Gasunie owns, manages and maintains the large pressure gas transport network in The Netherlands and a part of Germany; also, Gasunie invests in various other projects related to renewable gases and gas transport outside the Netherlands. Gasunie was founded in 1963 by the Dutch state. The transport network contains approximately 16.000 kilometers of pipes and is connected to various international pipe lines and installations. Approximately 125 milliard cubic meters (25% of the European gas demand) a year flows through the Gasunie network.

The developed model will be applied on pressure control components in GDSs. The function of the pressure control components and the effects of failures are explained in Chapter 2. The decision to use this subject as case study is motivated by the relatively large share of failures caused by these components in the total number of failures at these stations. Also, there are a number of practical complexities that occur specifically at the pressure control components in GDS, resulting from amongst others the variety in installed base, the requirements in the replacement policies, the maintenance concepts and the required resources to replace components. These complexities are explained in the following paragraphs. These complexities are interesting to study for Gasunie as well. For these reasons, the case study of soft parts of gas pressure control components is chosen.

There is a complex installed base of the pressure control components. The installed base consists of nine manufacturers and various types and diameter sizes per manufacturer. Nearly all types contain soft parts that are uniquely produced for a particular type and diameter size. Also, the various types and diameter sizes limit the options to replace components without adaptations in the size of the connected pipes, as will be explained further in this part. Because of the variety in types in the installed base and the distinct sizes per type, it is hard to manage the availability of components necessary to replace failed components in a small time frame. Therefore, the replacement strategy of Gasunie with respect to (parts of) pressure control components is hard to manage.

One of the possible improvements in the maintenance concept of the pressure control components is the replacement strategy of the soft parts. Until 1997, all soft parts were replaced preventively every four years. In 1997, Gasunie decided to stop the preventive replacements of soft parts, because the number of maintenance induced failures were relatively high: there were twice as much failures in the first year after replacement as in the other years. Most soft parts were not replaced after their last preventive replacement. For most of the GDSs, this last preventive replacement this was between the start of 1993 and the start of 1997. There is a small number of GDSs that had their last preventive replacement of soft parts between 1991 and 1993. The latter group of GDSs was part of a test case in order to analyze the effects of ending the preventive replacements. Therefore, the average age of the soft parts is around five times higher than the replacement age in the maintenance concept before 1998. Therefore, a number of maintenance engineers argue that the soft parts might soon reach an age where preventive replacement would be less expensive than the current maintenance concept, containing corrective replacements only. In that case, the maintenance concept might be improved by using preventive replacements of soft parts. Also, KPI targets regarding availability of GDSs are met during the last years (see Section 2.6); however, if the arguments of the mentioned maintenance engineers are right, then the scores on KPI targets might decline in the future. Therefore, it would be useful for Gasunie to test the statements of the mentioned maintenance engineers.

The replacement policy of Gasunie on the pressure control components leads to extra constraints in the replacement strategy. For most soft parts, the policy is to allow the replacement by OEM parts only. A large number of components and their soft parts are not available anymore at the OEM. This unavailability is caused by the fact that the components are much older than their expected lifetime: some pressure control components are 60 years old, while their expected lifetime was 25 years. For a small number of soft parts, Gasunie bought replicates at specialized companies. However, a large number of component types suffer permanent supply disruption, which means that the parts are not available anymore at the OEM, while Gasunie does not allow replacement by other manufacturers´ products. Therefore, a required replacement of a soft part often leads to a required replacement of a complete component. The replacement of a complete component is far more expensive, takes longer repair time and is more complex to manage than a replacement of soft parts, as will be explained in the next paragraph.

The replacement of a complete component often requires various resources. When a complete gas pressure component needs to be replaced, there is a large probability that the failed component needs to be replaced by another type, with another size. This is caused by the fact that for a large part of the current components, the supply is disrupted, as explained in the last paragraph. For such a replacement, a pipe is required with a specific size. Because of the complexity caused by the large number of distinct types and sizes, this usually requires a long repair time and high costs. A large number of failures in a short time frame could possibly result in long lead times to deliver all required pipes. When the repair time is longer than Gasunie polices allow, an emergency installation needs to be placed. An emergency installation solves the problem that after failure of a street or GDS, it is possible that there is no redundancy anymore. The emergency installation then ensures redundancy and thereby the required availability level. There is only a limited number of emergency installations available. Therefore, it would be useful for Gasunie to study the consequences of aging of soft parts in the coming years, for the demand of emergency installations.

The redundancy in the gas network of Gasunie could decrease the consequences of failures in pressure control components. As will be explained in Section 2.1, there is redundancy in streets per GDS and in RNC GDSs per client. However, when the replacement activities and the redundancy in the network cannot prevent the occurrence of a non-delivery of gas to a part of the network, the consequences could cost a large amount of money, which is explained in detail in Section 2.5.

As is described in the previous paragraphs, there is a high complexity in the range of possible effects of failures of pressure control components on costs and availability. It is hard to quantify the costs and availability effects for all scenarios. Therefore, the case study on pressure control components is a perfect case to develop the model to determine the optimal replacement times of (parts of) components, based on maintenance costs and availability effects. Due to the complexity in input in the case study, from costs and availability effects of failures, it is a perfect case to show how to handle complexities in the model. Next to this, it can be concluded that the current policy to replace (soft parts of) pressure control components only correctively, could possibly result in the situation that the number of failures in the installed base is too high to solve in a short time frame with available resources. It could be useful for Gasunie to get more insight in this statement. For these reasons, the model to determine the optimal replacement times of (parts of) components will be developed using a case study on gas pressure control components.

A possible solution to the problem regarding permanent supply disruptions, is decreasing the permanent supply disruption level by either offering extra money to the OEMs to restart the production of the soft parts, or allowing the use of soft parts produced by other manufacturers. The latter option will be called the use of ‘replicated soft parts’ in this study. If the OEM of a certain regulator type restarts the production, or an alternative manufacturer is found for a certain regulator type, then there is no permanent supply disruption anymore for these regulators. According to expert opinions, the main problem in finding alternative manufacturers are the certification issues in gas transport networks. Another option is the temporary use of replicated soft parts. In this case, the temporary use of soft parts is allowed in order to delay the required replacement of the failed obsolete complete component. Then, the obsolete complete component can be replaced somewhere during the year after the failure. This saves costs of launching an emergency installation. When using replicated soft parts only temporarily, less certification issues are expected compared to the permanent use of replicated soft parts. The options described in this paragraph, will be analyzed as well. These analyses are reported in Chapter 6.

1.3 Theoretical framework

This theoretical framework gives a small introduction in the importance of maintenance and studies in the literature that could provide insights that might help to develop a model to determine the optimal replacement times of (parts of) components, based on costs and availability effects. A more extended literature research will be reported in Chapter 3, after the context of the case study is explained in more detail in Chapter 2.

Maintenance is defined as "a set of activities with the purpose to restore the unit to a state in which it can perform the functions for which the unit is designed" (Dhillon, 2002). Muchiri et al. (2011) list five objectives of maintenance: "ensuring the plant functionality (availability, reliability, product quality etc.); ensuring the plant achieves its design life; ensuring plant and environmental safety; ensuring cost effectiveness in maintenance; and effective use of resources (energy and raw materials)". Various researchers highlight the importance of maintenance. Waeyenbergh & Pintelon (2002) point out that well-performed maintenance could decrease lifecycle costs and increase overall performance of the company. Fraser et. al (2015) mention that an increasing number of industry managers consider maintenance as a profit generating function; the same holds for the view that maintenance can be crucial for the long-term future of organizations.

Maintenance policies can be divided in two categories: corrective maintenance (CM) and preventive maintenance (PM). Corrective maintenance is a policy where the repair or replacement of a unit is performed after it has failed. Tsang (1995) gives two possible drawbacks of these policies: high levels of machine downtime and high maintenance costs to solve sudden failures. Preventive maintenance is a policy where the repair or replacement of a unit is performed before it has failed. Advantages of preventive maintenance are that it could decrease failure costs and machine downtime, and increase safety and product quality (Usher et al., 1998). However, a drawback of PM policies is that maintenance usually is done more often compared to CM policies.

According to experts at Gasunie, main drivers of failures for the case study in this research are calendar time and usage (see Appendix C). These drivers of failures suggest that literature towards time-based maintenance could provide insights in developing a model to determine the optimal replacement times of (parts of) components. Time-based maintenance is one of the most frequently used maintenance policies.

One of the three policies belonging to the range of commonly used preventive maintenance policies are the already mentioned time-based maintenance (TBM) policies (De Jonge, 2017). TBM is a maintenance policy in which maintenance actions are performed periodically with predetermined schedules (Peng et al., 2010). TBM can be based on calendar time and usage time; other characteristics of this policy are described in Chapter 3. Next to TBM, there are two other commonly used preventive maintenance policies: condition-based maintenance (CBM) and opportunistic maintenance (De Jonge, 2017). When using CBM, maintenance activities are scheduled based on information collected through condition-monitoring processes, such as data about the degradation level of components. These condition-monitoring processes can occur either continuously or during periodic inspections. Opportunistic maintenance policies are often used when dependencies exist between units in multi-unit systems. Under opportunistic maintenance policies, preventive or corrective maintenance activities at a certain unit are used as an opportunity to maintain dependent units as well. A relatively new type of PM policies is the concept of predictive maintenance policies. These policies use process parameters in order to evaluate the condition of units; based on these evaluations, maintenance activities are scheduled (Park et al., 2016). More details of the policy types described in this paragraph are given in Chapter 3.

The described policies could possibly be useful in limitation. Limitation is "the determination of preventive maintenance thresholds in order to minimize failure and replacement costs" (Gits, 1992). Two conditions are required for the usefulness of performing limitation: failure rates must be increasing and the costs of a single PM activity must be smaller than the costs of a single CM activity. For the Gasunie case, both conditions hold. When these conditions hold, the optimal timing of a preventive maintenance activity can be determined. This is done by comparisons between the average total maintenance costs per time unit for each limit or set of limits (Gits, 1992). Two important questions to solve the problem in the described case study are therefore: which policy can be used and which limits do result in optimal costs and availability of the pressure control components.

After the context of the case study is explained in more detail in Chapter 2, Chapter 3 will contain the report of a more extended literature study that is done in order to adapt literature models to the Gasunie case.

1.4 Research objectives

The main goal of this research is to develop a model to determine the optimal replacement times of soft parts of pressure control components, based on costs and availability effects. With this model, it should be possible to determine at which lifetime (or other condition) per component a preventive or opportunistic replacement must be performed in order to achieve optimal replacement times, and which expected costs and expected availabilities belong to this replacement times. By using pressure control components as case study, optimal replacement times for the pressure control components can be recommended to Gasunie, including an indication of the costs and availability effects corresponding to these replacement times. Availability effects, in this context, refer to the consequences of reaching a low availability level of GDSs. A low availability level results in large costs and low scores on KPI targets, as is explained in Sections 2.4 and 2.7.

Next to these optimal replacement times, the effects of changes in various resource supply disruption parameters on the optimal costs and availabilities are interesting. Permanent supply disruption, in this context, is defined as *the impossibility to order all required units at OEMs or other allowed manufacturers.* As explained in the problem statement, there is permanent supply disruption of a large part of the (soft) parts of pressure control components. Changes in the permanent supply disruptions of both the soft parts of the obsolete components and other required replacement resources will be analysed. By analysing the results of changes in these parameters on the optimal costs and availabilities, recommendations can be done for changes in the permanent supply disruption of replacement resources, in order to decrease costs and availability effects.

1.5 Scope

The model should provide the determination of:

- The optimal thresholds to replace (parts of) components preventively or opportunistically, based on costs and availability;
- The effects of changes in various resource supply disruption parameters on the optimal costs and availability levels.

The following factors are out of scope:

- Changes in maintenance concept with respect to the intervals of inspections. The inspection intervals are set in the Dutch law and will be taken for granted for the case study as well.
- End of lifetime/last time buy decisions.

1.6 Research questions

In this report, the following questions will be answered:

1. Which aspects in the Gasunie case influence the decision which maintenance policy to use?
2. Which models in literature can be used to determine optimal replacement times of components based on costs and availability effects?
3. How can these models be adapted to develop a model to determine the optimal replacement times of soft parts of Gasunies pressure control components?
4. What are the optimal replacement times for Gasunies soft parts of pressure control components?
5. Which recommendations can be made based on the effects of decreasing permanent supply disruption levels on the optimal replacement times, costs and availabilities for the pressure control components?

1.7 Research steps

The research steps follow from the research questions. Chapter 2 reports a detailed description of a context analysis, which answers research question 1. The second research question is answered in chapter 3. This chapter reviews a literature research that is done according to the requirements of the model. These requirements are based on the identified potential improvements and risks of the maintenance concept in the second chapter. Chapter 4 presents the model developed for the case of Gasunie. Chapter 5 gives the optimal replacement times of soft parts of gas pressure control systems. Chapter 6 gives the results of various sensitivity analyses. Finally, conclusions, discussion and recommendations are reported in Chapter 7.

2. Analysis of the current situation

This chapter starts with descriptions of Gas Delivery Stations (GDSs), GDS components and the current maintenance concept of GDSs. Then, the current replacement scenarios of soft parts, hard parts and complete pressure control components are given, including the costs and replacement durations per scenario. Next, costs of failures of pressure control components are provided. Then, this chapter provides the results of data analyses towards the failure rates per component, scores on KPIs with respect to availability of components, and frequencies of failure effects. Finally, conclusions of these analyses of the current situation are given.

Some information in this public version of the thesis is hidden, due to confidentiality issues. As is explained in the Section 'Notes for the reader', just before the start of Chapter 1, (parts of) the confidential version can be requested at Gasunie.

2.1 Description of the components in the case study

Description of a gas delivery station (GDS)

The Gasunie natural gas transportation system contains a central transmission grid (HTL) with a pressure level around 66 bar, and regional transmission grids (RTL) with a pressure level around 40 bar. A Gas Delivery Station is a station where the gas is delivered from the RTL network to the client. The client can either be a regional grid company, in which case it is called an RNC GDS, or a power plant or other industry, in which case it is called an Industrial GDS. There are 675 RNC GDSs and 325 industrial GDSs.

Depending on the customer, the gas is supplied at different pressures. With most clients, Gasunie agreed to deliver the gas at a pressure between 3 and 8 bar. The required decrease in pressure when delivering the gas from the RTL to the client on the right pressure, takes place in a GDS.

The main functions of a GDS are:

- gas pressure reduction and control;
- gas heating, to make sure the delivered gas is at the right temperature (usually around 5 degrees Celsius), after the gas is cooled down due to the decrease in pressure level;
- measurement of the flow and quality of the delivered gas, to determine the price of the delivered gas;
- odorization, in case this is not already done at a previous station.

The Gasunie transport network contains approximately 1000 GDSs. Most GDSs consist of two or three streets; a relatively small number of GDSs contains four, five, or six streets. All streets are built in a *(N-1)*-out-of-*N* setting, with *N* as number of streets per GDS and *N-1* as required number of delivering streets during demand peaks. A GDS in a 2-out-of-3 setting is able to automatically change into a 1-out-of-3 setting when demand is low; same holds for other values of *N*. Each street contains the required components to perform all required functions autonomously. In Figure 1, a description of the order of the components in a GDS street is shown. The required components perform the following functions:

a. gas filtering;
b. gas heating;

c. gas pressure safety;
d. gas pressure control;
e. flow measurement;
f. closing/blocking the installation.

In Figure 1, the pressure control system is marked. The gas pressure control system is important in this research, because the case study will be on this system. The gas pressure control systems contains one or two major components and between one and four smaller components, which all together control the gas pressure level in the street. These components are described in the next paragraph.

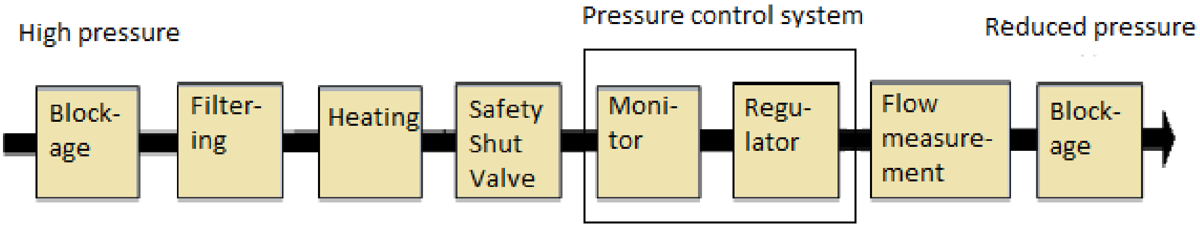

Figure 1: Functional depiction of a GDS street

Figure 2 depicts a GDS containing two streets and a boiler system containing several boilers shared by the two streets. The input of the header on the left is the Gasunie RTL transport network. The output of the header on the right is the network of the client. The two streets form a 1-out-of-2 system. As already mentioned, a GDS can contain more streets as well. The upper part of Figure 2 shows an RMS street; the lower part shows an RSS street. The meaning of RMS and RSS is described the following paragraphs.

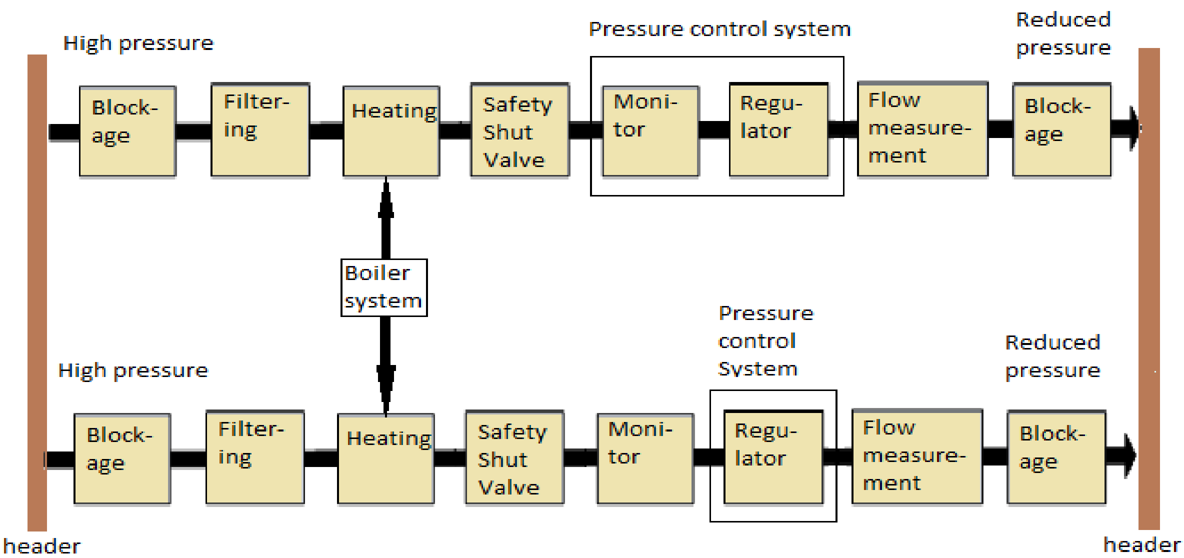

Figure 2: A GDS with an RMS and an RSS street

The network of Gasunie is built in such a way, that it is often possible to deliver gas via other RNC GDSs to the clients of failed RNC GDSs. This depends on the connections in the gas transport networks of both Gasunie and its clients (the Regional Network Companies), and on the demand at the moment of failure: in the winter, gas demand is often too high to compensate a failed GDS by another GDS. Standalone means that there is no connection to the clients possible via other GDSs. More information can be found in Appendix O.

Description of the pressure control system

The pressure control system contains one or two major components. These are either:

- A Regulator and Monitor in a configuration with a single Safety shut valve (RMS configuration), where the Regulator and Monitor together form a 1-out-of-2 pressure control system and the Monitor and Safety shut valve together form a 1-out-of-2 pressure safety system, or;
- A Regulator in a configuration with two Safety shut valves (RSS configuration), where the two safety shut valves together form a 1-out-of-2 system.

The functioning and differences between the two configurations is explained in the following paragraphs.

The main functions of the gas pressure level control components are:

- Pressure reduction of incoming gas to the pressure level that was agreed with the client;
- Assuring the gas delivery by the back-up street when the pressure level delivered by the delivering street is too low.

The main function of the safety shut valves is to assure the delivering street closes when the gas pressure exceeds a certain pressure level. In contrast to the regulator and monitor, a safety shut can only close or open a street, while regulators and monitors can vary between open, close and all levels between open and close. Appendix D gives detailed explanation and illustrations of the components.

In the RMS configuration, the regulator controls the gas pressure initially. If the regulator fails, the pressure increases and the monitor, which is set to work at a higher pressure level than the regulator, takes over the pressure controlling function. If the monitor fails as well, the pressure increases again. Then, the safety shut valve, which is set to work at a higher pressure level than the monitor, shuts down immediately. The pressure level of the outlet gas decreases, until the level is reached where the stand-by street is set to take over the function of the delivering street. This level usually is slightly below the level where the delivering street was set on.

In the RSS configuration, the gas pressure is controlled in a different way. Similar to RMS, the regulator controls the gas pressure initially. For RSS, pressure increase due to regulator failure leads to closure of the first safety shut valve, to prevent the delivered gas pressure to exceed a certain safety level. When the first safety shut valve fails to close, the second safety shut valve closes. Similar to RMS, the stand-by takes over the function of the delivering street.

When the gas pressure level of the output of the GDS street is lower than the pressure level agreed with the client, the back-up street starts delivering gas. This is the case for both the RMS and the RSS configuration. In the most commonly used settings, the back-up street starts delivering at a pressure level of 7,8 bar, while the delivering street delivers at an 8 bar pressure level.

A regulator or a monitor usually is connected with smaller regulators, which size is around 1/6th of the regular regulators: the aid pressure regulator and pilot pressure regulator. Aid and pilot pressure regulators smoothen the control function of the regulator/monitor, by regulating the inlet flow of the main regulator according to the level of the outlet pressure of the street. A three-stage regulating mechanism takes place. First, the outlet pressure of the main regulator is input for the aid pressure regulator, which is input for the pilot pressure regulator. This input of the pilot pressure regulator influences the regulating function of the main regulator. This main regulator controls the outlet flow of the GDS street. This is further explained in Annex D. Not all regulators and monitors are connected to aid and pilot pressure regulators; according to a SAP analysis, there is approximately one aid and one pilot pressure regulator per street. Therefore, in this research will be assumed that there is one combination of an aid and a pilot pressure regulator in each street.

Most streets contain an RSS configuration. Also, RSS is recommended to install in new GDSs, because the RSS provides a higher level of security to the pressure safety, responds faster, has lower total costs of ownership, less emissions and is easier to repair, according to [5]. The configurations are shown in Figure 2.

Description of the soft parts in the gas pressure control components

Regulators, monitors and aid and pilot pressure regulators consist mainly of steal parts and soft parts. The soft parts are usually made from rubber, teflon or similar soft materials. According to the maintenance experts of Gasunie, almost all (more than 90%) of the failures of the pressure control components are caused by failures of soft parts in the pressure control components. In Annex D, the component types and their parts are shown.

The soft parts differ per type of regulator, monitor and aid and pilot pressure regulator. In Annex D, all types are described. The functions of the soft parts can be summarized by the following explanations:

- A diaphragm is the main pressure controlling part of the component. It is located in an actuator. On both sides of the diaphragm, a certain pressure level is created. Usually, a small flow of gas from the outlet of the GDS street is directed to one side of the diaphragm; therefore, the pressure level at this side is equal to the outlet pressure level. The other side of the diaphragm is connected to the pilot pressure regulator. This pilot pressure regulator regulates the pressure level at this side of the diaphragm in such a way that this pressure level is equal to the required pressure level of the outlet of the GDS street. Depending on the prevailing pressure on the diaphragm, the diaphragm moves to a side. A valve, connected to the diaphragm, moves, and an aisle opens or closes (partly) for gas flow through the aisle.
- O-rings, seal rings and valve seals prevent a gas leak between separate parts in the component or gas leak from the component to the atmosphere.

Failures in soft parts of the pressure control components

In Appendix B, the main effects of failures in soft parts of pressure control components are explained. This part can be summarized as follows:

- Failure of a diaphragm can cause gas delivery on a wrong pressure level, which at a certain deviation level automatically causes the take-over of the controlling function by the monitor (if available) and, when there is no monitor (RSS configuration) or the monitor fails to deliver gas (RMS configuration) at the required pressure levels as well, ultimately the back-up street takes over the delivery of gas;

- The same effect can be caused by an o-ring, seal ring or valve seal, however, a wear-out of one of these parts has less effects on the pressure level and therefore the probability of a street failing to deliver gas due to the wear-out of one of these parts is smaller;
- The wear-out of an o-ring, seal ring or valve seal can, depending on the position of the part, cause a gas leak to the atmosphere;

The main drivers of failure are, according to expert opinions, calendar time and usage. Usage, in this context, means that there is a gas flow through the component, causing deforming in the soft parts. There is no causal relation between failure of one of the described (parts of) components on the failure of (parts of) other gas pressure control components or other components in a GDS. Further explanation of the drivers of failure can be found in Appendices C and E. Failure rates per component are given in Section 2.5.

2.2 Current maintenance concept

The current maintenance concept for GDSs is summarized already in Chapter 1. The maintenance concept contains inspections and corrective replacements based on occurring failures during operation or failures detected during inspections. As is described as well in Chapter 1, there were no preventive replacements of (soft parts of) components since 1997. The last preventive replacements of soft parts were between 1991 and 1997: most of the GDSs had the last preventive replacement of soft parts between 1993 and 1997; however, there is a small number of GDSs that had their last preventive replacement of soft parts between 1991 and 1993. The latter group of GDSs was part of a test case in order to analyze the effects of ending the preventive replacements.

The inspection interval is three months (hereafter referred to as 3M). Once a year, the three months inspection is combined with a more extensive inspection (hereafter referred to as yearly inspection). During these inspections, the technicians could find various reasons for the replacement of a (soft part of a) pressure control component. The following list contains these reasons and the inspection where the failure should be found (a more detailed list is provided in Appendix A):

- Gas leaks to the atmosphere (3M inspection)
- Gas leaks between separate parts in the components, resulting in out of spec outlet pressures, that could lead to the unavailability of the street in a short time frame (3M inspection)
- Failures in stand-by streets, that result in a failure to take over the delivering street (3M inspection)
- Failures in the monitors, that result in a failure to take over the function of the regulator (3M inspection)
- Failures in the safety shut valves (3M inspection) and safety blow off mechanisms, that could result in the gas pressure level to exceed a certain safety level (yearly inspection)

When a failure is found during inspection, the technicians solve the problem directly by replacement of the failed part, or the maintenance planners plan a separate replacement task. This decision is based on the required effort to solve the problem and the expected effects of delaying the replacement. When a failure is detected that does not influence the delivery of gas immediately but can influence the delivery soon, a replacement is planned as a separately planned task, not combined with one of the following (standard) inspections.

When a failure is recognized during operation, two technicians visit the GDS and close the failed street, unless the street already is closed automatically. Failures are recognized during operation in three ways: alarms, complaints by clients and (less frequent occurring) notifications of a smell of gas by people in the neighborhood. There are gas flow measurement devices in all GDS streets, that are able to detect the take-over of the street by another street and/or the closure of a safety shut valve. These devices send messages about these detections to AMAS (an alarm system in Gasunies headquarter). Also, an alarm is sent when the monitor in an RMS street takes over the function of a regulator, or when the safety shut valve closes.

Replacements and inspections are always done by (at least) two technicians. There is a large number of technicians, who are all skilled to perform inspections, closing of the street after failures during operation, and replacement of (parts of) components. There are technicians and Central Warehouse employees available during day and night.

2.3 The corrective replacement scenarios and their costs and replacement duration

There are five major scenarios possible for the required resources and spare parts per corrective replacement. Costs and minimal replacement times per scenario are given in this section and explained further in Appendix G. In Section 5.4, frequencies per scenario are given. In Appendix G is explained that an opportunistic replacement of the soft parts of a regulator or monitor costs 0,5 SC, and a preventive replacement of soft parts of a regulator or monitor costs 0,86 SC. These costs are lower than the costs of a corrective replacement, as shown in the following paragraph.

Scenario 1: failure solved by replacement of the soft parts

This scenario occurs when the soft parts of the failed component are still available on stock. In that case, usually all soft parts (both the failed soft parts and the soft parts that were not failed) are replaced.

Replacement of all soft parts of a regulator or monitor costs 1 SC on average, and takes a minimal replacement time of less than a working day (exact duration is hidden in this public version of this thesis). For soft parts of aid and pilot regulators, costs are 0,613 SC and minimal replacement time of less than a working day (exact duration is hidden in this public version of this thesis).

Scenario 2: failure solved by replacement of the component without changing connected pipes

The replacement of a whole component is required when the soft parts required to solve the failure are not available on stock or cannot be supplied. Also, the replacement of a whole component is required when there is an unrepairable failure in a hard part of a component, which rarely occurs (see Section 2.5). When a regulator or monitor can be replaced by the same type or another type with the same size, there are no changes in connected pipes required. Aid and pilot pressure regulators can always be replaced without changing connected pipes.

Replacing a regulator or monitor without changing connected pipes costs around 12,3 SC and takes a minimal replacement time of less than a working day. For aid and pilot regulators, costs are around 4,2 SC and minimal replacement time is less than a working day. Because there are technicians and Central Warehouse employees available day and night, there is usually no extra time required.

Scenario 3: failure solved by replacement of the component and changing connected pipes
The explanation of scenario 2 mentions when the replacement of a whole component is required. When a complete component has to be replaced and the component cannot be replaced by the same type or another type with the same size, there is a change in connected pipes required. As mentioned earlier, aid and pilot pressure regulators can always be replaced without changing pipes.

The bottlenecks of this replacement scenario are the lead times of the pipe cutting in the pipe factory in Deventer or external pipe factories, and the inspections of the new pipes. It takes between three days and three weeks to measure the required pipe lengths, deliver all pipes on the right size and install and check the new pipes. The pipes are on stock, but need to be cut on the right size by the factory in Deventer (department OLS) or by other, external parties. Due to a large variety in the installed base, it is hardly possible to build the pipes in the required sizes on stock. For preventive replacements, the usual lead time is between one week and three weeks, depending on the availability of the pipe inspectors. In emergency situations it is allowed to plan the inspection after the pipe is installed. In that case, it is possible to perform the replacement on the third day after the failure. Currently, a maximum of ten GDS streets per day can be equipped with pipes in emergency situations, based on the required technicians skilled to install the pipes.

Replacing a regulator or monitor including changes in pipes costs around 23,8 SC. It takes a minimal replacement time of three days in emergency situations and around two weeks in regular situations. The two weeks in regular situations contain the time to plan the required inspections.

Scenario 4: the launch of an emergency installation is required to replace a failed GDS
The purpose of launching an emergency installation is solve the problem that after failure of a street or GDS, it is possible that there is no redundancy anymore. The emergency installation then ensures redundancy and thereby the required availability. Therefore, scenario 4 occurs only occurs after failure of a street or GDS; this means as well that scenario 4 only occurs in combination with one of the other three scenarios. A launch occurs when the time to solve the failure via one of the other scenarios, is longer than the maximum repair time as is set by Gasunies risk management. The maximum repair time as is set at the moment of failure by Gasunie risk management depends on the criticality of the GDS, the (expected) demand after the failure and the costs of launching an emergency GDS; however, in almost all cases the maximum repair time is the same day, see Appendix F.

The following emergency installations are available, according to the subject matter expert (the exact number per installation type is deleted, due to confidentiality issues):

- A number of emergency GDSs (EGDSs) are owned by Gasunie. An EGDS is a complete GDS, which can be connected with the inlet and outlet of the failed GDS. During the use of an emergency GDS, the failed GDS can be repaired.

- A number of emergency skids are owned by Gasunie. An emergency skid is a single street which can be used during the repair of a GDS street. However, an emergency skid does not contain a gas flow measurement device, resulting in problems in determining the fees. Therefore, a skid usually is only used for a single day, after arrangements are made with the client about extrapolating the usual price of delivered gas. If it is necessary, a gas flow measurement device can be added. There are a number of gas flow measurement devices available.
- There is a number of trailers filled with gas, which should be enough to deliver gas to the outlet of a GDS for two days.
- Gasunie has a first claim on a number of EGDSs to rent at an external party. The external party keeps three other EGDSs, which might be rented if available.
- Other options could be to rent EGDSs at other companies.

In the current planning, usually only a very small number of the EGDSs owned by Gasunie are used for emergency situations. It can be concluded that the number of EGDSs is more than the required number. If the number of required emergency installations would suddenly exceed the availability of these installations, extra emergency GDSs can be provided by external parties and by recycling old GDSs. The lead time of a new emergency GDS satisfying all rules set by Gasunie management, is 9 months. However, a failed GDS can be used as emergency GDS after repair of failures and putting the GDS in a trailer. This takes around two months. This solution would not satisfy the regular Gasunie rules, but could be used in emergency situations. Based on the low demand on EGDSs in the current setting and the possibilities to use other installations in emergency situations, it can be concluded that the number of EGDSs should not be a bottleneck in the future.

In Appendix L, a list of available emergency installations is given, including their size, maximum capacity level, installation time and costs. This appendix shows that costs of installing emergency installations vary heavily. Based on [4] and [13], the average costs per EGDS are 14,67 SC per launch. Installation times vary between 1 and 3 days.

Scenario 5: hard and soft parts need to be replaced
The replacement of hard and soft parts is required when hard parts in the component have failed. Replacement of hard parts usually means that the connected soft parts inside the component also have to be replaced, because soft parts break during the disassembling of the component. Costs of these replacements in total are 1,3 SC for regulators or monitors, and 0,91 SC for aid and pilot pressure regulators.

Extra costs for visiting GDS after failure during operation
Note that, next to the described replacement costs in this section, there are expected costs of visiting the GDS after detection of a failure during operation. These costs are the average costs per visit per component type multiplied by the ratio of failures per component type that require a visit, which is equal to the ratio of failures that is detected during operation. These can be quantified as 0,10 SC, 0,10 SC and 0,09 SC for every unscheduled regulator, monitor and aid and pilot pressure regulator replacement, respectively. More details are in Appendix G.

Influence of inventory levels on replacement scenarios

As is explained in this section, the inventory levels of parts partly determine which replacement scenario is possible after a failure occurred. It can be assumed that when there is no permanent supply disruption, it is always possible to solve the failure by replacing only the required units; the same holds when all required units are on stock in the (undocumented) inventory.

An analysis of procurement databases (see Appendix J) showed that there is no permanent supply disruption for only a small part of the installed base of regulators (20%) and monitors (17%). If supply of a component type is not disrupted, it can be assumed that there are always components of that component type available at the central warehouse of Gasunie. Therefore, Failures of these components can always be solved by scenario 1 replacements (see Section 2.3). For 16% of the regulators and 25% of the monitors, there are only one, two or three soft parts per component disrupted. In these cases, it is sometimes possible to repair a component in scenario 1, depending on which of the soft parts failed and the exact position of the failed soft part. For the other 64% of the regulators and 68% of the monitors, the supply of at least four of the soft parts per component is disrupted. A failure of soft parts in these components can only be solved in scenario 1 when there are possibilities to repair a component with permanent supply disruptions. Next to available units on stock, experts mention the existence of undocumented inventories in busses of technicians. According to expert opinions, it is common practice to call other regions to ask for specific soft parts in undocumented inventories if a region does not hold these soft parts themselves.

The level of undocumented inventories per component type is very hard to determine exactly. For this reason, in Chapters 5 and 6 (results and sensitivity analyses), various scenarios will be analysed. In these chapters, estimations on the frequencies of replacement scenarios 2,3, and 4, will be explained as well.

2.4 The costs caused by the failure effects

There are two main failure costs types for pressure control components: the non-delivery of gas to clients, and costs due to gas leaks.

The costs of non-delivery have to be paid when the replacement scenarios and redundancy in the Gasunie network cannot prevent the occurrence of a non-delivery. Non-delivery means that there is no gas delivery to the client via any of the GDSs in the gas network of Gasunie. Gas transport companies and ACM made agreements about the restitution every single household and industry must receive when they do not receive gas. The amount of restitution depends on the duration of non-delivery. The amounts are shown in Tablle 1. The amounts are deleted due to confidentiality issues.

Type of client	Duration of non-delivery	Restitution amount per client	Additional costs for every next four hours
Household connected to an RNC GDS	4 - 8 hours		
Commercials connected to an RNC GDS	4 - 8 hours		
Industries connected to an RNC GDS	4 - 8 hours		

Table 1: Restitution costs per connected party when non-delivery occurs

When gas delivery to the RNC fails, it is dangerous to open the gas delivery directly after repair. Every household needs to be informed before the gas delivery starts again, to prevent explosions due to gas cookers which were still in use during the gas delivery failure. Because of the required visits to all households on a GDS, a delivery failure could take a large amount of time, despite the fact that usually the cause of the non-delivery can be solved relatively fast.

Based on expert opinion and data of connected households, commercials and industries per GDS, the average costs per transport break can be set on 195,17 SC. Details can be found in Appendix O.

Next to these restitution costs, there are amongst others costs to compensate for damage caused by non-delivery, costs to visit all connected households, image costs and safety and environmental consequences. These costs are not taken into account. Also, the probability that Gasunie does not have to pay the compensation costs after a transport break, is not taken into account. Chapter 6 gives sensitivity analyses that show the impact of excluding these costs.

Other failure costs are revenue losses due to gas leaks to the atmosphere. According to estimations by Gasunie in [15*], a regular leak in pressure control components results in a small gas loss. Together with experts, the average costs of a gas leak from pressure control components to the atmosphere is determined to be 0,14 SC. The exact details of the average costs of gas losses per gas leak are hidden in this public version. The average loss of gas in m^3 per gas leak is based on the average gas loss per gas leak per day, multiplied by the average duration of a gas leak. These were tested by Gasunie in an earlier research. Thereafter, this amount of gas is multiplied by the costs per m^3 of gas that Gasunie considers. The costs per m^3 of lost gas is the cost price of gas plus the costs of 'environmental footprint'. The latter costs are added by Gasunie in all calculations of new maintenance policies. The 'environmental footprint costs' were introduced in order to reduce the environmental footprint of Gasunie.

2.5 Failure rates per component

In this section, the failure rates for all pressure control components are provided. In this research, the following sub systems per street are distinguished including their component types:

- Regulator [sub system 1]:
    - The aggregated total of soft parts of regulator [component type 1]
    - The aggregated total of hard parts of regulator [component type 2]
    - Encapsulation of regulator [component type 3]
- Monitor [sub system 2]
    - The aggregated total of soft parts of monitor [component type 4]
    - The aggregated total of hard parts of monitor [component type 5]
    - Encapsulation of monitor [component type 6]
- Aid & pilot pressure regulator [sub system 3]
    - The aggregated total of soft parts of aid & pilot pressure regulator [comp. type 7]
    - The aggregated total of hard parts of aid & pilot pressure regulator [comp. type 8]
    - Encapsulation of aid & pilot pressure regulator [component type 9]
- Replacements of any other complete component in a GDS street [sub system 4]
    - The aggregated total of complete other components [component type 10]

*A failure of an *encapsulation of a component* means that the component is unable to be repaired, even if all spare parts are available. Usually, such a failure is caused by holes in the encapsulation of the component, or corrosion at the encapsulation part. In these cases, the complete component becomes useless.

The failure rate can be defined as the non-cumulated number of failures of a unit of a specific age divided by the number of units that reached that age during the years 1991 up to and including 2016. Therefore, the failure rate is equal to:

$$failure\ rate = \frac{\mathrm{f(t)}}{1 - \mathrm{F(t)}}$$

with f as number of failed units at age t in the population, and F(t) as the cumulative number of failed units before age t in the population.

To determine the failure rates of the soft parts, failures during the years 1999 up to and including 2016 are analysed. Analyses are accomplished on data in Gasunies ERP system SAP and in Rayondis, the predecessor of SAP until 1999. In SAP, Gasunie technicians provide announcements of observed failures and performed maintenance tasks, and orders of (parts of) components required to repair or replace a component. Based on the texts of these orders and announcements, it was estimated which failures of component parts there were, and at which dates. Next to the analysis on SAP data, Rayondis data is analysed to determine in which year the last preventive replacement of soft parts per GDS is performed.

Two data analyses are performed. In the first analysis the orders and announcements from January 1999 until December 2016 on 87 selected GDSs were analysed. The GDSs were selected based on the orders from the start of 2012 until the end of 2015. These orders were filtered on orders of components booked on the GDSs. From the GDSs with orders, 87 were selected randomly. A sample was chosen because selecting all 1.000 GDSs would take too much time. This selection method was chosen because it was an easy method, and order data from these years seemed to be the most reliable available data. A drawback of this selection method is that the GDSs were selected on the failure of at least one component during 2012-2015. Selecting only the GDSs with failed components from 2012 until 2015, could slightly influence the frequency of failures for the higher ages. Therefore, a second analysis is done in which 36 GDSs were selected completely randomly. In this analysis, failure rates of ages higher than 16 were comparable to the failure rates found in the first analysis. In the first analysis, 31,2% of the regulators in the total installed base failed during the ages 17 and 23 years, while in the second analysis, 29,3% of the regulators failed during these ages. The comparable failure ages can be explained by several reasons. First, the selection method also selected GDSs with replacements in other components that the gas pressure control components, and even selected GDSs with replacements in the boiler system that is outside the GDS streets (see Figure 2) or even repairs of the buildings in which the GDSs are located. Also, all GDSs contain several streets. Therefore, also a very large number of streets was selected without replacements during 2012/2015. Based on the comparable failure rates for higher ages, it can be concluded that the first and second analysis show the same failure trends. For this reason, the failures detected in the first analysis and the failures detected in the second analysis, are merged into one database. More information about the content and possible drawbacks of the two analyses can be found in Appendix H.

An important note is that failure data from Rayondis is very hard to collect. Therefore, there is no information (easily) accessible in SAP or Rayondis about failures until 1999. This means that there is little information about failures in the first seven years of pressure control components. Therefore, a report of 1996 [7] is used to determine the failure rates for the first years. This report gives the number of failures per year on regulators, monitors and aid and pilot pressure regulators during the years 1988/1994. Also, this research mentioned that in the first year after replacement of soft parts of regulators, the number of failures was twice as large as in the other years, due to maintenance induced failures. During these years, all soft parts were replaced every four years. The information in this report is implemented in the failure rate analyses in the following way:

- Failure rates in the first four years per component type are assumed to be equal to the average number of failures per unit of that component type per year as described in [7]; however, for regulators, 2/5th of the number of failures as described in [7] are assumed to have occurred in the first year, due to the maintenance induced failures. The other 3/5th is divided over the 2nd, 3rd, and 4th year.
- The 5th, 6th and 7th year get the same failure rate as the 2nd, 3rd, and 4th year;
- The assumption is made that the first failure per component at the age of 8 years or more that is found in SAP data, is the first failure of that component.

Failure rates of soft parts of regulators (first failures per component)

In Figure 3, the failure rates of soft parts of regulators can be found, as a result of the described analyses. In these analyses, only the first failure after the last preventive replacement is taken into account; analyses towards 'second' failures are described in the next paragraphs. All ages are rounded upwards.

There were 316 regulators in the selected GDSs. In this group of 316 regulators, there was a large number of regulators (exact number is deleted in this public version of the thesis) that did not fail yet, all with an age of at least 20 years. The latter regulators are taken into account as censored data. Ages of 24 years and higher are not shown in Figure 3, because there is only a small number of regulators of the 316 selected regulators that became 24 years or older during 1999/2016.

The pattern in Figure 3 suggests that after a high failure rate during the first year, the failure rate is approximately constant until the 17th year. In the 17th year, the failure rate starts to increase. As is explained in Section 2.1, main drivers of failures of soft parts of pressure control components are calendar time and usage. Calendar time leads to drying of the rubber in soft parts, while vibration and aging processes (described in Appendix E) due to usage lead to wear-out of soft parts.

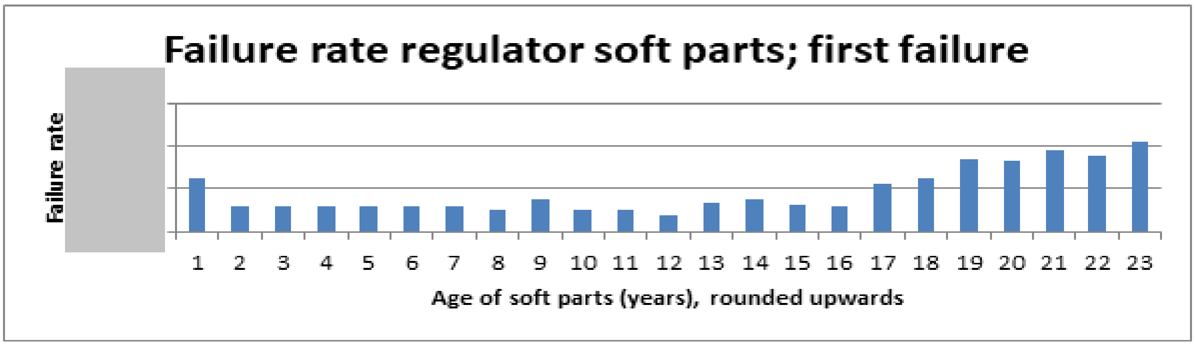

Figure 3: Failure rate of regulators, based on failure data from SAP and Rayondis

A well-known concept in reliability engineering is the so called bathtub curve, consisting of *infant mortality failures*, *random failures* and *wear-out failures*. According to Engelhard & Greiner (2003), the weighted sum of the three failure rates can be used to determine the failure rate of components subject to failures in a bathtub curve. Lai & Xie (1995) did this as well for two Weibull curves, an increasing and a decreasing Weibull curve. Therefore, the bathtub curve failure rate is:

$$F(x) = Finfantmortality(x) + Frandomfailures(x) + Fwearout(x)$$

with *Finfantmortality(x)* as the cdf of the infant mortality failure rate, *Frandomfailures(x)* as the cdf of the random failures failure rate, and *Fwear-out(x)* as the cdf of the wear-out failure rate.

Based on [7], it can be assumed that maintenance induced failures only occur in the first year. Based on the trend in Figure 3, it can be assumed that the wear-out failures do not highly influence the failure rate until the 16^{th} year. Therefore, a regression analysis is done in Excel towards the trend during the second up to and including the 16^{th} year, with the hypothesis that there is no significant increase or decrease between the second and 16^{th} year. This regression analysis is done to test whether there is an increase or decrease from the second up to and including the 16^{th} year that is significant and not negligible practically. According to the regression analysis, there is no such increase or decrease: the slope of the regression line is $0{,}9*10^3$, and the 95% CI of the slope is $(-7*10^3 ; 6*10^3)$. Therefore, the average failure rate of the second up to and including the 16^{th} year is considered to be the failure rate of the random failures. The infant mortality failures are in the first year only and this failure rate is considered to be the difference between the total first year failure rate and the random failure rate. Exact failure rates are hidden in this public version of this thesis.

The number of failures due to wear-out per year are calculated by the total failures per year minus the failure rates of random failures and infant mortality failures. The regulators that did not fail yet are taken into account as censored data. With these failure data, the wear-out failure distribution is analyzed by performing a maximum likelihood estimation on a Weibull distribution. The results of these analyses are hidden in this public version of this thesis. Figure 4 shows the empirical data and the estimated total failure rate distribution consisting of infant mortality failures, random failures and wear-out failures.

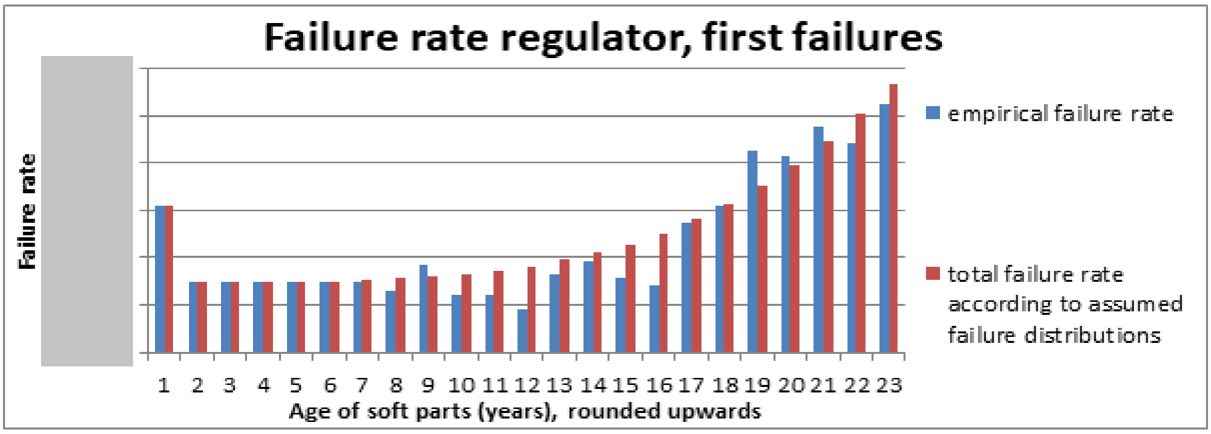

Figure 4: Empirical failure rate of soft parts of regulators, and the total failure rate according to assumed failure distributions

Failure rates of regulators after the component failed for the first time

During the first analysis, some failures (exact number is deleted in this public version of the thesis) were detected that were not the first failures of a component, but the second failure. These are not shown in Figure 3, because this figure only shows the failure rates for the first failure. After a failure, usually all soft parts are replaced, which implies that the failure rate for the second failures is similar to the failure rate of the first failures. This analysis shows that the failure rate is slightly higher after the first failure. The times between the first corrective replacement and the second failures are shown in Figure 5. In the group of regulators that failed during 1999 and 2016 there are a number of censored data points due to regulators that did not fail after the last failure of a regulator; these cases are not shown in Figure 5.

The failure rate of these ´following failures´ appears to be constant. A regression analysis towards the trend during the first up to and including the 14th year showed no significant increase or decrease with practical meaning in the first fourteen years: the slope of the regression line is 0,01, while the 95% CI of the slope is (-0,19;0,19). Therefore, the average failure rate of the first fourteen years is assumed to be the failure rate of the random failures. Next to these random failures, the same wear-out failures distribution as for the first failures can be assumed for the following failures as for the first failures, because the material and the conditions are the same. The exact failure rates are hidden in this public version of this thesis.

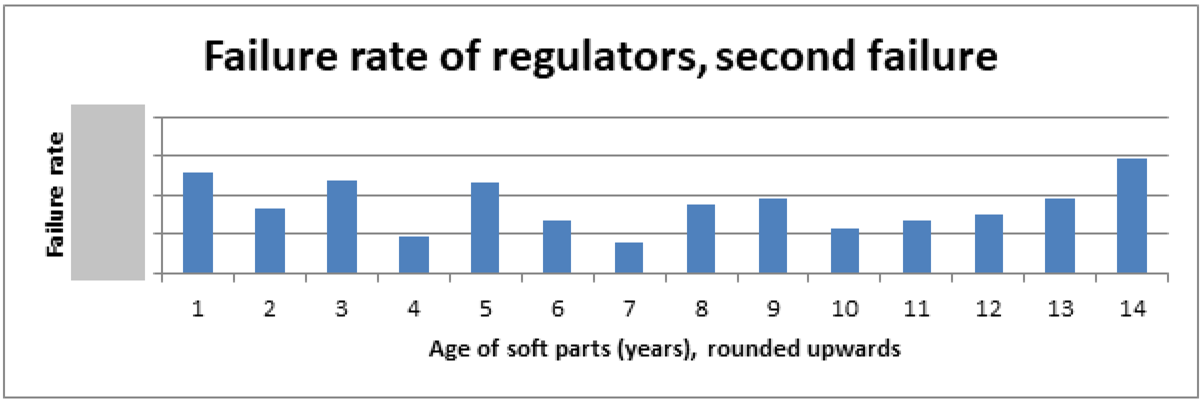

Figure 5 Failure rates of regulator soft parts after the first corrective replacement

Another conclusion is that the random failure rates of the second failure (see Figure 5) on average are slightly higher than for the first failure (see Figure 4). Reasons for these different failure rates can be the various circumstances per GDS and corrective replacements of soft parts that are performed not as well as the preventive replacements that were performed until 1997.

Because data on the third and fourth failures is available in only very few cases, the assumption is made that the failure rate after the second failure is similar to the failure rate of the second failure rate.

Failure rates of soft parts of monitors

In a similar way as for regulators, the failure rates for the first failures per age of monitors are determined. The results are shown in Figure 6. The failure rates are analysed on the same 226 GDS streets as for the first analysis on regulators. However, the number of analysed monitors, which is 122, is smaller than the group of regulators. The main reason for the low number of analysed monitors is that the RMS configuration is disappearing: after a failure of a monitor, this component will be replaced by a safety shut down valve, as is described in [11]. In this group of 122 monitors, a small number of first failures of monitors were detected(exact number is deleted in this public version of the thesis). There was a relatively high number of censored data points, compared to the number of censored data points in the analysis of regulator soft parts. The difference is that most monitor failures are detected after the failure of a regulator: a monitor takes over the function of a regulator only after a regulator failure and during inspections.

A remarkable conclusion after collecting the failure data of soft parts of monitors, is that there is no clear bathtub shape visible, in contrast to the failure rates of the soft parts of regulators. A maximum likelihood estimation analysis is done in Engineered Software Inc. (1999) for a single Weibull distribution. The results of these analyses are hidden in this public version of this thesis.

No analysis is done towards the failure rate of monitor soft parts after the first failure has occurred, because the number of second failures is very small. It will be assumed that the failure rate after the first failure is equal to the failure rate before the first failure. For regulators, the difference between first and second failure rate was not very large as well.

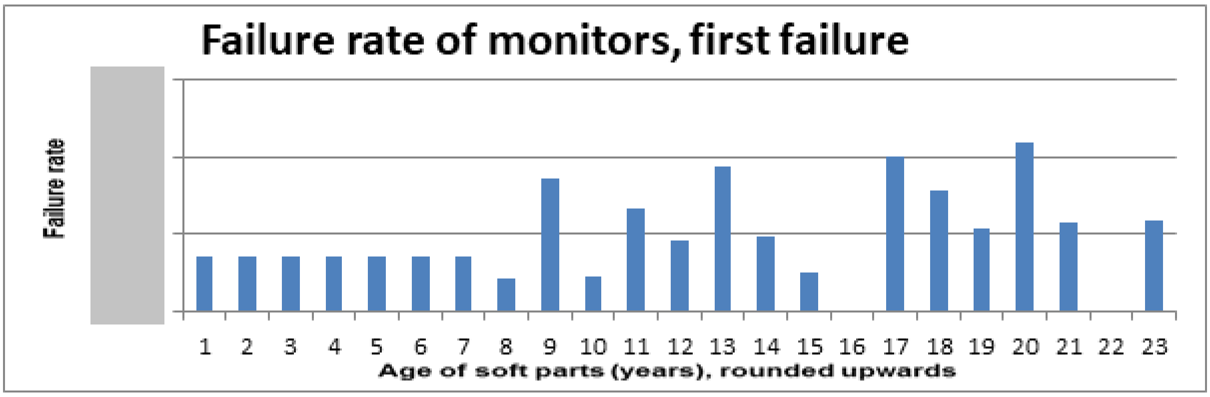

Figure 6: Failure rates of soft parts of monitors

Failure rates of soft parts of aid and pilot pressure regulators

In a similar way as for regulators, the failure rates for the first failures per age of aid and pilot pressure regulators are determined. Aid and pilot pressure regulators are merged as one component in this research, because this usually is also the case in the data in SAP. The results are shown in Figure 7. The failure rates are analysed on the same 226 GDS streets as for the first analysis on regulators. From the 226 streets, there are 216 streets with an aid pressure regulator and/or pressure regulator. The failures of aid and pilot pressure regulators do not show such a clear influence of aging as the failures of the regulators (compare Figure 7 with Figure 4). This appears to correspond with the expert opinions that aid and pilot pressure regulators are smaller and more fragile and therefore less resistant to random failures such as pollution in gas.

A regression analysis in Excel showed that there is no significant increase or decrease with practical meaning during the second year up to and including the 23rd year: the slope of the regression line is $4*10^{-3}$, while the 95% CI is ($-1*10^{-3}$; $8*10^{-3}$). A maximum likelihood estimation analysis is done in Engineered Software Inc. (1999) for an exponential distribution. The results of this analysis are hidden in this public version of this thesis.

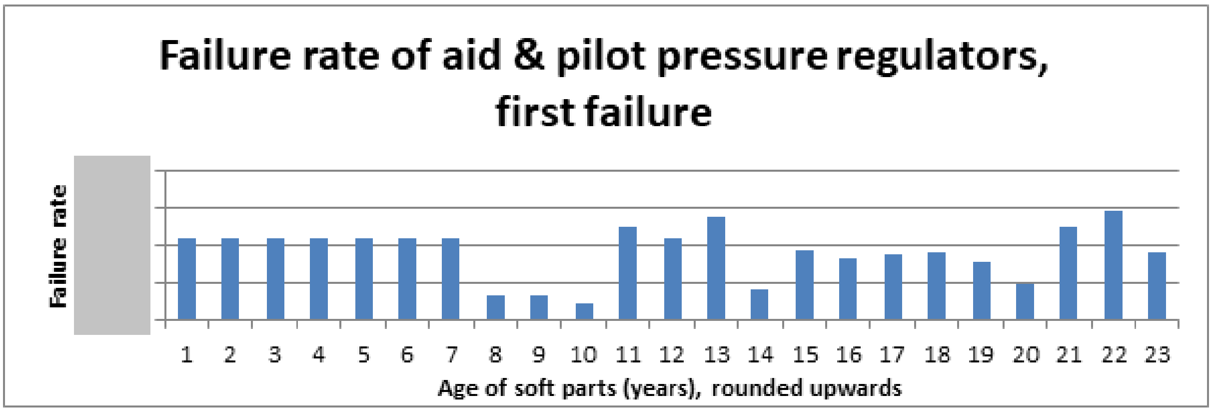

Figure 7: Failure rates of soft parts of aid and pilot pressure regulators

Failure rates of soft parts of a comparable regulator type

Appendix N describes a research done by a former employee of Gasunie in 2007 on regulators on another station type in Gasunies transport network. This research strengthens the conclusion that an increase in failures in soft parts of regulators can be expected after the known failure rates of the first until the 23rd year.The research was done towards the failure rate of soft parts of regulators in Gasunies HTL blockage stations. The conditions and materials of these regulator soft parts are comparable to regulators of GDSs. There are some differences between the functioning of the regulators in HTL blockage stations and regulators in GDSs; however, it can be argued that these differences would imply a longer useful lifetime of the HTL blockage regulators. The conclusions of the research done in 2007 resulted in the decision by Gasunie to replace all soft parts of these HTL blockage regulators every 25 years.

Failure rates of hard parts in regulators, monitors and aid & pilot pressure regulators

Mean time to failure of a hard part in a regulator, monitor and aid and pilot pressure regulator are 120, 125, and 71 years, respectively. This follows from a SAP analysis on the failures of hard parts in these components in the first 7,5 months of 2017. In this analysis is assumed that the useful lifetime of these hard parts is exponentially distributed. This assumption is motivated by the fact that none of the maintenance experts noticed an increase or decrease of failures of hard parts in the last years.

Failure rates of encapsulations of regulators, monitors and aid & pilot pressure regulators

In Appendix K, a research is described of Gasunie employees towards the mean time to replace control components in GDS streets. From this research follows that the number of replacements of each component type in GDS streets, and therefore regulators and monitors as well, is constant. Therefore, an exponential failure distribution can be used. Mean time to failures of regulator and monitors are 70 and 250 years. Aid and pilot pressure regulators were no subject of this research. According to experts, there are more replacements of these components than regulator replacements. In this research, it is assumed that the ratio of replacements of complete aid and pilot pressure regulators and regulators, is equal to the ratio of their hard part failures. Therefore, a mean time to failure of 42 years is assumed.

Failure rate of other components in the GDS

The research described in the last paragraph, shows the expected number of replacements per component type in GDS streets. Using the MTTFs as used in their research for all components in GDS streets together (see Appendix K), it can be concluded that there are between 150 and 160 replacements of (parts of) components other than pressure control components in the complete installed base of 1000 GDSs.

2.6 Scores on KPIs with respect to availability

This Section shows the performance of the GDSs in the current maintenance concept. Also, it shows which performance indicators are most important for Gasunie. These KPIs will be used to compare the performance of various maintenance concepts in Chapters 5 and 6.

Gasunie has set four KPIs with respect to the availability of the gas delivery. There are three KPIs for other failure effects: the delivery of off spec gas (≤9 times per year) and the leaks of gas to the atmosphere (≤ 1 leak per year with safety consequences, and ≤ 6 other leaks per year). However, most off spec deliveries are caused by a failure in the boiler (causes low temperature gas), a failure in the filter (causes pollution in the gas), or a failure in the odorization device; while most leaks to the atmosphere occur in the pipe network of Gasunie. Therefore, the focus in assessing the potential to improve the performance of the maintenance concept of the pressure control components, should be on the KPIs with respect to the availability of the gas transport. For these reasons, only the KPIs with respect to availability will be assessed. These KPIs are found in documents about availability requirements and service level agreements, see [3], [2] and [16]. For a GDS, the following applies:

1. Unavailability of the GDS station: the frequency of a GDS completely blocked (no more gas supply possible by this GDS), external causes excluded, should be lower than 0,0045 times per year per GDS station. This is equal to 4,95 times per year for the total installed base.
2. Unavailability of the GDS streets: the frequency of a failing street, external causes excluded, should be lower than 0,048 times per year per GDS station. This is equal to 52,8 times per year for the total installed base.
3. Number of transport breaks (no gas delivery to client or not enough), not caused by the network of the client, should be lower than 3 per year

4. Number of failed GDSs, not caused by upstream activities or clients, should be lower than 6 per year.

The difference between a transport break and a failing GDS is that a GDS could also fail without a transport break. This occurs either when no gas delivery was required until the failed GDS was repaired or another GDS is able to deliver gas to the client during the repair time of the failed GDS.

An important note is that Gasunie will probably use only KPI 3 and 4 in the next years. Therefore, the focus will be on KPI 3 and 4.

In Table 2, scores on KPIs 3 and 4 in 2013/2016 are given, based on information from [14] and [17]. The actual scores on the KPIs are equal to or better than their target scores. Because Table 2 contains confidential information, the exact scores are hidden in this public version.

KPI	Description	Target (per year)	Score 2013	Score 2014	Score 2015	Score 2016
3	Transport breaks	<3				
4	Failed GDSs	<6				

Table 2: Scores on KPIs with respect to availability requirements from 2013 until 2016

Scores on KPI 1 and 2 meet their target scores as well. That can be concluded after data analyses in SAP. These analyses are not explained in detail here, due to confidentiality issues. Next to the fact that the KPI scores are met during the last years, another interesting conclusion can be made regarding the difference between the RMS and RSS configuration (configurations are described in Section 2.1). An analysis showed that the scores for RMS streets are better than the scores for RSS streets. This holds both for the scores on KPI 1 (frequency of unavailable GDSs should be lower than 0,0045 per GDS per year) and the scores on KPI 2 (frequency of unavailable streets should be lower than 0,048 per street per year). The ratio of unavailable GDSs (KPI1) for RSS: RMS was around 2:1. Ratio of unavailable streets (KPI2) for RSS:RMS was around 3:2. As explained in part 2.1, Gasunie decided, despite the lower KPI scores of RSS streets and the fact that the KPI scores of RSS streets were very close to missing the KPI target, to use the RSS configuration as the standard configuration for all new GDS streets. This means that all failed monitors will be replaced by a safety shut valve, which automatically results in a RMS street becoming a RSS street. By using more RSS streets, the number of failed streets might increase in the future, due to the higher probability of street failure in RSS streets.

Most important conclusion of this Section is that, according to the available data, it seemed that all target scores were met during the last years.

2.7 Frequency of failure effects during the last years

This section lists the possible effects of failures per pressure control component, and the frequency per failure effect. Next to this, this section gives the frequencies and (internal and external) causes of the most important failure effects in GDSs.

Frequencies of failure effects caused by soft components

In Table 3, the frequencies of failure effects caused by regulators´ soft components are provided. These frequencies are the results of an analysis towards the causes and occurring effects of 59 failures of gas pressure regulators. These 59 cases were found during the analyses as described in Section 2.5. Table 3 shows that for 60,9% of the failures, there is no (known) effect. These failures were either found during inspections or the failure announcements were caused by e.g. wrong settings by technicians, failures of other components, failures caused by wrong actions of CCP (department that controls the network from the HQ of Gasunie), or fluctuation of pressure or flow. For 11,9% of the failures, there are gas leaks to the outside. 15,3% of the failures in regulators results in unavailability of the regulator (for RMS configuration) or complete GDS street (RSS configuration). Other effects of failures are complaints of out-of-spec delivery of gas by clients and complaints of inconvenient loud noise by people in the neighborhood.

Failure effect caused by regulators	Percentage of failures with this effect, occurred during operation	Percentage of failures with this effect, detected during inspections	Total percentage of failures with this effect
No (known) effect	20,2	40,7	60,9
Gas leak to outside	5,1	6,8	11,9
Complaints regarding noise	3,4	3,4	6,8
Unavailability of regulator or street	15,3	3,4	18,7
Complaint by client	1,8	0,0	1,8
Total	45,7	54,3	100

Table 3: Effects per failure of a soft parts of a regulator

The same is done for 30 monitor failures. Table 4 shows that for 80% of the failures, there is no (known) effect. For 20% of the failures, there are gas leaks to the outside. None of the 30 analyzed failures in monitors result in unavailability of a GDS street.

Failure effects caused by monitors	Percentage of failures with this effect, occurred during operation	Percentage of failures with this effect, detected during inspections	Total percentage of failures with this effect
No (known) effect	0,0	13,3	13,3
No effect yet	36,7	33,3	70
Gas leak to outside	10	6,7	16,7
Total	46,6	53,4	100

Table 4: Effects per failure of a soft part of a monitor

The same is done for 56 aid and pilot pressure regulator (combinations). Table 5 shows that for 7,1% of the failures, there are gas leaks to the outside. Only 3,6% of the failures in aid and pilot pressure regulators result in unavailability of regulator or complete GDS street. The other failures did not result in unavailability of gas transport or gas leaks.

Failure effects caused by aid & pilot regulator (combinations)	Percentage of failures with this effect, occurred during operation	Percentage of failures with this effect, detected during inspections	Total percentage of failures with this effect
Fluctuating pressure, no effect yet	10,7	25,0	35,7
Too high/low pressure, no effect yet	8,9	19,7	23,2
Gas leak to outside	3,6	3,6	7,1
Street delivery failure	3,6	0,0	3,6
Noise complaint	0,0	1,8	1,8
No effect	8,9	5,4	14,3
Effect unknown	5,4	3,6	8,9
Total	41,0	59,0	100

Table 5: Effects per failure of a soft parts of an aid and pilot pressure regulator

Detectability of failures during inspections

To check the results of the reported analyses towards the failure effects per failure, an analysis is performed on the number of orders during inspections and the number of orders due to failures during operation. In the analysis towards the percentage of orders during inspections, all orders of soft parts since 1999 were filtered by the article numbers of diaphragm types in regulators and monitors, and it appeared that 55% of the diaphragm types were ordered during inspections. Filtering the same list on orders since 2008 as well, results in a detection of failure by inspection score of 60%. Filtering the same list on orders since 2011 gives a score of 61%. These percentages are slightly higher than the 54, 53, 59 % as shown in Tables 3, 4 and 5. The small differences might be caused by the use of undocumented inventories.

Frequencies of failure effects caused by hard components

To avoid high complexity, the assumption is done in this research that the effects of failures of hard parts of a certain component are equal to the failure effects per failure of its soft parts (see Tables 3,4, and 5). The same holds for a required replacement of a complete component. In reality, the effects of failures might be slightly different; however, only a small part of the failures is caused by other than soft parts, and therefore this assumption will not result in large deviations from reality.

The frequencies and causes of street delivery failures

One of the KPIs on GDSs (see Section 2.6) is about the number of street failures per GDS per year. A street delivery failure means that a street in a GDS is not able to deliver gas to the outlet anymore. Note that a failure (as described in Section 2.5) in a component is not necessarily the same as a street failure, see Table 3. A street delivery failure is the most important failure effect, because the main KPIs are based on delivery failures. Therefore, an analysis is done towards the causes of street delivery failures between 2012 and 2016, as reported by technicians.

From SAP, all registered street delivery failures are collected from the years 2012 until 2016 (using codes 260 and 50 on query IW69). This analysis showed a number of street delivery failures during the years 2012-2016. The exact number is hidden in this public version of the thesis. The analysis showed that next to the internally caused failures there are on average 18 street delivery failures per year caused externally and two failures per year caused by human errors.

In Table 6, the results of an analysis towards the causes of the internally caused street delivery failures are shown. It can be concluded that at least 2/3rd of the street delivery failures caused by internal failures is caused by failures in pressure control components (see Table 6). Also, 23% of the internally caused street delivery failures are caused by safety shut valves that close without a known reason, while 10,5% of these failures are caused by other or unknown causes. Frequencies in Table 6 are deleted from this public version of the thesis due to confidentiality issues.

Cause	Frequency	Percentage
regulator failure		39,5
aid/pilot pressure regulator failure		24,3
monitor failure		2,6
safety shut valve closed for unknown reason		23,0
other/unknown causes		10,5

Table 6: Causes of all 152 internally caused street delivery failures during the years 2012/2016

The frequencies and causes of failures of complete GDSs

Based on street and station delivery failures of last years, it is determined that the probability of failure of a complete GDS after a street delivery failure is 1,1%. Due to confidentiality issues, the details of these analyses are hidden.

2.8 Conclusions Chapter 2

The major results presented in chapter 2 are summarized in the following points:

1. The scores on KPIs with respect to availability are met last years: during the years 2013/2016, the number of GDS delivery failures and transport breaks were lower than the target scores of 6 and 3, respectively;
2. However, there could be a potential to improve the current maintenance concept because there is an increase in failure rate for soft parts of regulators at ages higher than 16 years (Figure 4, Section 2.5);
3. There is an increase of failures of soft parts of monitors for higher ages as well. However, this increase is not that clear as for regulators (Figure 6, Section 2.5). This makes it harder to save costs by determining optimal times for preventive replacement of monitors;
4. It does not save costs to replace soft parts of aid and pilot pressure regulators preventively, because there is no significant increase in failure rate per age (Figure 7, Section 2.5). This makes it impossible to save money by performing preventive replacements;
5. There are options to perform opportunistic replacements as well: there are between 150 and 160 replacements of (parts of) components in GDS streets per year besides the replacements of (parts of) gas pressure control systems, for a total installed base of 1000 GDSs. These replacements form opportunities to replace soft parts of regulators and monitors. As will be defined in Chapter 4, replacements of other (parts of) components in the pressure control

system form opportunities for preventive replacement of soft parts of regulators and monitors as well;

6. There is a large potential to save money by replicating the soft parts of regulators for which the supply is disrupted, which is the case for around 65% of the regulators and monitors in the installed base of Gasunie.

Chapter 4 explains a model that could assist in solving problems 2, 3, 5, and 6 that are mentioned above. In the following chapters of this report, these problems will be referred to as *the Gasunie case*.

3. Literature review

This chapter provides the results of a literature review on models that could be used either directly or in a modified form in order to solve *the Gasunie case* (for case description, see Section 2.8). The chapter starts with aspects in literature that are important in determining which models could be useful in the Gasunie case. Then, an overview of potentially useful literature models is given. Then, the suitability of the described literature models for the case is discussed. Finally, the conclusions of this chapter are presented.

3.1 Requirements of the model

This section discusses aspects in literature that are related to the suitability of the maintenance concepts used in literature for the Gasunie case.

Multi-unit systems

The first important aspect in determining optimal replacement times in the Gasunie case, is that it deals with multi-unit systems. Cho & Parlar (1991) define multi-unit maintenance models as "models concerned with optimal maintenance policies for a system consisting of several units of machines or many pieces of equipment, which may or may not depend on each other economically, stochastically or structurally". In multi-unit systems, the condition of the system depends on the conditions of the units in the system.

In the Gasunie case, the pressure control system of a street is a multi-unit system consisting of various units, such as a regulator, monitor, and aid and pilot pressure regulator (see Figure 1 and 2, Section 2.1) , and these units form multi-unit systems as well: a component contains three (groups of) parts: soft parts, hard parts and the encapsulation of the component. The following paragraph explains the dependencies between components in the pressure control system.

Dependencies between units in multi-unit systems

According to Nowakowski & Werbinka (2009), interactions between components in multi-unit systems can be caused by economic dependence, structural dependence and stochastic dependence between components. Nicolai and Dekker (2008) explain these terms as well:

- if economic dependence between units exists, performing maintenance on several units simultaneously instead of performing maintenance on units individually, either decreases costs, due to economies of scale and downtime opportunities, or increases costs, due to e.g. high downtime costs;
- If stochastic dependence between units exists, the condition of a unit influences the condition of other units;
- If structural dependence between units exists, maintenance on a failed unit cannot be performed without performing maintenance on other, non-failed units.

Nicolai and Dekker (2008) state that economic dependence could provide costs savings in terms of *economies of scale* and *downtime opportunities. Economies of scale* could exist due to *shared set-up costs* and *general economies of scale*. Set-up costs are the costs of required preparations before actual maintenance can be performed. These set-up costs can be shared when several units are maintained simultaneously. Nicolai and Dekker (2008) define single set-ups and multiple set-ups. The existence of multiple set-ups imply that there is a hierarchy of set-ups. An example regarding the case study is given in the next paragraph. *General economies* of scale imply that performing maintenance on several units in multi-unit systems simultaneously is less expensive than performing maintenance of these units individually. *Downtime opportunities* often exist in systems in series, where a failure of a single unit immediately results in a failure of the complete system. In case the system is down anyway, this downtime opportunity can be used to simultaneously maintain other units as well.

In the Gasunie case there are multiple set-ups. Therefore, replacing both soft and hard parts of both a regulator and a monitor in the same street at the same time, could lead to a multiple set-up costs saving. The two layers of set-ups are:

- Replacement of a (part of a) component is only possible when the complete street is closed and gas in the GDS street is blown off;
- Replacing parts of a component requires disassembling the component.

Next to this, failure of a component leads to downtime opportunities for other components in the street. There are no stochastic dependencies in the Gasunie case. There are structural dependencies: disassembling a component to replace a failed hard or soft part leads to the necessary replacement of all soft parts, due to reforming of certain soft parts while disassembling.

Useful maintenance policies for multi-unit systems with dependencies between units

If dependencies between units in a multi-unit system exists, then it could be useful to perform group maintenance policies, opportunity-based maintenance policies, and/or cannibalization maintenance policies (Nowakowski & Werbinka, 2009). Two very common-used maintenance policies, age and block replacement models, could be useful for maintenance optimization of single-unit systems and for multi-unit systems without any dependencies between units. The basic concepts of common-used single-unit and multi-unit maintenance policies are given in Section 3.2.

Usage-based maintenance models are not useful in this case, because usage of the soft parts of pressure control components is hard to track: records of the usage (time) are available for only the last seven years, and even these data are very hard to collect. Also, condition monitoring is out of scope of this research. Non-continuous condition-based maintenance already occurs during inspections. The inspection intervals are considered as fixed and therefore optimization of these intervals are out of scope of this research. Continuous condition-based maintenance is out of scope of this research as well, because, to the knowledge of this research, there is no easily implementable method to determine the level of degradation of soft parts in the components.

Redundancy in streets

As mentioned in Section 2.1, an important property of GDSs is that there is redundancy in streets. However, in analyzing the failure rates and failure effects (see Chapter 2) it seemed to be very hard to distinguish delivering streets and back-up streets per GDS; also, changes are made with respect to delivery settings sometimes. Therefore, streets were not separated based on these properties, and failure rates and failure effects were determined by analyzing all streets together.

Based on the method of analysis as explained in the previous paragraph, the redundancy of streets per GDS in the Gasunie case can be defined as a hot-standby redundancy. Hot-standby redundancy means that all components are subject to failure and have the same failure rate; other forms of redundancy are cold-standby redundancy, where standby components cannot fail and warm redundancy, where standby components are subject to failure with a failure rate lower than the failure rate of active components (Moghaddas et al., 2012). Chapter 7 gives some extra notes about the assumed form of standby redundancy.

Olde Keizer et al. (2016) show that there is only a small number of articles that consider both redundancy and economic dependences. They refer to articles that consider maintenance policies for systems with redundancy in the following policy types: corrective maintenance; block-based maintenance; corrective maintenance initiated after failure of a certain number of components; maintenance of both failed and degraded components after failure of a certain number of components.

Redundancy is the most common-used method of increasing availability of systems (Moghaddas et al. , 2012), which is the reason that GDSs are designed redundantly as well. However, in the Gasunie case, not only the availability of the system is relevant: the number of failed streets already is a KPI. Next to this, to estimate the number of failed GDS and the corresponding failure costs, a fixed probability of GDS delivery failure when a street delivery occurs can be used as well (see sections 2.7 and 4.7).

Permanent supply disruption of spare parts

As explained in Section 2.3, optimizing the replacement policy for soft parts of pressure control components is complex due to the permanent supply disruption of a large part of the soft parts in the installed base. The supply disruption influences the replacement scenarios and replacement costs (see Section 2.5). When there are permanent supply disruptions of soft parts of a certain regulator, this implies that the complete component has to be replaced when a soft part fails; also, due to structural dependences, a failure of a hard part means that the complete component has to be replaced. It is assumed that the newly installed components do not suffer supply disruptions.

Clavareau and Labeau (2009) study maintenance and replacement policies under technological obsolescence. Their model uses Monte Carlo simulations regarding the decision between preventive replacement of obsolete components, so that their residual lifetime is wasted, and corrective replacements, which usually implies a higher number of failures. Section 6.3 contains sensitivity analyses with respect to preventive replacements of obsolete complete components.

Imperfect replacement of soft parts during CM

As is shown in Section 2.5, the failure rate of soft parts is slightly higher after the first failure of soft parts at a regulator than it was before the first failure. This suggests that corrective replacements of soft parts sometimes are performed imperfectly. It can be assumed that PM and OM are perfect replacements, because then the situation is comparable to the PM as is done until 1997.

Finite planning with stationary rules

According to Dekker, Wildeman and Van der Duyn Schouten (1997), the planning method in maintenance models with economic dependence can be classified as either stationary or dynamic. In stationary models, a stable situation is assumed over a long term; also, often an infinite planning horizon is used. In dynamic models, decisions may dynamically change over the planning horizon. According to Nicolai and Dekker (2008) most articles in literature use an infinite horizon. When a finite horizon is used, usually a residual value is implemented to quantify the system value at the end of the planning horizon.

In the Gasunie case, a finite horizon can be assumed according to the horizon that is used by Gasunie in their maintenance optimization calculations. In these calculations, the year 2065 is used as last year in the planning horizon; no residual values are used. This method is used in this research as well.

3.2 Models in the literature

Focus in this research is on multi-unit systems, due to the existence of dependencies between units. Dependencies between the units in a system cause the inability to apply multi-unit system optimization models on single-unit systems (Castanier, 2005). When applying single-unit maintenance models on multi-unit systems, optimal solutions can only be found if there are no dependencies between units (Cho & Parlar, 1991). However, Laggoune et al. (2010[1]) state that most maintenance policies in literature are extensions of the age replacement model of Barlow and Hunter (see next paragraphs) with a focus on single-unit systems, even though most systems in reality are multi-unit systems. Review articles, for example Wang (2002), listed common-used extensions of these single-unit systems that could be interesting for the Gasunie case as well. Therefore, common-used maintenance policies of both single-unit and multi-units are explained in the following paragraphs.

Single-unit maintenance policies

The described maintenance policies assume that: “the units are subject to failures with an increasing failure rate; there are infinitely many disposable identical units with independent and identically distributed lifetimes; and the salvage value of the unit is negligible” (Wang, 2002). In the Gasunie case, for most spare part types the number of available spares is limited.

A basic model in the range of *age-dependent PM policies* is the *age replacement policy*. In the age replacement model, costs are either PM costs c_0 after fixed operational time T, or CM costs c_1 if a failure occurs before T; after PM is performed, the unit is as good as new. Average costs g(T) per time unit for PM interval T are (Gertsbakh, 2013):

$$g(T) = \frac{c_0 R(T) + c_1 F(T)}{\int_0^T R(t)dt}$$

with F(t) as cumulative distribution function (c.d.f.) of the units lifetime, f(t) as probability distribution function (p.d.f.) of the units lifetime and R(t) as survival probability function (R(t) = 1 – F(t)). Explanations of c.d.f. and p.d.f can be found in Law (2015). As is already mentioned earlier, CM costs c_1 are higher than PM costs c_0.

The age replacement model is developed by Barlow & Hunter (1960). It is one of the most popular decision models used in time-based maintenance policies (Aven & Jensen, 1999). The class of age-dependent PM policies consists of the age replacement model and a number of extensions (Wang, 2000). Under all PM policies in this class, PM is performed at a predetermined age and CM is performed at failure. PM and CM can be either minimal, imperfect, or perfect; definitions of these terms are provided in the following paragraphs. The predetermined replacement age is measured from the time of last replacement. Therefore, major drawbacks of age replacement policies are that replacement times cannot be easily planned and keeping track of the age per item is required.

The overview of Wang (2002) gives several relatively small extensions of the age replacement model, which are amongst others: replacing a unit at age *T* or at number *N* of failures at the unit, whichever occurs first, with minimal repair at failure between replacements; adding probabilities of perfect repair or minimal repair after failure; and adding several types of failure and performing replacement at the *n*th failure of a certain type.

Under *block replacement policies*, preventive replacement is performed after a fixed time *T*, regardless of the failures that occurred before *T*. When failures occur, CM is done with costs c_1. In the basic model, both PM and CM completely renew the unit. Advantages of this maintenance policy are the possibility to combine several periodic maintenance activities and the fact that it is not required to keep track of the age of each item. Average costs g(T) per time unit for PM interval T are:

$$g(T) = \frac{c_0 + c_1 m(T)}{T}$$

with *m(T)* as mean number of failures in (0,*T*) ((Gertsbakh, 2013)).

An extension of block replacement policies is a *block replacement with minimal repair at failures policy*. Under this policy, minimal repair is done after each failure with costs c_1; also, units are repaired into an as-good-as-new state during PM with costs c_0. Minimal repair means that the unit is restored to the condition it had just before the failure: repair at t_0 solves the failure, but does not change the failure rate at t_0. Average costs *g(T)* per time unit for PM interval *T* are (Gertsbakh, 2013):

$$g(T) = \frac{c_0 + c_1 \int_0^T \lambda(t) dt}{T}$$

with *λ(t)* is the failure rate function: *λ(t)* = $\int_0^T \lambda(t) dt$.

A similar replacement policy is possible with imperfect maintenance instead of minimal repair. After a perfect maintenance activity, the equipment is as good as new. After an imperfect maintenance activity, the equipment is not assumed to be as good as new, but only younger than before the maintenance activity (Chaudhuri and Sahu, 1977; Pham & Wang, 1996). Various methods of dealing with imperfectness of maintenance can be found in Pham & Wang (1996).

Under *block replacement in case of hidden failure policies*, there is preventive replacement after fixed period *T* with costs c_0. Failures before *T* remain hidden, with costs *K* for each time unit that the hidden failure exists. Average costs *g(T)* per time unit for PM interval *T* are (Gertsbakh, 2013):

$$g(T) = \frac{c_0 + K \int_0^T (T - t) f(t) dt}{T}$$

Another example of a block replacement policy is Berg and Epstein (1976) who modified the policy by setting an age limit: when a units age at the scheduled block replacement time is less than the age limit, the unit is not replaced. Then, the unit is replaced not earlier than the next failure occurs or the next block replacement time starts.

Under *failure limit policies*, reliability indicators are defined per unit.PM on a unit is only performed when these reliability indicators reach a predetermined level (Wang, 2002); failures are corrected by repairs. The goal of this policy is to keep the unit above a predetermined reliability level.

Under *sequential PM policies*, PM is performed at time intervals that decrease in duration as time passes (Wang, 2002). This policy uses the common assumption that units require more frequent maintenance when the units reach higher ages.

Under *repair limit policies*, repair costs are estimated directly after a failure. Repair is only performed if the estimated repair costs do not exceed a predetermined level of repair costs. An example is the *repair time limit policy* (Nakagawa and Osaki, 1974), where the unit is repaired only if the required repair time does not exceed a predetermined time T; otherwise, the unit is replaced.

Under *repair number counting policies*, units are replaced at the *n*th failure; each failure before the *n*th failure is solved by minimal repair.

Multi-unit maintenance policies

The field of group maintenance policies can be divided into group, cannibalization and opportunistic maintenance policies (Cho & Parlar, 1991; Nowakowski & Werbinka, 2009).

Under *group maintenance policies*, the objective is to find optimum replacement times, in which the *optimum* is determined in terms of reliability or costs of the complete group of units. Under this type of policy, maintenance on all units in a group is performed after a certain condition is fulfilled. This condition is usually based on time and or costs. Nowakowski and Werbińka (2009) give the three main problems regarding group maintenance policies for multi-unit systems: grouping units that are replaced simultaneously after a unit fails, implementing redundancy in system designs with the objective of cost reduction, and maintenance scheduling of units per group.

A modification of group maintenance policies is a *multi-unit block maintenance policy*, where all units are replaced preventively at periodic intervals, regardless of their states.

Under *cannibalization policies*, the components of non-operative machines are ‘cannibalized´ in order to repair other machines. This is often done when the repair of a failed machine requires certain components that are in the cannibalized machine (Nowakowski and Werbińka, 2009). These policies are typically used when there are supply disruptions of components.

In *opportunity based age replacement*, maintenance is performed when an opportunity exists. Failures and scheduled downtime of a unit in the system can form such opportunities. Usually, these opportunities for preventive replacement are implemented in the model by a Poisson process with intensity λ (Gertsbakh, 2013). Preventive replacements are done at the first opportunity after T, with costs of replacement c_0. After failures, corrective replacements are performed with costs c_1. In that case, average costs *g(T)* per time unit for *T* are (Gertsbakh, 2013):

$$g(T) = \frac{c_0 + (c_1 - c_0)\left\{F(T) + \int_T^{\infty} f(t)e^{-\lambda(t-T)}dt\right\}}{\int_0^T R(T)dt + \int_T^{\infty} R(t)e^{-\lambda(t-T)}dt}$$

Zhang & Zeng (2015) gives four common-used opportunistic maintenance policy types: *age-based maintenance* (ABM) strategy; *failure-rate-tolerance-based maintenance* (FBM) strategy; *control limit strategy of condition-based maintenance* (CBM) strategy; and *CBM strategy based on proportional hazards model (PHM)*. The CBM and PHM replacement policies are about condition-based maintenance and will not be explained in this article.

Rander and Jorgenson (1963) proposed the first *ABM opportunistic maintenance model*: the (n_i, N) strategy. In this strategy, a unit *i* can be replaced in three ways: correctively after its failure, preventively after the unit reaches its PM age *N*, and opportunistically after failure of another unit if the age of the *i* is above its opportunity replacement age threshold n_i. In this model, the opportunity-based replacement age threshold n_i is lower than preventive replacement age *N*. Berg (1978) extended this model for a 2-unit system. Van der Duyn Schouten and Vanneste (1992) extended this model for a two-component series system: again, a unit is replaced when it has failed or when its age has reached the value *N*, or when the age of the unit is higher than *n* when the other unit has failed ($n \leq N$).

The failure-rate-tolerance-based opportunistic replacement policy ($L - u$, L) is developed by Zheng and Fard (1992). In this policy, a unit can be replaced in three ways: correctively after its failure, preventively after exceeding the failure rate limit *L,* and opportunistically when one of the units in the group is replaced: in the latter case, all other units in the group with failure rate above $L - u$ are replaced as well.

Several authors proposed modified opportunity-based maintenance models. Zhou et al. (2009) developed an opportunistic maintenance scheduling algorithm for multi-unit systems in series. The authors integrated a ratio of imperfectness in maintenance actions. In the algorithms, the objective is to minimize systems short-term cumulative opportunistic maintenance costs. This is done by selecting reliability thresholds and maintenance action combinations.

Lagounne et al. (2009) developed a decision model based on multi-grouping optimization to determine PM actions for series systems. Their method seems to be interesting for the Gasunie case because it deals with corrective, preventive and opportunistic maintenance simultaneously; also, the authors claim that the method is useful even for large numbers of units per system. The objective of their method is to find preventive replacement times that minimize total costs. The authors used a total expected cost per cycle that includes the expected preventive, corrective and opportunistic replacements per cycle, with the PM interval of the unit with the longest PM interval as cycle length. Also, they added a decision-making criterion for opportunistic replacement: additional costs of OM of the unit should be lower than the costs of failure of the unit multiplied by the probability of failure until the next preventive replacement. In the Gasunie case, there are no preventive replacements in the maintenance concept (yet), and the duration until next replacements depends on the failure behavior of all components in the GDS. Therefore, the described decision-making criterion is very complex in the Gasunie case. A static threshold for OM (for example, a minimum age after which a unit might be replaced opportunistically) would be more useful.

The biggest drawbacks of opportunity-based maintenance are that it could lead to problems regarding the planning of work preparations, components ordering and making sure that there is a maintenance crew available (Laggoune et al., 2010 [2]). Laggoune et al. (2010 [2]) mention as well that most of the authors in this field used oversimplified assumptions. Most multi-unit systems in these models consist of only two or three units. An example is a model developed by Zhang & Zeng (2015). They developed a deterioration state space partition method for OM modeling of multi-unit systems. The degradation state per unit *i* is divided into four zones. The four zones are named to the replacement strategy used for the unit when so called 'maintenance decision points' occur: stochastic degradation, opportunistic replacement zone, preventive replacement zone, and corrective replacement zone. The term deterioration state space suggests that this method is only useful for CBM, however, the authors claim that the method can be used with other decision variables such as age and failure rate as well. A problem with this method, as is explained by the authors themselves, is that the complexity of the method grows exponentially when the number of units in a multi-unit system increases. The method is only verified for one, two and three units per system.

The problem with respect to complexity for opportunity-based maintenance policies are in line with the findings of Nowakowski and Werbińka (2009), who state that most multi-unit maintenance models are too difficult to optimize and therefore hard to use in practice.

3.3 Suitability of the maintenance concepts for the case

The policy types described in part 3.2 contained some interesting options for the Gasunie case. As already explained, multi-unit system policies are most interesting. However, cannibalization policies are not an option due to Dutch laws regarding gas transport and the reuse of used products. Group maintenance policies for this case are very complex due to the variety in components per street and component ages per street. Opportunistic maintenance policies are interesting; however, the described models contained too much simplified assumptions and would not work in the Gasunie case. Comparing simulations with various combinations of preventive replacement and opportunistic replacement thresholds therefore is most promising.

Alrabghi and Tiwari (2015) mention that optimal parameter values in many maintenance policies are not analytically traceable. In their opinion, this problem makes simulation the better choice; also, simulation would give opportunities for experimenting and helps to provide better understanding of the system when the system is complex. The authors give an extensive list of studies that concluded that simulation is preferred over analytical approaches. Another conclusion of Alrabghi and Tiwari (2015) is that simulation has the advantage of better possibilities in verification and validating the results. The mentioned advantages of experimenting and verification and validation are important in the Gasunie case, because there is a number of maintenance factors that might be changed in the coming years, such as the inspection interval of three months, or are hard to determine, such as the level of undocumented inventory. By using a simulation approach, experiments can be done with various parameter value combinations.

Objective of the simulations is to find optimal thresholds for PM and OM of soft parts of regulators and monitors. This approach is comparable to the approaches by Rander & Jorgenson (1963), Berg (1978), and Van der Duyn Schouten & Vanneste (1992). In the last article, the authors already explain that their approach is very hard to perform analytically for three or more components.

When using such a simulation approach, implementing some of the single-unit maintenance models and modifications might be useful as well. A number of modifications is given that use a certain decision variable to determine whether replacement should occur after a failure, such as: replacement after a number of failures per unit or per system; using various failure types and replacement after *n*th failure of a certain type; repair limit policies; repair number counting policies. In the Gasunie case, these modifications are useless, because delaying the replacement of failed soft parts of pressure control components is very risky. The extension by adding hidden failure costs sounds promising due to the existence of hidden failures that result in gas leaks; however, the costs per gas leak can be estimated by a fixed costs, as is done in Section 2.5. More promising for further research are the concepts of sequential PM policies, adding probabilities of imperfect or minimal repair, and block replacement with minimal age for replacement.

3.4 Conclusions of literature review

The following conclusions can be made based on this chapter:

1. Determination of preventive and opportunistic maintenance thresholds based on ages of soft parts of regulators and monitors is most promising. Note that the difference between preventive and opportunistic is made, as the following sentence explains. A unit i can be replaced in three ways: correctively after its failure, preventively after the unit reaches its PM age N, and opportunistically after failure of another unit if the age of the i is above its opportunity replacement age threshold n_i. Opportunity replacement age threshold n_i is lower than preventive replacement age N;
2. To determine the optimal threshold ages, a simulation model can be used. Simulation suits the required flexibility in the sensitivity analyses in Chapter 6 as well. The simulation model is explained in Chapter 4.

4. Description of the model

This chapter explains the type of simulation used, objectives of the simulation, model logic, input and output of the model, assumptions used and it gives further explanations of the steps used in the model. Also, it reports the verification and validation process of the model.

4.1 Type of simulation used

To simulate replacements at physical GDSs, a mathematical model is developed. Excel VBA is used for flexibility in further use by Gasunie. The model is a dynamic and terminating model: it represents the evolvement of the installed base of GDSs over a period of 71 years. The model simulates replacements from 1994 to 2065; 1994 is the average year of last preventive replacement of soft parts, while 2065 is the year used in various long term maintenance planning forecasts. The years 1994/2017 form a warmup period before the PM and OM replacements might start in 2018. Also, the years until 2017 form an opportunity to validate the model with the number of failures in last years in real life.

The model forms a discrete event simulation model that simulates the events of replacements. In Law (2015) discrete event simulation is defined as *the modelling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time*. In the model, two states can be distinguished: either a replacement occurred in a year, or not. For every replacement of any component at the GDS street, the remaining useful lifetimes per component get a new value for each replaced component; for every non-replaced component, remaining lifetimes decrease by the time between the two last replacement years. Next-event time-advance is used, with as event *the occurrence of a preventive or corrective replacement of at least one of the components per GDS street per year*. Each of these described events can occur only once per GDS street per year in the model due to the fact that fixed intervals of a year are used. Motivation behind using a discrete event simulation model with intervals of one year can be found in the first assumption in the list of Section 4.5. Stochastic simulation is used with respect to useful lifetimes and availabilities of spare parts.

4.2 Objectives

The model shows the scores on KPIs (street delivery failures per year, GDS station delivery failures per year, and transport breaks per year), total failure costs (due to gas leaks and transport breaks), total replacement costs and most important the total costs, which are equal to the failure plus replacement costs, for various combinations of four decision variables. The four decision variables are the PM age and the OM age threshold of both regulator soft parts and monitor soft parts. Chapter 2 reports analyses that showed that PM or OM of soft parts of aid and pilot pressure regulators do not save costs. Optimal values for the PM age and the OM age thresholds can be found by determining the combination of thresholds that minimizes total costs. As explained in Section 1.3, opportunity-based maintenance is a preventive maintenance policy and therefore the distinction between OM and PM age as used in this research must be clarified to prevent misunderstandings:

- *OM age* is age after which the first opportunity leads to an opportunistic replacement
- *PM age* is the threshold to perform a preventive replacement without an opportunity

These parameters are similar to the parameters used in the *(n_i, N)* policy by amongst others Rander & Jorgenson (1963); see Section 3.2 for explanation of this policy.

Opportunities for OM can be defined as "t*he occurrence of a preventive or corrective replacement of any other component type [type 1 to 10, see below] in a GDS street"*. Component types are given in the following paragraphs. A replacement in another street in the GDS is not an opportunity, because there are no *downtime opportunities* or *economies of scale* (see Section 3.2) due to street disassembling; also, a replacement of components outside the GDS street do not require disassembling of the street; furthermore, all maintenance activities at GDS that do not require replacement of any of the ten described component types in the GDS street, are too short to form an opportunity. This means as well that the inspections (see Section 2.2) do not form opportunities.

As is described in Section 2.5 as well, a GDS street can be defined as a system with sub systems and components in the following way:

- Regulator [sub system 1]:
    - The aggregated total of soft parts of a regulator [component type 1]
    - The aggregated total of hard parts of a regulator [component type 2]
    - Encapsulation of a regulator [component type 3]
- Monitor [sub system 2]
    - The aggregated total of soft parts of a monitor [component type 4]
    - The aggregated total of hard parts of a monitor [component type 5]
    - Encapsulation of a monitor [component type 6]
- Aid & pilot pressure regulator [sub system 3]
    - The aggregated total of soft parts of an aid & pilot pressure regulator [comp. type 7]
    - The aggregated total of hard parts of an aid & pilot pressure regulator [comp. type 8]
    - Encapsulation of an aid & pilot pressure regulator [component type 9]
- Replacements of any other complete component in a GDS street [sub system 4]
    - The aggregated total of complete other components [component type 10]

Objective is to find the optimal combination of values for the following thresholds:

- T_1, which is the age of regulator soft parts after which the first opportunity leads to opportunistic replacement of regulator soft parts [component type 1]
- T_2, which is the PM age for soft parts of regulators [component type 1]
- T_3, which is the age of monitor soft parts after which the first opportunity leads to opportunistic replacement of monitor soft parts [component type 4]
- T_4, which is the PM age for soft parts of monitors [component type 4]

In the simulation model, all other replacements in GDS streets occur correctively. For RSS configuration streets (see Section 2.1), sub system 2 and its components do not exist. In that case, remaining lifetimes of these components are set to a very large value. The failures of the extra safety shut valve (in comparison with a RMS configuration street) are represented by adjusting the failure rate of component type 10. Details can be found in Appendix S.

Objectives next to determination of the optimal age thresholds

Next to the optimization of the four age thresholds, various sensitivity analyses are performed to measure the influence of various variables on the outcomes. The most important sensitivity analysis is the one for the permanent supply disruption of soft parts. With the results of this analysis, the value of replicating new soft parts can be estimated. More details can be found in Chapter 6.

4.3 Model logic

The model consists of four main steps. These steps are given below including their most important sub steps. In Section 4.6, an outline of these steps is given; in Appendix S, these steps are explained in high detail.

- Step 1: initialization
    - Assign lifetimes to the components by random number generation
- Step 2: determination of the next replacement year for the GDS street
    - Determine the year of next replacement at GDS street
- Step 3: simulation of the replacements
    - Step 3a: determination of replacement scenarios (if conditions per replacement scenario hold)
        - PM of soft parts [components 1 and 4]
        - OM of soft parts [components 1 and 4]
        - Corrective replacements* of soft parts [comp. 1,4 and 7]
        - Corrective replacement* of hard parts [comp. 2,5 and 8]
        - Corrective replacements* of complete components due to failure of encapsulations [comp. 3,6 and 9] or failure of parts with disrupted supply
        - Corrective replacement* of 'other components´ [component 10]
    - Step 3b: resetting the lifetimes and inventory levels after replacement
        - Update the lifetime properties of non-replaced components
        - Assign a new randomized lifetime to the new components (via step 2)
        - Update the inventory levels after replacement
- Step 4: computation of the results
    - Step 4a: computation of the KPI scores and costs per year
    - Step 4b: computation of the results per discrete event simulation run (period of 72 years)

* Definition of *corrective replacement:* replacement where no scheduled PM or OM occurs based on their age thresholds. In real life, these replacements could occur after failures during operation and after detection of failures during inspections. These inspections result in the fact that a large part of the 'failed' soft parts are replaced before the failures cause major effects, as explained in Section 2.7.

Both step 1 and 4 are done once per simulation run. These steps are only the initialization and the computation of results; details can be found in Appendix S. Major calculations are done in step 2 and step 3. Step 2, the determination of the next replacement year for the GDS, is done once for each GDS in the simulation. After step 2, step 3 is done multiple times per simulation run: in this step, for each year is checked for each GDS street whether replacements of one of the components of the street is required. Every time that a replacement of at least one component in a street is required in a particular year, the model determines for all components in the GDS whether a replacement of the component is required and in which scenario. Lifetimes and inventory levels per component are updated afterwards. After step 3, step 2 is done again, until the last GDS street is done in the last year of the simulation and step 4 starts. Appendix P contains a process flow diagram of these steps.

Figure 8 shows the process flow diagram of Step 3a, the most important step in the model. The figure shows all steps required to determine the replacement scenario per component type, for each sub system. The steps in this figure are subsequently done for each of the four sub systems in each street that requires a replacement in a specific year; exemptions will be explained later in this section.

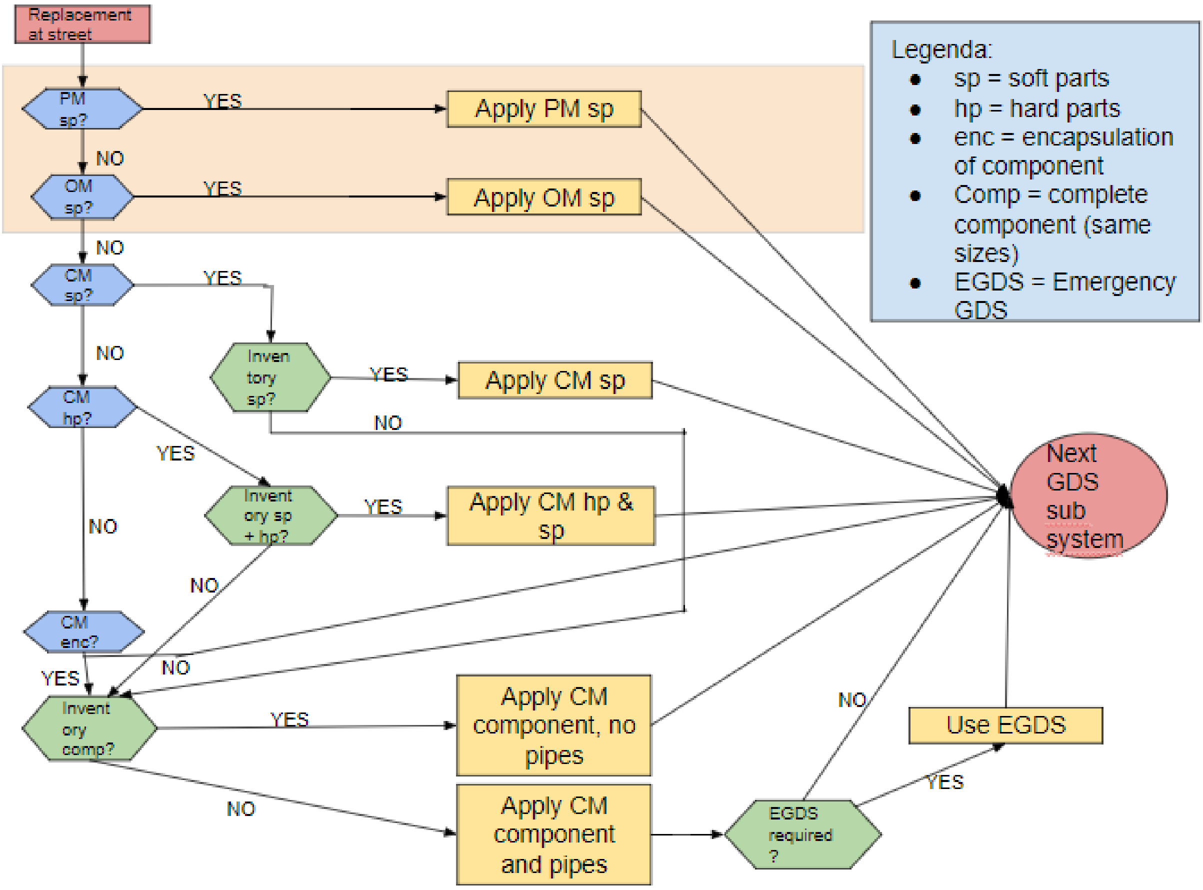

Figure 8: Process flow diagram of Step 3a (contains the most important sub steps in the simulation model)

The logic is as follows: the event 'replacement at street' occurs every time a preventive or corrective replacement is required on at least one component in the street; opportunistic replacements do not cause the occurrence of this event. If the described event occurs, the model checks for each sub system type first whether the conditions for PM of soft parts are fulfilled; if not, the model checks whether the conditions for OM of soft parts are fulfilled; the same holds for respectively the corrective replacement of soft parts (scenario 1), corrective replacement of hard parts (scenario 5), and corrective replacement of complete sub system (scenario 2 or 3, depending on the availability of a component with the same sizes in the inventory). Scenarios are described in Section 2.3. These steps are performed for each sub system (regulator, monitor, aid and pilot pressure regulator and 'other components'). As is described in Section 2.3 as well, Figure 8 shows that inventory level is a major aspect in determining the required replacement scenario.

For regulators and monitors, all steps are performed. For aid and pilot pressure regulators, the steps in the orange rectangle above (OM and PM of soft parts) are not performed, because the analyses described in Section 2.5 showed that there is no clear increase in failure rate for the soft parts of these components, and therefore PM and OM for aid and pilot pressure regulator soft parts would not save any costs. For the sub system 'other components', only corrective replacements in scenario in Scenario 3 are performed; therefore, this diagram does not hold for this component type.

4.4 Input and output of the model

Table 7 gives all parameters used in the model.

Variable/ parameter type	Variable/Parameter	**Section** with description	Part of sensitivity analyses
Input factors	OM age for soft parts of regulators and monitors (T_1 and T_3)	4.2	-
	PM age for soft parts of regulators and monitors (T_2 and T_4)	4.2	-
	Population numbers (such as standalone GDSs, non-standalone GDSs, GDS streets, numbers per component)	2.1	No
	Failure rates for first failures of soft parts, hard parts and encapsulations per pressure control component type and for following failures of soft parts of regulators; failure rates of other components in GDS streets	2.5	Yes
	Number of street delivery failures caused by other components than regulators	2.7	No
	Probability of complete GDS failure after a single street fails	2.7	Yes
	Probability of transport break after a non-standalone GDS fails	5	Yes
	Failure costs per gas leak and per delivery failure of complete GDSs	2.4	Yes
	Replacement costs per replacement scenario	2.3	No
	Failure effects per failure per pressure control component	2.7	Yes
	Permanent supply disruption of components (parts)	4.7	Yes
	(Undocumented) inventory levels per component type	6	Yes
Responses	Expected scores on KPIs per year: exp. numbers of street delivery failures, GDS delivery failures, transport breaks	-	-
	Expected total failure costs per year due to gas leaks and transport breaks	-	-
	Expected total replacement costs per scenario per year	-	-

Table 7: Variables and parameters used in the simulation model

4.5 Assumptions used in the model

The following list presents the assumptions that are implemented in the model. These assumptions are mainly implemented to decrease complexity in either the simulation process or the required data analyses that were reported in Chapter 2. The assumptions regarding values of input parameters are listed in Section 4.7. The assumptions regarding modelling are:

- Failure rates are per year, because the use of failure rates per year during the failure rate analyses in Section 2.5 decreased the complexity of these failure rate analyses. Using these failure rates per year decreases the simulation process complexity and simulation time as well. Also, maintenance intervals of complete years are most practical for Gasunie. This assumption means as well that the minimal duration between two replacements of the same component is one year, and simulation intervals of a year are used. The model is a periodic model in which a period is 1 year;
- Replacements of components in a GDS street occur separately, with opportunistic replacements of soft parts as only exceptions. In reality, the replacement of components

other than soft parts could occur opportunistically as well, which decreases the number of opportunities. This assumption is added to decrease complexity with a negligible effect on the simulation outcomes;

- When the conditions for PM of a soft part hold, PM is planned. OM is not possible anymore when the year of PM is reached. In reality, it could occur that PM is planned but an opportunity occurs before the PM is actually performed. This assumption is added to decrease complexity with a negligible effect on the simulation outcomes;
- The following probabilities are used as constants (values are described in Chapter 5), instead of simulating their outcome:
    - probability of a scenario 4 replacement (emergency installation is required) when a scenario 3 replacement is required (complete component is replaced and connected pipes are changed);
    - ratios of failure effects per failure per component type;
    - probability of GDS delivery failure when a street delivery failure occurs;
    - probability of GDS delivery failure of a standalone GDS when a GDS delivery failure occurs;
    - probability of a transport break when a GDS delivery failure occurs for a non-standalone GDS;

  Using constants instead of simulating the outcomes decreases complexity and should have no impact on the average results per year.
- Number of street delivery failures caused by other components than regulators is constant and equal to the average number of reported street delivery failures caused by other components than regulators during the years 2012/2016. This assumption decreases complexity and will have no influence on the average results per year;
- Failure costs per failure type and replacement costs per replacement scenario are fixed. In reality, these costs could differ due to variation in circumstances. Average values are used to decrease complexity; this assumption should have no impact on the average results per year;
- Useful lifetimes of encapsulations of components are exponentially distributed, as well as the useful lifetimes of hard parts of components. This assumption is done because a research [4] turned out that the installed base of GDS components was in its constant failure rate phase;
- Failures of hard parts or encapsulations of components are subject to the same ratios of failure effects per failure as failures of soft parts. This assumption is done to decrease the required data analyses in this research. Because the failure rates of hard parts and encapsulations are much lower than the failure rate of the soft parts (see Section 2.5), this assumption will have only minor effect on the simulation outcomes;
- All components with permanent supply disruptions of a certain component type use the same (undocumented) inventory. In reality, there are various types of regulators, monitors, and aid and pilot pressure regulators, and therefore distinct (undocumented) inventories. This assumption is done to decrease complexity of the data analyses performed to fulfil this research. Chapter 7 reports about the consequences of this assumption.
- Replaced components cannot be used in other components again, according to law regarding gas transport.

4.6 Explanation of the steps used in the model

In the following paragraphs, an outline of the steps and sub steps described in Section 4.3 is given. More details can be found in Appendix S.

Step 1: Initialization

Define object used in the simulation

In the VBA program, three classes are defined: GDSs, Streets and Components. Each GDS contains a number of objects from the class Streets, and each Street contains ten objects from the class Components. The Streets and Components are chosen in such a way that it represents the installed base of GDSs.

By using random number generation, a number of streets, equal to the ratio of RMS streets in the installed base, received a Boolean value *True* for the property *RMS.* This property is used to indicate whether or not a street contains an RMS configuration.

The property *failure rate category* is used to assign a failure rate distribution to the component. There are 12 failure rate categories: one for the first failure for each of the ten component types, one for the second failure of regulator soft parts, and a failure rate for component type 'other components' when RSS configuration is used instead of RMS configuration.

The property *permanent supply disruption* is a Boolean variable used to indicate whether or not the supply of parts for a component type is disrupted. Again, random number generation is used for assigning the values for each component in the sample, according to the ratio of components in the installed base for which the supply is disrupted.

Assign remaining lifetimes to the components

To generate a random lifetime per component based on the failure rates per age of the component, random number variates are used in combination with the inverse transform method.

Define inventory levels per component type

In the initialization, also the inventory level for each component type is assigned. As is explained is Section 2.3, there are (undocumented) inventories in busses of technicians, that could be used when there are permanent supply disruptions of the required component type. The following formula is used for the probability of such a possibility at time *t*:

*P(AvailableInventory;t) = LB(c) + (UB(c) - LB(c)) * (InventoryLevel(c;t) / InitialInventoryLevel(c)*

with LB(c) as the probability that a replacement of component type *c* can be done by creative solutions by technicians when no (undocumented) inventory is left anymore, such as buying these parts at other gas transport companies; *UB(c)* as the probability that a replacement of component type *c* can be done with these creative solutions or the left (undocumented) inventory at the start of 2018; *InventoryLevel(c;t)* as the inventory level at time *t* of component type *c; and InitialInventoryLevel(c)*as the inventory level of component type *c* at the start of 2018. This formula represents the expected decrease in (undocumented) inventory level during the coming years, depending on the number of required parts from this (undocumented) inventory.

Step 2: Determination of the next year of replacement for the GDS

Determine duration until next replacement at GDS street

The duration until next replacement at a GDS street is either the minimum remaining lifetime per component in the GDS, which leads to a corrective replacement, or the time until the first PM activity has to be done on regulator or monitor soft parts. The PM activities are performed when the PM threshold age is reached.

Determine the year of next replacement at GDS street

The year of the next replacement at a particular GDS street is equal to the year of the last replacement at that GDS street plus the duration until the next replacement at that GDS street as described in the last paragraph.

Step 3a: Determination of replacement scenarios

Only when the *year of next replacement at GDS street* (see last paragraph) is reached in the simulation model, then Step 3 is started for that GDS street. Each time Step 3 is started, the program simulates all required replacements that have to be done in that year. These replacements can be:

- PM of regulator and/or monitor soft parts;
- OM of regulator and/or monitor soft parts;
- Corrective replacements of soft parts, hard parts, and encapsulations/complete components of one or more of the gas pressure control components regulator, monitor, and aid and pilot pressure regulator;
- Corrective replacement of the aggregated component type 'other components' in the street.

The following rules are used for the replacement scenarios:

- For PM of soft parts, the age of soft parts must be higher than the threshold age for PM; there shall not be permanent supply disruptions of the required soft parts, and the remaining lifetimes of both hard parts and encapsulation must be more than 1 year (otherwise it is assumed that the condition of the component already suggests a replacement of the nearly-failed part)
- For OM, the same rules are used, with the exception that the OM age threshold is used instead of the PM age threshold. Also, OM is not done when the PM age threshold is already reached.
- Corrective replacement of soft parts does only occur after failure of a soft part. Also, as for PM and OM, the remaining lifetime of the hard parts and encapsulation must exceed 1 year. Also, there must be inventory available to replace the soft parts, otherwise the complete component has to be replaced.
- Corrective replacement of hard parts does only occur after failure of a hard part. Also, the remaining lifetime of the encapsulation must exceed 1 year. Also, there must be inventory available to replace the hard and soft parts, otherwise the complete component has to be replaced (replacement of hard parts also requires replacement of soft parts, see Section 3.2).
- Corrective replacement of complete components is done when either the encapsulation fails, or a failure of soft or hard parts cannot be solved due to unavailable inventory. When a complete component with the same size is available, the failed component is replaced in scenario 2 (complete component replacement without pipe changes). If there is no

component available with the same size, a scenario 3 replacement occurs (complete component with pipe changes).

- Corrective replacement of 'other components' occur when the aggregated component 'other components' reaches a remaining lifetime of 0.

Step 3b: Resetting the lifetimes and inventory levels after replacements

Reset the remaining lifetime of non-replaced components

If a replacement at GDS is done but no replacement occurred of component with component type *c*, the remaining lifetime of that component is updated.

Assign a new remaining lifetime to the new components (via step 2)

All replaced components get a new remaining lifetime via random number generation using the same logic as is explained in step 2. A special scenario is the replacement or regulator soft parts in "Scenario 1": these parts get a new remaining lifetime based on a special failure category, which is the 'second failure rate' (see Section 2.5) of regulator soft parts.

Reset the properties of the GDS with respect to last replacement at GDS street

After all replacements are determined, the year of the *last replacement at the GDS street* is set equal to the year of the *earliest replacement at GDS street*.

Reset the inventory levels after replacements

In case the (undocumented) inventory levels are used for a replacement, the (undocumented) inventory level is updated.

Step 4a: Compute the scores per year

In this step, failure, replacement and total costs are computed, as well as the scores on the most important KPIs: frequency of street delivery failures, GDS delivery failures, and transport breaks per year.

Calculate number of replacements per replacement scenario per year

For the corrective replacement scenarios 1 (soft parts), 2 (complete components, no pipe changes), 3 (complete components, plus pipe changes), scenario 5 (hard parts and soft parts), and the "OM" and "PM" replacements of soft parts, the frequencies per year are counted during the simulation. The frequency of scenario 4 (emergency installation required) is calculated by multiplying the number of scenario 3 replacements by the probability of scenario 4 given scenario 3.

Calculate expected number of gas leaks in pressure control components:

The expected number of gas leaks in pressure control components is equal to the number of failures per component type multiplied by the ratio of the failures that result in gas leaks to the total number of failures per component (see Section 2.7 for the latter ratios).

Calculate expected number of street delivery failures

The expected number of street delivery failures caused by regulators is equal to the total number of regulator failures multiplied by the ratio of the regulator failures that result in failure effect ´regulator unavailable' to the total number of regulator failures, multiplied by the ratio of streets that do not contain a monitor. When a monitor exists, the monitor takes over the regulating function of the regulator, thereby preventing a street delivery failure. Next to the street delivery failures caused by regulators, there is a constant number of street delivery failures caused by other components (for explanation, see Section 2.7).

Calculate expected number of GDS delivery failures

The expected number of GDS delivery failures is equal to the expected number of street delivery failures multiplied by the probability of a GDS delivery failure given a street delivery failure.

Calculate expected number of transport breaks

The expected number of standalone GDS delivery failures is equal to the expected number of GDS delivery failures multiplied by the ratio of standalone GDSs to the total number of GDSs, plus the number of non-standalone GDS delivery failures multiplied by the probability of transport break after failure of a non-standalone GDS.

Calculate total failure costs

Total failure costs are the costs of a gas leak multiplied by the expected number of gas leaks in pressure control components plus the costs of a transport break multiplied by the expected number of transport breaks.

Calculate total replacement costs

Total replacement costs are equal to the sum for all components *c* for all replacement scenarios *s,* of the number of replacements per component *c* in replacement scenario *s* multiplied by the replacement costs per replacement of component *c* in replacement scenario *s*:

(1) *Total replacement costs* = $\sum_{c,s} \left(Replacements(c,s) * Replacement\ costs(c,s)\right)$

with *Replacements(c,s)* as number of replacements of component *c* in scenario *s*.

Calculate total costs

The total costs are the sum of the total failure costs and the total replacement costs.

Step 4b: Compute results of discrete event simulation

In this step, the most important average results per year per discrete event simulation run are shown for the years 2018/2065. These results are the expected number of street delivery failures, the average expected failure costs due to gas leaks, the average expected failure costs due to GDS delivery failures, the average expected total replacement costs and the average expected total costs.

4.7 Verification of input value parameters and model assumptions

As values for input parameters for the analyses in Chapter 5, primarily the results of the analyses in Chapter 2 are used. The results of the analyses described in Chapter 2 and some appendices show that the following values for input parameters can be considered to be the true values:

- Permanent supply disruptions: the ratio of components with permanent supply disruptions is 0,25 for complete components and 0,35 for soft and hard parts of regulators and monitors. Explanation is in Appendix J;
- Probability of scenario 4 (emergency installation required) given scenario 3 (complete component, plus pipe changes) is 0,255. Explanation is in Appendix J;

- There is a constant number of street delivery failures per year caused by other components than regulators. The exact level of this constant number is hidden in this public version of this thesis. More information can be found in Section 2.7;
- GDS failure probability given street delivery failure is 0,011. Explanation is in Section 2.7 and Appendix M;
- Ratio of standalone GDSs in the total population is *a* (exact ratio is deleted in this public version); probability of a transport break given a failure of a standalone GDS is 1; probability of a transport break given a non-standalone GDS is 0,5 (Appendix O);
- Failure costs are 0,14 SC per gas leak and 195,17 SC per transport break, as mentioned already in Section 2.4;
- Replacement costs per scenario are 0,5 SC for an opportunistic replacement and 0,86 SC for a preventive replacement of soft parts of regulators and monitors. In Section 2.3 and Appendix G, the costs per replacement scenario are described;
- Failure rates and failure effects per failure per component type are presented in Sections 2.5 and 2.7.
- Data about (undocumented) inventory level can be found in Appendix J.

In separate meetings with three expert opinions, all assumptions and input parameter values were checked. The results of data analyses were discussed, as well as the assumptions made for the cases that the available data would take very long time to analyze. There were a number of input parameter values that the experts could not confirm with complete certainty, however, their true values were at least very close to reality, in their eyes. Also, in their opinion the assumptions were done with valid arguments and thereby the best available information was used. These input parameter values were:

- The failure rates of soft parts and hard parts for regulators, monitors and aid and pilot pressure regulators;
- The failure effects per failure for each of the described component types;

These input parameter values mentioned in the last paragraph are subject to sensitivity analyses in Chapter 6.

As mentioned in Section 2.3, it is very hard to determine the exact levels of (undocumented) inventories per component type. Therefore, the sensitivity analyses in Chapter 6 will be performed by using three levels of undocumented inventories per component type: one based on estimates by technicians, one with higher levels and one with lower levels.

4.8 Validation of model results

In order to validate the model, the number of street delivery failures in reality and in the model is compared. The number of street delivery failures is used, because the SAP data of these failures are the most reliable available data. Also, these data are much easier accessible than other data about failures (such as the number of replaced soft parts and total replacement costs).

To validate the model, three results are compared:

- The number of street delivery failures registered in SAP during the years 2012-2016;

- The number of street delivery failures during 2004-2013, according to a previous study by a Gasunie employee;
- The average number of street delivery failures over the years 2012-2016 in the simulation model. In this simulation model, OM and PM age thresholds were chosen in such a way that no OM or PM was performed before 2016.

The results of the analyses show that the scores for the three sources are comparable. The ratio of street delivery failures, according to the three sources, is 0,82:1,04:1. According to expert opinion, the simulation output is sufficiently close to reality. The difference in results between the simulation and the real life system might be explained by street delivery failures that were not registered. Also, there are several databases available, and not always all databases are updated after a street delivery failure. Taking into consideration the relatively small differences between the simulation output and the real life data, and the explanation of experts, the simulation output seems to be valid.

4.9 Conclusions Chapter 4

The most important conclusions of Chapter 4 are:

1. A discrete event simulation model is developed in Excel VBA. This model can be used to determine preventive and opportunistic maintenance thresholds based on ages of soft parts of gas pressure control components. Note that the difference between preventive and opportunistic is made, as the following sentence explains. A unit i can be replaced in three ways: correctively after its failure, preventively after the unit reaches its PM age N, and opportunistically after failure of another unit if the age of the i is above its opportunity replacement age threshold n_i. Opportunity replacement age threshold n_i is lower than preventive replacement age N;
2. The model is described in Chapter 4, and validation of the most reliable data (number of street delivery failures) is done. It seemed that the number of street delivery failures in the VBA model is comparable to the results of two independent studies towards the number of street delivery failures per year at Gasunie;
3. Input parameter numbers and assumptions, and the verification of these numbers, are described in Chapter 4.

5. Results

Objective of the analyses in this chapter is to find an optimal *age configuration*, which can be defined as *combination of values for the four age thresholds* as described earlier in Section 4.2 .These age thresholds are about the replacement of soft parts of regulators and monitors only: as Section 2.8 concluded, preventively replacing the soft parts of aid and pilot pressure regulator does not save costs. The results of this chapter show a top 5 of configurations and the main scores per configuration: scores on KPIs, failure costs, replacement costs and total costs. First, the method of obtaining results is given. Then, a number of adjustments to the model described in Chapter 4 is explained. Finally, the results and corresponding conclusions are given.

5.1 Method of obtaining results

It is practically impossible to simulate all possible age configurations a decent number of times. The total number of possible age configurations for T1, T2, T3 and T4 is:

$$\sum_{i=1}^{i=n1} \sum_{j=1}^{j=n2} (i * (n1 - i) + 1) * (j * (n2 - j) + 1)$$

With n_1 as number of possible threshold ages (in years) for T_1, n_2 as number of possible threshold ages (in years) for T_3, and $T_2 > T_1$ and $T_4 > T_3$.

Total number of possibilities for $n_1 = 43$ and $n_2 = 73$ is 110.941. The values for n_1 and n_2 are determined by using the maximum ages the soft part can reach during the simulation period 1994-2065: the maximum useful lifetime of a regulator soft part could reach is assumed to be 42, as is shown in Section 2.5, and maximum age a monitor soft part could reach is larger than the number of years between 1994 and 2065 and therefore 72 is the maximum age the soft part can reach during the simulation. Next to the possible replacement ages that follow from the maximum ages that the parts can reach, the replacement ages 43 (regulator) and 73 (monitor) are added to represent the scenario that no opportunistic or preventive replacement is performed on the regulator (monitor).

Because the number of possible configurations is large, the concept of response surface methodology is used in order to select a smaller experimental area. This method uses *factors,* which are the input parameters and assumptions composing a model, and *responses,* which are the output performance measures (Law, 2015). Using these factors and responses, quadratic regression models can be found. The next paragraph explains how this is done. More explanation of the response surface methodology can be found in Law (2015). The same holds for the following concepts that are introduced in the rest of this Section: Latin hypercubes, stepwise regression method and quadratic regression models.

First, Latin hypercube designs are developed. Then, responses are determined by taking the average of 1.000 replications per design point in these Latin hypercubes. Then, quadratic regression models are found by using the concept of stepwise regression. In the first step of this stepwise regression method, all 14 factors (T1, until T4, $T1^2$ until $T4^2$, and the interactions between T1 and T2, T1 and T3, T1 and T4, T2 and T3, T2 and T4, T3 and T4) are included. In each following step of the stepwise regression analyses, it is checked whether the P-value of any factor is higher than the removal level of 0.15; if not, the stepwise regression method is finished, otherwise, the factor with the highest P-value is deleted and the regression analysis is performed again. This is done until there are no factors with a P-value higher than 0.15. Directly after each removal of a factor, the adjusted R-square values are evaluated, in order to estimate the fit of the regression model. After the last step of the stepwise regression method, the fit of the regression model is checked on other design points in the area of the Latin hypercube. These comparisons are done as follows: design points are chosen that were not used as design points in the initial Latin hypercubes, and their simulation results are compared with the results of using the factor values for each of these design points in the fitted regression model. When the responses of the simulations are comparable to the results of the regression model for the same design points, the fitted regression model is considered to be valid.

The method described in the last paragraph, is performed in two iterations: first, a relatively broad experimental area is chosen as input for the Latin hypercube design, and based on the results of the first regression model, a smaller experimental area is chosen as input for the second Latin hypercube model. Motivation behind this logic is that on forehand, there is not much information about the location of the global costs minimum; after the first iteration, there is more information and it is possible to focus on a smaller area.

Objective of the described method is to find a relatively small number of configurations that are all close to the optimal solution as indicated by the fitted regression model. When a relatively small number of configurations is found, the selected configurations are all simulated with 3.000 replications. These 3.000 replications are sufficient to meet the convergence criteria as given in Appendix Q. After obtaining the averages of the 3.000 replications for each configuration, the optimal configuration is determined. Two-sample *t*-tests for equal means are used to determine whether the differences between the expected total costs per configuration are significant at an alpha level of 0,05. More information about this method can be found in Snedecor & Cochran (1989).

5.2 Adjustments to the model as described in Chapter 4

As mentioned in the introduction of this chapter, the objective of the analyses in this chapter is to find the top 5 best configurations in terms of total costs *related to soft parts of regulators and monitors*. In order to focus on the costs and benefits of preventive and opportunistic replacement of soft parts only, a number of adjustments is done to the basic model as described in Chapter 4. These adjustments are the following:

- only costs related to regulator soft parts and monitor soft parts are taken into consideration. This means that only the replacement costs of scenario 1, OM and PM of regulators and monitors are taken into consideration, and the failure costs due to gas leaks and transport breaks caused by regulators and monitors;
- all supply disruption input parameters are set on “False”. This means that all required soft parts are considered as always available at the OEM. As explained in Chapter 4, OM and PM replacements of soft parts of certain regulators and monitors are only beneficial when there are no permanent supply disruptions of the soft parts of these regulators and monitors;

Motivations are in the next paragraph. Changes in the code behind the model are shown in Appendix I.

The motivation behind implementing these rules is that the replacement costs of complete regulators and monitors is much higher than the replacement costs of soft parts. When the replacements of complete component would be taken into consideration as well, the main factors in the model would be the number of required replacements of complete regulators and monitors. To measure the effect of opportunistic or preventive replacements, the large influence of the complete component replacements would require very large numbers of replications. Because, as explained in the introduction of this chapter, the main goal of the analyses in this chapter is to find the optimal age replacement configuration, the other costs are not taken into consideration. After determining the optimal age replacement configuration, the effects of implementing the optimal age replacement configuration in the standard settings (so, without using the described adjustments) are given in Section 5.4 and in the sensitivity analyses of Chapter 6.

5.3 Analyses of results

As explained in Section 5.1, the method of obtaining results contains two iterations of constructing quadratic regression models of total costs per year, and ultimately a comparison of the results of 3.000 replications of a number of configurations that seem to be close to optimum.

First iteration

As the method of obtaining results (Section 5.1) already mentioned, the first step is to develop a Latin hypercube design. A large experimental design is chosen as a first iteration: ages of 15 years up to and including 35 years for T1, 20 years up to and including 43 years for T2, 30/60 for T3 and 40/73 for T4. The total number of design points was 48, which is slightly more than the recommended minimum number of design points of 10 times the number of tested factors (Loeppky et al., 2009). The stepwise regression method (described in Section 5.1) gave the following regression model for total costs (TC):

$$TC\ (SC/year) = 251 – 1*T1{,}1 – 4{,}5*T2 – 0{,}37*T4 + 0{,}022*T1^2 + 0{,}059*T2^2 + 4{,}0*10^{-3}*T3^2 + 4{,}6*10^{-3}T4^2 – 6*10^{-3}*T3*T4$$

An Excel solver is used to minimize total costs by changing the values for T1, T2, T3 and T4.The following constraint were used: T1, T2, T3 and T4 are integer, T1 ≤ T2 (OM age threshold should be lower than PM age threshold), T3 ≤ T4, and T1 and T2 both smaller or equal to the maximum age of regulator soft parts (43, see Section 5.1), and T3 and T4 both smaller or equal to the maximum age of monitor soft parts (73, see Section 5.1). The solver gave as optimal age configuration the values 25-38-57-73 for T1-T2-T3-T4. Total costs were 137,18 SC per year.

Another interesting conclusion about the optimal age configuration can be drawn after the first simulations: 90,9% of the costs related to soft parts of regulators and monitors is caused by the failure and replacement costs of regulators, and only 9,1% is caused by monitor soft parts. This can be explained by the much higher failure rate of regulators (see Section 2.5) and the higher failure costs of regulator failures that often lead to street delivery failures and thereby costs due to transport breaks. In the regression model, the higher coefficients for T1 and T2 compared to T3 and T4, correspond with the higher importance of the regulator soft parts.

To validate the regression model, the adjusted R-squared is evaluated, and the fitted regression model is compared with new design points (as explained in Section 5.1 as well). The adjusted R-squared is the very high value of 0,965. This suggests that the regression model fits the responses very well. This sufficient fit can also be found in Figure 9, which presents a plot of the predicted responses versus the responses by simulation. Also, a comparison between the predicted responses by the regression model and the simulation results for 48 other design points, showed that only for two design points the difference in total costs per year exceeded 1,33 SC.

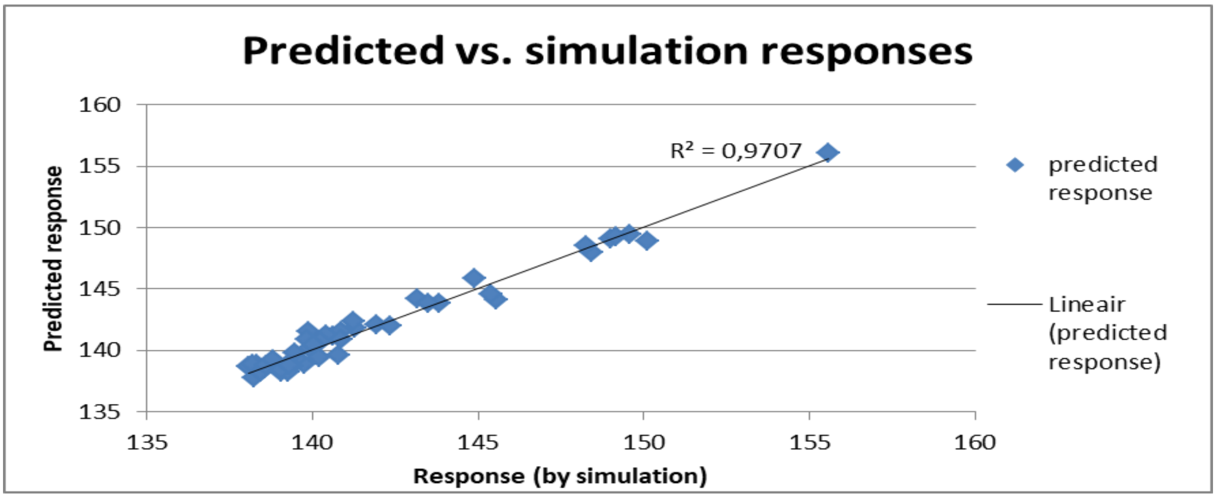

Figure 9: Plot of predicted responses by the regression model versus responses found by simulation (first iteration)

Second iteration

In order to focus on a smaller experimental area, another iteration of the Latin hypercube design and stepwise regression is performed. Based on the results of the first iteration, which show an optimal configuration of 25-38-57-73, Latin hypercubes are developed by using the values 20, 21,…,29, 30 for T1; 33, 34,…,42, 43 for T2; 48, 50,…, 66, 68 for T3; and 63, 64,…, 72, 73 for T4. The stepwise regression method gave the following regression model for total costs (TC) in SC per year:

$TC\ (SC/year) = 163{,}8 - 1{,}54*T1 - 1{,}39*T2 + 0{,}67*T4 + 0{,}032*T1^2 + 0{,}023*T2^2 + 0{,}017*T1*T2 - 0{,}011*T1*T4 - 0{,}012*T2*T4$

An Excel solver found minimal TC of 137,58 SC for the configuration 26-39-73-73, by using the same constraints as given in the first iteration. The adjusted R-squared value of the regression model is slightly lower than during the first iteration, but still high: 0,77. A comparison between the predicted responses by the regression model and the simulation results for 17 other design points in the experimental area, showed that for 2 design points the difference in total costs per year exceeded 0,67 SC. Figure 10 shows the plot between the predicted responses versus responses by simulation.

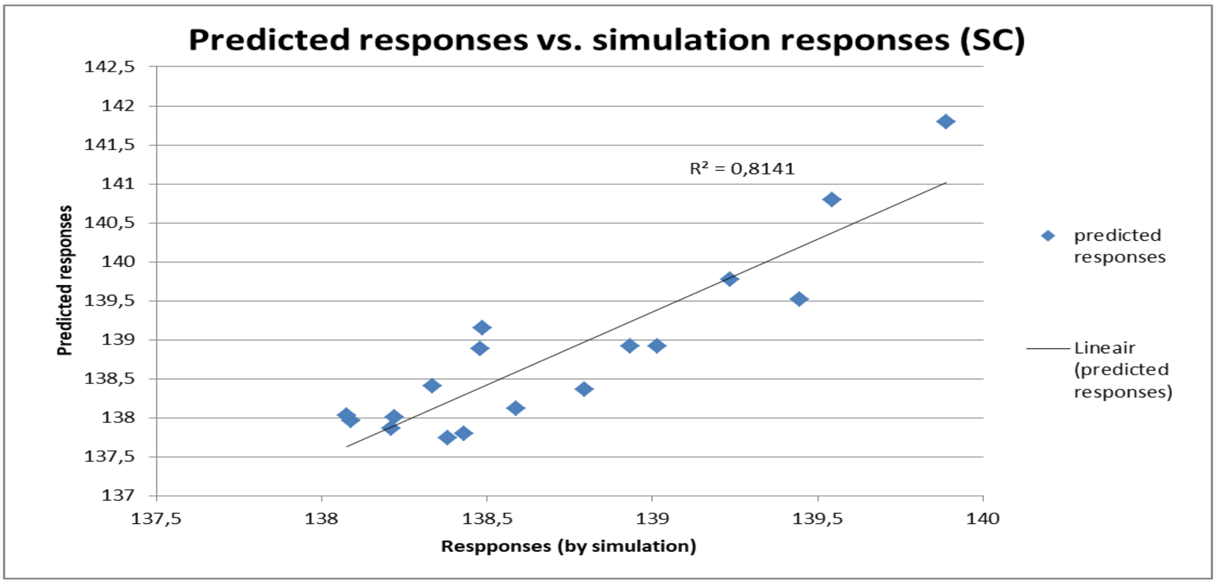

Figure 10: Plot of predicted responses by the regression model versus responses found by simulation (second iteration)

Looking at the two plots of the predicted responses vs. responses by simulation, the regression model of the first iteration seems to predict the responses better (see Figure 9) than the regression model of the second iteration (see Figure 10). The difference can possibly be explained by the variance in responses, that is caused by the number of replications that is too low to get converged averages: only 1.000 averages are performed, while 3.000 replications per design point are required to meet the convergence criteria as stated in Appendix Q. Also, by focusing on a smaller Latin hypercube, the ratio of variance that can be explained by the factors of the regression model, decreases, which results in a worse fit of predicted versus simulated responses.

The optimal age configurations for the two regression models, 25-38-57-73 and 25-37-73-73, are comparable for at least T1, T2, and T4. The difference in T3 might as well be partly explained by the very low part of total costs that is related to monitor soft parts (as already mentioned, this is only 9,1% of costs related to regulator and monitor soft parts). This low part means that the influence of T3 on total costs is relatively low. To solve these problems, a regression model is developed of T3 and T3 only, using the data of monitor related costs of the first two iterations. This regression model gave optimal values for T3 and T4 of 65 and 73 years.

Experiments with the age configurations that seem to be close to optimum

Based on the results of the regression analyses, 54 age configurations were simulated with 3.000 simulations. These configurations contain all possible combinations of the values 23, 25 and 27 years for T1; 35, 37 and 39 years for T2; 62, 65 and 68 years for T3; and 70 and 73 years for T4. Table 8 shows the results for the top 5 configurations in terms of total costs related to regulator and monitor soft parts per year. In Table 29 in Appendix T, the results of the top 15 configurations are given. Table 8 shows that the configuration 25-37-68-73 results in the lowest total costs: 137,3 SC per year.

T1 (OM reg.)	T2 (PM reg.)	T3 (OM mon.)	T4 (PM mon.)	TC/year related to reg. (SC)	TC/year related to mon. (SC)	TC per year related to reg. and mon. (SC)
25	37	68	73	125,0	12,2	137,2
25	35	68	73	125,2	12,0	137,3
23	37	68	73	125,3	12,0	137,3
27	35	68	73	125,3	12,0	137,3
23	39	62	73	125,0	12,4	137,4

Table 8: Top 5 of configurations based on total costs per year

Another conclusion that can be made based on the results of these simulations, is that most configurations with a value of 68 for T3 score better than the same configurations with a value of 62 or 65 for T3. This suggest that a higher age for opportunistic replacement of monitor soft parts could result in even lower costs. To test this statement, the best combination of T1 and T2 (25 and 37, see Table 8) is simulated with values 73 for T4 and 69, 71 and 73 for T3. To be absolutely sure, the same combinations are simulated with the values 40, 45, 50 and 55 for T4 as well. Number of replications was 3.000. The results are given in Table 30 in Appendix T. These results show that the configuration with a value of 73 for T3 resulted in the lowest costs. Therefore, it can be concluded that opportunistic replacement of monitor soft parts does not save costs.

After concluding that the value of 73 is optimal for both T3 and T4, and thus OM or PM replacements for monitor soft parts do not save costs, focus can be changed towards the optimization of T1 and T2, the OM and PM age thresholds of regulator soft parts. In Table 9, the top 5 configurations are given, based on the total costs per year related to regulator soft parts. The top 10 is given in Table 31 in Appendix T. The differences between the best configurations are very small: the second best configuration, which has a value of 27 for T1 instead of 25 as in the best configuration, has a total costs of only 0,023 SC per year more than the best configuration. Because of the very small differences between the best configurations, it can be concluded that configurations that were not in the experiments (e.g. configurations with a value of 26 for T1, which is exactly between the simulated values of 25 and 27 for T2) will not result in significant extra costs savings.

T1 (OM regulator)	T2 (PM regulator)	Total costs related to regulator soft parts /year (SC)
25	37	124,00
27	37	125,02
23	39	125,02
25	35	125,14
23	35	125,20

Table 9: Costs related to regulator soft parts for configurations of T1, T2. Values of T3 and T4 are held constant at 73

That opportunistic and preventive replacements of regulator soft parts by using the configuration 25-37-73-73 are less expensive than the run-to-failure configuration can be assumed to be true, because:

- As given in Section 2.5, replacement costs of OM are lower than PM and CM: 0,5, 0,86, and 1 SC, respectively;
- The costs of the extra visit to the GDS in case of a corrective replacement can be quantified to be 0,10 SC. By opportunistic replacements, this visit is prevented;

- Failure costs can be quantified to be 0.22 SC. This statement will be explained in Section 6.1. By opportunistic replacements, these failure costs are prevented;
- The survival rates at T=25 and T=37 for regulator soft parts are 0,16 and 0,02, respectively, while the survival rate is 0 at T = 43.

For monitors, opportunistic or preventive replacements do not save costs. This can be assumed to be true, because:

- Failure costs are much lower than regulator failure costs, because monitor failures do not cause street delivery failures, and only 16,7% of the monitor failures cause gas leaks (failure cost per gas leak are 0,14 SC, see Section 2.4);
- Survival rate at T=73 for monitor soft parts is higher than for regulator soft parts: 0,15.

The difference between total costs for the best configuration and total costs related to regulator soft parts for the run-to-failure configuration (43-43-73-73) of 128,17 SC per year, is 3,23 SC per year. Note that this difference means the difference in total costs for the scenario that there are no permanent supply disruptions for soft parts of regulators and monitors. In reality, there are permanent supply disruptions, which decrease the costs savings that can be reached by OM and PM of soft parts. Therefore, the only conclusion that can be made is that the configuration 25-37-73-73 is the optimal configuration; in Section 5.4, analyses will be performed that show the potential costs savings that can be achieved by implementing this optimal configuration.

5.4 Effects of using the optimal age configurations in the Gasunie case

The results on KPIs (average street delivery failures per year, average GDS delivery failure per year, average transport breaks per year) and failure, replacement and total costs per year, for the top 5 configurations are shown in Table 10. Also, results for the run-to-failure configuration 43-43-73-73 are shown in the last row of this table. In contrast to the analyses in Section 5.3, the simulation results in this section take into consideration all failure and replacement costs of regulator, monitor and aid and pilot pressure regulator together. By using all costs together, these results form a basis for comparison in the sensitivity analyses in Chapter 6. All permanent supply disruption and inventory parameters as described in Section 4.7 are used. 15.000 replications per age threshold configurations are performed. This number of replications is based on the convergence criteria as explained in Appendix Q.

As can be found in the column ‘total costs/year’, differences in total costs per year between the configurations are very small. This is caused by the large costs of replacements of complete components and emergency installation launches, in comparison with the replacements of soft parts only. The number of these replacements is large: 26,7 complete regulator replacement without pipe changes, 29,5 replacements of complete regulators with pipe changes, and 7,5 replacements of complete regulators where emergency GDS is required; for monitors, these numbers are 4, 4, and 1, respectively. These data can be found in Tables 32, 33 and 34 in Appendix T.

Age thres-hold conf.	Gas leaks /year	Street del. failures /year	Station del. failures /year	Trans-port breaks /year	Total failure costs /year (SC)	Total replace-ment costs /year **(SC)**	Total costs /year **(SC)**	Costs related to regulator soft parts	Frequency of CM/OM/ PM of regulator soft parts / year
25-37-*	26,83	54,403	0,598	0,479	97,19	1734,29	1831,48	98,22	71,8/6,0/0,6
27-37-*	26,81	54,463	0,599	0,479	97,29	1733,64	1830,93	98,28	71,8/4,2/1,7
23-39-*	26,76	54,357	0,598	0,478	97,10	1733,26	1830,36	98,52	71,5/8,5/0,0
25-35-*	26,79	54,364	0,598	0,478	97,12	1734,92	1832,04	98,47	71,5/5,9/1,5
23-35-*	26,71	54,313	0,597	0,478	97,02	1733,46	1830,48	98,41	71,1/8,4/0,5
43-43-*	27,25	54,807	0,603	0,482	97,94	1734,81	1832,75	99,33	75,3/0,0/0,0

Table 10: Simulation results of using the age configurations in the current installed base of Gasunie

*means: 73-73 (opportunistic and preventive replacement thresholds of monitor soft parts)

More clear conclusions can be drawn based on analyses of the costs related to opportunistic, preventive and corrective replacements of regulator and monitor soft parts only. The last column of Table 10 contains the frequency of each of CM, PM and OM per year for the total installed base. As this column shows, the frequency of opportunistic and preventive replacements of regulator soft parts is low. In the top 5 configurations, the maximum number of opportunistic replacements is only 8,5 per year, while the maximum number of preventive replacements is only 1,7 per year. The column directly next to the last column contains all costs failure and replacement costs related to these replacements of soft parts only. This column shows that the costs for the configuration 43-43-73-73 are around 1,07 SC per year higher than the optimal configuration 25-37-73-73. Note that these cost differences are lower than during the analyses of Section 5.3, where was assumed that there were no permanent supply disruptions. This difference is caused by the fact that when supply of soft parts is disrupted, the simulation does not implement OM or PM replacements of soft parts. A Two-sample T-test for equal means at an alpha level of 0,05 is performed for amongst others the following samples: the total costs related to regulator soft parts per replication of the optimal age configuration, and the total costs related to regulator soft parts per replication of the run-to-failure configuration. This test showed that the costs for the run-to-failure configurations are significantly higher than the costs for the optimal age configuration: a T-value of 11.02 was found, while a T-value of 1,96 was required to reject the hypothesis that the two groups of responses had equal means. More details can be found in Appendix U. The difference between the optimal and run-to-failure configuration in terms of street delivery failures is around 0,4 street delivery failure per year; difference in terms of transport breaks is 0,003 per year. These scores show that the optimal configuration saves costs and scores better on KPI scores. However, the differences in terms of costs and KPI scores between the optimal and run-to-failure configuration are very small.

Other interesting conclusions can be made based on the number of street delivery failures, station delivery failures and transport breaks. Table 10 shows that even for the run-to-failure configuration, the average number of street delivery failures per year is only 54,8. On average 18 of these failures are caused by external factors (see Section 2.6). The resulting number of internally caused street delivery failures is 36,8. This frequency is much lower than the KPI target of 52,8 (see Section 2.6). Average number of station delivery failures and transport breaks are only 0,60 and 0,48, respectively, while their targets are scores below 6 and 3 per year, respectively (see Section 2.6). Note that the number of street delivery failures in the simulation contains non-technical failures such as human errors as well. However, the number of station delivery failures does only include the number of station delivery failures that are caused by these street delivery failures: non-technical errors such as human errors or problems in the pipe networks that cause station delivery failures, are not taken into consideration. The same holds for the average number of transport breaks. Therefore, conclusions about reaching the KPIs with respect to station delivery failures and transport breaks, cannot be made based on these numbers alone. What can be concluded, is that the optimal configuration saves only 0,003 transport breaks per year in comparison with the run-to-failure configuration.

As the more detailed results of these simulations in Appendix T show, the average number of replacements of regulators and monitors that require emergency GDSs, is only 8,5 per year. Therefore, it can be concluded that a large number of emergency GDS launches in a short time frame, are very unlikely to occur. The same holds for the number of regulator (29,5) and monitor (4) replacements where changes in connected pipes are required.

5.5 Conclusions Chapter 5

The main conclusions of Chapter 5 are:

- Optimal preventive replacement time for regulator soft parts is 37 years in combination with the age threshold of 25 years for an opportunistic replacement; for monitors, opportunistic and preventive replacements do not save costs;
- Using these replacement thresholds will save around 1,07 SC per year in comparison with replacing both regulator and monitor soft parts only correctively. This is a relatively small cost saving for Gasunie. It can highly be doubted whether this small costs saving is worth all extra planning effort.;
- These replacement thresholds result in a frequency of CM, OM and PM of regulator soft parts of 71,8, 6,0 and 0,6, respectively. Using the current replacement policy (corrective replacements only) results in 75,3 replacement of regulator soft parts per year;
- Using these replacement thresholds saves 0,40 street delivery failure per year in comparison with replacing regulator and monitor soft parts only correctively (54,40 vs. 54,80);
- Using these replacement thresholds saves 0,003 transport breaks per year in comparison with replacing regulator and monitor soft parts only correctively (0,479 vs. 0,482);
- The average number of replacements of regulators and monitors that require emergency GDSs during the years 2018/2065, is only 8,5 per year. Therefore can be concluded that a large number of emergency GDS launches in a short time frame, is very unlikely to occur.

As is mentioned in Section 5.4, the costs related to replacement of regulator soft parts only are very small (only 98,2 SC per year for the optimal age configuration) compared to the total costs for gas pressure control components: 1831,5 SC. This is caused by the much higher costs of replacing complete components, which sometimes require pipe changes and launches of emergency GDSs as well. In Chapter 6, the results of sensitivity analyses are given. A number of the conclusions in these analyses give suggestions for methods to reduce these costs. Also, Chapter 6 presents the results of sensitivity analyses regarding the optimal replacement times of regulator soft parts.

6. Sensitivity analyses

This chapter reports analyses towards the effects on KPI scores and total costs per age configuration due to changes in various input parameters. Section 6.1 reports sensitivity analyses with respect to the age configurations as given in Chapter 5. Sensitivity analyses are reported regarding failure costs of regulator failures and the level of failure rates. Section 6.2 shows the results of analyses towards the cost savings by decreasing the permanent supply disruptions of soft parts. This cost saving is, as explained in the scope in Section 1.5, one of the main goals of this research, together with determining the optimal age configurations for the gas pressure control components. In Section 6.3, analyses are reported towards replacement times for complete regulators suffering permanent supply disruptions of soft parts. These analyses show whether it would save costs to replace regulators suffering permanent supply disruptions opportunistically or preventively, and which age thresholds should be used.

In Chapter 6, the same values for input parameters and assumptions are used as mentioned in Chapter 4 and in Section 5.4, unless other values and assumptions are mentioned. This means that the shown costs savings correspond with the actual costs savings that can be achieved in the Gasunie case.

6.1 Sensitivity analyses with respect to optimal replacement times of soft parts

Failure costs of regulator failures

Using the assumptions as mentioned in Section 4.7, the failure costs per regulator failure can be considered to be 0,215 SC. To summarize the most relevant assumptions in Section 4.7, this amount of costs is based on the following information. The true values of *a,d* and *e* are hidden in this public version of the thesis.

- A probability of 0,153 that a regulator failure results in an unavailable regulator;
- A probability of *a* that an unavailable regulator leads to a street delivery failure (based on the number of RSS and RMS configurations: as explained in Section 2.1, a monitor could take over the function of a regulator);
- A probability of 0,011 that a street delivery failure causes a station delivery failure;
- A probability of *d* that a station is standalone. For these stations, a station delivery failure always results in a transport break. There is a probability of *e* that a station delivery on a non-standalone station causes a transport break. The values of *d* and *e* are hidden due to confidentiality issues;
- Failure costs of transport break are 195,17 SC;
- Probability that a regulator failure leads to a gas leak is 0,119. Failure costs per gas leak are 0,14 SC.

Therefore, average failure costs are: $0{,}153 * a * 0{,}011 * (d+e) * 195{,}17$ SC $+ 0{,}119 * 0{,}14$ SC $= 0{,}215$ SC. However, the values of the parameters presented above, were subject to a number of assumptions and based on average data for large numbers of GDSs. Exact costs per station delivery failure could differ heavily between GDSs. Therefore, sensitivity analyses are performed in order to give optimal age configurations for various values of regulator failure costs. The sensitivity analyses are performed by using the values 0,067, 0,13, 0,40, 0,53, and 0,667 SC as failure costs of a regulator failure. This is done by changing the value of the failure costs of a transport break in the model as described in

Chapter 4. Note that multiplying the costs of a transport break with a certain factor, results in the same effects as multiplying one of the other related variables in the last paragraph with the same factor. The method of obtaining results is the method as described in Section 5.1. An exception on this method is that the monitor age thresholds T3 and T4 were both held constant at 73 years.

The results in Table 11 show that the optimal age configuration depends on the value of the failure costs of regulators. When the failure costs increase, optimal age thresholds are found with lower ages. The last column of Table 11 shows the difference in costs between the optimal age configuration per level of regulator failure costs and the run-to-failure configuration for the same level of regulator failure costs. This cost difference is the costs savings potential by using the optimal age configuration for each regulator that does not suffer supply disruptions. This means that the shown costs savings in Table 11 are the actual costs savings that can be achieved by implementing the optimal age configurations. It is shown that the costs savings potential increases for higher levels of regulator failure costs: for a failure costs level of 0,67 SC, yearly costs savings are 2,73 SC. This is still a relatively low cost saving for Gasunie. It can be doubted whether this small costs saving is worth all extra planning effort.

Regu-lator Failure costs (SC)	Optimal age configu-ration	Frequency of CM/OM/PM of regulator soft parts per year	Costs (SC) related to regulator soft parts for optimal age conf.	Costs (SC) related to regulator soft parts for age conf. 43-43-73-73	Difference in costs (SC) between using optimal age configuration and using age conf. 43-43-73-73
0,067	27-38-73-73	72,3/4,4/0,60	87,30	88,12	0,82
0,13	25-37-73-73	71,9/5,9/0,58	92,28	93,14	0,86
0,27	23-38-73-73	71,1/8,3/0,44	102,00	103,18	1,18
0,33	23-38-73-73	71,1/8,3/0,44	106,74	108,20	1,46
0,40	22-36-73-73	70,5/9,3/1,08	111,55	113,22	1,67
0,53	20-36-73-73	69,9/11,8/0,99	121,24	123,26	2,02
0,67	20-36-73-73	69,9/11,8/0,99	130,57	133,30	2,73

Table 11: Optimal age configuration and corresponding costs, for various levels of regulator failure costs

Higher and lower failure rates

The following sensitivity analyses show the effects of changing the failure rates of regulator and monitor soft parts. As lower and higher failure rates of these soft parts, the boundaries of the 95% confidence intervals of the failure rate analyses in Section 2.5 are used. Note that for regulator soft parts, the failure rate contained early life failures, random failures and wear-out failures. For regulators, the early life failure rate and random failure rate were held constant, while the boundaries of the 95% confidence intervals of the wear-out failure rate were used. The best configurations are selected after 3.000 replications per age configuration, with the higher (lower) failure rates as input. After the best three age configurations are selected, these three age configurations, the optimal age configuration as given in Chapter 5, and the run-to-failure configuration are simulated with 15.000 replications. These simulations are performed in order to determine the potential costs savings of using the best age configurations. The number of replications is based on the convergence criteria as explained in Appendix Q.

Results of the 15.000 replications with the lower failure rates for regulator and monitor soft parts are shown in Table 12. This table shows the best three configurations in terms of costs for regulator and monitor soft parts. It shows that the optimal configuration is 28-39-73-73. These optimal ages are higher or equal to the optimal age configuration ages for the failure rates as given in Chapter 5 (25-37-73-73). This is caused by the lower failure rates. Costs savings of around 1,13 SC per year can be achieved by using the age thresholds of 28 and 39 for OM and PM of regulator soft parts. This can be found in the third column of Table 12. Costs savings when using the optimal age configuration as given in Chapter 5, 25-37-73-73, saves costs of 0,93 SC related to regulator soft parts per year. Therefore, it can be concluded that costs savings for the lower failure rates 0,93 SC) are only slightly lower than the costs savings were for the estimated failure rates in Section 5.4 (costs savings in Section 5.4 were 1,07 SC).

Age configuration	Total costs (SC) per year	Total costs (SC) related to regulator soft parts	Total costs (SC) related to monitor soft parts	Frequency of CM/OM/ PM of regulator soft parts
28-39-73-73	1823,47	95,10	7,50	70,29/3,93/0,52
26-39-73-73	1824,11	95,13	7,48	69,80/5,39/0,46
27-39-73-73	1824,16	95,20	7,54	70,12/4,62/0,50
25-37-73-73	1823,34	95,30	7,49	69,05/6,65/1,06
43-43-73-73	1824,96	96,23	7,50	72,98/0,00/0,00

Table 12: Total costs per year and total costs related to regulator soft parts, for the three best configurations and the run-to-failure configuration. In these analyses, the lower failure rates are used

Results of the 15.000 replications with the higher failure rates for regulator and monitor soft parts are shown in Table 13. This table shows the best three configurations in terms of costs for regulator and monitor soft parts. It shows that the optimal configuration is 24-37-73-73. These optimal ages for T2, T3 and T4 are lower or equal to the optimal age configuration ages for the estimated failure rates as given in Chapter 5 (25-37-73-73). This could be caused by the higher failure rates. Costs savings of around 1,2 SC can be achieved by using the age thresholds of 24 and 37 for OM and PM of regulator soft parts. This can be found in the third column of Table 13. Costs savings when using the optimal age configuration as given in Chapter 5, 25-37-73-73, saves around 1,13 SC costs related to regulator soft parts per year. Therefore, it can be concluded that the costs savings for the higher failure rates (1,13 SC) are comparable to the costs savings as indicated for the estimated failure rates in Section 5.4 (costs savings in Section 5.4 were 1,07 SC). However, these costs savings are still negligible for Gasunie. It can be doubted whether this small costs saving is worth all extra planning effort.

Age configuration	Total costs (SC) per year	Total costs (SC) related to regulator soft parts	Total costs (SC) related to monitor soft parts	Frequency of CM/OM/ PM of regulator soft parts
24-37-73-73	1829,19	96,05	8,08	69,24/7,69/1,05
25-37-73-73	1828,08	96,10	8,07	69,73/6,23/1,20
26-37-73-73	1828,18	96,05	8,09	69,95/5,38/1,31
26-36-73-73	1829,93	96,17	8,08	70,03/5,24/1,40
43-43-73-73	1830,55	97,24	8,07	73,74/0,00/0,00

Table 13: Total costs per year and total costs related to regulator soft parts, for the three best configurations and the run-to-failure configuration. In these analyses, the higher failure rates are used

6.2 Costs savings by decreasing the permanent supply disruption level

Permanent supply disruption levels

As is explained in Section 1.5, one of the main goals in this research is to determine the value of replicating soft parts for component that currently suffer permanent supply disruptions of soft parts. This value can be determined by calculating the difference between costs per year with the current permanent supply disruptions level and costs per year for lower permanent supply disruption levels.

Twelve options are simulated, based on combinations of four values of permanent supply disruptions of soft parts and three values of (undocumented) inventory levels. Number of replications per option was 15.000 based on the convergence criteria as explained in Appendix Q.. The results are compared with the results for the current permanent supply disruption level, which is 0.65, as presented in Section 2.3. Three values of (undocumented) inventory levels are used. The levels heavily influence the results, because these (undocumented) inventories are used when supply is disrupted; however, when no (undocumented) inventory is left, the replacement costs are more expensive because a complete component needs to be replaced, as Section 2.3 explains. As explained in Section 4.6, the following formula is used to simulate the probability that there is (undocumented) inventory left for a replacement at time *t:*

*P(AvailableInventory;t) = LB(c) + (UB(c) - LB(c)) * (InventoryLevel(c;t) / InitialInventoryLevel(c)*

with *LB(c)* as the probability that a replacement of component type *c* can be done by creative solutions by technicians when no (undocumented) inventory is left anymore, such as buying these parts at other gas transport companies; *UB(c)* as the probability that a replacement of component type *c* can be done with creative solutions or the left (undocumented) inventory at the start of 2018; *InventoryLevel(c;t)* as the inventory level at time t of component type c; and *InitialInventoryLevel(c)* as the inventory level of component type c at the start of 2018.

The values of *LB(c)* and *UB(c)* are chosen based on statements of technicians; the three chosen (undocumented) inventory levels per component type are a very low estimate, very high estimate and a value in-between. Details can be found in Appendix J. Note that conclusions based on these assumptions must be made carefully, because the true values of undocumented inventory levels, LB(c) and UB(c) could not be approved with complete certainty by the experts of Gasunie. For decisions about replicating the soft parts of e.g. a certain regulator type, the true levels for that type need to be investigated, as will be explained in Chapter 7. Then, the simulation model could be used again.

The total costs per year, which is equal to the replacement costs plus failure costs, are shown in Table 14. Note that these costs contain all costs related to soft parts, however, costs for other replacement scenarios are included as well. Costs are shown for all failures and replacements related to one of the gas pressure control component types. The three columns called ‘difference’ show the difference in costs between the costs between the current permanent supply disruption level and the permanent supply disruption level in that row, for costs related to regulators, monitors and aid and pilot pressure regulators, respectively.

In Table 14 it can be found that decreasing the permanent supply disruption level of regulator soft parts from 0.65 to 0.4 would save costs of around 163,73 SC per year (for an inventory level of 200 parts per component type). In Section 1.2.2 is explained that decreasing the permanent supply disruption level can be done by offering extra money to the OEMs to restart the production of the soft parts, or buying soft parts at other manufacturers, which are called 'replicated soft parts' in this study. Exact costs savings depend on the level of inventory: when inventory level is higher, costs savings are lower. The costs savings for the same decrease in supply disruption level are around 36 SC for monitor soft parts and around 24,67 SC for aid and pilot pressure regulator soft parts. Note that these costs savings are the costs savings per year, measured over a period of 48 years. Therefore, decreasing supply disruption level of regulator soft parts from 0.65 to 0.4 would result in a costs saving of 48* 163,73 SC = 7.860 SC until 2065. This means that if Gasunie could assure the delivery of soft parts from now until 2065 for a regulator type that is in 25% of the GDS streets, this investment would ultimately save costs when the price of this investment is lower than 7.860 SC.

Supply disrup-tion level	Age confi-guration	Inven-tory level	Regulator TC/year (SC)	Differ-ence (SC)	Monitor TC/year (SC)	Differ-ence (SC)	Aid &Pilot press. reg. TC/year (SC)	Differ-ence (SC)
0.65	25-37-73-73	400	1291,07	-	150,47	-	311,13	-
0.6	25-37-73-73	400	1249,60	41,53	145,07	5,40	304,87	6,27
0.5	25-37-73-73	400	1174,87	116,20	133,47	17,00	293,80	17,33
0.4	25-37-73-73	400	1105,27	185,87	118,20	32,27	284,87	26,27
0.65	25-37-73-73	200	1280,13	-	169,53	-	316,47	-
0.6	25-37-73-73	200	1244,67	35,53	156,40	13,13	310,40	6,13
0.5	25-37-73-73	200	1179,33	100,87	143,60	26,00	301,93	14,53
0.4	25-37-73-73	200	1116,40	163,73	133,27	36,27	291,73	24,73
0.65	25-37-73-73	20	1273,40	-	203,73	-	322,80	-
0.6	25-37-73-73	20	1244,20	29,20	197,73	6,00	319,53	3,27
0.5	25-37-73-73	20	1190,87	82,53	184,33	19,40	311,47	11,33
0.4	25-37-73-73	20	1137,07	136,27	171,20	32,53	303,53	19,27

Table 14: Total costs in SC per year per sub system for various levels of supply disruptions and (undocumented) inventory

As mentioned in the last paragraph, the cost savings of decreasing the supply disruption level from 0,65 to 0,4 for an inventory level of 200 per component type, are 163,73 SC. This large costs savings is caused by the decrease in complete component replacements, while the number of failures that can be solved by soft parts (or hard parts and soft parts together) increases. The more detailed results in Tables 38 and 39 in Appendix T show the frequency per year for each replacement scenario. These tables show that for an inventory level of 200 and a permanent supply disruption level of 0,65, per year there are 56,2 complete regulator replacements and in total 92,4 replacements where soft parts are used. The latter is the sum of the frequencies for scenario 1 (corrective replacement soft parts only), OM and PM of soft parts, and scenario 5 (replacement of hard and soft parts). For an inventory level of 200 and a permanent supply disruption level of 0,4, these frequencies are 48,2 and 101,2, respectively. So, the decrease in permanent supply disruption results in 8,8 extra replacements where soft parts are used, and a decrease of 8,0 complete component replacements per year. The yearly costs savings of 163,73 SC by decreasing the soft part supply disruptions level, can be reached by 8,8 extra soft parts per year. As is given in Section 2.3, the average price of 8,8 (non-disrupted) soft parts at an OEM is 8,8* 0,17 SC = 1,4 SC. Therefore it is very likely that there is a large profit margin of investing in replicated soft parts. The exact profit margin depends on the investment costs, such as costs of selecting the right company for buying soft part replicates.

In Tables 38 and 39 of Appendix T, the data are shown of similar simulations with the run-to-failure configuration 43-43-73-73.

The temporary use of replicated soft parts after failures

Another possibility to save costs is to allow the use of replicated soft parts in obsolete regulators and monitors only temporarily. *Temporarily use* in this context means that when a soft part of a component fails, replicated soft parts are used for one year maximally, after which the complete component is replaced. With this implementation, emergency installation costs can be prevented because the replacement of the complete component can be delayed and performed at a predetermined time. The use of this option might suffer less certification issues than the permanent use of replicated soft parts. This is explained as well in Section 1.2.2. The temporary use of replicated soft parts causes extra costs of the extra corrective replacement of the failed soft parts by replicated soft parts. These costs are 1 SC (see Section 2.3). In the simulation model, the following changes are implemented:

1. A temporary use of a replicated regulator (monitor) soft part occurs when there is a soft part failure of a regulator (monitor) that suffers from permanent supply disruptions from both the soft parts and the complete regulator (monitor), and no (undocumented) inventory for both the soft parts and the complete component is available. These conditions are the conditions for a scenario 3 replacement (replacement of complete component and changes in pipes required);
2. If (1) holds, the costs savings are 0,255* 14,67 SC – 1 SC, which is equal to the probability that an emergency GDS is required during a scenario 3 replacement (see Section 4.7) multiplied by the costs of such an emergency GDS launch, minus the costs of an extra corrective replacement of soft parts.

In Appendix I, the corresponding code changes are shown.

Results of this concept are in Table 15. Results are shown after 15.000 replications for each of the nine options. Again, total costs are all failure and replacement costs for each replacement scenario, and regulator and monitor costs are distinguished. Aid and pilot pressure regulators are not included, because their replacements do not require emergency installations. The simulations are performed with the optimal age configuration 25-37-73-73. The results in Table 15 show that the costs savings by temporarily use of replicated regulator soft parts could save costs between 35,27 SC and 63,8 SC per year, depending on the supply disruption level and inventory level; for monitor soft parts, these values are 10,2 SC and 4,8 SC. For the estimated values in the current situation (permanent supply disruption level of 0,65 and (undocumented) inventory level of 200), the costs savings are 60,53 SC for regulators and 9,2 SC for monitors. Also, there is a clear trend visible that for lower permanent supply disruption levels, the possible cost savings by using temporary replicated soft parts for obsolete complete components, is lower. This trend is caused by the fact that only for complete components that suffer from permanent supply disruptions, cost savings could occur.

Supply disruption level	Inventory level	TC/year, using temporary replicated soft parts (SC)		TC/year, without using temporary replicated soft parts (SC)		Cost savings using temporary replicated soft parts (SC)	
		Regulator	**Monitor**	**Regulator**	**Monitor**	**Regulator**	**Monitor**
0,65	400	1289,33	150,67	1226,00	142,67	63,80	7,93
0,6	400	1254,67	144,00	1195,33	136,67	58,73	7,47
0,5	400	1183,33	132,67	1134,67	126,67	48,73	6,27
0,4	400	1109,33	120,00	1070,67	115,33	38,60	4,80
0,65	200	1282,67	170,67	1222,00	161,33	60,53	9,20
0,6	200	1248,67	163,33	1192,67	154,67	55,80	8,40
0,5	200	1185,33	147,33	1138,67	140,67	46,73	6,80
0,4	200	1117,33	134,00	1080,00	128,67	37,53	5,20
0,65	20	1273,33	204,67	1216,00	194,00	57,80	10,20
0,6	20	1244,00	198,67	1190,67	189,33	53,20	9,33
0,5	20	1190,67	183,33	1146,67	176,00	44,20	7,67
0,4	20	1131,33	172,67	1096,00	166,67	35,27	6,07

Table 15: Total costs savings by allowing temporary use of replicated soft parts, per sub system and for various levels of permanent supply disruption and (undocumented) inventory

6.3 Replacement of obsolete regulators

Replacing obsolete regulators

Another analysis is done towards the effects of performing opportunistic replacements of regulators with permanent supply disruptions of soft parts, based on the age of their soft parts.

Opportunistic replacements of regulators could save costs: as mentioned in Chapter 5, 0,255 of the corrective regulator replacements require an emergency GDS which costs 14,67 SC; failure costs of 0,215 SC are prevented; the first visit after regulator failure is prevented, which is quantified to be 0,103 SC; and an estimated amount of design and management costs of 3,33 SC could be saved when a regulator is replaced simultaneously with another component instead of replacing both components correctively. Therefore, the difference in costs between a single opportunistic regulator replacement and a corrective regulator replacement is 7,39 SC. More details can be found in Appendix R.

Note that an opportunity for opportunistic replacement of a complete regulator differs from the opportunity as defined for the opportunistic replacement of soft parts of gas pressure control components. Only replacements of a complete monitor (component type 6) for which pipe changes are required, and a complete component in the component type ‘other component’ (component type) form an opportunity for a replacement of a complete regulator, because only these replacements require pipe changes, just as the opportunistically replaced obsolete regulators.

Appendix I shows the changes made in the Excel VBA code in order to implement this new replacement rule.

In Table 16, the effects per OM threshold age, in which *age* is the age of the soft parts of the obsolete regulators, are given. The results are given for the values of 7,39 SC as costs difference between a single opportunistic regulator replacement and a corrective regulator replacement, and a number of values close to this value for the cost difference. In Table 16, the costs savings per year are shown for ages below 32 years only, because the number of opportunistic replacements of complete regulators per year is very low for higher ages. The results were collected after 15.000 runs per option. The table shows that for a cost saving of 7,39 SC, using the OM threshold age of 24 for all obsolete regulators results in the highest costs savings of around 10,0 SC per year. Based on this result, it can be concluded that costs savings can be achieved by opportunistic replacement of all obsolete regulators with an age of 24 years or higher, for which no replicated soft parts will be made in the future. Note that simulations with thresholds below 24 years do not make any sense, because the start year of simulation is 1994 (average year of last replacement of regulator soft parts, see Section 4.3) and first year of implementation of new replacement rules in the simulation is 2018.

As Table 16 shows, the number of opportunistic replacements for an OM threshold age of 24 is only 1,93. This can be caused by the low number of opportunities. As explained earlier in this Section, only replacements of complete monitors and replacements of complete components of the component type ‘other component’ form opportunities.

OM thres-hold age	OM re-placements of reg. per year	Costs savings (SC) for cost difference of 6,00 SC	Costs savings (SC) for cost difference of 6,67 SC	Costs savings (SC) for cost difference of 7,39 SC	Costs savings (SC) for cost difference of 8,00 SC	Costs savings (SC) for cost difference of 8,67 SC
24	1,93	1,29	7,30	8,59	9,98	11,15
25	1,52	1,25	4,92	5,93	7,03	7,95
26	1,34	1,18	3,78	4,68	5,66	6,47
27	1,20	1,11	4,00	4,81	5,68	6,41
28	1,06	1,28	4,31	5,02	5,79	6,43
29	0,92	1,25	2,63	3,25	3,92	4,48
30	0,65	1,19	1,39	1,82	2,30	2,69
31	0,53	1,12	1,51	1,86	2,25	2,57

Table 16: Costs savings per year for various OM threshold ages for the replacement of obsolete regulators and for various levels of costs differences between a corrective and an opportunistic replacement

6.4 Conclusions Chapter 6

After this chapter, the following conclusions can be made:

1. The optimal replacement times of regulator soft parts depend on the failure costs of regulators. For regulator failure costs of 0,67 SC (which is equal to 3,1 times the estimated failure costs), the optimal replacement thresholds are 20 years for opportunistic replacements and 36 years for preventive replacements. For this level of failure costs, using the optimal age replacement thresholds instead of only performing corrective replacements saves 2,73 SC per year for the complete installed base of Gasunie;
2. Sensitivity analyses showed that using the age configuration 25-37-73-73 still results in costs savings for slightly higher en lower failure rates of soft parts of regulator and monitor. In these analyses, the boundaries of the 95% confidence intervals of the estimated failure rates as shown in Section 2.5 were used;
3. There is a large potential in the permanent use of replicated soft parts for pressure control components: decreasing the permanent supply disruption level of regulator soft parts from 0,65 to 0,4, leads to a costs saving of around 167,73 SC per year. For monitors and aid and

pilot pressure regulators, the costs savings are around 36,27 and 24,67 SC per year, respectively;

4. Another explained option is the temporary use of replicated soft parts, in order to delay the required replacement of complete regulators and thereby to prevent the required launch of emergency GDSs. This results in costs savings per year of around 60,53 SC for a permanent supply disruption level of 0,65;
5. Opportunistic replacement of complete regulators for which the supply of soft parts is disrupted, could save costs for Gasunie. Using the estimated costs difference of 7,39 SC between a single opportunistic replacement of an obsolete regulator instead of a single corrective replacement of a regulator, the total costs savings per year are around 10 SC for an opportunistic age threshold of 24 years for the soft parts of the obsolete regulator. In this analysis, the current permanent supply disruption level of 0.65 is used;

Note that the exact costs savings for conclusions 3, 4 and 5 depend on the current level of (undocumented) inventory as well. The costs savings mentioned in the conclusions above can be reached for a (undocumented) inventory level of 200 spare parts per component type. In Chapter 6, analyses are performed with levels of 10 and 400 parts as well.

7. Conclusions, Discussion and Recommendations

7.1 Conclusions and Discussion

The main goal of the reported research work was to develop a model to determine the optimal replacement times of certain parts, known as soft parts, of pressure control components at gas delivery stations of Gasunie. These replacement times are based on costs (replacement and failure costs) and availability effects. Availability effects, in this context, refer to the consequences of reaching a low availability level of GDSs. A low availability level results in large costs and low scores on KPI targets. Next to these optimal replacement times, the effects of decreasing the permanent supply disruption levels on costs and availabilities are analysed. Permanent supply disruption is defined as *the impossibility to order all required units at OEMs or other allowed manufacturers.* The permanent supply disruption level is *the ratio of components of a component type that suffer permanent supply disruptions, to the total amount of components of that component type in the installed base of Gasunie.* The permanent supply disruption level could be decreased by either offering extra money to the OEMs to restart the production of the soft parts, or allowing the use of soft parts produced by other manufacturers. In the latter case, these soft parts are called 'replicated soft parts'. If the OEM of a certain regulator type restarts the production, or an alternative manufacturer is found for a certain regulator type, then there is no permanent supply disruption anymore for these regulators. According to expert opinions, the main problem in finding alternative manufacturers are the certification issues in gas transport networks. Another option is the temporary use of replicated soft parts. In this case, the temporary use of soft parts is allowed in order to delay the required replacement of the failed obsolete complete component. Then, the obsolete complete component can be replaced somewhere during the year after the failure. This saves costs of launching an emergency installation. When using replicated soft parts only temporarily, less certification issues are expected compared to the permanent use of replicated soft parts. Therefore, also an analysis is reported towards the potential costs savings by allowing temporary use of replicated soft parts, for regulators that suffer permanent supply disruptions of soft parts. Furthermore, an analysis is reported towards the potential costs savings by opportunistic replacement of complete regulators that suffer permanent supply disruptions of soft parts. The costs and availability effects per scenario are determined using a discrete event simulation model in Excel VBA. After the described analyses, the following conclusions can be made:

1. Based on an analysis of the specific characteristics influencing the replacement planning in the case study on one hand, and a literature research towards determination of optimal replacement times on the other hand, the use of opportunistic and preventive age replacement thresholds were selected as most suitable in the case study.
2. Optimal preventive replacement time for regulator soft parts is 37 years in combination with an age threshold of 25 years for opportunistic replacement. Using these replacement thresholds for all regulators that do not suffer permanent supply disruptions, Gasunie could save only around 1,067 SC per year in comparison with replacing regulator soft parts only correctively, as is done currently. It can highly be doubted whether this small costs saving is worth all extra planning effort.
3. Sensitivity analyses showed that the potential costs savings are much higher for larger regulator failure costs. For this reason, opportunistic and preventive replacements of regulator soft parts could save costs especially for the GDSs suffering the largest failure costs.

However, even if all regulators would suffer failure costs of 3,1 times the estimated average failure costs of regulators, then the optimal age replacement thresholds would lead to costs savings of only 2,73 SC per year. However, it can be doubted whether this small costs saving is worth all extra planning effort.

4. Opportunistic and preventive replacement of soft parts of monitors and aid and pilot pressure regulators do not save costs.
5. There is a large potential in using replicated soft parts for pressure control components: decreasing the permanent supply disruption level of regulator soft parts from 0,65 to 0,4, leads to a costs saving of around 163,73 per year. For monitors and aid and pilot pressure regulators, these amounts are 36,27 SC and 24,73 SC per year, respectively.
6. Allowing the use of replicated soft parts only for temporarily use after failure of obsolete regulators, in order to delay the required replacement of complete regulators and thereby preventing the required launch of Emergency GDSs, saves around 60,53 SC per year.
7. In case that for none of the regulator types replicated soft parts will be used, opportunistic replacement of complete obsolete regulators saves costs for Gasunie. Using the estimated costs difference of 7,39 SC between an opportunistic replacement of a single obsolete regulator and a corrective replacement of a regulator, the total costs savings per year are around 10 SC. This costs saving can be reached by using an opportunistic age threshold of 24 years of the soft parts of the obsolete regulator.

The small costs savings opportunistic and preventive replacement of soft parts can be explained by the low failure costs of the gas pressure control components. Because of the large redundancy in streets and GDSs in the network of Gasunie, the probability that a failure of a gas pressure control component results in large failure costs, is very low. The costs savings by using replicated soft parts permanently are much higher. These high costs savings are caused by the decrease in the number of replacements of complete components, while the number of required replacements of soft parts increases. The replacement costs of a complete component are much higher than the replacement costs of soft parts only. The temporary use of replicated soft parts only saves costs by preventing the launch of an Emergency GDS. However, this delay does not prevent the required replacement of the complete component. Therefore, the costs savings by using replicated soft parts only temporarily are lower than the costs savings when using the replicated soft parts permanently. The costs savings by opportunistic replacements of obsolete regulators are relatively low. This is caused by the fact that in this context, only replacements of complete components in the same GDS street form opportunities for OM of complete regulators. This results in a low number of opportunistic replacements per year.

Gasunie could use the findings of this report to decrease the total maintenance costs. If Gasunie decides to use these findings, special attention must be given to a number of assumptions that is made in order to fulfill the analyses. Some data were very hard to collect, such as the failure costs of a transport break and the prices per replacement scenario. These costs could vary highly, depending on the specific circumstances of the failure or replacement. Also, some data were hard to interpret, such as the announcements of failures by technicians in SAP. Therefore, the reliability of the failure rate distributions and the failure effects might be not fully optimal. Therefore, the true values of the mentioned factors in this paragraph were estimated using the best provided information and expert opinions. Also, while performing the failure rate analyses of Section 2.5, hot stand-by redundancy was assumed. In real life, the type of redundancy at GDSs is warm; also, in some regions the roles of delivering street and stand-by street are swapped between streets regularly, while in other regions the same streets are either delivering streets or stand-by streets for years. The latter depends on the preferences of the regional manager and therefore these settings vary per region. More information about these and other assumptions can be found in Chapter 2 and Sections 4.4 and 4.5. The impact of the described assumptions needs to be investigated before major decisions are based on the findings of this research. When these investigations are performed, the described model could be used again to collect simulation results and subsequently to decide about new replacement strategies.

This report shows how to determine optimal replacement times in a case study full of complexity due to both case-specific practical issues, such as permanent supply disruptions, structural dependencies between components and various possible replacement scenarios, and complexity due to hard to interpret data. Therefore, it broadens the field of research on optimal replacement times in a very practical context. As is mentioned in the theoretical framework and introduction of this paper, a large number of researchers stated that there was insufficient focus on the use of optimal replacement times in a practical context. Other organizations challenging this problem might use the framework of this paper as an example to solve this problem. Also, the use of a simulation model in Excel VBA seemed to be a fast, reliable and relatively easy method to indicate the levels of potential costs savings for various scenarios.

7.2 Recommendations for Gasunie

This Section presents recommendations for Gasunie, regarding the replacement strategy for (soft parts of) gas pressure control components, increasing the efficiency of maintenance optimization studies at Gasunie in general, and the decision to use RSS configurations in all new or renovated GDS streets. The following recommendations are made:

1. Replicate as much as possible soft parts of gas pressure control components that suffer permanent supply disruptions of soft parts, in order to use these soft parts permanently;
2. If the permanent use of replicated soft parts is not possible for certain types of components, then use replicated soft parts temporary;
3. If both the permanent and the temporary use of replicated soft parts is impossible, then opportunistic replacement of this obsolete regulators at the first opportunity is the best solution. The opportunistic replacement threshold is an age of 24 years for the soft parts;
4. Small costs savings can be achieved by using the age replacement thresholds of 37 and 25 years for preventive replacement of regulator soft parts and the opportunistic replacement of regulator soft parts, respectively. However, It can be doubted whether this small costs saving is worth all extra planning effort;
5. Do not use opportunistic or preventive replacement of soft parts of monitors and aid and pilot pressure regulators, because these replacements do not save costs;
6. During this study, a number of assumptions had to be made to fulfill the performed analyses. These assumptions are described or referred to in Section 7.1. An important conclusion regarding these assumptions is that the context analysis, as presented in Chapter 2, provided some new insights. In order to perform studies regarding maintenance optimization more efficiently, it could be useful to use a number of the outcomes of this context analysis. The findings can be added to a comprehensive list of fundamental basic assumptions of performance-related data of GDSs. For example, the quantification of average failure costs of

a *street delivery failure* (which frequency is part of one of the KPIs of Gasunie) as used in this paper, could be used in other studies as well.

7. Standardize the design and component types of the GDSs. As mentioned in Chapter 2, there are differences between GDSs in, such as: configuration, component types, and length of pipes between components. Standardizing the newly renovated GDSs in one or more of the mentioned factors decreases complexity in both maintenance and maintenance optimization studies.
8. Categorize the installed base of GDSs based on the potential failure costs per GDS, and consider distinct maintenance concepts per group. As the sensitivity analyses in Section 6.1 show, the optimal replacement times for regulator soft parts, as well as the potential costs savings, are influenced by the level of the failure costs that could be assigned to a regulator failure. Exact failure costs could differ per GDS, depending on the number of households connected to the GDS and the contracts with the connected industries. Because of this difference in failure costs, it might be useful to categorize the GDSs in groups depending on the failure costs per GDS, and study the effect of maintenance activities on total costs for each group. It might turn out that a specific maintenance activity decreases total costs when performed at an 'important' GDS, while the same maintenance activity increases total costs when performed at a less important GDS.
9. The categorization of GDSs, as mentioned in the 8th recommendation, could be used for another purpose: the GDSs with the lowest failure costs could be used as test cases for new maintenance concepts.
10. The frequency of replacements of complete components, as estimated in this study, can be used to determine the number of required Emergency GDSs in the coming years. This study showed that the average number of replacements of regulators and monitors that require Emergency GDSs during the years 2018/2065, is only 8,5 per year. Earlier research showed that the average number of complete component replacements of other components than gas pressure control components in GDS streets, is around 128 replacements per year. Using the assumption that most Emergency GDSs are used no longer than a week, the current base of Emergency GDSs seems to be relatively large.
11. Reconsider the decision to use an RSS configuration for each new or renovated GDS street (see Section 2.1). This research showed that the failure rate of monitors, as well as the costs of the effects per failure of a monitor, is very low, as is reported in Sections 2.5 and 2.7. Also, during meetings with experts, it seemed that a number of experts criticized the decision to use RSS configuration for new GDS streets.

References literature

Alrabghi, A., & Tiwari, A. (2015). State of the art in simulation-based optimization for maintenance systems. *Computers & Industrial Engineering, 82*, 167-182. https://doi.org/10.1016/j.cie.2014.12.022

Aven, T., & Jensen, U. (1999). *Stochastic models in reliability*. Second edition. New York, NY: Springer Science+Business Media.

Barlow, R., & Hunter, L. (1960). Optimum preventive maintenance policies. *Operations Research*, *8*(1), 90-100. https://doi.org/10.1287/opre.8.1.90

Blanchard, B.S., Verm, D., & Peterson, E.L. (1995). *Maintainability: A key to effective serviceability and maintenance management*. New York, NY: John Wiley & Sons.

Carroll, T. (2016). Succesful selection of oil and gas seals. *World Pumps*, *2016*(9), 28-30. https://doi.org/10.1016/S0262-1762(16)30235-8

Castanier, B., Grall, A., & Bérenguer, C. (2005). A condition-based maintenance policy with non-periodic inspections for a two-unit series system. *Reliability Engineering & Systems Safety, 87*(1), 109-120. https://doi.org/10.1016/j.ress.2004.04.013

Chaudhuri, D., & Sahu, K.C. (1977). Preventive maintenance intervals for optimal reliability of detoriorating systems. *IEEE Transactions on Reliability, R-26*(5), 371-372. DOI**:** 10.1109/TR.1977.5220209

Cho, D.I., & Parlar, M. (1991). A survey of maintenance models for multi-unit systems. *European Journal of Operational Research, 51*(1), 1-23. https://doi.org/10.1016/0377-2217(91)90141-H

Clavareau, J., & Labeau, P. (2009). Maintenance and replacement policies under technological obsolescence. *Reliability Engineering and System Safety*, *94*(2), 370-281. https://doi.org/10.1016/j.ress.2008.03.033

Dekker, R., WIldeman, R.E, & Van der Duyn Schouten, F.A. (1997). A review of multi-component maintenance models with economic dependence. *Mathematical Method of Operations Research, 45*(3), 411-435. https://doi.org/10.1007/BF01194788

Dhillon, B.S. (2002). *Engineering maintenance : A modern approach*. Florida: CRC Press.

Engelhard, F., & Greiner, S. (2003). ParEs - A Parameter-Estimation-Tool. In *International Conference on Dependable Systems and Networks*. San Francisco, California. 10.1109/DSN.2003.1209968

Engineered Software Inc. (1999). *Reliabililty & Maintenance Analyst,* (Version 4.7). [CD-Rom]. Rochester, New York: Engineered Software, Inc.

Fraser, K., Hvolby, H., & Tseng, T. (2015). Maintenance management models: A study of the published literature to identify empirical evidence. *International Journal of Quality & Reliability Management, 32*(6), 635-664. https://doi.org/10.1108/IJQRM-11-2013-0185

Garg, A., &Deshmukh, S.G. (2006). Maintenance management: Literature review and directions. *Journal of Quality Maintenance Engineering, 12*(3), 205-238. https://doi.org/10.1108/1355251061068

Gits, C.W. (1992). Design of maintenance concepts. *International Journal of Production Economics, 24*(3), 217-226. https://doi.org/10.1016/0925-5273(92)90133-R

Gertsbakh, I. (2013). *Reliability Theory: with Applications to Preventive Maintenance* (p. 67-102).New York: Springer.

Hsieh, C. (2005). Replacement and standby redundancy policies in a deteriorating system with aging and random shocks. *Computers & Operations Research*, *32*(9), 2297-2308. https://doi.org/10.1016/j.cor.2004.03.004

de Jonge, B. (2017). Maintenance Optimization based on Mathematical Modeling[Groningen]: University of Groningen, SOM research school

de Jonge, B., Klingenberg, W., Teunter, R.H., & Tinga, T. (2015). Optimum maintenance strategy under uncertainty in the lifetime distribution. *Reliability Engineering and System Safety, 133,* 59-67. https://doi.org/10.1016/j.ress.2014.09.013

Laggoune, R., Chateauneuf, A., & Aissani, D. (2009). Opportunistic policy for optimal preventive maintenance of a multi-component system in continuous operating units. *Computers and Chemical Engineering, 33*(9), 1499-1510. https://doi.org/10.1016/j.compchemeng.2009.03.003

Laggoune, R., Chateauneuf, A., & Aissani, D. (2010) [1]. Impact of few failure data on the opportunistic replacement policy for multi-component systems. *Reliability Engineering and System Safety 2010, 95*(2), 108-119. https://doi.org/10.1016/j.ress.2009.08.007

Laggoune, R., Chateauneuf, A., & Aissani, D. (2010) [2]. Preventive maintenance scheduling for a multi-component system with non-negligible replacement time. *International Journal of System Science 2010, 41*(7), 747-761. http://dx.doi.org/10.1080/00207720903230765

Xie, M., & Lai, C. D. (1995). Reliability analysis using an additive Weibull model with bathtub-shaped failure rate function. *Reliability Engineering & System Safety*, *52*, 87–93. https://doi.org/10.1016/0951-8320(95)00149-2

Law, A.M.. (2015). *Simulation Modeling and Analysis: Fifth Edition* ((p. 214-241; p. 556-576; p. 629-679). New York: McGraw-Hill Education.

Loeppky, J.L., Sacks, J., & Welch, W.J. (2009). Choosing the sample size of a computer experiment: a practical guide. *Technometrics, 51,* 366-376.

Moghaddas, R., Zuo, M.J., & Pandey, M. (2012). Optimal design and maintenance of a repairable multi-state system with standby components. *Journal of Statistical Planning and Inference, 142*(8), 2409-2420. https://doi.org/10.1016/j.jspi.2012.02.045

Muchiri, P. Pintelon, L., Gelders, L., & Martin, H. (2011). Development of maintenance function performance measurement framework and indicators. *International Journal of Production Economics, 131*(1), *295-302*. https://doi.org/10.1016/j.ijpe.2010.04.039

Nicolai, R.P., & Dekker, R. (2008). Optimal Maintenance of Multi-component Systems : A review. Complex System Maintenance Handbook. Londen: Springer. 263-286. https://doi.org/10.1007/978-1-84800-011-7_11

Nowakowski, T., & Werbińka, S. (2009). On problems of multicomponent system maintenance modelling. *International Journal of Automation and Computing*, *6*(4), 364-378. https://doi.org/10.1007/s11633-009-0364-4

Olde Keizer, M.C.A., Teunter, R.H., & Veldman, J. (2016). Clustering condition-based maintenance for systems with redundancy and economic dependencies. *European Journal of Operational Research ,251*(2), 531-540*.* https://doi.org/10.1016/j.ejor.2015.11.008

Park, C., Moon, D., Do, N., & Bae, S.M. (2016). A predictive maintenance approach based on real-time internal parameter monitoring. *The International Journal of Advanced Manufacturing Technology, 85*(1), 623-632. https://doi.org/10.1007/s00170-015-7981-6

Peng, Y., Dong, M., & Zuo, M.J. (2010). Current status of machine prognostics in condition-based maintenance, a review. *Interational Journal of Advanced Manufacturing Technology, 50*(1-4), 297-313. https://doi.org/10.1007/s00170-009-2482-0

Pham, H., & Wang, H., 1996. Imperfect maintenance. *European Journal of Operational Research, 94*(3)*,* 425-438. https://doi.org/10.1016/S0377-2217(96)00099-9

Rander R., & Jorgenson D.W. (1963). Opportunistic replacement of a single part in the presence of several monitored parts. *Management Science 1963, 10*(1), 70-84. https://doi.org/10.1287/mnsc.10.1.70

Scarf, P.A. (1997). On the application of mathematical models in maintenance. *European Journal of Operations Research, 99*(3), 493-506. https://doi.org/10.1016/S0377-2217(96)00316-5

Sharma, A., Yadava, G., & Deshmukh, S. (2011). A literature review and future perspectives on maintenance optimization. *Journal of Quality in Maintenance Engineering, 17*(1), 5-25. https://doi.org/10.1108/13552511111116222

de Smidt-Destombes, K.S., Van der Heijden M.C., & Van Harten A. (2004). On the availability of a k-out-of-n system given limited spares and repair capacity under a condition-based maintenance strategy. *Reliability Engineering and System Safety, 83*(3), 287-300. https://doi.org/10.1016/j.ress.2003.10.004

Snedecor, G.W., & Cochran, W.C. (1989). *Statistical Methods, Eighth Edition.* Iowa: Iowa State University Press.

Tsang, A.H.C. (1995). Condition-based maintenance tools and decision making. *Journal of Quality in Maintenance Engineering, 1*(3), 3-17. https://doi.org/10.1108/13552519510096355

Usher, S.J.H., Kamal, A., & Syed, W.H. (1998). Cost optimal preventive maintenance and replacement scheduling. *IEEE. Transactions on Reliability*, *30*(12), 1121-1128. http://dx.doi.org/10.1080/07408179808966568

Van der Duyn Schouten, F.A., & Vanneste, S.G. (1990). Analysis and computation of (n,N)-strategies for maintenance of a two-component system. *European Journal of Operational Research, 48*(2), 260-278. https://doi.org/10.1016/0377-2217(90)90379-P

Van Horenbeek, A., Buré, J., Cattrysse, D., Pintelon, L., & Vansteenwegen, P. (2013). Joint maintenance and inventory optimization systems: A review. *International Journal of Production Economics*, *143*(2), 499-508. https://doi.org/10.1016/j.ijpe.2012.04.001

Van Horenbeek, A., Pintelon, L., & Muchiri, P. (2010). Maintenance optimization models and criteria. *International Journal of System Assurance Engineering and Management, 1*(3), 189-200. https://doi.org/10.1007/s13198-011-0045-x

Wang, H., 2002. A survey of maintenance policies of deteriorating systems. *European Journal of Operational Research, 139*(3), 469-489. https://doi.org/10.1016/S0377-2217(01)00197-7

Wayenbergh, G., & Pintelon, L. (2002). A framework for maintenance concept development. *International Journal of Production Economics*, *77*(3), 299–313. https://doi.org/10.1016/S0925-5273(01)00156-6

Woo, C.S., Choi S.S., Lee S.B., & Kim, H.S. (2010). Useful lifetime prediction of rubber components using accelerated testing. *IEEE Transactions on Reliability, 59* (1), 11-17. DOI: 10.1109/TR.2010.2042103

Zhang, X., & Zeng, J. (2015). A general modeling method for opportunistic maintenance modeling of multi-unit systems. *Reliability Engineering and System Safety*, *140*, 176-190. https://doi.org/10.1016/j.ress.2015.03.030

Zheng, X.M., & Fard, N. (1992). Hazard-rate tolerance method for an opportunistic replacement policy. *IEEE Transactions on Reliability 1992, 41*(1),13-20. DOI: 10.1109/24.126664

Zhou, X., Xi, L., & Lee, J., (2009). Opportunistic preventive maintenance scheduling for a multi-unit series system based on dynamic programming. *International Journal of Production Economics, 118*(2), 361–366.

References Gasunie documents

[1] Functional requirements regarding reliability, availability and maintainability of Gasunie assets. Nederlandse Gasunie, Gasunie Technical Standard Design Specification Systems OSS-25-E. http://dis/Home/DocumentCodeRedirect?strDocumentcode=GTS_OSS-25-E&strType=digdoc. N.V.. Consulted Feb. 16th, 2017.

[2] http://departments/sites/operations/O/SLA/2015/SLA%20GTS-O/LA%2015.0495%20SLA%20GTS%20-%20Operations%2017-04-2015.pdf. Definitions in LAM 13.0281, LA 14.0862

[3] GTS_OSA-25-N, version 3.

[4] Voorstel maatregelen n.a.v. stoppen GNIP-GOSsen.

[5] http://dis.gasunie.nl/Home/DocumentCodeRedirect?strDocumentcode=GTS_OSS-02-N/1

[6] GOS-001 OBIS

[7]http://dis/Resultaat/Resultaat/OpenDocumentPopup?strdocumentId=226106&strType=SCANDOC

[8] Hersteldduur bij werken met onvolledige installaties. memorandum 16.0615

[9] http://dis.gasunie.nl/Resultaat/Resultaat/OpenDocumentPopup?strdocumentId=20192123.

[10] Onderhoudsconcept drukbeheersing

[11] http://dis.gasunie.nl/Resultaat/Resultaat/OpenDocumentPopup?strdocumentId=21791847

[12] Bijlage bij OE 14.1893 - RSS versus RMS voor GOSSEN.

[13] Begrotingsformulier N398 Beerzerveld.

[14] http://dis.gasunie.nl/Resultaat/Resultaat/OpenDocumentPopup?strdocumentId=21154895

[15]http://departments/sites/operations/OK/OKOE/CM/MVO/Gedeelde%20%20documenten/Forms/AllItems.aspx?Paged=TRUE&p_FileLeafRef=Repair%20Order%20Gasunie%20Ommen%20%2d%20Sector%2027%20%2d%202015%2epdf&p_ID=247&PageFirstRow=271&&View={74886FA7-1FCA-4B89-B9AD-C9C7DFC0272D}&InitialTabId=Ribbon%2EDocument&VisibilityContext=WSSTabPersistence

[16] http://departments/sites/operations/O/SLA/2017/SLA%20GTS%20B.V.%20GGS%20B.V.%20-%20Operations%20en%20Projects/LA%2016.0706%20SLA%20GTS_GGS%20-%20O.pdf

[17] Maandrapportages 2013/2015 van December van elk jaar. Found at http://departments/sites/operations/O/SLA/Forms/AllItems.aspx

[18] TAM 07.M.060

[19] Degradation of polymer materials – partial report of EDGaR C1-1 project : Integrity consequences of new gases. KEMA DNV. March 18th 2014.

[20] Overview report – partial report of EDGaR C1-1 project : Integrity consequences of new gases. NV Nederlandse Gasunie. January 16th 2015.

[21] LA 17.0306.

[22] https://combinedtraders.nl/category/marktupdate/

[23] https://www.nrc.nl/nieuws/2016/12/07/energieagenda-kamp-einde-aan-koken-op-gas-5684284-a1535388.

[24] MVO beleid Gasunie.

[25] G16GS012. Samenvatting prijs deelrenovatie GOSSEN 2016

Appendix A: Inspection activities to detect relevant failures

This appendix presents the maintenance activities related to gas pressure control components that occur during both types of inspection. The average effective inspection times are approximately 1,5 and 5 hours, for the 3M inspection and the yearly inspection (including one of the 3M inspections) respectively.

Inspection type	Component	Task
3M	Complete GDS	Check the state of every component and check especially on leaks of gas, oil, water and all alarms
3M	Complete GDS	Check the score on the gas leak measuring device, and compare this score with the previous score
3M	Safety shut valves and blockages	Check whether all start and end blockages and safety shut valves are open
3M	Streets	Check whether the right streets are in function
3M	Pressure control components	Check whether the regulators, monitors, and aid and pilot pressure regulators are set on the right pressure level
3M	Monitor	Check whether the inlet pressure of the monitor is equal to the outlet pressure of the monitor. This indicates that the monitor does not influence the pressure of the outlet of the street. The monitor should only influence this pressure after the regulator fails
3M	Stand-by street	Decrease the gas pressure level of the outlet of the delivering street by slowly closing the end blockage of the street. The stand-by street should take over the function of the delivering street at the right pressure level. Let the stand-by street deliver gas for 20 minutes
3M	All streets	Check the outlet pressures of each street
Yearly	Regulators	Check the safety blow off mechanism by increasing the pressure in the regulator
Yearly	All delivering streets	Close the end blockage of the street. Check whether the outlet pressure of the regulator changes, in order to detect intern gas leaks.
Yearly	Stand-by street	Check the state of the stand-by street by closing the delivering street. The stand-by street should take over its function on a slightly lower pressure level
Yearly	Monitors	Check the state of the monitors by increasing the pressure level until the pressure level is reached where the monitor should take over the function of the regulator
Yearly	Safety shut valves	Check the state of the safety shut valves by increasing the pressure level until the pressure level is reached where the safety shut valve should close the street

Table 17: Activities during inspections

Appendix B: Negative effects of failures of gas pressure control components

This appendix explains the negative effects of failures in gas pressure control components in a qualitative way.

There are four major effects of failures of gas pressure control components:

- There flows too much gas through the regulator and/or monitor, resulting in a too high pressure in the outlet of the street, ultimately automatically resulting in the closure of the street;
- There flows too little gas through the regulator and/or monitor, resulting in a too low pressure in the outlet of the street;
- Gas leak to the atmosphere;
- Other failure effects when both the gas pressure control components and the gas pressure safety components (defined in Section 2.1) fail.

Too much or too little gas flow through the regulators and/or monitors is usually caused by a failure in a diaphragm; gas leaks to the atmosphere are usually caused by a failure in a seal or o-ring.

Too much gas through the regulators and/or monitors

As already mentioned in Section 2.1, there is an important difference between the RMS and RSS configuration, with respect to redundancy. In a RMS setting, the monitor is set to take over the function of the regulator when the outlet pressure reaches a certain level (usually, the regulator is set on an outlet pressure of 8,0 bar; the monitor takes over at 8,2 bar). Therefore, only one of these two components needs to work in order to control the gas pressure. In the RSS configuration, there is no monitor. If the regulator fails, there is no other component to control the gas pressure, and there is only the safety system to shut down the street.

The exact working of these components is as follows. When a failure in the regulator and/or monitor results in too much gas flowing through the street, the outlet pressure increases. Then, in an RMS configuration, the regulator *fails open* (this means that the failure causes the regulator to open completely) and the monitor should take over the regulating function. When the monitor fails to deliver gas at the right pressure level, the monitor *fails closed* (this means that the failure causes the monitor to close completely). In an RSS configuration, the regulator fails closed if the gas pressure is too high, and the stand-by street takes over the regulating function. The failed street can only start to control again after a manual reset of the street. Depending on the required capacity at that moment, failures in more than one street can result in not enough delivery to the client of the GDS.

Too little gas through the regulators and/or monitors

When a failure in the regulator and/or monitor results in too little gas flowing through the street, the outlet pressure decreases. Then, a stand-by street needs to take over (partly) the function of the street that delivers too little gas. The stand-by street are set in such a way that it starts delivering gas when the outlet pressure reaches a certain level (usually, the stand-by street starts to take over at 7,8 bar while the delivering street is set on 8,0 bar). The failed street stays delivering gas. When the stand-by street does not start delivering, there can be a lack of gas for the client. Then, there is again a failure of gas delivery to the client.

Gas leak to the atmosphere

A gas leak to the atmosphere can be caused by a failure in either a regulator, monitor, aid pressure regulator or pilot pressure regulator. Usually, this failure mode is caused by a leak in a seal or o-ring.

Failure of regulators and/or monitors and other components in the GDS

When the regulator (RSS) or regulator and monitor (RMS) let too much gas flow through a street and the safety shut valve(s) in the same street does not close, the gas pressure level after the GDS exceeds the agreed level. When the pressure level exceeds the agreed level only slightly (until a half bar above the regular pressure level), Gasunie will receive less money for this off spec gas, but there is not a safety problem. However, when the pressure level increases to 16 bar, this could cause explosions in the gas transport network of the client. In a small number of GDSs there is a safety blow off mechanism in the outlet of the street, which blows off gas to the atmosphere when the outlet pressure exceeds a certain level. Usually, this safety blow off mechanism starts to blow off gas when the pressure level reaches the regular pressure level plus 0,5 bar: usually, this is 8,5 bar. The frequency of the described explosions is negligible.

Appendix C: Drivers of failures of the soft parts according to experts

This appendix presents the drivers of failures of gas pressure component soft parts, as a result of a research including meetings with maintenance experts of Gasunie. The drivers of failure per component, and the influence of failures in a component on the failure probability of other components in the GDS street, are shown.

According to Gasunies maintenance experts, the failures described in Chapter 2 are mainly driven by wear-out due to calendar time and deforming due to usage. Due to calendar time, the soft parts dry, resulting in failures. Due to deforming during usage, the soft parts become more fragile. The wear of the soft parts is higher for the parts with a lot of motion.

An interviewed regional maintenance manager estimates that calendar time related issues (especially drying) leads to approximately 50% of the failures, while usage leads to approximately 40%. He estimates human errors and pollution in the gas to lead to approximately 9% of the failures. The most frequently occurring human error is painting the hard and soft parts together. Due to this paint, the hard and soft parts could stick together. After the paint is dried, the soft parts could break during their regular movements. The remaining percent contains a large number of causes with a very low frequency.

Another regional maintenance manager estimates approximately the same percentages: 47,5% due to calendar time, 47,5% due to usage and 4% due to human errors and pollution in the gas.

Another characteristic that is considered to influence the number of failures of the soft parts, is the type of gas transported in the GDS. Some gasses contain more pollution. Also, a high amount of sulfur in the gas is expected to increase the speed of the wear- out process. Therefore, Gasunie has set a maximum on the amount of sulfur in the gas.

According to maintenance experts of Gasunie, there is no causation between failure of one of the described components on the failure of other gas pressure control components or other components in a GDS. Also, the wear-out of soft parts of a component does not influence the wear-out of other soft parts in the component.

There is no causation between the closure of a safety shut valve in one street and the corresponding take over by the stand-by street, and failures in this stand-by street. The difference in failure behavior between a delivering street in function and a stand-by street that has to take over the function of another street, is unclear. Some maintenance experts consider the stand-by street to be more prone to failures, while others argue that they are less prone to failures. Probably this depends on the policy in the region where the component is: some regional managers give their staff commands to set the street in worst state as the delivering street and the street in best state as stand-by street, in order to recognize failures earlier; other regional managers do not give these orders. Another factor that makes it hard to determine whether stand-by streets suffer a higher or lower failure rates, is that failures could remain hidden: failures in stand-by street usually are detected during inspections only.

Appendix D: Descriptions of regulators, monitors, and aid and pilot pressure regulators

This appendix gives descriptions and illustrations of a number of regulator, monitor and aid and pilot pressure regulator types. The intention of this appendix is to give the reader a short view into the technical details of the component types. Illustrations are retrieved from Gasunie documents and SAP data.

Regulator RMG 145C

This regulator contains various hard parts and as soft parts a diaphragm, three o-rings and five seals. Above the diaphragm in the actuator, the gas from the pilot pressure presses down the diaphragm. Below the diaphragm, the pressure level is equal to the outlet pressure of the street, that flows in the monitor via the pipe. The outlet pressure and the four springs push up the diaphragm. Depending on the prevailing pressure level, the rod opens or closes the aisle.

Figure 11 shows a depiction of the regulator and the positions of the soft parts. Figure 12 shows a less detailed depiction of the regulator. The o-rings at position 72 in Figure 11 seal the space between the diaphragm and both parts around the diaphragm. The Teflon seal at position 41 prevents a gas leak from the actuator to the outside of the regulator. The valve seal at position 96 and the o-ring at position 71 prevent a gas leak between the inlet pressure and outlet pressure parts. The seals at positions 45 and 65 prevent a gas leak from the springs part below to the outside of the regulator. The o-ring at position 70 seals the partition between the inlet part of the regulator and the outside. The o-ring at position 97/98 seals the partition between the down part of the regulator and the inlet pressure part. The seal at position 41 seals the partition between the outlet part and the down part of the actuator.

Wear-out of part	Position number	Supply disruption	Effect if failure occurs
Diaphragm	55	Yes	Gas flow between the pilot pressure part and outlet pressure part in the actuator via the diaphragm. Because the pilot part usually has a higher pressure level, the pilot pressure part level will decrease and the aisle will close (partly).
O-ring	72	No	Gas leak from the actuator to the outside of the regulator
Seal	41	Yes	Because the outlet pressure level of the street is slightly higher than the pressure in the down part of the actuator, there will flow gas from the outlet part to the downside of the actuator and the aisle will close (partly).
Seal	97/98	Yes/Yes	Gas leak from the inlet pressure part to the down part of the regulator. The pressure level in the down part of the regulator increases, and the aisle will close (partly).
O-ring	70	Yes	Gas leak to the outside of the regulator
O-ring and seal	71 and 96	No/Yes	Gas leak from between the inlet and outlet parts. Because inlet part usually has a higher pressure level, the outlet pressure level will increase.
Seals	45, 64 and 105	Yes/No/Yes	Gas leak to the outside of the regulator

Table 18: Soft parts of regulator RMG 145C

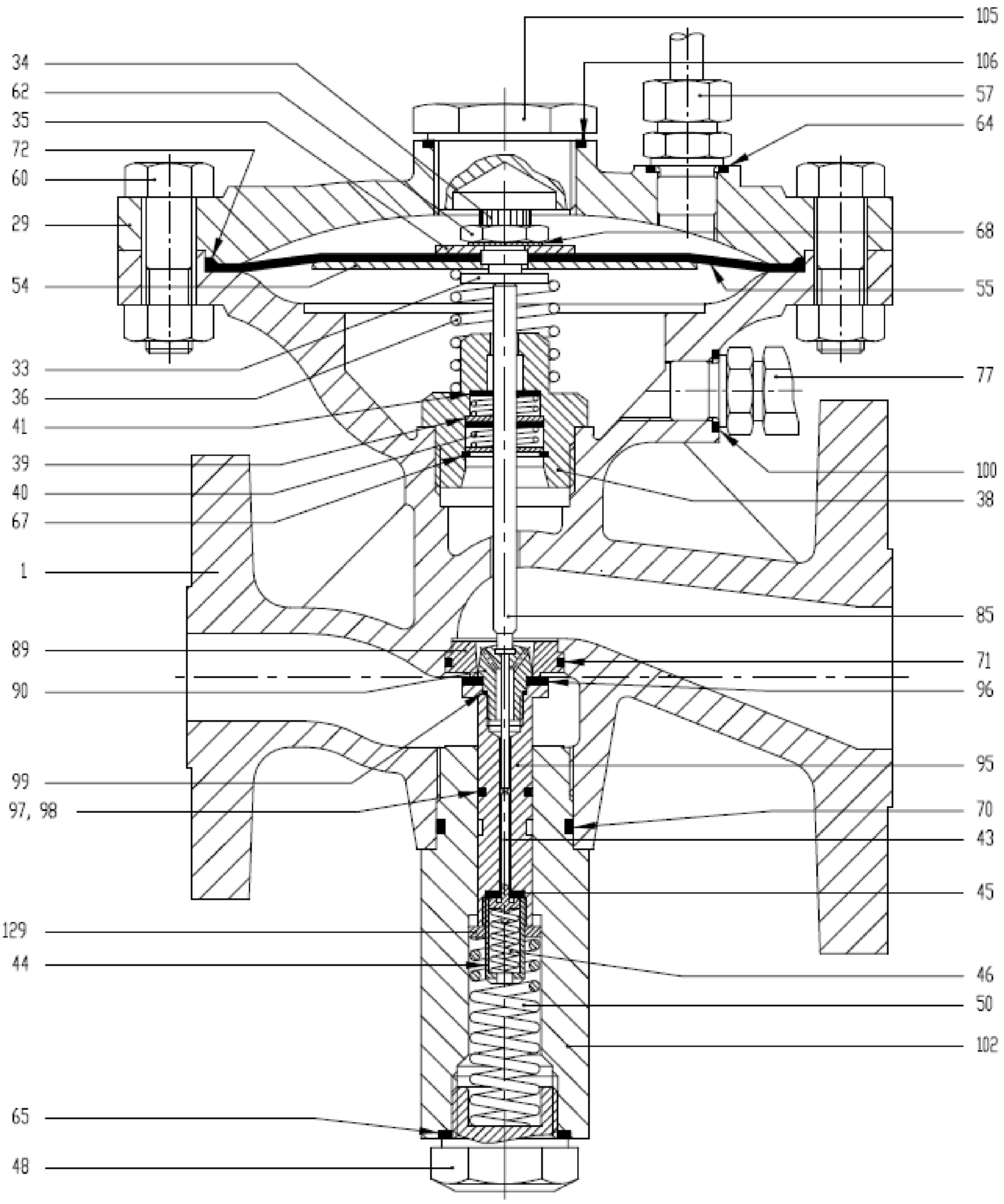

Figure 11: Depiction of a regulator RMG 145C

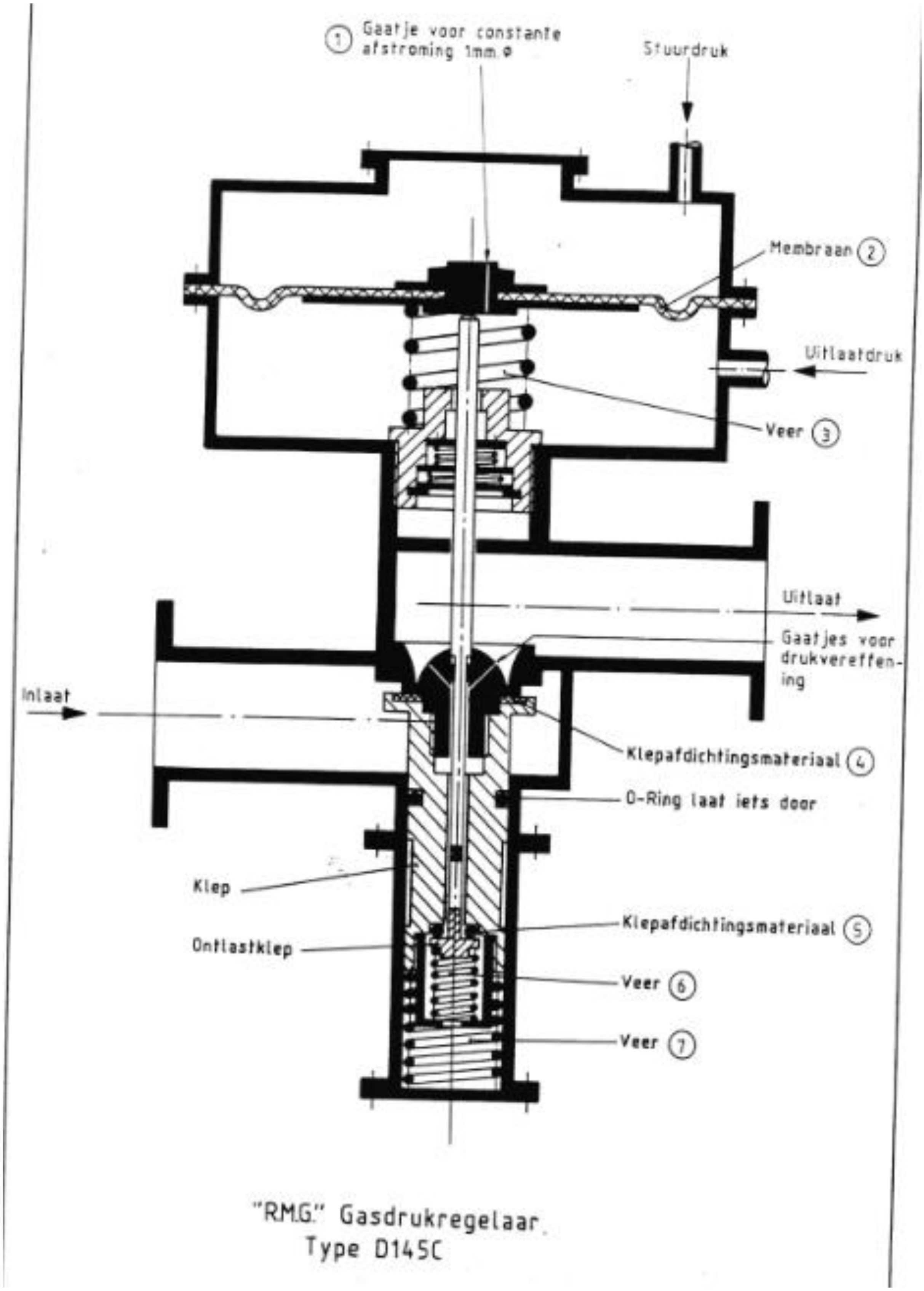

Figure 12: Depiction of a regulator RMG 145C

Monitor Francel SCGN 50/80 MAMM 269/374

This monitor contains various hard parts and as soft parts a diaphragm, six o-rings and a gasket as soft parts. Above the diaphragm, the gas from the pilot pressure presses down the diaphragm. Below the diaphragm, the pressure level is equal to the outlet pressure of the street, that flows in the monitor via the pipe. This outlet pressure and the spring push up the diaphragm. Depending on the prevailing pressure level, the rod opens or closes the aisle.

Figure 13 shows a depiction of the monitor and the positions of the soft parts. Figure 14 shows a less detailed depiction of the monitor. The o-rings at both positions with position number 14 (see Figure 13), keep the rod parts in the right setting. The o-rings at positions 20, 21 and 22 seal the partition between the actuator part and the outlet pressure part. The o-ring at position 9 seals the partition between the outlet and inlet pressure parts. The gasket at position 11 seals the steal parts below.

Wear-out of part	Position number	Supply disruption	Effect if failure occurs
Diaphragm	3	Yes	Gas flow between the pilot pressure part and outlet pressure part in the actuator via the diaphragm. Because pilot part usually has a higher pressure level, the pilot pressure part level will decrease and the aisle will close (partly).
O-ring	14	No	After wear-out of both o-rings: gas flow from between the pilot pressure part and outlet pressure part in the actuator via the o-rings in the rod. Because pilot part usually has a higher pressure level, the pilot pressure part level will decrease and the aisle will close (partly).
O-ring	20, 22	No	Gas flow between down part of actuator and outlet part. Because the outlet pressure level of the street usually is slightly higher, there will flow a very small amount of gas to the actuator. The aisle will close slightly
O-ring	21	No	Gas leak to the outside of the monitor. The aisle will open (partly)
O-ring	9	No	Gas flow from between the inlet and outlet parts. Because inlet part usually has a higher pressure level, the outlet pressure level will increase.
Gasket	11	Yes	Gas leak to the outside of the monitor

Table 19: Soft parts of monitor Francel SCGN 50/80 MAMM 269/374

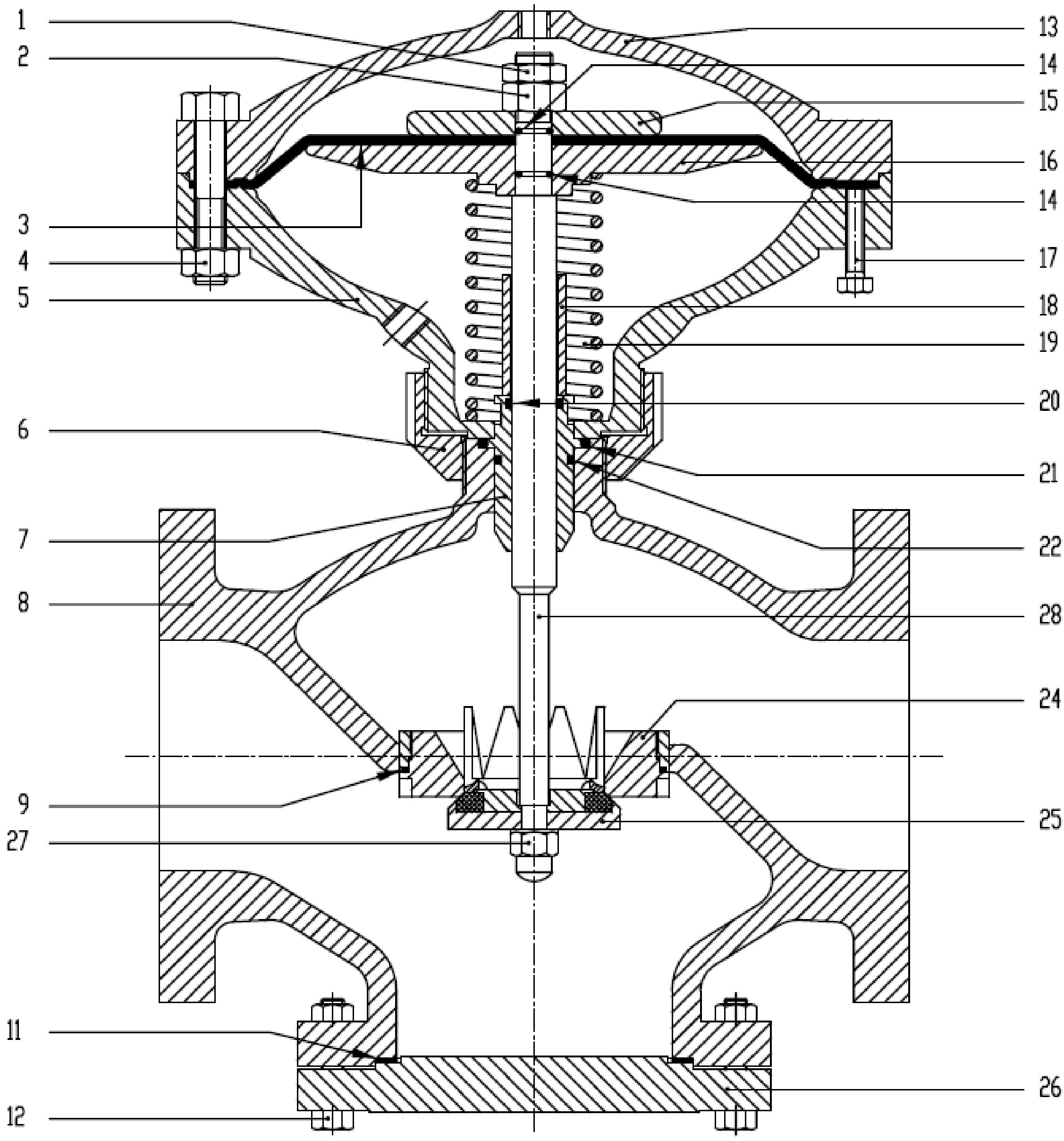

Figure 13: Depiction of a monitor Francel SCGN 50/80 MAMM 269/374

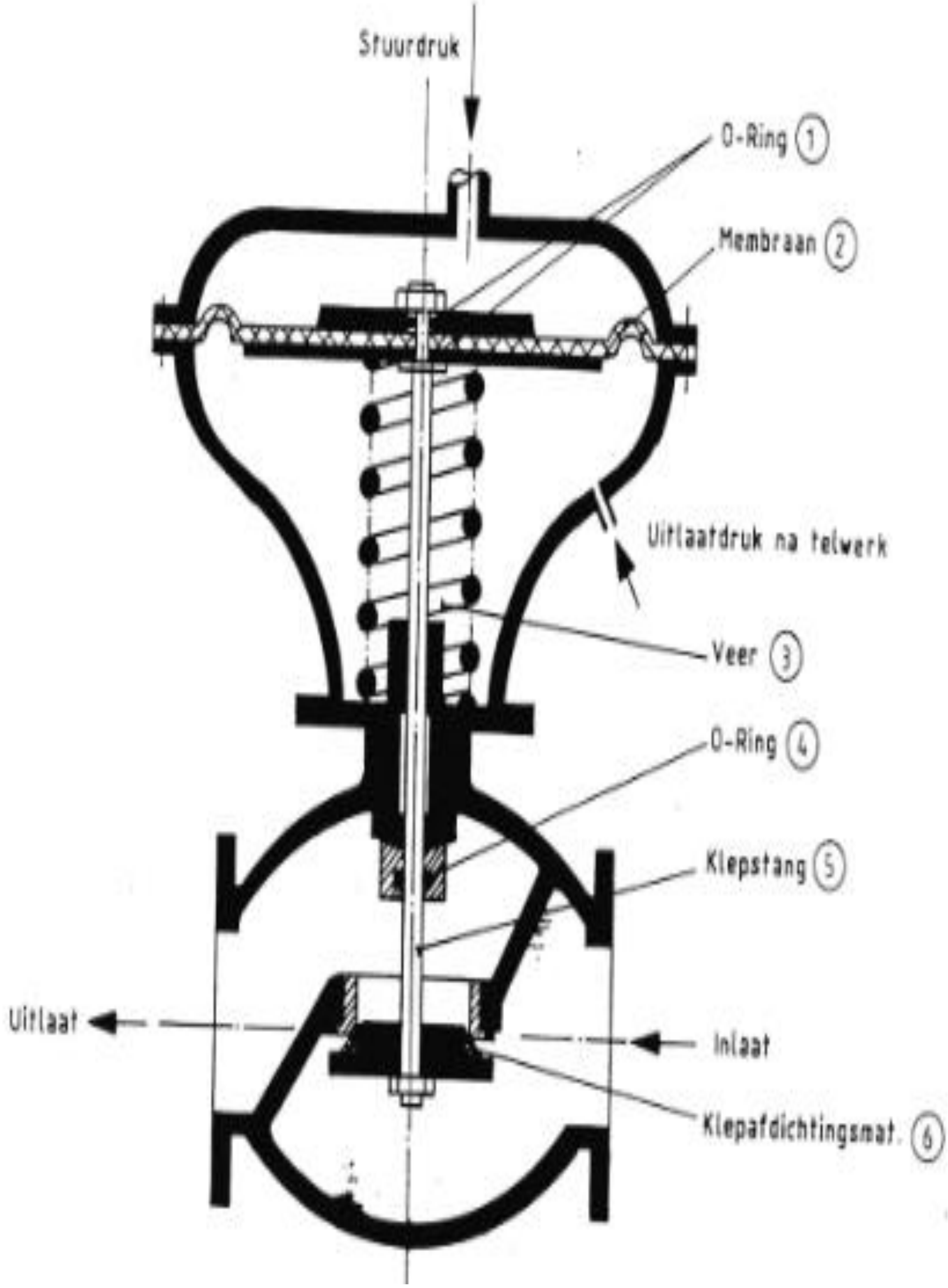

Figure 14: Depiction of a monitor Francel SCGN 50/80 MAMM 269/374

Aid pressure regulator Tartarini

Aid and pilot pressure regulators smoothen the control function of the regulator. They do this by regulating the inlet flow of the main regulator according to the level of the outlet pressure of the street. By using aid and pilot pressure regulators, a three-stage regulating mechanism takes place: . A three-stage regulating mechanism takes place. First, the outlet pressure of the main regulator is input for the aid pressure regulator, which is input for the pilot pressure regulator. This input of the pilot pressure regulator influences the regulating function of the main regulator. This main regulator controls the outlet flow of the GDS street.

This aid pressure regulator contains various hard parts and a diaphragm, an o-ring and a valve seal as soft parts. The spring above the diaphragm presses down the diaphragm. The spring is set on a specific setting to keep the aid pressure on the right level. Below the diaphragm, the pressure comes from the inlet pressure that flows into the aid pressure regulator via the pipe on the downside. Above the diaphragm, there is extra pressure from the outlet of the street. Depending on the prevailing force, the aisle is closed or open. By closing or opening this aisle, the pilot pressure level is adjusted to the right level. The aid pressure gas comes into the pilot pressure regulator via the opening on the downside of the pilot pressure regulator on the next page.

Figure 15 shows a depiction of the aid pressure regulator and the positions of the soft parts. Figure 16 shows a less detailed depiction of the aid pressure regulator. The o-ring at position 16 (see Figure 15) prevents a gas leak from the inlet pressure part to the outside of the aid pressure regulator. The valve seal at position 10 seals the partition between the inlet pressure part and the aid pressure part when the valve is pushed down.

Wear-out of part	Position number	Supply disruption	Effect if failure occurs
Diaphragm	6	Yes	Gas flow between the aid pressure part of the actuator and the top part of the actuator via the diaphragm. Because the outlet part usually has a lower pressure level, the aisle will close (partly) and the aid pressure decreases. This leads ultimately to a lower outlet pressure of the regulator/monitor connected to the aid pressure regulator
O-ring	16	No	Gas leak from the inlet pressure part to the outside of the aid pressure regulator and the aid pressure decreases. This leads ultimately to a lower outlet pressure of the regulator/monitor connected to the aid pressure regulator
Valve seal	10	No	There flows gas from the inlet pressure part to the actuator. The aisle opens (partly) and the aid pressure increases. This leads ultimately to a higher outlet pressure of the regulator/monitor connected to the aid pressure regulator

Table 20: Soft parts of aid pressure regulator Tartarini

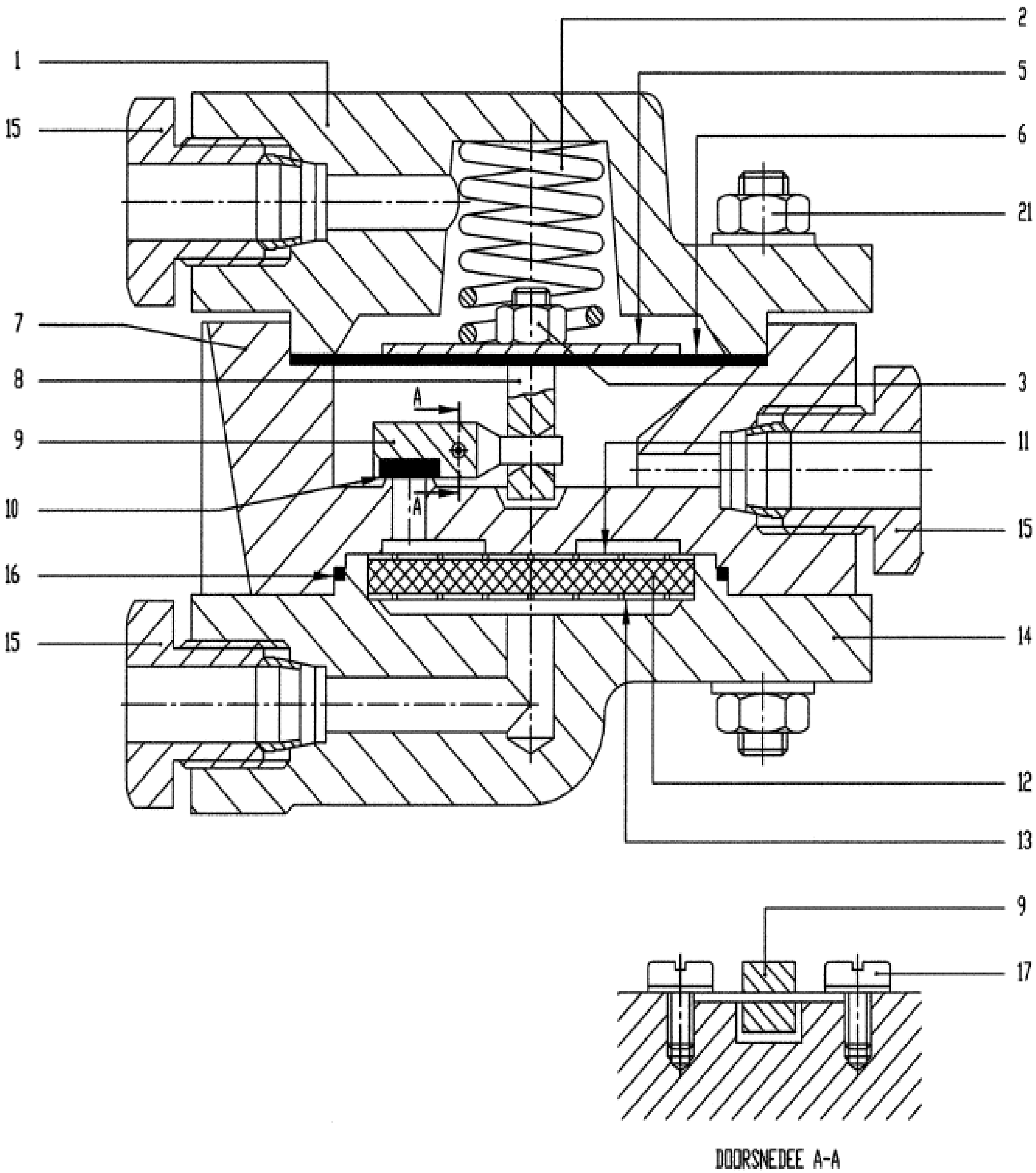

Figure 15: Depiction of aid pressure regulator Tartarini

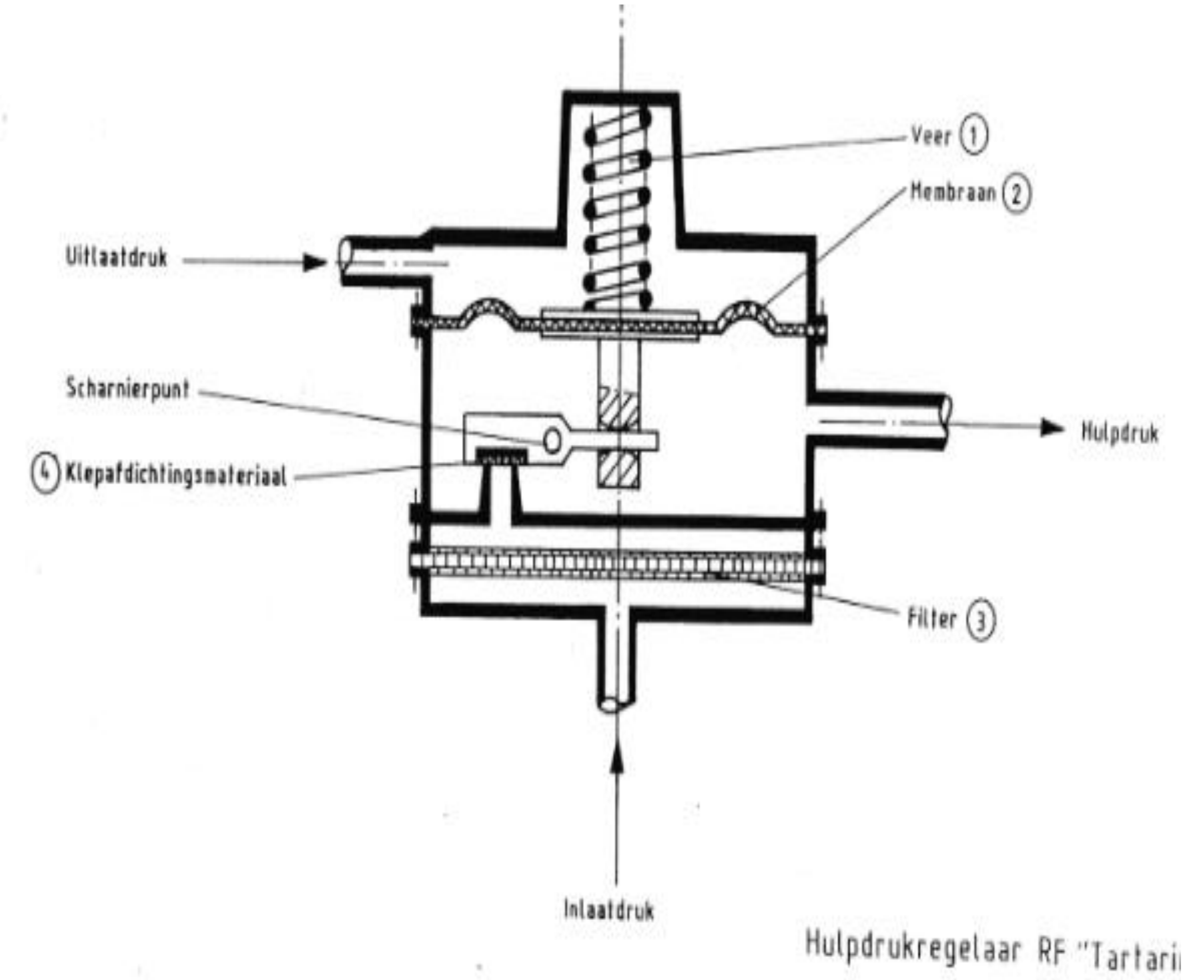

Figure 16: Depiction of aid pressure regulator Tartarini

Pilot pressure regulator Tartarini

Aid and pilot pressure regulators smoothen the control function of the regulator. They do this by regulating the inlet flow of the main regulator according to the level of the outlet pressure of the street. By using aid and pilot pressure regulators, a three-stage regulating mechanism takes place: . A three-stage regulating mechanism takes place. First, the outlet pressure of the main regulator is input for the aid pressure regulator, which is input for the pilot pressure regulator. This input of the pilot pressure regulator influences the regulating function of the main regulator. This main regulator controls the outlet flow of the GDS street.

This pilot pressure regulator contains various hard parts and a diaphragm, an o-ring and a valve seal as soft parts. The spring above the diaphragm presses down the diaphragm. The spring is set on a specific setting to keep the pilot pressure on the right level. Below the diaphragm, the pressure level comes from the outlet gas that flows in the actuator via the pipe. This outlet pressure pushes up the diaphragm. Depending on the prevailing force, the valve opens or closes the aisle from the outlet pressure part to the pilot pressure part on two spots. By closing or opening this aisle, the pilot pressure level is adjusted to the right level. The aid pressure gas flows into the pilot pressure regulator via the opening on the downside of the pilot pressure regulator.

Figure 17 shows a depiction of the pilot pressure regulator and the positions of the soft parts. Figure 18 shows a less detailed depiction of the pilot pressure regulator. The o-ring at position 24 (see Figure 17) prevents the gas flow from the aid pressure part to the lowest part of the actuator when the valve is pushed up completely. The valve seal at position 21 seals the partition between the aid pressure part and the pilot pressure part and the lower part of the actuator when the valve is pushed down.

Wear-out of part	Position number	Supply disruption	Effect if failure occurs
Diaphragm	10	Yes	Gas flow between the outlet pressure part of the actuator and the top part of the actuator via the diaphragm. Because the outlet part of the street usually has a higher pressure level, the aisle will close (partly). Pilot pressure decreases, which leads to a lower outlet pressure of the regulator/monitor connected to the aid pressure regulator
O-ring	24	No	There will be gas flow from the aid pressure part to the outlet pressure part (part below the diaphragm). Pilot pressure decreases, which leads to a lower outlet pressure of the regulator/monitor connected to the aid pressure regulator
Valve seal	21	Yes	Gas flow from the aid pressure pipe to the lowest past of the actuator and the pilot pressure part. Pilot pressure increases, which leads to a higher outlet pressure of the regulator/monitor connected to the aid pressure regulator

Table 21: Soft parts of pilot pressure regulator Tartarini

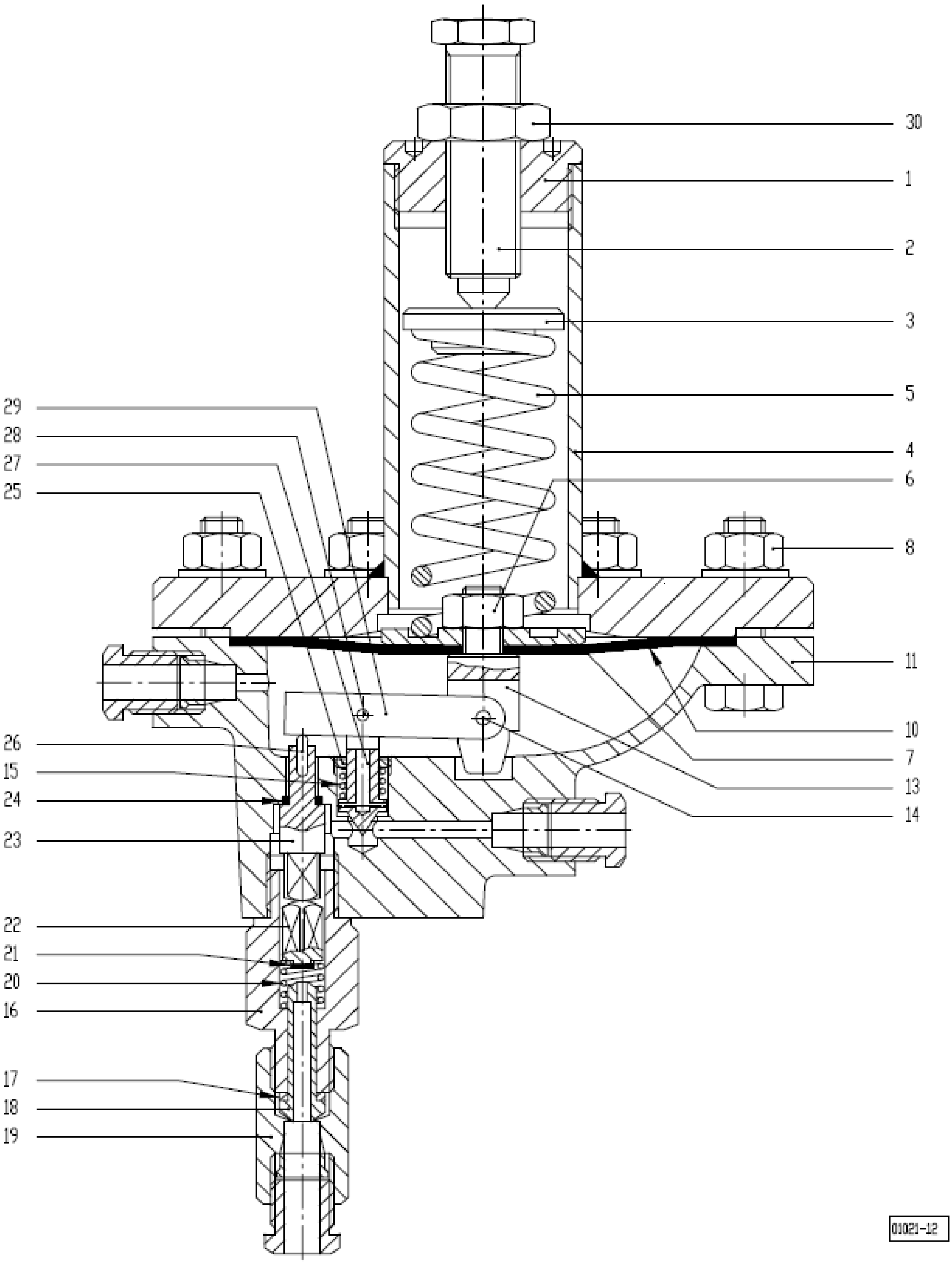

Figure 17: Depiction of pilot pressure regulator Tartarini

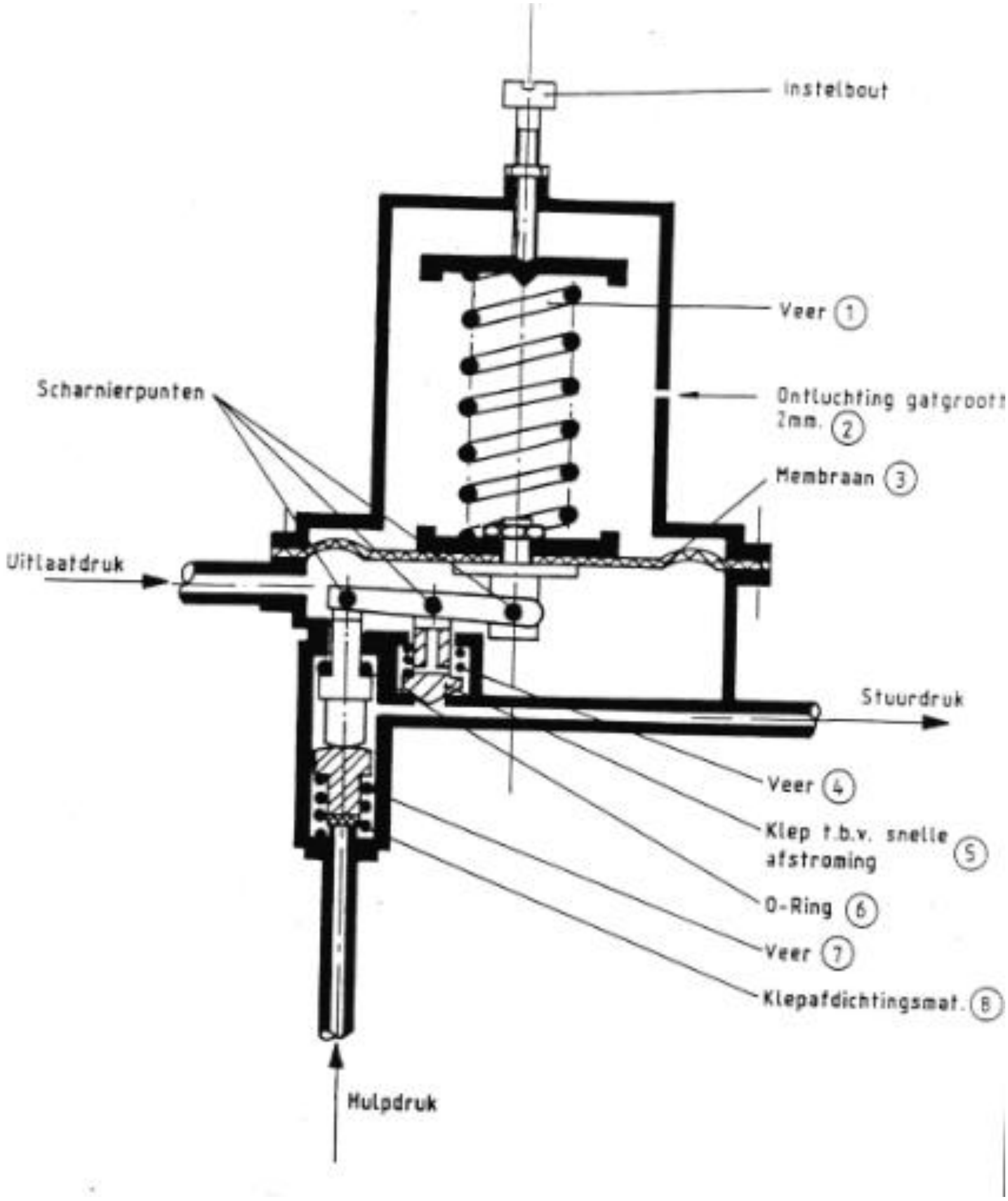

Figure 18: Depiction of pilot pressure regulator Tartarini

Appendix E: Wear-out of soft parts

This appendix contains a short introduction into the chemical issues related to the wear-out of soft parts of gas pressure control components.

Wear of rubber can be influenced by chemical, mechanical and thermal factors (expert opinion). When used for a long time, rubber could age and harden. Thereby, the soft parts lose their capability to stretch and damp (Woo et al., 2010). This process depends on the circumstances, the polymer type and the type of additives used. Uually, this process is a result of several factors and interactions between these factors (Woo et al., 2010). These factors are various process parameters and usage condition. Examples of these parameters and conditions are temperature, UV light, and chemical attack. Because of these factors, the useful lifetime is very hard to estimate. Carroll (2016) states that changes to material elasticity due to time or physical environment could lower the reliability of seals.

Important definitions are given by [19]:

Rubber:	"a material composed of long chainlike molecules, or polymers, that are capable of recovering their original shape after being stretched to great extents"[19].
Polymer:	"a large molecule composed of many repeated subunits, known as monomers"[19].
Monomer:	"a molecule that may bind chemically to other molecules to form a polymer"[19].
Additives:	"molecules of other substances that are embedded between the polymer´s chains, influencing the polymer´s properties and/or appearance, for example its UV resistance, resistance to chemical substances, its material strength or its color"[19].

Polymers can be prone to degradation, swelling and permeation [19],[20].
Polymer *degradation* means: "*polymer is physically or chemically altered, causing the equipment to fail or leak"*[19]. Polymer *swelling* means: "*molecules ´enter´ the polymer, resulting in a volume change, which can lead to leakage*"[19]. *Permeation* occurs in the following three steps:

- "*Adsorption and solution of the permeate into the polymer;*
- *Diffusion of permeate inside the polymer;*
- *Desorption or evaporation of permeate at the opposite surface*"[20].

Commonly applied polymers in the gas network are Nitrile rubber (Buna-N, NBR), Polytetrafluorethene (Teflon, PTFE), Fluor elastomers (FDM, FKM, Viton) [20]. [19] states that common-used rubber types in pressure control components, such as PTFE, NBR and Viton, are prone to permeation and swelling.

In [20] is stated that in order to prevent degradation and swelling of polymers, the following measures are identified in order to mitigate risks when Gasunie introduces new types of gas in its network:

- Prevent presence of nitrogen compounds (amines, ammonia) and sulfur compounds (hydrogen sulfide, mercaptans), aromatic and halogenated compounds and terpenes in gas;
- Prevent rapid decompression in case of high CO2 concentration
- Prevent/limit temperature (fluctuations)
- Prevent/limit pressure (fluctuations)

On page 12 of [21] a number of gas components is listed that cause the described mechanisms: Saturated hydrocarbons (ethane, butane, pentane, 2-methylbutane, 2.2-dimethylbutane, 2.2-dimethylpropane, 3-methylpentane), cyclic hydrocarbons (methyl cyclohexane), aromatic hydrocarbon (xylene, ethylbenzene, sulfur compounds (hydrogen sulfide, carbonyl sulfide),and other gas components (oxygen, carbon dioxide, carbon monoxide, hydrogen, nitrogen).

Appendix F: Policies regarding the maximum allowed repair time of street delivery failure

This appendix is hidden due to confidentiality issues. In the confidential version, this appendix gives the maximum time to repair policies as used for GDSs of Gasunie. It contains decision flow diagrams including explanations. These diagrams show in which cases Emergency GDS are required.

The Asset Management and the Operations department of Gasunie agreed on a policy framework containing the maximum allowed times to repair a failed street [8]. In Figures 19 (RNC GDSs) and 20 (Industrial GDSs), determination models for the maximum allowed times to repair are shown.

[DELETED]

Figure 19: Maximum time to repair for various scenarios of street delivery failure of an RNC GDS

[DELETED]

Figure 20: Maximum time to repair for various scenarios of street delivery failure of an industrial GDS

Also, the confidential version of this thesis contains the policies towards the launch of an emergency installation. As explained in Sections 1.2 and 2.3, the purpose of launching an emergency installation is to solve the problem that after failure of a street or GDS, it is possible that there is no redundancy anymore. The emergency installation then ensures redundancy and thereby the required availability. The main conclusion of the confidential version of this Appendix is the following:
Based on the given diagram in Figure 21, and the required minimum time to change pipes in replacement scenario 3 of three days (see Section 2.3), it can be assumed that all unplanned scenario 3 replacements require an emergency GDS.

[DELETED]

Figure 21: Decision flow diagram for launch of an Emergency GDS

Appendix G: Costs and minimal replacement times per scenario

This appendix presents the costs and minimal replacement times for each of the scenarios described in Section 2.5. Also, it explains the costs of OM and PM of regulator and monitor soft parts. **A part of the content of the tables in this context is hidden due to confidentiality issues.**

Corrective replacements

Scenario 1: replacement of soft parts only

The total costs based on Table 22, which shows all costs per corrective replacement in scenario 1, is 1,14 SC. Because around half of the corrective replacements is done scheduled after a failure is detected during inspections, and in these cases the costs for transport is far less expensive, the total costs per replacement in scenario 1 is set on 1 SC (regulator and monitor) and 0,61 SC (aid and pilot pressure regulator).

A part of the content of the tables in this context is hidden due to confidentiality issues.

cost type	Replacement duration	transport hours	Employees required	Wage (SC) /hour	transport costs/hour (SC)	material costs (SC)	Total costs (SC) *
Wages technicians							0,64/ 0,32
wages component transporter							0,27
travel costs technicians							0,013
travel costs component transporter							0,053
material							0,17/ 0,10
Min. Time to replace							

Table 22: Costs of replacement for scenario 1 (replacement of soft parts only)

*Material costs are 0,17 SC for a regulator or monitor in scenario 1 and 0,10 SC for an aid or pilot pressure regulator, respectively, in scenario 1.

Scenario 2: failure can only be solved by replacement of component; no change of pipes required

Total costs can be found in Table 23 for aid and pilot pressure regulators: 4,2 SC per replacement. Costs for regulator and monitor replacements are 12,33 SC, based on [25] and expert opinion of the author of [25]. Table 23 shows the replacement costs for aid and pilot pressure regulators. A part of the content of the tables in this context is hidden due to confidentiality issues.

cost type	Replace-ment duration	transport hours	Employees required	Wage(SC)/ hour	transport costs (SC)/hour	material costs (SC)*	Total costs (SC)
wages technicians							0,27
wages component transporter							0,27
travel costs technicians							0,013
travel costs component transporter							0,053
Material costs							3,6
Min. Time to replace							

Table 23: Costs of a corrective replacement of a complete aid and pilot pressure regulator (scenario 2 aid and pilot pressure regulator)

Average material prices are determined based on prices of a sample of pressure control components, provided by the Purchasing department of Gasunie.

Scenario 3: failure can only be solved by replacement of component, change of pipes required
Replacement of a regulator or monitor with change of pipes takes eight hours for two technicians. The total travel time for the technicians is around one hour. The total travel time to bring the component and pipes from Deventer to the technicians is around four hours. Minimum time to replace is three days, due to the required pipes, as described in Section 2.3. Total costs are 23,8 SC for a regulator or monitor. This is based on [25] and expert opinions of the author of [25]. Aid and pilot pressure regulators are not replaced in this scenario.

Scenario 4: launch of an emergency installation
See Appendix L.

Scenario 5: replacement of a hard part is required
It holds that when a hard part fails, the soft parts have to be replaced as well (see Section 2.3). Therefore, the costs are the same as scenario 1 plus the price of the failed hard parts. Costs are the same as scenario 1, plus 0,3 SC, which is the average price of a hard part in a regulator or monitor, based on data of Gasunies Purchasing department. Therefore, costs are 1,3 SC (regulator or monitor) and 0,93 SC (aid and pilot pressure regulator).

Opportunistic and preventive replacements

Scenario 'OM'
Costs are 0,5 SC for regulators and monitors, based on costs of material and an estimated extra repair time of a number of hours (confidential information), in comparison with the scenario that no OM is performed.

Scenario 'PM'

Costs are 0,86 SC for regulators and monitors, based on the costs of a scenario 1 replacement minus the costs of transport of components in scenario 1. Transport costs of components to the technicians in the particular region can be done opportunistically, when the replacement is planned on forehand.

Extra costs and a summary of costs per scenario

Extra costs due to first visit/summary of costs per scenario

As explained in Section 2.2, there are costs possible next to the described costs in this appendix, due to the required visiting the GDS when a failure occurs during operation. These costs only occur when the failure occurs during operation. Based on expert opinions, the duration of these visits is estimated. The visits are nearly always done by two technicians. The costs per visit can be estimated to be equal to the resulting wage costs plus the transport costs. Because these costs only occur during operation, these costs can be multiplied by the ratio of failures detected during operation, as are given in Section 2.7. Using these ratios and the same costs for wages and transport as in the rest of this Appendix is done, the expected costs of visits per replacement can be calculated. Results are given in Table 24. In this table, the prices of all other scenarios are summarized as well.

Replacement scenario	Replacement costs (SC) per replacement	Avg. costs (SC) of visit after regulator failure	Avg. costs (SC) of visit after monitor failure	Avg. costs (SC) of visit after aid & pilot pressure regulator failure
Scenario 1 r&m	1,00	0,10	0,11	0,00
OM r&m	0,50	0,00	0,00	0,00
PM r&m	0,86	0,00	0,00	0,00
Scenario 5 r&m	1,30	0,10	0,11	0,00
Scenario 2 r&m	12,33	0,10	0,11	0,00
Scenario 3 r&m	23,80	0,10	0,11	0,00
Scenario 4 r&m	14,67	0,00	0,00	0,00
Scenario 1 a&p	0,61	0,00	0,00	0,09
Scenario 5 a&p	0,91	0,00	0,00	0,09
Scenario 2 a&p	4,20	0,00	0,00	0,09

Table 24: Summary of replacement and visit costs per replacement scenario

Appendix H: Data analyses performed to estimate the failure rate of gas pressure control components

This appendix explains the method of data analysing that is used to perform the analyses towards the failure rates of the three types of gas pressure control components. The two types of SAP data analyses are already explained in Section 2.5. Tis appendix gives potential drawbacks of these methods. Then is explained why and how a number of small adjustments is done on the detected failure rates. Finally is given which method is used to find the failure distributions and parameters that are presented in Section 2.5.

Drawbacks of the used research method in the first and second analysis

There are a number of drawbacks of the described methods of estimating the failure rates of the soft parts of the gas pressure control components of Gasunie. Certain factors influence the reliability of the orders and announcements in SAP. These are:

- Technicians sometimes do not provide (easy to understand) explanations of their observations and maintenance activities. These explanations are hard to understand as an outsider;
- A large part of the component failures is caused by other problems. However, discovering these causes takes a long research time, because the explanations of the causes are often in other announcements by technicians;
- The texts in the announcements were analyzed to estimate which part exactly failed. This analysis is subject to human errors and misunderstandings;
- Because the last preventive replacements of soft parts at the GDSs are performed between 1991 and 1997 (differs per GDS), the number of analyzed pressure control components older than 19 years old is low. Nineteen years is the difference between 2016, the last year in the SAP analyses, and 1997. This probably reduced the detected failures at ages of 19 years and older;
- SAP is introduced in 1999. The orders and announcements before 1999 are unknown. They are in the previous database Rayondis, but it would take too much time to collect these data.

The given drawbacks resulted in a number of adjustments to the detected data. These adjustments are described in the following paragraph.

Analyses and adjustments of the results of the first and second analysis for regulators

For the analysis of failure rates, the last factor in the list of drawbacks of last paragraph, is most important. The result of the last factor is that there is no information about failures until 1999. Because the last preventive replacements of soft parts of gas pressure control components were between 1991 and 1997 (differs per GDS), there is very little information about failures in the first seven years of the lifetime of the soft parts. Therefore, a report of 1996 [7] is used to determine the failure rates for the first seven years. This report gives the number of failures per year on regulators, monitors and aid and pilot pressure regulators during the years 1988/1994.

The results of the first analysis, the second analysis and the information of the first seven years of regulators, were merged into Figure 6 in Section 2.5. In Section 2.5 is explained how the data in [7] is used to determine the failure rates of the first 7 years of regulators.

Analyses of monitors and aid and pilot pressure regulators

The analyses of failure rates of soft parts of monitors and aid and pilot pressure regulators are done in a similar way as the analyses of the regulator soft parts. The information from [7] is used to determine the failure rates for the first seven years. This information is merged with the data from the first and second analysis to determine the failure rates.

Estimation of parameters

The estimations of parameters are performed in a Engineered Software Inc. (1999). This CD contains a software program developed specially to determine failure rate distributions and corresponding parameters of input data such as failure data.

Appendix I: Code changes at standard model in order to perform sensitivity analyses

This appendix gives the changes in code required to perform the analyses of Section 5.3 and the sensitivity analyses in Chapter 6. The described changes are performed to adjust the standard model described in Chapter 4. Therefore, all changes compared to the standard model in Chapter 4 are given.

Code changes for Sections 5.3

All frequencies of replacements other than soft parts of regulators and monitors, are changed into 0 per year. This means that there are no failure costs (due to gas leaks or transport breaks) caused by failures other than failures of soft parts of regulators and monitors; also, there are no replacement costs for parts other than soft parts of regulators and monitors.

Code changes for Sections 5.4

No changes compared to standard model as described in Chapter 4.

Code changes for Section 6.1

Sensitivity analyses of failure costs of regulators

In order to select the optimal age configuration per value of failure costs of regulators, the adjusted model as described in Section 5.3 was used first. Thereafter, the effects of using these optimal age configurations in the Gasunie case, were determined. In the latter simulation model, there were no changes compared to the standard model as described in Chapter 4. Only changes in levels for input variables were changed: sensitivity analyses are done by adjusting the failure costs per transport break.

Sensitivity analyses of failure rates of regulators and monitors

In order to select the best three age configurations per value of failure costs of regulators, the adjusted model as described in Section 5.3 was used first. Thereafter, the effects of using these optimal age configurations in the Gasunie case, were determined. In the latter simulation model, there were no changes compared to the standard model as described in Chapter 4. Only changes in levels for input variables were changed: the failure rates of regulators and monitors were changed.

Code changes for Section 6.2

Sensitivity analyses of permanent supply disruption level

No changes compared to standard model as described in Chapter 4. Only changes in levels for input variables: the permanent supply disruption levels and inventory levels were changed.

Use of temporary replicates of soft parts of regulators and monitors

The following changes are implemented in the standard model as described in Chapter 4:

- An extra scenario (scenario 6) is added for regulator and monitor replacements;
- This scenario occurs if the following conditions hold: There is a soft part failure of a regulator (monitor) that suffers from permanent supply disruptions from both the soft parts and the complete regulator (monitor), and no (undocumented) inventory for both the soft parts and the complete component is available. These conditions are the conditions for a scenario 3 replacement (replacement of complete component and changes in pipes required);
- The extra scenario does not change the rest of the code, so the required scenario 3 replacement of the complete component still occurs;

- When determining the replacement costs, the total replacement costs per component type are reduced by: the costs savings of 0.255*14,67 SC -1 SC per occurrence of *scenario 6**the number of occurrences of *scenario 6* per year for that component.

Code changes for Section 6.3

Opportunistic replacement of obsolete regulators based on the age of the soft parts of regulator

As input is added:

- The threshold age for an opportunistic replacement of an obsolete regulator.
- The costs savings level between a single opportunistic replacement of a complete regulator and a single corrective replacement of a complete regulator, in scenario 3. These are quantified in Section 6.3.

The following changes are implemented in the standard model as described in Chapter 4:

- An extra scenario (scenario 6) is added for regulator replacements;
- This scenario occurs if the following conditions hold:
    - There is an opportunity for opportunistic replacement in the GDS street. As explained in Section 6.3, this means that there is a replacement of a complete monitor or a replacement of the component type 'other components'. In the code, this means that the *remaining lifetime of the component* of either component type 6 (monitor) or component type 10 ('other components') must be equal to the *duration until next replacement at the street*;
    - The regulator in the street suffers from permanent supply disruptions of soft parts;
    - The regulator soft parts are older than the threshold age for an opportunistic replacement of an obsolete regulator.
- When this scenario occurs, the *remaining lifetime of the component* of the regulator is set equal to *the duration until next replacement at the street*. Thereby, the regulator is replaced during the next replacement*;*
- When determining the replacement costs, the total replacement costs for regulators are reduced by: *the costs savings level between a single opportunistic replacement of a complete regulator and a single corrective replacement of a complete regulator ** the number of occurrences of *scenario 6* per year for the regulators.

Appendix J: Ratios of permanent supply disruption, inventory availability, and the use of emergency installations

This appendix gives more details about the motivation behind the following assumptions/values of input parameters: permanent supply disruption per component type, inventory availability per component type, and the probability that an emergency installation is required (scenario 4) when a complete component has to be replaced (scenario 3).

Permanent supply disruption per component type

A research in SAP on the 17th of March 2017 showed that from the 2032 regulators in the field on that date recorded in SAP, there were 421 regulators without permanent supply disruptions of soft parts. For 320 regulators only one, two or three soft parts were disrupted. For monitors, only for 120 of the 717 monitors in the installed base there were no permanent supply disruptions, while for 173 monitors only one, two or three soft parts per monitor were disrupted. The percentages given mean that for 20% of the regulators and 17% of the monitors there are no permanent supply disruptions, while for 16% of the regulators and 25% of the monitors, only between one and three soft parts per component are disrupted. In these cases, it is often possible to repair a component in scenario 1, unless one of the unavailable soft parts has failed. In the model, it will be assumed that 65% of the components suffer permanent supply disruptions of soft parts, which corresponds with the estimates of experts. Other expert opinions are that the permanent supply disruptions of components´ hard parts is approximately the same as the permanent supply disruptions of their soft parts. Also, these experts mentioned that for a part of the components itself the supply is disrupted, while the supply of their soft and hard parts are not disrupted yet. Therefore, the permanent supply disruption levels of 75% for complete components and 65% of soft and hard parts are assumed.

Inventory availability per component type

As already mentioned, it is very hard to identify the number of soft parts per component type in the undocumented inventories. The same holds for the probability that there is enough inventory/other solutions to replace in the less expensive scenario at 01-01-2018 (row 'highest probability') and the probability that there is enough inventory/other solutions to replace in the less expensive scenario when the (undocumented) inventory is completely diminished. Estimates based on statements of technicians and regional maintenance managers are given in Table 25. In the sensitivity analyses in Chapter 6, analyses are done with inventory levels 20 and 400 for each component type as well.

	Regulator			Monitor			Aid and pilot pressure regulator			Other
	SP	**HP**	**CC**	**SP**	**HP**	**CC**	**SP**	**HP**	**CC**	
Lowest probability	0,2	0,05	0,1	0,2	0,05	0,1	0,2	0,05	1	1
Highest probability	0,6	0,7	0,7	0,6	0,7	0,7	0,6	0,7	1	1
Inventory 01-01-2018	200	200	200	200	200	200	200	200	200	1

Table 25: Inventory availability levels per component type

Probability of scenario 4 (launch of an emergency installation) given that scenario 3 occurs at regulator or monitor

The ratio of scenario 4 (emergency installation required) to the total number of failures in scenario 3 (replacement of complete component) of regulators or monitors, is assumed to be 0,255. For scenario 1 and 2, no emergency installations are required.

The ratio of 0,255 is based on the failure effects in Table 3 in part 2.7. This table shows that 54,3% of the failures of regulators is detected during inspections. When a failure is detected during inspections, usually no emergency installation is required. The reason behind this is that there is enough time to plan a replacement and deliver pipes before a major failure effect occurs (such as a large gas leak, or street delivery failure) caused by the failure. The failures that are not detected during inspections are 45,7% of the failures. The 45,7% of failures that are not detected during inspections contain failures that do not have a (known) failure effect (20,2% of the total failures) and failures that do have a (known) failure effect (25,5% of the total failures.

It can be assumed that most of the failures for which a known failure effect occurs, need to be solved fast and therefore require an Emergency GDS; for most failures without a known failure effect, a replacement will not be required immediately. The reason behind the possibility to delay the replacement a couple of days, is the same as the reason behind the possibility to delay the replacement after detection of a failure during inspections: there is enough time to plan the replacement before a major failure effect occurs (such as a large gas leak, or street delivery failure).

The latter does not hold for failures during operation that result in a known failure effect. These failures already caused a major failure effect. Then, it can be assumed that there is nearly always an emergency installation required. There might be a relatively small number of failures where a known failure effect exists that do *not* require to be immediately solved due to the maximum allowed repair times (see Appendix F). Then, this delay could imply that there is no emergency installation required. On the other hand, there might be a relatively small number of failures where *not* a known failure effect exists, that do require to be immediately solved and therefore require an emergency GDS. To summarize: there might be a number of failures where a known failure effect exists but an emergency installation is not required; also, there might be a number of failures where not a known failure effect exists but an emergency installation is required. These two types of occurrences are assumed to compensate each other. Therefore, the ratio of 0,255 is assumed.

Appendix K: Mean times to fail of other components in GDS streets

This appendix gives the results of a research by a Gasunie employee towards the mean time to fail of gas pressure components and other components in GDS streets.

In Table 26, the Mean Time To Fail (MTTF) numbers are shown that Gasunie uses in their reliability studies [4] for the components in GDS streets. These MTTFs are assumed to be parameters in a constant failure rate function, because the same research found out that the majority of the failure rates of GDS components is constant over the last years. MTTF in this context can be defined as the mean time before replacement of a complete component. Failures that can be solved by replacing parts of components only, are not included in these MTTF determinations. Therefore, failures of soft and hard parts of regulators and monitors, do not influence their MTTFs.

To determine the MTTFs, SAP data were analysed first; based on the results of this SAP analysis, lower and upper bounds of the MTTFs were selected in expert panel meetings. In this research, the average of the lower and upper bounds are used as failure rates for the given components, as Table 26 shows in the last column.

MTTFs of flow measurement devices were not in the scope of the research. The flow measurement devices are replaced preventively every 30 years. Therefore, these replacements are added.

Using the MTTF as shown in the last column, the number of complete regulator and monitor replacements per year for the complete installed base is 35 and 2.9, respectively. These numbers are calculated by dividing the installed base by the MTTF used in this research (fourth column). This can be done because the random failure phase failure rate is described by an Exponential distribution. Using the same logic, total number of replacements per year for all complete components in the street besides regulators and monitors, can be determined to be around 128 per year for the complete installed base. However, the true value is slightly higher, because the RSS streets contain an extra safety shut valve. The higher failure rate of the *other complete components in a GDS street, outside the gas pressure control components* for RSS streets compared to RMS streets is explained in the next paragraphs.

Component	MTTF lower bound (years)	MTTF upper bound (years)	MTTF used in this research
Inlet blockage	123	246	185
Filter	2.000	5.000	3.500
Heat exchanger	500	700	600
Safety shut valve	106	246	176
Monitor	150	350	250
Regulator	50	90	70
Flow measurement device	**	**	30
Outlet blockage	116	232	174

Table 26: The used MTTFs as input for Gasunies reliability studies

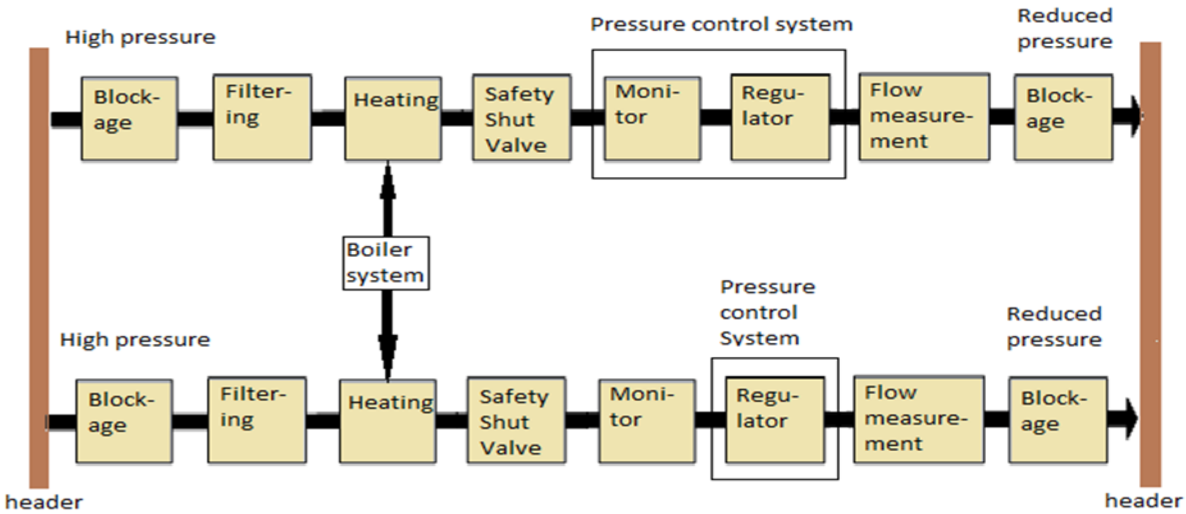

Figure 22: A GDS with an RMS and an RSS street

The mentioned 128 replacements of complete components per year are not the only replacements besides the (parts of) gas pressure control components. According to a SAP analysis, the soft parts of safety shut valves are replaced relatively often. For the other components in Table 26 besides regulators and monitors, the number of replacements of hard or soft parts are negligible. The total number of replacements of safety shut valve (parts) during the last years is more than the number of replacements that can be based on the MTTF of *complete* safety shut valves as given in Table 26. Therefore is assumed that the number of replacements following from the MTTFs in Table 26, is the number of replacements of encapsulations of safety shut valves; the difference between this number of replacements and the number of replacements per year in SAP during the last years, is assumed to be the number of failures of hard and soft parts of safety shut valves. Using these numbers and an Exponential failure rate distribution, the MTTF of the aggregated failure rate of hard and soft parts of safety shut valves is 104.8.

Using the data described above, the following failure rates for the 'other components' in a GDS street can be determined:

- For an RMS street, the failure rate for 'other components' is:
  $\sum_{i=1}^{i=6} 1/MTTF(i)$ *+ 1/104.8 = 1/16,22*
  with for i = 1 up to and including 6 the components inlet blockage, filter, heat exchanger, safety shut valve, flow measurement device and outlet blockage (see Table 26) and 104.8 as MTTF of hard and soft parts of safety shut valves
- For an RSS street, the failure rate for 'other components' is:
  $\sum_{i=1}^{i=6} 1/MTTF(i)$ *+ 1/MTTF(encapsulation safety shut valve) + 1/104.8 + 1/104.8 = 1/13,01*
  with for i = 1 up to and including 6 the components inlet blockage, filter, heat exchanger, safety shut valve, flow measurement device and outlet blockage (see Table 26) and 104.8 as MTTF of hard and soft parts of safety shut valves.

Difference between the failure rates is that for RSS streets, the failure rate of an extra safety shut valve is added to 'other components'. Therefore, extra failures of the encapsulation of safety shut valves are added (an increase of *1/MTTF(encapsulation safety shut valve))* and extra failures of the soft and hard parts of the safety shut valve are added (an increase of 1/104.8).

Appendix L: Directly available emergency installations

This appendix provides a list of the directly available emergency installations, including the maximum capacity levels, sizes of inlet and outlet of these installations, installation time, and costs.

All installations are in one or more trucks per installation. Each EGDSs has a maximum capacity level, which limits the options in case an emergency installation is required: the capacity level must at least be equal to the expected demand peaks in the time of operation.

The information in Table 27 is deleted due to confidentiality issues.

Type	ID used at Gasunie	Size of inlet and outlet (inch)	Maximum capacity level (m^3/hour)*	Installation time**	Costs of installing this emergency installation (SC)	Extra costs (SC) per day***

Table 27: List of directly available emergency installations at Gasunie

*The maximum capacity according to the design standards. However, they can regulate slightly higher capacities safely for a couple of weeks.
** A bottleneck in the installation time can be the required length of the pipes to connect the RTL/HTL pipes with the emergency GDS. Also, the time to satisfy all safety rules can be one day longer than the given installation time, which is the time that it takes to replace the failed GDS.
***Average prices based on [13]. Some prices are extrapolated/interpolated.

Appendix M: Determination of the probability of station delivery failure after street delivery failure

In the confidential version of this thesis, this appendix gives the results of an analysis towards the probability of station delivery failure after street delivery failure. In this public version, the details are deleted due to confidentiality issues.

In the described analysis is investigated what the failure modes were of both the street delivery failures and station delivery failures of last years. The failure modes were amongst others regulator failure, aid and pilot pressure regulator failure, human errors, and failures in other parts of the Gasunie network. Also, a number of external causes were found, such as failures in the network of clients. Based on the frequencies of these failure modes, the probability of station delivery failure after street delivery failure was determined. Afterwards, the method and data were checked together with experts. Due to confidentiality issues, this public version does not contain the exact method of determining the probability of failure of a complete GDS after a street delivery failure.

The conclusion of this appendix in the confidential version of the thesis is:
In the simulations in Chapter 5, the value of 1,1% is used as probability of failure of a complete GDS after a street failure. In Section 6.1, sensitivity analyses are performed to indicate the consequences of using higher or lower failure costs. These sensitivity analyses indicate the effects of possible deviations from the mentioned value of 1,1%.

Table 28: Table that is used in the confidential version of this thesis, to determine the probability of station delivery failure after street delivery failure. Content is hidden due to confidentiality issues.

Appendix N: Failure rates of a comparable regulator type

This appendix summarizes the results of a research by a former employee of Gasunie. This research strengthens the conclusion that an increase in failures in soft parts of regulators can be expected after the known failure rates of the first until the 23rd year (see part 2.5).

In 2007, Gasunie did a research towards the failure rate of soft parts of regulators in HTL blockage stations. These soft parts and regulators are comparable to regulators of GDSs. Therefore, the results of that research could be interesting to estimate the failure rates of GDS regulator soft parts in the future. Based on the described research on HTL blockage regulators, Gasunie decided to replace all soft parts of these HTL blockage regulators every 25 years[18]. In interviews during the research towards the optimal replacement times of the soft parts of HTL blockage regulators, OEMs of these regulators recommended to replace all soft parts after 20 years.

In the described research, a large number (>50) failures on HTL blockage stations were analysed and their age at the time of failure was found. In a similar way as for the GDS regulators (see Section 2.5), the failure rate per age is determined by dividing the number of failures by the total number of regulators of that age. In the described research, the population per age was diverse and sometimes even zero, which influences the failure ratios. Therefore, only for ages with a population containing more than 10 regulators, the failure rates are shown in Figure 23. An increasing failure rate per age is visible.

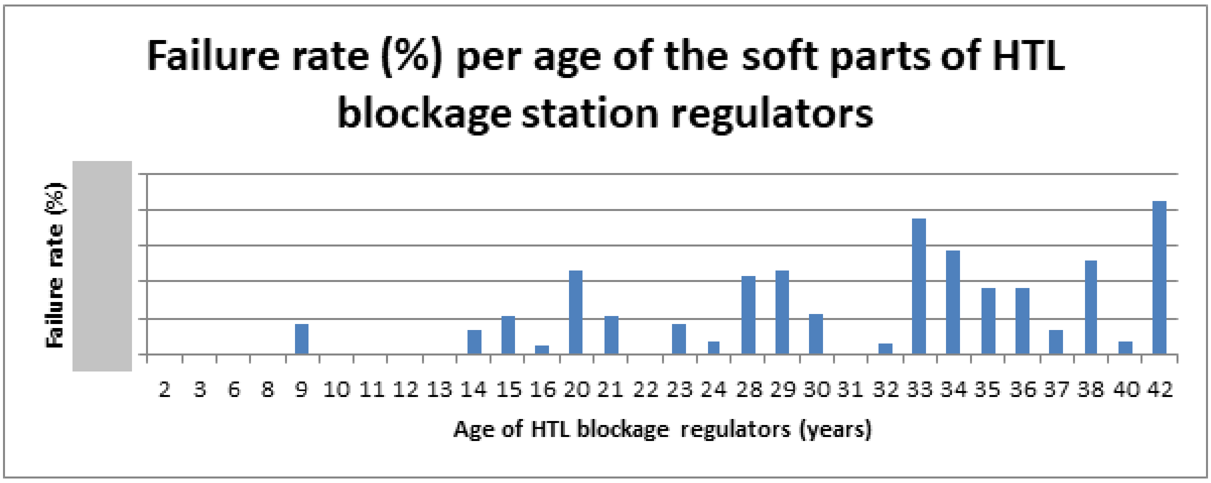

Figure 23: Failure rates of soft parts of HTL blockage regulators

Considering the similarities in material of the regulator types, it can be assumed that the soft parts of regulators in GDSs are subject to a similar useful life time as the soft parts in regulators in HTL blockages. However, there are some differences between the regulators in HTL blockages and GDSs. The differences are about the functioning, the pressure levels and temperatures in and around the regulators:

- HTL blockage regulators are almost always open, unless the HTL network needs to be closed or a maintenance activity occurs. There is one inspection per year, and the frequency of HTL blockage closures in function is less than 0,5 per HTL blockage per year. The total time to open the regulator is less than three minutes for every type of HTL blockage regulator. In total, a HTL blockage regulator regulates gas flow for less than 5 minutes per year (1,5 times per year*3 minutes per time). In regular GDS streets, regulators are permanently regulating the gas pressure level. As a result, the diaphragm of the regulators in the regular GDS street is permanently deformed, while the diaphragms of the HTL blockage regulators are deformed only seldom.

- It can be assumed that failures in HTL blockage regulators are detected later than failures in GDS regulators that occur at the same time, due to very short operation times of these HTL blockage regulators.
- The gas pressure of the inlet gas of HTL blockages is around 66 bar, while the inlet gas flow of GDSs usually is around 40 bar.
- Gas in GDSs is warmed, while gas in HTL blockage regulators is slightly colder.
- HTL blockage regulators are located outside; GDSs inside a small building, not subject to rain and wind.

Considering the influences of deforming and aging of soft parts on their useful lifetime (described in Appendices C and E), the first two differences will influence the useful lifetime more than the last three differences. This could explain the larger number or regulator failures on lower ages in Section 2.5 (results for GDS regulator soft parts), compared to the results for HTL blockage station regulator soft parts in Figure 23. The expected lifetime of soft parts in GDS regulators is lower than the expected lifetime of HTL blockage regulators.

The research described in this Appendix corresponds with the conclusion of Section 2.5 that the detected increase in failures of pressure control components in GDSs for ages of 17 until 23 will probably continue for higher ages. This can be concluded based on the detected increase in failures after 17 years for GDS regulators (see Section 2.5), the detected increase in failures of HTL blockage regulators' soft parts for ages of 28 and higher, and the described similarities and differences between the GDS regulators and the HTL blockage regulators.

Appendix O: Determination of failure costs of a transport break

Due to confidentiality issues, exact costs and numbers, used during the determination of failure costs of a transport break, are changed into letters.

Based on expert opinions and data of the Risk management department, the following list of conclusions can be made of the failure costs per transport break:

- The 1.000 GDSs contain *a* Industrial GDSs and *b* RNC GDSs.
- Almost all Industrial GDSs are standalone;
- The *b* RNC GDSs contain *c* standalone GDSs and *d* non-standalone GDSs.
- The *d* non-standalone RNC GDSs can be considered standalone in the period with low gas demand. This period is equal to *e* year per year. (Exact ratio is left in this public version due to confidentiality issues);
- Therefore, on average *f* of the GDS delivery failures are on standalone GDSs, with *f* equal to *(a+c)/(a+c+d*e)*
- The stand-alone RNC GDSs are on average smaller in terms of connected parties. Exact numbers are deleted from this public version, because of confidentiality issues;
- Using the compensation costs per household, commercial and industry, and the number of these parties connected per standalone GDS and non-standalone GDS, the average compensation costs are around *g* SC for standalone RNC GDSs and *h* SC for non-standalone RNC GDSs.
- Weighted average of failure costs per transport break are therefore *f***g* SC + (1-*f*)* *h* SC = 195,17 SC.

These conclusions are based on the following numbers:

- Data of connected households, commercials and industries per GDS, given by the Risk management department
- The same numbers for average demand in m3/h per connected commercial or industry are used as Gasunies Risk management department uses. These numbers are used to calculate the number of connected commercials and industries per GDS. Gasunie only gets the total gas flow per year per group; the ratios for average demand in m^3/h are used by the Gasunie Risk management department to estimate the number of connections by commercials and industries per GDS.
- The compensation costs for the first eight hours as given in Section 2.4. These are used to calculate the costs per group of GDSs (standalone versus non-standalone) by multiplying the numbers of connected households, commercials and industries by the compensation costs per type of connected party.
- The costs per transport break per GDS in the installed base of Gasunie are maximized by the maximum compensation costs Gasunie pays to the RNCs.

Appendix P: Process flow diagram of main steps in model

Figure 24 shows the main steps of the model in a flow chart. Note that in step 1, the variable *Year* is set on the first year of simulation, and the variable *GDS* is set on 1 (in the VBA program, longer names are used; as can be found in Section 4.6 and Appendix S).

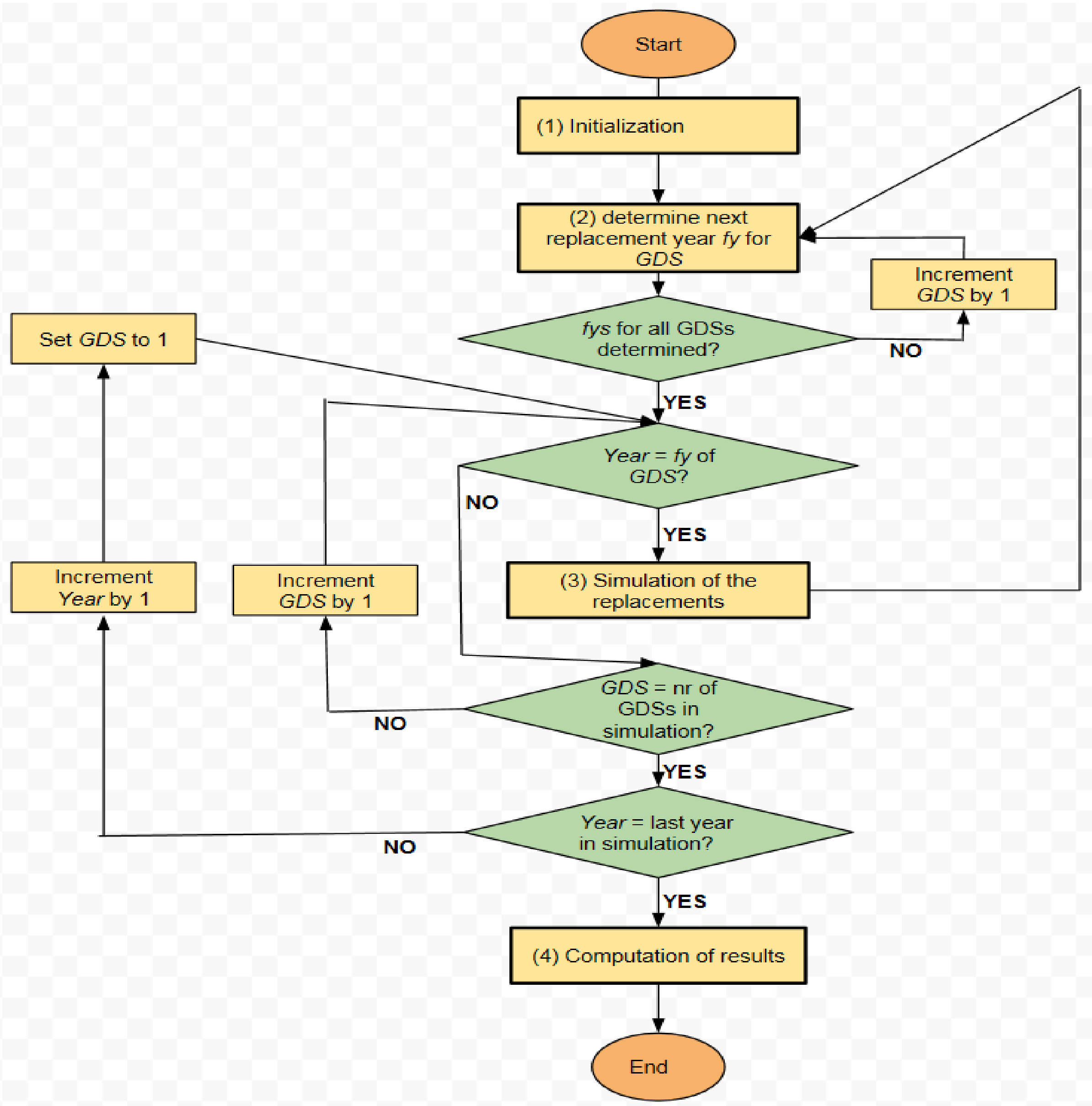

Figure 24: Flow chart of the main steps in the simulation model

Next to these steps, the VBA program shows explanatory texts on the Excel sheets during step 1 and shows the results per year and per discrete event simulation on the Excel sheets during step 4. More information about the described steps is in Appendix S.

Appendix Q: Convergence criteria and required number of replications per simulation

This appendix gives the convergence criteria that are used to determine the number of replications required per simulation to find sufficiently converged results, and the number of replications that followed from these calculations. Two analyses with respect to convergence of means are performed:

- Analyses on the convergence of the simulation model as used to select the optimal age thresholds. This model is used in Sections 5.3 and 6.1. In these sections, the simulation model was changed to focus on costs related to soft parts of regulators and monitors only. Only costs for replacements and failures of soft parts of regulators and monitors were taken into consideration, and it was assumed that there were no supply disruptions of these soft parts. The motivation behind this decision is explained in Section 5.2. Changes in code are explained in Sections 5.3 and 6.1, and Appendix I.
- Analyses on the convergence of the standard model as described in Chapter 4. This model is used to measure the effects of implementation per age configurations in the Gasunie case. This model is used for Sections 5.4, parts of the analyses in Section 6.1, and Sections 6.2 and 6.3. In these simulations, all costs are taken into consideration: failure and replacement costs of soft parts of components, and failure and replacement costs of hard parts and encapsulations of components as well. Also, the estimated permanent supply disruption levels were taken into consideration. Because of the larger costs of replacements of hard parts and complete components, the total costs are much higher. Also, these costs result in larger standard deviations and therefore higher numbers of required replications to find sufficiently converged results.

Simulation model as used for selection of the optimal age configurations

Before running the simulation model to perform the analyses as described in Chapters 5.3 and 6.1, the required number of replications per simulation is determined. To determine the required number of replications, four configurations were simulated 12.000 times. For each of the four configurations and for each of the 12.000 replications, the moving average of the replications was compared with the average over 12.000 replications. The following can be concluded:

- From the 2.958th run up to and including the 12.000th run, none of the four moving averages is outside the interval (average-0,5 SC, average+0,5 SC).
- From the 5.358th run up to and including the 12.000th run, none of the four moving averages is outside the interval (average-0,33 SC, average+0,33 SC).
- From the 7.882th run up to and including the 12.000th run, none of the four moving averages is outside the interval (average-0,17 SC, average+0,17 SC).
- From the 9.380th run up to and including the 12.000th run, none of the four moving averages is outside the interval (average-0,07 SC, average+0,07 SC).

A number of replications per configuration of 3.000 is chosen, based on the results mentioned above and the assumption that 0,5 SC per year are not very high costs for Gasunie.

Simulation model as used for Sections 5.4, 6.2, 6.3

Before running the simulation model to perform the analyses as described in Chapters 5.3 and 6.1, the required number of replications per simulation is determined. To determine the required number of replications, four configurations were simulated 20.000 times. For each of the four configurations and for each of the 20.000 replications, the moving average of the replications was compared with the average over 20.000 replications. The following can be concluded:

- From the 10.048th run up to and including the 20.000th run, none of the four moving averages is outside the interval (average-3,3 SC, average+3,3 SC).
- From the 11.380th run up to and including the 20.000th run, none of the four moving averages is outside the interval (average-2,67 SC, average+2,67 SC).
- From the 12.991th run up to and including the 20.000th run, none of the four moving averages is outside the interval (average-2 SC, average+2 SC).
- From the 14.804th run up to and including the 20.000th run, none of the four moving averages is outside the interval (average-1,33 SC, average+1,33 SC).

A number of replications per configuration of 15.000 is chosen, based on the results mentioned above and the assumption that 1,33 SC per year are not very high costs for Gasunie.

Appendix R: Difference in costs between a single opportunistic replacement of a complete regulator and a single corrective replacement of a complete regulator

This appendix explains the use of 7,37 SC as difference in costs between a single opportunistic replacement of a complete regulator and a single corrective replacement of a complete regulator. This amount of costs difference is used in Section 6.3.

The mentioned costs difference is based on the following differences:

- 0,255 of the corrective regulator replacements require emergency installations → costs savings by opportunistic replacement = 0,255 * 14,67 SC = 3,74 SC.
- Failure costs are prevented. Failure can be estimated to be 0,215 SC per failure (see Chapter 5 and Appendix G).
- The costs of the first visit after a failure is not required anymore. These are 0,10 SC for regulators (see Chapter 5 and Appendix G).
- Opportunistically replacing a complete regulator saves around 3,33 SC of design and management costs compared with another corrective replacement next to the replacement of the failed (other) component that lead to the opportunity.

The replacement costs of a corrective replacement of a regulator are 23,90 SC (see Chapter 5 and Appendix G).

In Section 6.3, various levels of costs differences are used in sensitivity analyses: the explained amount of 7,37 SC, and a number of amounts close to this amount.

Appendix S: Details of steps in simulation model

This appendix gives the details of steps used in the simulation model. The outline of these steps is already given in Section 4.6.The explanation consists of 5 steps: four steps which are equal to the four steps as given in Sections 4.3 and 4.6, and a part "other required codes" that explains parts belonging to more than one of the four steps simultaneously.

Step 1: Initialization

In the VBA program, three classes are defined: GDSs, Streets and Components. Each GDS contains a number of objects from the class Streets, and each Street contains ten objects from the class Components. The model uses 50 GDSs as sample of the total installed base of 1.000 GDSs. Each GDS consists of a number of streets between two and five. The frequencies of numbers of streets per GDS are based on the frequencies of numbers of streets per GDS in the total installed base. The properties per class are the following (explanations will follow after this list):

- GDSs:
  - Name
  - Number of streets
- Streets, with properties:
  - RMS
  - Duration until next replacement
  - Year of last replacement at street
  - Year of earliest replacement at street
  - <u>*Component (as member of class Components)*</u>
- Components, with properties:
  - Type of component
  - Failure rate category
  - Last replacement of component (starts at 1994)
  - Remaining lifetime of component
  - Permanent supply disruptions

1. Declare Replacements Array

The array that contains the numbers of replacements per year *o*, per scenario *p*, and per sub system *q*, is reset at 0 for each possible combination of *o, p, and q.*

2. Define GDSs, Streets and Components

- The Classes are called as described above. For each GDS *i* (i between 1 and 50) the name of GDS *i* is "GDS *i"*. The same method is used for assigning the number of the *Streets* per *GDS* and the component type *k* of Components*.* For each of the 10 component types *k,* one component is assigned to each Street*;*
- The property *number of streets* per GDS get a value by using random number variates, based on the numbers of streets per GDSs as in the real life case;
- A number of Streets get a Boolean value "True" for the property *RMS* using random number variates, based on the number of RMS streets in the real life case;
- *Year of last replacement* starts at 1994 for each Street;

- The following properties of *streets* are determined in Step 2: *Duration until next replacement* and *Year of earliest replacement at street*;
- *Failure rate category* per Component is equal to its *component type k*;
- *Last replacement of component* starts at 1994 for each component;
- *Remaining lifetime of component* is assigned in substep "Step 1→Randomize remaining lifetime of component";
- *Permanent supply disruption of component* is assigned in the substep "Step 1→Define Permanent Supply Disruptions".

3. **Randomize remaining lifetime of component**

To generate a random lifetime per component based on the failure rates per age of the component, two steps are performed. First, a random number between 0 and 1 is generated. Then, the *remaining lifetime* of component is calculated using the inverse transformation method:

(1) *Remaining lifetime of component = min i: F(i) ≥ random number*

with *F(i)* as the cumulative failure rate of the specific component type for age *i*. After each replacement in the simulation, the value of the remaining lifetime will be updated, as is explained later.

4. Define Permanent Supply Disruptions

The property *permanent supply disruption* per Component per Street per *GDS* is assigned based on random number variates using the permanent supply disruption level per component type.

5. Define Inventory Levels

The inventory levels are used as input for the simulation. These inventory levels are used for the formula that calculates the probability of available inventory, as described in Section 4.6.

6. Determine Configurations

The property *RMS* per Street per GDS is assigned based on random number variates using the number of RMS streets in the total installed base of Gasunie. If a street is an RSS street, the following is changed:

- Property *RMS* of object Street gets a value "False".
- All monitor components (component type 4, 5 and 6) get a value for property *remaining lifetime per component* of 250 years and a value "True" for property *permanent supply disruption.* With this implementations, the component (parts) cannot be replaced either correctively anymore, because the *remaining lifetime* is too large. By changing the value for *permanent supply disruption* into "True", no preventive or opportunistic replacements are performed anymore, because one of the conditions is that there is no permanent supply disruption (see Step 3).
- Component type 10 ("Other Components") get a new, higher rate category: this is done because another safety shut valve is added to the "Other Components". The safety shut valve replaced the monitor (see Section 2.1). The implementation in the code is that the property *failure rate category* of the Component with Component type 10, gets a value of 12

for *failure rate category.* Input for this failure rate category is the failure rate of failure rate category 10 + the failure rate of an extra safety shut valve. Further explanation and data of these failure rates are given in Appendix K.

Step 2: Determination of the next year of replacement of the street

Determine duration until next replacement at Street

The *duration until next replacement* at a Street is either the minimum *remaining lifetime per component* in the Street, or the time until the first PM activity is done on regulator or monitor soft parts. As is explained in the subsection 'PM of component', conditions for PM are amongst others that it can only be performed when there are no permanent supply disruptions of the soft parts and the year of PM is 2018 or later.

(1) *Duration until next replacement = min (max (2018, last replacement of component c + PMAge of component c : c ∈ {1 ,4}, d(c) ∈ {false}); RLT (c) : c ∈ [1..10])*

with *d(c)* as the *permanent supply disruption* of component with type of component *c*, *RLT(c)* as *remaining lifetime of component* with type of component *c*.

Determine the year of *earliest replacement at Street*

The year of the *next replacement* at a Street is equal to the *year of the last replacement at Street* of that Street plus the *duration until the next replacement* at that Street.

(2) *Earliest replacement at Street = Year of last replacement at Street + Duration until next replacement*

Step 3a: Determination of replacement scenarios

Apply PM at component(s)

PM of regulator soft parts can be performed in a particular year when:

- the age of the soft parts is higher than the threshold age for PM;
- the year of PM is 2018 or later;
- the required soft parts do not suffer permanent supply disruptions;
- the remaining lifetime during the year of PM of the soft parts must be more than 1 year;
- the remaining lifetime of the hard parts and complete component is more than 1 year: if remaining lifetime of the hard parts or complete component is less than 1 year, it can be assumed that PM is cancelled because the condition of hard parts or complete component already shows that replacement of the complete component is necessary on short term.

(3) *(Earliest Replacement at Street – Last replacement at Component(c) >= PMAge(c) ∧ Earliest Replacement at Street >= 2018 ∧ d(c) ∈ {false} ∧ RLT(c) > Duration until next replacement at Street ∧ RLT(c+1)>= Earliest Replacement at Street ∧ RLT (c+2) >= Earliest Replacement at Street) : c ∈ {1,4}*
→ Nr of Replacements (Earliest Replacement at Street, PM soft parts, subsystem) = Nr of Replacements (Earliest Replacement at Street, PM soft parts, subsystem) + 1

with *d(c)* as *permanent supply disruption* of component with type of component *c*; *Number of Replacements (Earliest Replacement at Street, PM soft parts, subsystem)* as number of replacements in year of *Earliest Replacement at Street*, of scenario 'PM soft parts' for *subsystem* that contains the component with component type *c*; *RLT(c)* as *remaining lifetime of component* with component type *c*; *subsystem* as one of the four subsystems regulator (component types 1/3), monitor (component types 4/6), aid and pilot pressure regulator (component type 7/9(and 'other components' (component type 10).

No PM is performed when one of the conditions does not hold.

Apply OM at component(s)
Conditions for PM do hold for OM, with the exception that for OM the age of the soft parts must be higher than the threshold age for OM instead of the threshold age for PM. An extra condition is that OM is not done when PM is already planned in that year, so year of last replacement of the component with type of component *c* may not be equal to year of *earliest replacement at street*.

(4) *(Earliest Replacement at Street – Last replacement at Component(c) >= OMAge(c) ∧ Earliest Replacement at Street >= 2018 ∧ d(c) ∈{false} ∧ RLT(c) > Duration until next replacement at Street ∧ RLT(c+1)>= Earliest Replacement at Street ∧ RLT (c+2) >= Earliest Replacement at Street ∧ Earliest Replacement at Street ≠ Last replacement at Component (c)): c ∈ {1,4}*
→ Nr of Replacements (Earliest Replacement at Street, PM soft parts, subsystem) = Nr of Replacements (Earliest Replacement at Street, OM soft parts, subsystem) + 1

with *d(c)* as *permanent supply disruption* of component with type of component *c*; *Number of Replacements (Earliest Replacement at Street, PM soft parts, subsystem)* as number of replacements in year of *Earliest Replacement at Street*, of scenario 'OM soft parts' for *subsystem* that contains the component with type of component c; *RLT(c)* as *remaining lifetime of component* with type of component *c; subsystem* as one of the four subsystems regulator, monitor, aid and pilot pressure regulator and 'other components'.

No OM is performed when one of the conditions does not hold.

Apply corrective replacements of soft parts (components 1,4 and 7)
A replacement occurs for a component in the *year of the next replacement at the Street* if it holds that the *remaining lifetime of the component* is equal to the *duration until the next replacement at the Street.* These properties are explained in formulas 3 and 4. The conditions for a scenario 1 replacement of soft parts of pressure control components (component numbers 1, 4 and 7) are:

- no PM or OM is already performed in the year of next replacement, so year of *last replacement of component* with type *c* may not be equal to year of *earliest replacement at street*
- as for PM of soft parts, the remaining lifetime of component *c* must be lower than the remaining lifetimes of component *c + 1* and *c+2*.
- there must be available inventory to perform the regular replacement of soft parts. Note that available inventory means that either supply is not disrupted, or (hidden) inventory is available.

If only the first two conditions hold, the replacement of soft parts is impossible and the replacement of a complete component is required. Then, the *remaining lifetime of component c + 2* is set equal to the *duration until the next replacement*.

(5) ((*RLT(c) = Duration until next replacement ∧ Last Replacement of c ≠ Earliest Replacement at Street ∧ RLT(c) < RLT(c +1) ∧ RLT( )c < RLT(c +2) ∧ b(c) ∈{true}) : c ∈ {1, 4, 7}*
→ Nr of Replacements (Earliest Replacement at Street, scen1, subsystem) = Nr of Replacements (Earliest Replacement at Street, scen1, subsystem) + 1)
∧
((RLT(c) = Duration until next replacement ∧ Last Replacement of c ≠ Earliest Replacement at Street ∧ RLT(c) < RLT(c+1) ∧ RLT( )c < RLT(c +2) ∧ b(c) ∈{false}) : c ∈ {1, 4, 7} → RLT(c+2) = Duration until next replacement)

with *b(c)* as inventory availability of component with type of component *c*.

Apply corrective replacements of hard parts (components 2,5 and 8)
The conditions for a scenario 5 replacement of hard parts of pressure control components (component numbers 2, 5 and 8) are:

- the remaining lifetime of component *c* must be lower than the remaining lifetimes of component *c +1*: it can be assumed that the regular replacement of hard parts is cancelled when the condition of complete component already shows that the replacement of the complete component is necessary on short term.
- there must be available inventory to perform the regular replacement of hard parts. Note that available inventory means that either supply is not disrupted, or (undocumented) inventory is available, and that both hard parts and soft parts are required.

If only the first condition holds, the replacement of hard parts is impossible and the replacement of a complete component is required. Then, the remaining lifetime of component *c + 1* is set equal to the duration until the next replacement.

(6) ((*RLT(c) = Duration until next replacement ∧ RLT(c) < RLT(c +1) ∧ b(c) ∈{true} ∧ b(c-1) ∈ {true}) : c ∈ {2, 5, 8}*
→ Nr of Replacements (Earliest Replacement at Street, scen5, subsystem) = Nr of Replacements (Earliest Replacement at Street, scen5, subsystem) + 1)
∧
((RLT(c) = Duration until next replacement ∧ RLT(c) < RLT(c+1) ∧ b(c) ∈{false} V b(c-1) ∈ {false} : c ∈ {2, 5, 8}) → RLT(c+1) = Duration until next replacement)

Apply corrective replacements of complete pressure control components (components 3,6 and 9)
A replacement occurs for a component in the *year of the next replacement at the Street* if it holds that the *remaining lifetime of the component* is equal to the *duration until the next replacement at the Street*. Note that the *remaining lifetime* can also be set at the *duration until next replacement* because of a failure of soft parts or hard parts (see (5) and (6)). For a complete component (component numbers 3, 6 and 9), there must be inventory available to perform the replacement of

the complete component in scenario 2. If this condition does not hold, a scenario 3 replacement occurs.

(7) *((RLT c = Duration until next replacement ∧ b(c) ∈{true}) : c ∈ {3,6,9} → Nr of Replacements (Earliest Replacement at Street, scen2, subsystem) = Nr of Replacements (Earliest Replacement at Street, scen2, subsystem) + 1)*
∧
((RLT c = Duration until next replacement ∧ b(c) ∈{false}) : c ∈ {3,6,9} → Nr of Replacements (Earliest Replacement at Street, scen3, subsystem) = Nr of Replacements (Earliest Replacement at Street, scen3, subsystem) + 1)

An exception is the replacement of aid and pilot pressure regulators: these are always in scenario 2. Also, there can be a special case when a complete monitor is replaced. All monitors that cannot be replaced by a similar monitor, are replaced by a safety shut valve (see Section 2.1). This occurs if there are both permanent supply disruptions of this monitor and there is no monitor available with exactly the same sizes (so, if there is no inventory available). Then, the adjustments to the Street are done according to the implementations given in “Step 1→ Determine Configurations”.

Apply corrective replacement of ‘other components´ (component 10)
A replacement occurs for a component in the year of the next replacement at the GDS if it holds that the remaining lifetime of the component is equal to the *duration until the next replacement at the Street* (compare formulas 3 and 4). Replacements of this component type always occur in scenario 3.

Step 3b: Resetting the lifetimes and inventory levels after replacements

Reset the remaining lifetime of non-replaced components
If a replacement at one of the components in the Street, but no replacement occurred of component with component type *c*, the *remaining lifetime* of that component is decreased by the *duration until the next replacement* (the time between the replacement in that year and the last replacement before that year).

(8) *RLT(c) = RLT(c) - Duration until next replacement*

Assign a new remaining lifetime to the new components (via step 2)
All replaced components get a new *remaining lifetime* via random number generation using their *failure rate categories*. Note that all replaced component types get a new remaining lifetime: e.g. when a complete component is replaced, both the complete component and its hard and soft parts get new lifetimes. The new randomized lifetimes are calculated via “Step 1 → Randomize remaining lifetimes”.

A special scenario is the replacement in Scenario 1 of component type 1: these regulator soft parts get a new *remaining lifetime* based on failure category 11, which is the “second failure rate” of regulator soft parts. This is further explained in “Other required code parts → Second failure rate of regulator soft parts”.

Reset the properties of the Street with respect to *last replacement at Street*

After all replacements are determined, the *year of the last replacement* at the Street is set equal to the year of the *earliest replacement at Street*.

Reset the permanent supply disruption property per component type

All components that are replaced without using the (undocumented) inventory of the previous, failed component, get "False" as *permanent supply disruption* property. Note that this means as well that when a new and non-disrupted complete component is used, also the soft and hard parts get "False" as *permanent supply disruption* property.

Reset the inventory levels after replacements

In case the (undocumented) inventory levels are used for a replacement, (which cannot be the case when there are no permanent supply disruptions, see step 1), the (undocumented) inventory level has to be updated:

(9) InventoryLevel(c) = Max(InventoryLevel(c) - 1, 0)

Note that this formula is used as well for *c-1* (soft parts) when *c* is a hard part, due to structural dependencies.

Step 4a: Compute the scores per year

Calculate number of replacements per replacement scenario per year

For the corrective replacement scenarios 1 (soft parts), 2 (complete components, no pipes), 3 (complete components, plus pipes), scenario 5 (hard parts and soft parts), and the "OM" and "PM" replacements of soft parts, the frequencies per year are counted during the simulation. These frequencies are multiplied by 20, because the sample of 50 GDSs is $1/20^{th}$ of the real life installed base. The frequency of scenario 4 (emergency installation required) is calculated by multiplying the number of scenario 3 replacements by the probability of scenario 4 given scenario 3. Note that only for regulators and monitors, scenario 4 occurs, because aid and pilot pressure regulators are always replaced in scenario 2.

Calculate expected number of gas leaks in pressure control components:

The expected number of gas leaks in pressure control components is equal to the number of failures per component type and the ratio of the failures that result in gas leaks to the total number of failures per component. The latter ratios can be found in Section 2.7.

$$(10)\ \textit{Expected number of gas leaks per year} = \sum_{subsystem=1}^{subsystem=3}(CMsubsystem\ *\ FEgasleak, subsystem)$$

with *CMsubsystem* as number of corrective replacements for *subsystem* (regulator(1), monitor(2) and aid and pilot pressure regulator(3)); their number of corrective replacements contains scenario 1, scenario 2, scenario 3 and scenario 5 replacements. $FEgasleak, subsystem$ is the ratio of failures with failure effect *gas leak* to the total number of failures for a certain *subsystem.*

Calculate expected number of street delivery failures

The expected number of street delivery failures caused by regulators is equal to the total number of regulator failures multiplied by the ratio of the regulator failures that result in failure effect ´regulator unavailable' to the total number of regulator failures, multiplied by the ratio of streets that do not contain a monitor. When a monitor exists, the monitor takes over the regulating function of the regulator, thereby preventing a street delivery failure. Next to the street delivery failures caused by regulators, there is a constant number of street delivery failures caused by other components (for explanation, see Section 2.7).

(11) Expected number of street delivery failures = $(CMreg \, * \, FEreg.unavailable, reg \, * \, (STREETS - MON)/STREETS)$ *+ number of street delivery failures caused by other failures*

with $CMreg$ as number of corrective replacements of sub system *regulators*; $FEreg.unavailable, reg$ as the ratio of failures with failure effect '*regulator unavailable'* to the total number of failures for regulators (ratios can be found in Section 2.7); *STREETS* as total number of streets in the installed base; and *MON* as number of monitors in the installed base.

Calculate expected number of GDS delivery failures

The expected number of GDS delivery failures is equal to the expected number of street delivery failures multiplied by the probability of a GDS delivery failure given a street delivery failure.

*(12)Expected number of GDS delivery failures = Expected number of street delivery failures * P(GDS delivery failure | street delivery failure)*

Calculate expected number of transport breaks

The expected number of standalone GDS delivery failures is equal to the expected number of GDS delivery failures multiplied by the ratio of standalone GDSs to the total number of GDSs. The number of non-standalone GDS delivery failures is equal to the total number of GDS delivery failures minus the number of standalone GDS delivery failures. Probability of a transport break after failure of a standalone GDS is 1. Expected number of transport breaks due to failure of non-standalone GDS delivery failures is equal to the number of non-standalone GDS delivery failures multiplied by the probability of a transport break after failure of a non-standalone GDS.

*(13)Expected number of transport breaks = Expected number of GDS delivery failures * #standalone GDSs /# GDSs + Expected number of non-standalone GDS delivery failures * (P transport break| failure non-standalone GDS)*

Calculate total failure costs

Total failure costs are the failure costs of a gas leak multiplied by the expected number of gas leaks in pressure control components plus the failure costs of a transport break multiplied by the expected number of transport breaks.

*(14)Total failure costs = Exp. number of Gas leaks ** $FCgasleak$ *+ Exp. number of transport breaks ** $FCtransportbreak$

Calculate total replacement costs

Total replacement costs are equal to the sum for all components *c* for all replacement scenarios *s,* of the number of replacements per component *c* in replacement scenario *s* multiplied by the replacement costs per replacement of component *c* in replacement scenario *s*.

$$(15) \text{Total replacement costs} = \sum_{c,s} (Replacements(c,s) * Replacement\ costs(c,s))$$

with *Replacements(c,s)* as number of replacements of component *c* in scenario *s*.

Calculate total costs

The total costs are the sum of the total failure costs and the total replacement costs.

Step 4b: Compute results of Discrete Event Simulation

In this step, the most important average results per year per discrete event simulation run are shown for the years 2018/2065. These results are the expected number of street delivery failures, the average expected failure costs due to gas leaks, the average expected failure costs due to GDS delivery failures, the average expected total replacement costs and the average expected total costs.

Other required code parts

Check inventory level

Inventory level is checked when a replacement is done after 2017. If there are no permanent supply disruptions for the required component type, then the inventory is available. Otherwise, the following formula is used:

*P(AvailableInventory;t) = LB(c) + (UB(c) - LB(c)) * (InventoryLevel(c;t) / InitialInventoryLevel(c)*

with *LB(c)* as the probability that a replacement of component type *c* can be done by creative solutions by technicians when no (undocumented) inventory is left anymore, such as buying these parts at other gas transport companies; *UB(c)* as the probability that a replacement of component type *c* can be done with creative solutions or the left (undocumented) inventory at the start of 2018; *InventoryLevel(c;t)* as the inventory level at time *t* of component type *c; and InitialInventoryLevel(c)*as the inventory level of component type *c* at the start of 2018.

By using this formula and random number generation is determined whether there is inventory available for the particular replacement.

If there is inventory available, the inventory is used and the inventory level decreases by 1.

Second failure rate of regulator soft parts

In order to represent the failure rate after the first failure of regulator soft parts (See Section 2.5), the latter failure rate is used as *failure category 11.* If a regulator soft part is replaced correctively in replacement scenario 1, then the soft parts get a new *remaining lifetime* by using the mentioned failure rate. This is done via random number variates in Step 1 → randomize remaining lifetime of component.

Appendix T: More details about results of simulations

This appendix shows more details about the simulation results of Chapters 5 and 6. Explanations are added for each table.

Chapter 5 results

Simulation results of Section 5.3: experiments with the age configurations that seem to be close to optimum

In Table 29, the total costs per year related to regulator soft parts and monitor soft parts are given per age configuration, as well as the total costs per year related to regulator or monitor soft parts.

T1 (OM reg.)	T2 (PM reg.)	T3 (OM mon.)	T4 (PM mon.)	TC/year related to regulator soft parts (SC)	TC/year related to monitor soft parts (SC)	TC/year related to reg. &mon. soft parts (SC)
25	37	68	73	125,00	12,16	137,15
25	35	68	73	125,22	12,05	137,27
23	37	68	73	125,25	12,03	137,28
27	35	68	73	125,32	12,01	137,33
23	39	62	73	125,02	12,37	137,39
27	37	62	73	125,02	12,41	137,43
25	37	65	73	125,14	12,30	137,44
23	37	62	73	125,21	12,30	137,50
25	35	62	73	125,14	12,40	137,54
23	35	68	73	125,51	12,03	137,54
27	37	68	73	125,39	12,18	137,58
23	35	65	73	125,29	12,30	137,58
25	35	65	73	125,20	12,39	137,59
27	37	65	73	125,39	12,22	137,61
25	37	62	73	125,24	12,38	137,62

Table 29: Simulation results of Section 5.3: experiments with the age configurations that seem to be close to optimum

Simulation results of Section 5.3: experiments with the age configurations that seem to be close to optimum, for various levels of age threshold for opportunistic replacement of monitor soft parts.

In Table 30, the total costs per year related to soft parts of monitors is given for the optimal age thresholds for T1, T2 and T4, and various values of T3. This analyses was performed in order to be sure that the value of 73 for T3 was the optimal value. This is explained in Section 5.3.

T1(OM reg.)	T2(PM reg.)	T3 (OM mon.)	T4(PM mon.)	TC/year related to monitor soft parts (SC)
25	37	40	73	13,65
25	37	45	73	13,25
25	37	50	73	13,00
25	37	55	73	12,69
25	37	69	73	12,10
25	37	71	73	11,98
25	37	73	73	11,87

Table 30: Simulation results of Section 5.3: experiments with the age configurations that seem to be close to optimum, for various levels of age threshold for opportunistic replacement of soft parts of monitors

Simulation results of Section 5.3: experiments with the age configurations that seem to be close to optimum, based on costs related to regulators

Table 31 shows the total cost per year related to soft parts of regulators, for various levels of T1 and T2.

T1(OM reg.)	T2(PM reg.)	T3 (OM mon.)	T4(PM mon.)	TC/year related to regulator soft parts (SC)
25	37	73	73	125,00
27	37	73	73	125,02
23	39	73	73	125,02
25	35	73	73	125,14
23	35	73	73	125,20
23	37	73	73	125,21
27	35	73	73	125,32
25	39	73	73	125,38
27	39	73	73	125,57

Table 31: Simulation results of Section 5.3: experiments with the age configurations that seem to be close to optimum, based on costs related to soft parts of regulators

Simulations results of Section 5.4: effects of using the optimal age configurations in the Gasunie case

Table 32 shows the total number of replacement per replacement scenario for regulators per year, for various age configurations.

Age Configuration	Regulator						
	CM soft parts	OM Soft parts	PM Soft parts	Hard +soft parts	Compl. Comp., no pipes	Compl. Comp. + pipes	Compl. Comp. + pipes + EGDS
25-37-73-73	71.81	6.00	0.61	13.94	26.74	29.49	7.49
27-37-73-73	71.82	4.21	1.71	13.93	26.75	29.49	7.49
23-39-73-73	71.50	8.45	0.01	13.89	26.71	29.48	7.49
25-35-73-73	71.47	5.86	1.51	13.96	26.73	29.49	7.49
23-35-73-73	71.12	8.38	0.51	13.93	26.69	29.46	7.48
43-43-73-73	75.32	0.00	0.00	13.95	26.73	29.47	7.49

Table 32: Simulations results of Section 5.4: effects of using the optimal age configurations in the Gasunie case (regulators)

Table 33 shows the total number of replacement per replacement scenario for monitors per year, for various age configurations.

Age Configuration	CM soft parts						
	CM soft parts	OM Soft parts	PM Soft parts	Hard +soft parts	Compl. Comp., no pipes	Compl. Comp. + pipes	Compl. Comp. + pipes + EGDS
25-37-73-73	7.12	0.00	0.00	3.18	3.95	3.90	0.99
27-37-73-73	7.12	0.00	0.00	3.17	3.95	3.91	0.99
23-39-73-73	7.12	0.00	0.00	3.16	3.94	3.91	0.99
25-35-73-73	7.12	0.00	0.00	3.18	3.97	3.92	1.00
23-35-73-73	7.12	0.00	0.00	3.17	3.95	3.94	1.00

43-43-73-73	7.12	0.00	0.00	3.21	3.97	3.94	1.00

Table 33: Simulations results of Section 5.4: effects of using the optimal age configurations in the Gasunie case (monitors)

Table 34 shows the total number of replacement per replacement scenario for aid and pilot pressure regulators per year, for various age configurations. Also, it shows the total costs per component type (regulator, monitor and aid and pilot pressure regulator) for all replacement scenarios together, and for costs related to soft parts only.

Age Configura-tion	Aid and pilot pressure regulator			Total costs (SC) related to regulator		Total costs (SC) related to monitor		Total costs (SC) related to aid & pilot press. regulator	
	Soft parts	Hard + soft parts	Compl. Comp, no pipes	Soft parts	Total	Soft parts	Total	Soft parts	Total
25-37-73-73	16.14	13.32	67.72	98,22	1280,16	8,04	169,56	11,56	316,49
27-37-73-73	16.13	13.31	67.44	98,28	1280,29	8,04	169,99	11,55	315,28
23-39-73-73	16.17	13.30	67.50	98,52	1279,67	8,04	169,90	11,58	315,53
25-35-73-73	16.22	13.35	67.58	98,47	1280,44	8,04	170,37	11,62	315,97
23-35-73-73	16.09	13.31	67.49	98,41	1278,89	8,04	170,86	11,53	315,47
43-43-73-73	16.16	13.30	67.53	99,33	1280,69	8,04	171,14	11,58	315,65

Table 34: Simulations results of Section 5.4: effects of using the optimal age configurations in the Gasunie case (aid and pilot pressure regulators)

In Section 5.4, per age configuration is shown the resulting gas leaks, street delivery failures, station delivery failures, transport breaks, failure costs, replacement costs, and total costs per year.

Chapter 6 results

Simulations results of Section 6.1: Number of corrective, opportunistic and preventive replacements per year for each age configuration

Table 35 shows the frequency of scenario 1, OM and PM of regulators for all age configurations close to the optimal age configuration as given in Section 5.4. These frequencies are used in order to determine the optimal age configurations in Section 6.1, for various levels of regulator failure costs. Note that these results were collected using the simulation model with adjustments as described in Section 5.3. So, the frequency per scenario in Table 35 is the frequency for the case that there are no permanent supply disruptions. The costs related to regulator soft parts of using the optimal age configuration per level of regulator failure costs, are given in Table 11 of Section 6.1. In Table 11, the actual permanent supply disruption levels are used.

Age configuration	Scen 1 regulator (CM of soft parts)	OM of regulator soft parts	PM of regulator soft parts
19-35-73-73	85.477	23.612	2.347
19-36-73-73	85.469	23.561	2.150
19-37-73-73	86.321	23.688	1.024
19-38-73-73	86.387	23.824	0.912
20-35-73-73	86.051	20.982	2.487
20-36-73-73	85.828	21.094	2.270
20-37-73-73	86.868	21.154	1.032
20-38-73-73	87.132	20.920	0.938
21-36-73-73	86.658	18.687	2.311
21-37-73-73	87.666	18.909	1.046
21-38-73-73	87.506	18.901	0.962
22-36-73-73	86.977	16.898	2.350
22-37-73-73	88.146	16.966	1.077
22-38-73-73	87.843	17.019	0.981
22-39-73-73	88.765	17.071	0.025
23-37-73-73	88.657	15.534	1.137
23-38-73-73	88.225	15.472	1.034
23-39-73-73	89.216	15.444	0.025
24-37-73-73	89.043	13.717	1.195
24-38-73-73	88.992	13.827	1.060
24-39-73-73	89.798	14.094	0.026
25-37-73-73	89.787	11.267	1.284
25-38-73-73	89.973	11.383	1.243
25-39-73-73	90.911	11.409	0.031
26-37-73-73	90.357	9.795	1.411
26-38-73-73	90.640	9.777	1.254
26-39-73-73	91.724	9.939	0.034
26-40-73-73	91.739	9.892	0.015
27-37-73-73	90.859	8.602	1.479
27-38-73-73	90.889	8.635	1.337
27-39-73-73	91.977	8.761	0.035
27-40-73-73	91.907	8.839	0.021
28-38-73-73	91.427	7.467	1.390
28-39-73-73	92.612	7.565	0.037
28-40-73-73	92.652	7.609	0.018

Table 35: Simulations results of Section 6.1: Number of corrective, opportunistic and preventive replacements per year for each age configuration

Simulations results of Section 6.1: simulation results for lower failure rates

Table 36 shows the frequencies of regulator and monitor replacements in scenario 1, OM and PM, for various age configurations. Also, it shows the costs related to regulator soft parts and monitor soft parts. These are the results for simulations with the lower failure rates as described in Section 6.1. Note that these results are collected with the simulation model after the changes as described in Section 5.3, in order to focus on costs related to regulator and monitor soft parts and to select the best age configurations. Therefore, amongst others the assumption is made in this model that there are no permanent supply disruptions of soft parts. The total costs without this assumption are collected as well. These are given in Table 12 in Section 6.1. These costs show the actual potential costs savings in the Gasunie case, with the actual permanent supply disruption level.

Age configu-ration	Freq. of scen1 (CM regulator soft parts)	Freq. of OM regulator soft parts	Freq. of PM regulator soft parts	Freq. of Scen1 (CM monitor soft parts)	Costs related to regulator soft parts (SC)	Costs related to monitor soft parts (SC)
28-39-73-73	80.53	10.86	2.23	9.89	113,55	11,16
26-39-73-73	80.02	12.38	2.15	10.00	113,56	11,29
27-39-73-73	80.95	9.62	2.35	9.96	113,58	11,24
27-41-73-73	81.36	11.13	0.86	9.92	113,60	11,20
29-39-73-73	81.39	8.25	2.55	10.00	113,64	11,30
28-40-73-73	81.77	9.94	1.02	9.96	113,67	11,25
27-37-73-73	79.50	10.50	4.17	9.96	113,68	11,25
26-40-73-73	80.85	12.59	0.91	10.02	113,69	11,31
28-37-73-73	79.83	9.27	4.40	9.98	113,69	11,27
28-41-73-73	81.83	10.07	0.93	10.08	113,73	11,38
26-37-73-73	79.05	12.12	4.02	9.99	113,76	11,27
27-40-73-73	81.44	11.12	0.98	9.94	113,80	11,22
26-38-73-73	80.10	12.22	2.45	10.04	113,84	11,33
30-39-73-73	82.05	6.52	2.84	9.93	113,91	11,21
28-38-73-73	81.07	9.46	2.68	9.99	113,94	11,28

Table 36: Simulations results of Section 6.1: simulation results for lower failure rates

Simulations results of Section 6.1: simulation results for higher failure rate

Table 37 shows the frequencies of regulator and monitor replacements in scenario 1, OM and PM, for various age configurations. Also, it shows the costs related to regulator soft parts and monitor soft parts. These are the results for simulations with the higher failure rates as described in Section 6.1. Note that these results are collected with the simulation model after the changes as described in Section 5.3, in order to focus on costs related to regulator and monitor soft parts and to select the best age configurations. Therefore, amongst others the assumption is made in this model that there are no permanent supply disruptions of soft parts. The total costs without this assumption are collected as well. These are given in Table 12 in Section 6.1. These costs show the actual potential costs savings in the Gasunie case, with the actual permanent supply disruption level.

Age configu-ration	Freq. of scen1 (CM regulator soft parts)	Freq. of OM regulator soft parts	Freq. of PM regulator soft parts	Freq. of CM monitor soft parts	Freq. of OM monitor soft parts	Costs related to reg. soft parts (SC)	Costs related to mon.soft parts (SC)
24-37-73-73	85,71	14,69	2,34	10,46	0,00	122,38	11,81
25-37-48-73	86,78	11,60	2,61	9,89	4,06	122,48	13,19
26-37-53-73	87,27	10,11	2,75	10,05	3,03	122,50	12,86
26-36-63-73	87,13	9,99	3,07	10,42	1,40	122,53	12,47
24-36-53-73	85,69	14,68	2,64	10,01	3,08	122,61	12,84
27-36-68-73	87,73	8,48	3,19	10,56	0,66	122,67	12,26
25-36-58-73	86,74	11,57	2,95	10,31	2,20	122,70	12,74
27-37-58-73	87,84	8,78	2,99	10,17	2,19	122,79	12,58

23-35-58-73	85,34	16,21	2,77	10,23	2,25	123,02	12,67
26-34-58-73	85,93	9,21	6,04	10,29	2,23	123,11	12,73
25-35-68-73	87,00	11,27	3,20	10,54	0,66	123,12	12,23
26-35-68-73	87,42	9,81	3,50	10,56	0,67	123,20	12,26
24-35-63-73	86,03	14,48	2,92	10,33	1,43	123,20	12,38
27-35-73-73	88,10	8,30	3,66	10,39	0,00	123,47	11,73
28-35-48-73	88,44	7,20	3,83	9,86	4,06	123,52	13,16

Table 37: Simulations results of Section 6.1: simulation results for higher failure rate

Simulations results of Section 6.2: simulation results for decreased permanent supply disruption levels

Table 38 gives the frequencies for each replacement scenario of regulators and monitors per year, for various of supply disruption levels and inventory levels. It shows the results for the optimal age configuration 25-37-73-73 and the run-to-failure age configuration 43-43-73-73.

Supply disrupt. Level.	Age Configur-ation	Inventory level	Frequency per year per regulator replacement						
			CM soft parts	OM Soft parts	PM Soft parts	Hard +soft parts	Compl. Comp., no pipes	Compl. Comp. + pipes	Compl. Comp. + pipes + EGDS
0.65	25-37-73-73	400	71.12	5.67	0.57	13.63	28.85	28.98	7.36
0.6	25-37-73-73	400	72.37	6.09	0.63	13.66	27.96	27.82	7.07
0.5	25-37-73-73	400	75.38	6.93	0.76	13.61	26.55	25.62	6.51
0.4	25-37-73-73	400	79.49	7.68	0.86	13.61	25.26	23.49	5.97
0.65	25-37-73-73	200	71.81	6	0.61	13.94	26.74	29.49	7.49
0.6	25-37-73-73	200	74.18	6.32	0.66	13.85	25.86	28.50	7.24
0.5	25-37-73-73	200	76.99	7.07	0.77	13.81	24.63	26.56	6.75
0.4	25-37-73-73	200	78.72	7.92	0.88	13.64	23.42	24.76	6.29
0.65	25-37-73-73	20	72.77	6.27	0.64	14.06	25.05	29.96	7.61
0.6	25-37-73-73	20	74.04	6.64	0.69	13.96	24.50	29.09	7.39
0.5	25-37-73-73	20	76.84	7.39	0.79	13.46	23.37	27.57	7.00
0.4	25-37-73-73	20	79.59	8.13	0.91	12.92	22.30	26.01	6.61
0.65	43-43-73-73	400	74.32	0.00	0.00	13.59	28.57	28.97	7.36
0.6	43-43-73-73	400	75.99	0.00	0.00	13.66	28.04	27.93	7.09
0.5	43-43-73-73	400	79.46	0.00	0.00	13.62	26.65	25.76	6.54
0.4	43-43-73-73	400	82.93	0.00	0.00	13.55	25.23	23.59	5.99
0.65	43-43-73-73	200	75.32	0.00	0.00	13.95	26.73	29.47	7.49
0.6	43-43-73-73	200	76.87	0.00	0.00	13.87	26.11	28.50	7.24
0.5	43-43-73-73	200	80.15	0.00	0.00	13.80	24.74	26.64	6.77
0.4	43-43-73-73	200	83.65	0.00	0.00	13.61	23.47	24.80	6.30
0.65	43-43-73-73	20	76.57	0.00	0.00	14.12	25.19	29.94	7.61
0.6	43-43-73-73	20	78.10	0.00	0.00	13.92	24.50	29.08	7.39
0.5	43-43-73-73	20	81.41	0.00	0.00	13.43	23.27	27.49	6.98
0.4	43-43-73-73	20	84.68	0.00	0.00	12.92	22.21	25.99	6.60

Supply disrupt Level.	**Age Configur-ation**	**Inven-tory level**	**Frequency per year per monitor replacement**				
			CM soft parts	**Hard+soft parts**	**Compl. Comp**	**Compl. Comp +**	**Compl. Comp +**

						pipes	pipes + EGDS
0.65	25-37-73-73	400	7.42	3.23	4.46	2.96	0.75
0.6	25-37-73-73	400	7.72	3.35	4.35	2.80	0.71
0.5	25-37-73-73	400	8.24	3.50	4.08	2.47	0.63
0.4	25-37-73-73	400	8.56	3.54	3.76	2.05	0.52
0.65	25-37-73-73	200	7.12	3.18	3.95	3.9	0.99
0.6	25-37-73-73	200	7.20	3.17	3.81	3.48	0.88
0.5	25-37-73-73	200	7.80	3.30	3.62	3.07	0.78
0.4	25-37-73-73	200	8.60	3.43	3.42	2.75	0.70
0.65	25-37-73-73	20	6.82	3.20	2.27	5.90	1.50
0.6	25-37-73-73	20	7.12	3.21	2.21	5.70	1.45
0.5	25-37-73-73	20	7.71	3.16	2.14	5.22	1.33
0.4	25-37-73-73	20	8.24	3.12	2.02	4.78	1.21
0.65	43-43-73-73	400	7.37	3.22	4.51	3.00	0.76
0.6	43-43-73-73	400	7.75	3.32	4.33	2.82	0.72
0.5	43-43-73-73	400	8.29	3.42	4.05	2.47	0.63
0.4	43-43-73-73	400	8.75	3.55	3.76	2.14	0.54
0.65	43-43-73-73	200	7.12	3.21	3.97	3.94	1.00
0.6	43-43-73-73	200	7.44	3.24	3.83	3.64	0.93
0.5	43-43-73-73	200	7.99	3.33	3.63	3.18	0.81
0.4	43-43-73-73	200	8.58	3.42	3.41	2.77	0.70
0.65	43-43-73-73	20	6.80	3.20	2.27	5.94	1.51
0.6	43-43-73-73	20	7.06	3.24	2.24	5.78	1.47
0.5	43-43-73-73	20	7.68	3.12	2.13	5.24	1.33
0.4	43-43-73-73	20	8.29	3.13	2.04	4.85	1.23

Table 38: Simulations results of Section 6.2: simulation results for decreased permanent supply disruption levels (I)

Table 39 gives the frequencies for each replacement scenario of aid and pilot pressure regulators per year, for various of permanent supply disruption levels and inventory levels. Also, it gives the total costs related to regulators, monitors and aid and pilot pressure regulators per year. Results are shown for the optimal age configuration 25-37-73-73 and the run-to-failure age configuration 43-43-73-73.

Supply disrupt Level.	Age Configur-ation	Inven-tory level	Aid&pilot press. Reg.			Total costs (SC) related to regulators	Total costs (SC) related to monitors	Total costs (SC) related to aid and pilot press. Reg.
			CM soft parts	Hard + soft parts	Compl. Comp + pipes			
0.65	25-37-73-73	400	17.17	14.25	66.09	1291,09	150,49	311,15
0.6	25-37-73-73	400	18.41	14.71	64.31	1249,57	145,06	304,86
0.5	25-37-73-73	400	21.08	15.53	61.10.	1174,88	133,46	293,79
0.4	25-37-73-73	400	23.61	16.62	58.35	1105,24	118,19	284,86
0.65	25-37-73-73	200	16.14	13.32	67.72	1280,21	169,65	316,49
0.6	25-37-73-73	200	17.45	13.72	65.99	1244,66	156,43	310,38
0.5	25-37-73-73	200	20.08	14.26	63.47	1179,32	143,57	301,96
0.4	25-37-73-73	200	22.48	14.48	60.64	1116,43	133,27	291,75
0.65	25-37-73-73	20	15.28	11.43	69.78	1273,38	203,71	322,80
0.6	25-37-73-73	20	16.51	11.41	68.82	1244,18	197,74	319,56
0.5	25-37-73-73	20	19.12	11.57	66.47	1190,84	184,32	311,46
0.4	25-37-73-73	20	21.70	11.71	64.16	1137,10	171,18	303,51
0.65	43-43-73-73	400	17.11	14.31	66.09	1288,06	151,99	311,18
0.6	43-43-73-73	400	18.42	14.78	64.25	1254,66	145,34	304,69
0.5	43-43-73-73	400	20.88	15.59	61.09	1181,29	132,94	293,64
0.4	43-43-73-73	400	23.37	16.30	58.12	1107,20	120,92	283,39
0.65	43-43-73-73	200	16.16	13.3	67.53	1280,72	171,05	315,66
0.6	43-43-73-73	200	17.33	13.61	65.96	1247,71	161,54	310,07
0.5	43-43-73-73	200	19.92	14.17	63.26	1182,83	146,86	300,89
0.4	43-43-73-73	200	22.41	14.48	60.70	1119,71	133,77	291,93
0.65	43-43-73-73	20	15.32	11.45	70.36	1276,21	204,91	325,38
0.6	43-43-73-73	20	16.56	11.42	68.94	1245,12	200,44	320,09
0.5	43-43-73-73	20	19.16	11.66	66.65	1189,02	184,71	312,37
0.4	43-43-73-73	20	21.67	11.73	64.27	1137,21	173,44	303,99

Table 39: Simulations results of Section 6.2: simulation results for decreased permanent supply disruption levels (II)

Appendix U: Two-sample T-tests for equal means of total costs related to regulator soft parts for the age configurations in Section 5.4

Table 40 shows the results of Two-sample T-tests for equal means (in terms of total costs per year related to regulator soft parts) between the age configurations. The table gives the mean of the 15.000 replications per age configuration in the second column and the standard deviation of the total costs per replication per configuration in the third column. With these values, the T-tests are performed. The resulting T-values are shown in the fourth column. Note that the value in row *i* shows the T-value regarding the Two-sample T-test for equal means between the optimal age configuration (as shown in row 1) and the age configuration in row *i.* In the fifth column, the degrees of freedom for each test are given. See Snedecor & Cochran (1989) for more explanation of these terms.

As is explained further in Snedecor & Cochran (1989), the null hypothesis that the two means are equal can be rejected if T is larger than $t_{1\text{-}\alpha/2,v}$, with $t_{1\text{-}\alpha/2,v}$ as critical value of the t-distribution with v degrees of freedom. Using an alpha level of 0,05 and the degrees of freedom in the fifth column, the T-value needs to be 1,96 in order to reject the stated null hypothesis. This holds for all age configurations. As already is mentioned, the T-values are given in the fourth column. These show that the mean total costs for the age configurations 23-39-73-73, 25-35-73-73 and 43-43-73-73 are significantly higher than the costs of the optimal age configuration, at an alpha level of 0,05. However, for the age configurations 23-39-73-73 and 25-35-73-73 the differences are relatively small. These small differences could be explained by variation in the simulations. The T-value of age configuration 43-43-73-73 is so large, that it can be assumed that the difference cannot be explained by variation in the simulations alone.

Age configuration	Mean of total costs (SC/year) related to soft parts per age configuration	Standard deviation of total costs (SC/year) related to soft parts per age configuration	T-value for difference between optimal age configuration and the age configuration in that row	Degrees of freedom
25-37-73-73	98,22	7,13	-	-
27-37-73-73	98,28	7,04	0.634	19497.2
23-39-73-73	98,52	6,99	3.042	19245.6
25-35-73-73	98,47	6,99	2.564	19240.3
23-35-73-73	98,41	7,03	1.906	19455.1
43-43-73-73	99,33	7,10	11.022	19822.9

Table 40: Two-sample T-tests for equal means of total costs related to regulator soft parts for the age configurations in Section 5.4