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Graduation assignment IEM: Maintenance Planning at Twente Milieu.

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Preface

This thesis marks the end of my life as an Industrial Engineering and Management student at the University of Twente. During the past years I have learned more than I could ever imagine when entering the university as a freshman in 2013.

I want to thank Twente Milieu and especially Ruben de Kruijff for the opportunity and the freedom they gave me to conduct this research on maintenance management of underground bins. My gratitude also goes to my colleagues Remco, Ewald and Annika who were always there to answer my questions about Twente Milieu and underground bin management.

Secondly, I want to thank my university supervisors Engin and Ipek Topan who always managed to find time to guide me in the right direction and give me valuable feedback to continue my research.

Thirdly, I would like to express my sincere gratitude to my parents and Robin and Quirine for always making me feel more than welcome back home in Ermelo and supporting me unconditionally. Due to them every weekend I could spend in Ermelo was enjoyable and gave me the motivation to finish my studies in Enschede.

And lastly I want thank everyone who made studying in Enschede such a great pleasure. De Eetclub, Darshana and Linda for all joyful moments spent together, all my Arriba teammates during the past seasons for so many good games and practices and all other people at Arriba who made my time at Arriba unforgettable.

Dimitry Brons,
Enschede, October 2019

Management summary

The public grounds management department of Twente Milieu maintains the underground bins in Twente by correctively repairing bins that fail due to several reasons. There are two types of corrective repair, (i) first line maintenance for failures in the electronics or above the ground and (ii) second line maintenance for failures in the mechanics of the bin for which the bin has to be lifted out the pit. Besides the corrective repairs, Twente Milieu hires an external company to carry out preventive maintenance to each underground bin twice a year. Preventive maintenance contains the washing, lubrication and inspection of the underground bin on the bin site.

Twente Milieu has the desire to insource preventive maintenance. This research seeks to add a preventive maintenance policy to the current corrective maintenance policy for maintaining underground bins. The introduction of preventive maintenance gives the opportunity to employ the mechanics at Startpunt, the name of the workshop in Borne.

The introduction of preventive maintenance at Startpunt has other projected advantages over the current situation. Firstly, money that is paid to an external company is invested in their own mechanics, who are educated at the same time. Secondly, the quality of the maintenance improves since the bins are maintained in a workshop instead of on the street. Thirdly, after the outsourced preventive maintenance Twente Milieu receives an inspection report which might lead to corrective repairs. Therefore, second line mechanics need to go to the bin site and carry out the repair, which requires extra movements. The number of these movements can be decreased by carrying out preventive maintenance at Startpunt and repair all errors at the same time.

From the current situation analysis we concluded that a lot of bins are visited at least once a year for corrective repair by either the first line or the second line mechanics. A visit can be used to repair the bin correctively and simultaneously as an opportunity to carry out preventive maintenance.

By conducting a literature review on maintenance management we found out that the failure distribution is an indicator of the effectiveness of preventive maintenance. There are two failure distributions that are commonly used in maintenance management; the exponential distribution for random failures and the Weibull distribution for wear out failures. Based on the failure distribution, the optimal preventive maintenance can be determined. To incorporate decisions based on events, we decided to carry out a discrete event simulation study as well.

To differentiate between maintenance methods, we consider four policies. (i) Corrective repair at the bin site, (ii) corrective replacement of a broken bin by a repaired bin from stock, (iii) age-based preventive replacement of an active bin by a repaired bin and (iv) opportunistic maintenance when a bin breaks down. Opportunistic maintenance in this case means using the opportunity of a failure of one bin, to give preventive maintenance to another bin that is active in the neighbourhood.

The failure distribution for underground bins is determinant for an effective preventive maintenance policy. To find the failure distribution we carried out a data analysis on the failure data. By looking at the time between failures of an underground bin, we found out that there are two relevant failure distributions. The failure distribution for first line failures which is exponentially distribution and the failure distribution for second line failures which is Weibull distributed with a value of β larger than 1. For this reason we concluded that preventive maintenance will only be effective for second line mechanics, consequently we leave the first line mechanics out of the scope for this research.

The failure distribution is the main input of the cost function maintenance planning model. The cost function shows that the effectiveness of an age-based preventive maintenance policy is strongly dependent on the costs for corrective and preventive maintenance.

The next step in this research is the incorporation of costs for downtime, making decisions based on events and opportunistic maintenance. We decided to carry out a discrete event simulation study to see what gains we can get from using the ability to respond to failures according to maintenance policies.

To optimize the maintenance policy we considered three input variables; (i) the weekly capacity of Startpunt, (ii) the preventive maintenance interval and (iii) a threshold of a number of days before bins are allowed to be repaired at Startpunt. The preventive maintenance threshold in the simulation study is introduced to determine a minimum time a bin has to be on the street before it is allowed to get preventive maintenance at Startpunt again. Failures before this threshold time are repaired on bin site. The results of the simulation study are measured in total costs for the maintenance strategy, the average downtime of bins and the number of maintenance actions by second line mechanics.

The simulation study shows that a shorter preventive maintenance interval leads to lower costs and a lower downtime, but to a lot of variability in the times bins are on the street. The variability is a measure to determine the average number of days between two instances of preventive maintenance intervals at Startpunt and the variance of this average. A higher preventive maintenance threshold contributes to the higher variability as well. The higher threshold leads to bins that are allowed to go to Startpunt earlier, which increases the deviation in the average time between two preventive maintenance instances. The increased variability is a negative consequence of such a strategy.

The desire to decrease the variability leads to an investigation on using a preventive maintenance interval of 365 days instead of 240 days. The goal is to have an average time between two preventive maintenance instances at Startpunt of around 365 days with a smaller variance. Using longer preventive maintenance results in costs that are higher than in the previous scenario, but leads to lower variability in the time between two preventive maintenance instances. The main advantage of the decreased variability is that the average time on the street of all bins is about the same, which makes it easier to stick to a maintenance planning, since the preventive maintenance planning becomes less responsive to failures occurring all through the municipality.

From the results of the simulation study based on the Hengelo case, we advise Twente milieu to start insourcing preventive maintenance activities to Startpunt on the bins in the municipality Hengelo with a preventive maintenance interval of one year and apply a preventive maintenance threshold of 90 days. These settings lead to improvement regarding costs, reduction of downtime and reduction of second line maintenance actions, compared to the current situation with outsourced preventive maintenance. In the near future, this process can be started by hiring the transportation truck and figuring out the capacity of Startpunt and how many bins can be transported on one day. This information can be used to assess the possibilities to scale up this maintenance policy to the underground bins in Enschede and the rest of Twente.

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Terminology

AWRS	System that communicates about the status of underground bins. For example, about how full the bin is, which is measured by the number of bags dropped into the bin, the level of the battery and the number of times it has been opened and by who.
KCC	System used by the customer service to communicate civilian complaints about underground bins to the maintenance department.
Wincar	System to keep track of the maintenance history of the underground bins. Work orders for all activities are booked in this system.
Webfleet	System to keep track of all trucks driving around. The TomTom route planner is part of this system which is present in every Twente Milieu truck.
Diftar	Differentiated fees for customers to dispose their waste. Based on the principle: “user pays”. If one disposes more waste, he must pay more disposal fees.
BOR	Public ground management; this department of Twente Milieu is responsible for the management of all public grounds in the municipalities.
MU	Moving unit, term in simulation model for a unit that moves through the system.
KPI	Key performance indicator.
Startpunt	Name of the workshop in Borne, where working and education is combined.
BWaste	Manufacturer of underground bins, company who carries out washing and lubrication in current situation and supplier of electronics for card readers and AWRS.

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1. Introduction

In this report, we execute a research on maintenance management of the underground bins at Twente Milieu. Section 1.1 introduces the company Twente Milieu. Section 1.2 gives reasons why this research is carried out at Twente Milieu. Chapter 1.3 defines the goal of the research. Section 1.4 explains the scope of this research. Section 1.5 states the research questions.

1.1 Twente Milieu

Twente Milieu collects the waste of the citizens in eight municipalities in Twente. Besides this, Twente Milieu is responsible for managing public grounds such as greenery in towns, preventing slippery roads and maintaining the sewage system. Besides these responsibilities on public grounds, the company owns five workshops to carry out maintenance activities on their trucks, machinery and public bins. These workshops are located in Enschede, Hengelo, Almelo, Oldenzaal and Borne.

The company was founded in 1997 when the waste collectors of Enschede, Almelo, Hengelo and Oldenzaal started working together to collect the waste. For a short period of time, the company was a mixed owned company with 35% of the shares were sold to a private company. In 2005 the municipalities got all shares back and Twente Milieu became a government company with their shares divided over eight municipalities in Twente. This means that Twente Milieu is commissioned by the municipalities and follows the waste and public grounds policy of the different municipalities.

The managing team on public grounds (BOR) is responsible for the maintenance of the public bins around the municipalities of Twente Milieu. The management of the underground bins is divided over three divisions. The placing department who is responsible for placing the underground bins in the street. This job includes digging a pit, transporting and installing the bin and assuring the street is repaired by an external company. The maintenance department is responsible for the coordination and execution of the maintenance teams on the street throughout the day. The workshop department is responsible for assembling new underground bins and repairing underground bins in one of the workshops of Twente Milieu. These repairs include mainly painting and welding, which cannot be carried out at the bin location.

1.2 Research motivation

The main maintenance activities of Twente Milieu are mainly in response to notifications by customers or waste collectors and are therefore corrective. For preventive maintenance Twente Milieu has a service contract with a company called BWaste which performs preventive maintenance actions (washing, inspection and lubrication) on every underground bin twice a year.

The current contract for preventive maintenance results in poor insights in the state of the underground bins. Besides this, the preventive maintenance is carried out at the bin location, and could possibly be done more thoroughly by insourcing the preventive maintenance activities. The BOR department has the desire to insource the preventive maintenance activities. The start of this process is scheduled in 2019 with a pilot by insourcing preventive maintenance on the underground bins in the municipality Hengelo. In this pilot, all underground bins are considered.

The three main reasons for Twente Milieu to insource preventive maintenance are as follows. In the first place to extend the life cycle of the underground bins by carrying out the preventive maintenance activities more thoroughly at workshops. In the second place, to give Twente Milieu better opportunities to keep track of the status of their assets. The third reason is that the amount of jobs for the employees at Startpunt is decreasing. In order to generate work for these employees, a social project of labour and education can continue which has great social value for Twente Milieu.

This research seeks to optimize the preventive maintenance process to be insourced by Twente Milieu. Preventive maintenance includes washing, lubricating and inspecting the underground bins at called Startpunt. Chapter 2 elaborates on this process.

1.3 Research goal

The goal of the research is to optimize the preventive maintenance process for underground bins at Twente Milieu by designing a maintenance model for Twente Milieu that includes corrective and preventive maintenance. The maintenance model should include a new process of preventive maintenance (washing, lubrication and inspection at Startpunt) and insourcing preventive maintenance needs to fit within the available capacity of Startpunt. In order to reach this goal, there are two sub goals, firstly to identify all relevant processes in the new situation after insourcing preventive maintenance, and secondly, to identify the relevant costs, constraints, failure distributions and opportunities. The findings of the two sub goals are combined into a maintenance planning of the underground bins in the municipalities of Twente.

1.4 Scope

Although Twente Milieu works in many different fields in order to manage the public grounds of the municipalities in Twente, this research focusses on the maintenance activities carried out at the public bin locations and at Startpunt. Only Startpunt is considered, since this workshop plays a key role in the maintenance of underground bins.

The scope of this research is the tactical level of the maintenance planning. During this research, some assumptions may be used about actions that not have been realized by Twente Milieu yet but are likely to happen in (near) future. Furthermore, routing is not in the scope of this research, so estimations about driving time between undergrounds will be rough.

In the past, Twente Milieu has had different suppliers for underground bins, due to the obligation to have public tenders. These different suppliers deliver different types of underground bins with different frameworks. Since the lifetime of an underground bin is longer than the time between these tenders, various types of bins are used. Not all bins are yet suitable for the proposed way of maintenance, so this research focusses only on the suitable bins of which the number is likely to rise in the future, which increases the practical use of this research.

1.5 Research questions

The main research question is: How can Twente Milieu optimize the preventive maintenance process of washing, lubricating and inspection of their underground bins?

To answer the main research question, the following sub questions are defined:

1. What is the current situation concerning corrective and preventive maintenance?
    i. What are the current processes at Twente Milieu?
    ii. What is the current approach for corrective maintenance?
    iii. What is the current approach for preventive maintenance?
    iv. What data is available to analyse the current situation?
    v. How to use this data to measure current performance?

Section 2.1 to 2.3 describe the current situation at Twente Milieu and give a brief description of waste collection in general, an explanation of the process of corrective maintenance, and an overview of the current preventive maintenance strategy. The sub questions concern the performance of the current maintenance strategies, both preventive and corrective.

2. How does the desired situation for Twente Milieu look like?
    i. What are the objectives of desired situation?
    ii. What are the constraints on the desired situation?
    iii. How is the desired situation influenced by the constraints by Twente Milieu?

Section 2.4 and 2.5 and describe the desired situation by Twente Milieu, namely to carry out the preventive maintenance by themselves. This requires insight into the opportunities and constraints of the desired situation.

3. Which methods can be found in literature about maintenance optimization and which are applicable to the case at Twente Milieu?
    i. What is the advantage of preventive maintenance?
    ii. What kind of preventive maintenance policies exist?
    iii. How can failure distributions be characterized?
    iv. What is opportunistic maintenance?
    v. How can discrete event simulation be used in this research?

Chapter 3 provides an overview of ideas and existing solutions in the literature. The results of this literature study can be used as a basis to design a solution for the research problem stated in chapter 1.

4. What approaches can we use to model and optimize the maintenance policy of Twente Milieu?
    i. What maintenance methods should we incorporate in the maintenance model?
    ii. What does a maintenance planning model for age-based maintenance look like?
    iii. What is the conceptual model for a discrete event simulation study for optimizing maintenance at Twente Milieu?

Chapter 4 builds on the ideas found in literature and presented in chapter 3. These ideas are used to develop an analytical maintenance planning model and a discrete event simulation model. Chapter 4 describes four maintenance (section 4.1) methods and how the maintenance methods are incorporated in the age-based maintenance planning model (section 4.3) and the discrete event simulation model (section 4.4).

5. What maintenance strategy optimizes maintenance in such a way that it fits within the capacity of Startpunt and includes more variability?
    i. What is the failure distribution that can be used in the proposed maintenance models?
    ii. What are the numerical results of using a time-based preventive maintenance strategy?
    iii. What are the results of the discrete event simulation study to implement the proposed maintenance methods at Twente Milieu?

Chapter 5 gives a numerical analysis on the two models described in chapter 4. The parameters for the failure distribution must be determined before analysing the model (section 5.1). Section 5.2 uses the failure distribution to show the use of working with a preventive maintenance interval. Section 5.3 extends the study with a discrete event simulation model, to analyse the variability in the proposed maintenance policy.

Chapter 6 states the main conclusions of this research and provides recommendations to Twente Milieu.

2. Current situation and desired situation

Chapter 2 describes the context of the research at Twente Milieu. Section 2.1 explains the way of collecting waste in the municipalities in Twente and we elaborate more on the main assets of this research, the public bins. Section 2.2 elaborates on the current maintenance methods and policy. Section 2.3 quantifies the current corrective maintenance strategy. Section 2.4 gives insight in how the desired situation for Twente Milieu looks like. We zoom into the process at Startpunt in section 2.5. Section 2.6 describes why we use Hengelo as a case study. Section 2.7 explains the conclusions that we can draw from the current and desired situation.

2.1 Waste collection

The waste collection in the municipalities served by Twente Milieu is done by different means and according to different policies in the municipalities. In the following sections the main way of waste collection will be discussed.

In order to dispose their waste, inhabitants of the municipalities fill three large bins (240 L), with residual waste, with paper waste and with bio waste. These bins are put along the streets on a biweekly basis. On these collection days, truck drivers from Twente Milieu empty the bins. The civilians pay a standardized fee for each time their residual waste bin is emptied, whereas the bio waste and paper waste bins are emptied for free.

These three bins are still used by a part of the inhabitants and Twente Milieu still collects the waste in these bins. However, the waste collection is shifting towards public underground bins located everywhere throughout the municipality, where inhabitants drop their waste in bags of 30 L.

2.1.1 Differentiated fees

Over the last two decades, more municipalities started to use differentiated fees (Diftar) for the collected waste. Consequently civilians have an incentive to reduce their waste and separate residuals better, thus lowering waste deposit costs. Over the years this strategy has contributed to a better separation of waste streams by civilians with a reduction in residual waste of 25% from 2016 to 2017 (Gemeente Enschede, 2019). The separation of public waste streams leads to partly filled bins along the roads or bins that are offered less frequently along the roads. In the future, Twente Milieu aims at collecting all waste via public bins, and thus abolishing the 240 L private bins.

2.1.2 Public bins

To give inhabitants the opportunity to dispose their separated waste streams such as glass and textile, public bins are installed at several places in the municipalities. The disposal of waste via these underground bins is free. Inhabitants still pay for the disposal of residual waste against a fee of €0,84 per bag of 30 L. Since the separation of waste streams leads to smaller amounts of residual waste, civilians start to dispose their residual waste more and more often in public bins where they pay per bag of residual waste they offer (Gemeente Enschede, 2019) instead of using their 240 L bin. These underground bins are widely available in the municipalities so all citizens have the opportunity to dispose their waste close to their home.

The municipalities do not have enough room in the infrastructure to have all bins above the ground so technologies have been developed to store the waste under streets and sidewalks in underground bins. In figure 1 we can see such an underground bin, which has a small area above the surface and a rather large (3-5 cubic meters) underground storage.

Twente Milieu has installed over 2500 underground bins in eight municipalities in the region of Twente (Twente Milieu, 2015). These underground bins are available to the citizens with a registered municipal environmental card. The containers are meant to collect paper, glass, residual, textile and packages to stimulate a secure separation of waste.

2.1.3 Composition of an underground bin

This section describes the underground bin and explains which components need maintenance. The underground bin has a black part above the ground and grey container are underground (Figure 1). On top of the bin, a carrying shaft is attached to the hull.

The black hull with an input slot that can be opened for waste streams with free disposal e.g. textile and glass. Besides, these slots can also be covered by a grey trommel as shown in figure 1, which allows the user to dispose just one bag of 30 L when it opens.

Figure 1 Underground bin

Inside the hull, an electric lock makes sure the trommel can only be opened once per card that is presented. There is also an electronic device with a card reader (figure 2), a memory and a data connection with the server. This smart box is used to register each bag dropped, open the lock when a valid card is presented and send daily the data to the server. The software that is used by this smart box is called Administrative Waste Registration System (AWRS).

Figure 2 Smart box with card reader

Outside the hull, a carrying shaft is attached to chains inside the bin. A crane pulls up the underground bin by using the carrying shaft and then opens the bottom of the bin above a waste truck. Table 1 summarizes the relevant components.

Administrative Waste Registration System (AWRS)

AWRS is the remote monitoring system that communicates the status of the underground bin to Twente Milieu. In the first place, it registers the number of garbage bags dropped in a bin, so it knows how full an underground bin is at any time. How full it is, is given as a percentage of the maximum number of bags in can take namely: $Fullness = \frac{Number\ of\ dropped\ bags}{Maximum\ number\ of\ bags} * 100\%$. Secondly it sends a report with the current battery statuses every night, so a dead battery can be quickly identified as a possible cause for problems. The AWRS also registers who opened the bin for the last time to drop a garbage bag. AWRS is also used to verify if problems have been resolved. For example, if one user makes a notification of a stuck bin, and another resolves the problem howsoever Twente Milieu knows the problem has been resolved since more garbage droppings have occurred after the first stuck notification.

Table 1 components of an underground bin

List of components	Function
Hull	Part of the bin that is above the ground. The hull contains an input slot for waste in the size suitable for the waste stream.
Smart box	The card reader that communicates with the server. After reading a presented valid card, it makes sure the lock opens and the trommel can make one rotation to take in one bag. The smart box registers the card number of the customer in order to make him pay to Twente Milieu. It can also read if a card is valid and stay closed for an invalid card. Lastly, every night, the smart box sends its data to a server so the maintenance department can read the data.
Trommel	The trommel closes the input slot of paid waste streams. The trommel is large enough to carry one 30 L garbage bag.
Lock	The lock can be opened by the smart box in order to make the trommel rotate once. This means that the trommel opens, the customer can drop one bag and the trommel closes again.
Battery	The battery is attached inside of the hull in order to give power to the lock and the smart box. When the battery is dead, it is replaced by a new one. Every night a battery status is sent to the server by the smart box.
Carrying shaft	On top of the bin, there is a carrying shaft so a crane can pull the underground bin out of the pit and empty it in the garbage truck.
Chains	The chains are attached to the carrying shaft and make sure the bottom of the underground bin can open to drop the waste into the garbage truck.

2.2 Maintenance methods

This section describes the information systems at Twente Milieu which are used for underground bin management. Secondly, the maintenance methods for the underground bins are described. There are two types of maintenance activities applied to underground bins: corrective maintenance which is carried out by mechanics of Twente Milieu and preventive maintenance which is outsourced to a company called BWaste.

2.2.1 Information systems

Real-time data is used to manage the maintenance. The main advantage of this is that the maintenance department decides upfront whether it is necessary to send mechanics to the underground bin or that the problem is caused by a customer because of a wrong or outdated card, for example. In the latter case, the failure is not in the bin itself, so the maintenance team is not necessary. The customer service and the customer with the failing card should seek for a solution together. This aspect is not taken into account in this research.

Customer contact centre (KCC)

Customer contact centre (KCC) is the information system by which the customer service communicates a civilian complaint or notification to the maintenance department. The maintenance department uses their other systems to check if there is a real problem and how to fit the underground bin in the maintenance schedule.

Wincar

Wincar is the information system where Twente Milieu registers the working hours of the mechanics on the road and at the workshops. In addition, a history of all maintenance actions to underground bins is registered in Wincar.

Routing programs
There are several programs used for routing purposes: Webfleet, TomTom, AWRS, and Garmin. Twente Milieu uses Webfleet including TomTom to keep track of their trucks during the day and to give the mechanics the possibility to navigate to a location. All bin locations are connected in AWRS and TomTom. In addition, a Garmin tool is used to optimize routes via multiple locations.

2.2.2 Corrective maintenance

Corrective maintenance is carried out by Twente Milieu in response to civilian complaints, notifications or waste collectors or digital warnings. Corrective maintenance can be above or below the ground and is carried out by two different departments called first line (above the ground) and second line (underground). These departments have their own car or truck, which is their working space.

Both lines drive all working days around in the municipalities and, they carry out (i) planned jobs which occurred overnight or the day before and (ii) respond to problems that occur during the day at one or more of the bins. The second line can lift the underground bin out of the ground by means of a crane and solve any problems with the pit or the frame of the bin. A frequently occurring problems for the second line are broken frames or a smelly air around the bins, because of the dirty pit. The first line can only solve problems concerning the electronics or the outside hull of the bins. Their main tasks are the replacement of batteries, card readers and locks. Besides this, they repair bins where garbage bags got stuck due to various causes.

The maintenance department plans corrective maintenance as immediate as possible to reduce downtime as much as possible. However, in most cases the corrective maintenance is postponed a few hours, which gives time to check AWRS to look into the bin data. The bin data check concerns what has happened to the underground bin in the time span between the failure notification and the moment the mechanics leave. They check when the bin has opened correctly for the last time, the last time it registered a customer card and how full the bin is. By this data, the maintenance department assesses the type of failure and send the right mechanics (first or second line).

If it is clear that no check is needed, the failure is sent to the first or second line immediately, which can go to the bin and repair immediately. This practice is a response to many unnecessary maintenance trips in the past and facilitated by the availability of real-time data from smart card readers.

The flowchart in figure 3 shows the corrective maintenance process and which departments are responsible for what part. This flowchart shows how Twente Milieu executes corrective repairs on a daily basis.

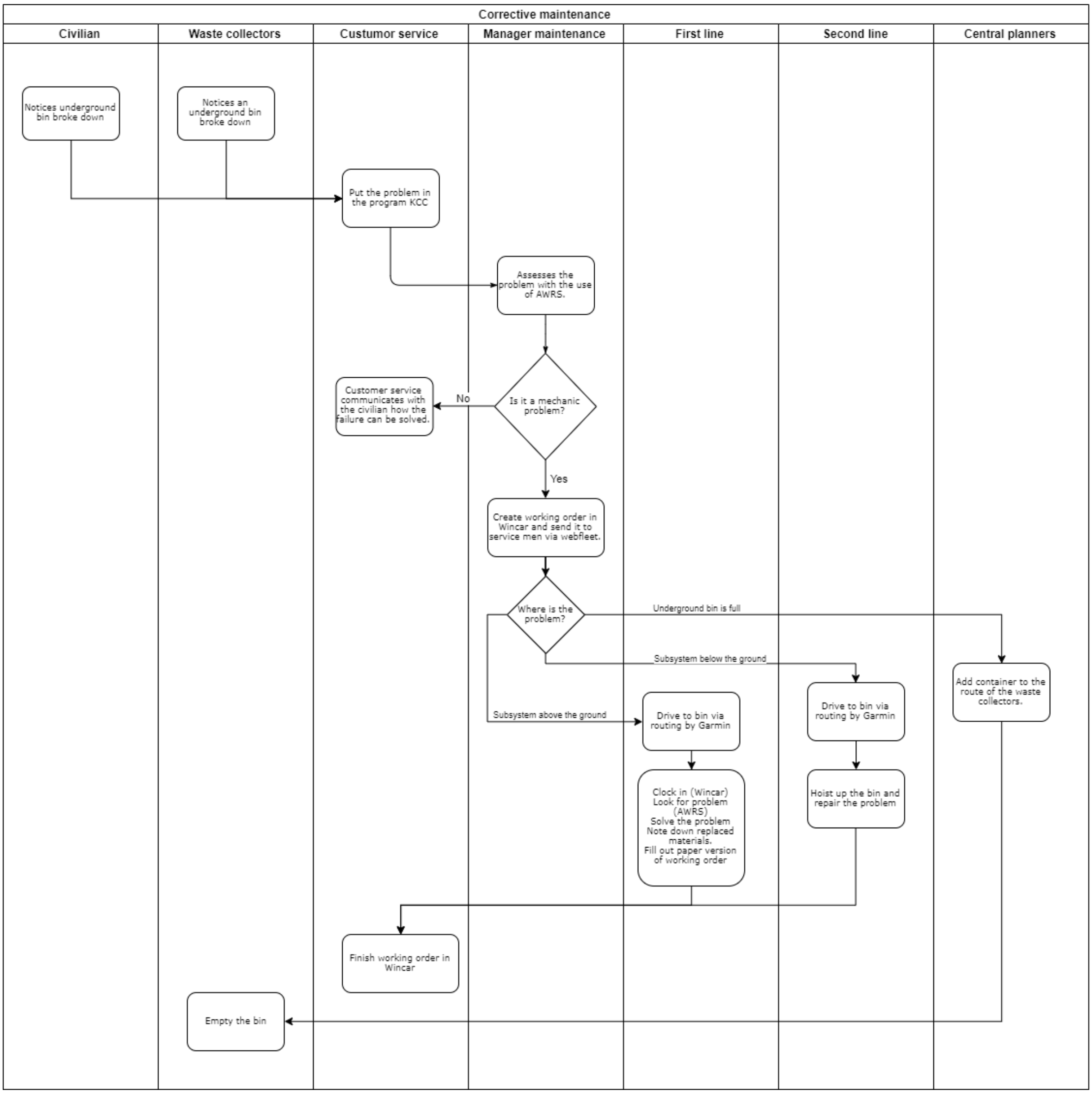

Figure 3, Current process for corrective maintenance

2.2.3 Consequences of downtime

It is important to keep downtime of underground bins as short as possible. Downtime is defined as the time where customers cannot dispose their waste in an underground bin. Too much downtime results in negative experiences for customers, neighbourhood inhabitants and lost revenues for Twente Milieu. With non-functioning bins, frequently people do not take their garbage back home but leave their garbage around the underground bin and do not pay for disposing waste and create a mess on public grounds as displayed in figure 4. For these reasons, it is important that failures are adequately resolved by both the first line and second line mechanics.

Figure 4 Illegal disposal of garbage bags

2.2.4 Preventive maintenance

As mentioned before, Twente Milieu has a service contract with BWaste who cleans the underground bins twice a year. Bin are cleaned at location with a high-pressure cleaner and by lubricating the bins with penetrating oil. , BWaste also cleans the pit to minimize smelly airs around the bins. Twente Milieu receives an inspection report about this preventive maintenance including the status of the underground bin. Twente Milieu pays BWaste €42,50 per container per year to carry out the described preventive maintenance activities.

The result of the activities by BWaste is a list of small issues or deficits for every bin cleaned by BWaste. These issues are in most cases resolved by second line mechanics of Twente Milieu, who can just like BWaste carry the bin out of the pit and repair minor issues.

2.3 Maintenance in numbers

This section seeks to quantify the current situation in terms of corrective and preventive maintenance by assessing how many work orders on corrective repairs are fulfilled by first- and second-line mechanics in a year. The data is obtained from Wincar (Twente Milieu, 2015), the internal work order system of Twente Milieu. For each task related to a public bin the mechanics make a work order with a specification of the maintenance carried out.

Five kinds of corrective maintenance activities are taken into account and specification follows of the kind of failure, its cause and the specific maintenance activity:

Corrective repairs: Maintenance after customer notification. These failures are mainly input slots that get stuck by the insertion of too large garbage bags. These maintenance actions normally do not take very long.

Vandalism maintenance: Maintenance that occurs from vandalism, for example, graffiti or demolishment of the input slots. These maintenance actions usually take somewhat longer because metals might need repair or the underground bin needs some paint or thorough washing with a high-pressure cleaner.

External digital maintenance: This includes all maintenance on the electronic parts of the underground bin. The electronic parts are the card reader and the battery which gives power to the lock and input slot. It is considered external since the costs for these repairs are paid by BWaste instead of Twente Milieu. The lead time for this kind of repairs depends on the age of the underground bin. For some bins, just a few screws are enough to carry out the maintenance, while for other bins, the whole electronic system needs to be unscrewed.

External corrective repairs: All repairs of non-electronic parts of the underground bins. These maintenance actions have different lead times.

Internal damage: This category is corrective repairs carried out on failures caused by the material handling by Twente Milieu workers. These failures are most often in the larger part of the underground bin, for example in the shaft to which the crane connects. Dents due to collisions between the crane and the underground bin is another example of internal damage. These damages often concern the metal frames or shaft and usually, the lead times for repair is long.

Table 2 Types of maintenance and their estimated lead times

Type of maintenance	**Operator**	**Repair lead time**
Corrective maintenance	First or second line	differs for line and job
Vandalism maintenance	First or second line	about 0.5 hour
External digital maintenance	First line	about 0.25 hour
External corrective maintenance	Second line	Over 2 hours
Internal damage	Second line	Long

Table 2 summarizes the maintenance methods, with the operating lines and estimated lead times. The rough estimations are based on the bookings for maintenance methods that include a large variety of jobs and execution times.

The number of corrective maintenance carried out has increased over the past years (Figure 5 and 6). This is due to two trends. The first trend is the increased number of underground bins in the streets and more municipalities being served by Twente Milieu. The second trend is the fact that internal damages are being monitored more securely, so there is more data available on what kinds of maintenance have been carried out.

An interesting mark in figure 5 is that large corrective maintenance activities which are internal damages and vandalism. These failures occur about 500 times per year as shown in figure 5.

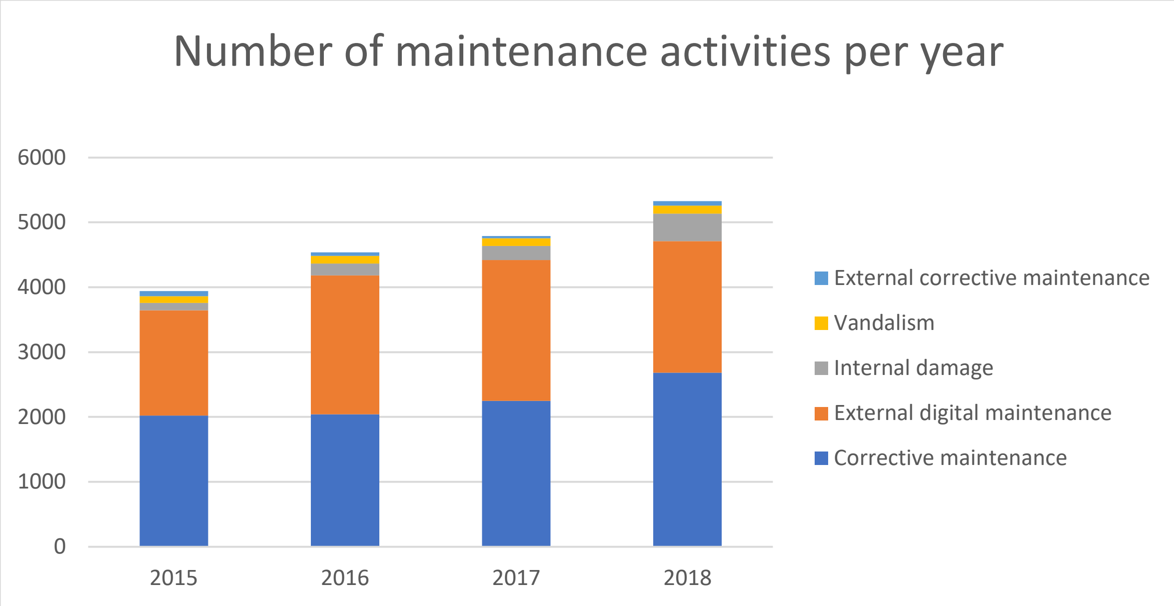

Figure 5 Maintenance activities per year

Figure 6 shows the frequency of visits per underground bin per year. The bins that are never visited are not shown, because this would generate an unbalanced dataset. Over 1600 underground bins are visited for corrective maintenance at least once in 2018, this is the sum of the bins that are visited once, twice, three times etc. These visits for corrective maintenance give opportunities for inspection or preventive maintenance. In addition, there is an opportunity for a full preventive maintenance treatment of washing, lubricating and inspection instead of activating the first- or second-line truck for corrective maintenance.

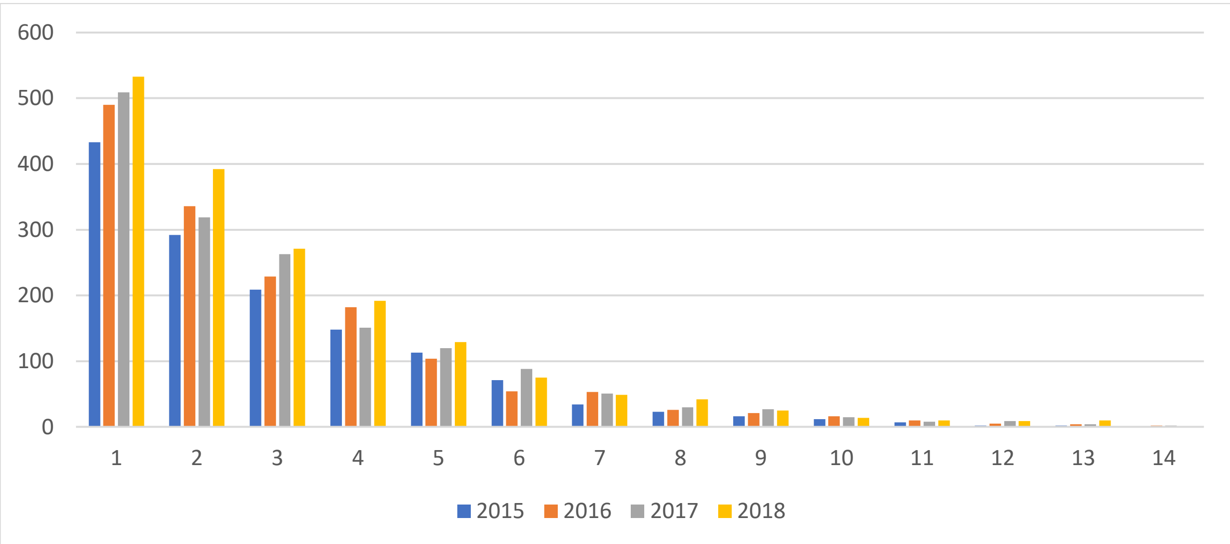

Figure 6 Histogram of the numbers of visits per underground bin per year

2.4 Desired Situation

This section explains the desired situation by Twente Milieu. The desired situation concerns the carrying out of preventive maintenance at the workshops of Twente Milieu, including washing, lubricating and inspecting the bin. The starting point for preventive maintenance is that every underground bin is regularly brought in a workshop.

Startpunt in Borne is the chosen workshop, primarily because this workshop has a social importance. Twente Milieu seeks to employ people with a distance to the labour marked in combination with technical schooling at the ROC school in Hengelo. By insourcing the preventive maintenance, money spent on washing, lubrication and inspection of the underground bins are invested in Twente Milieu labour instead of external labour.

In the current situation, Twente Milieu uses Startpunt only to assemble underground bins. The underground bins are delivered as raw materials and the mechanics assemble them to complete underground bins. However, the number of assembly jobs is decreasing, so using the workshop space and mechanics to carry out preventive maintenance is an opportunity to generate work for Startpunt.

Besides preventive maintenance at the workshop, the container might need to be more frequently washed on the street. This depends on the wishes of the municipality where the underground bins are located.

2.4.1 Advantages of the desired situation

In the end situation, each underground bin in a municipality in the service area of Twente Milieu can be replaced by any other washed, lubricated and inspected underground bin from the stock at Startpunt. During a replacement, the framework in the ground and the pit must be cleaned as well, which job is done BWaste during their washing round in the current situation.

An additional advantage of carrying out preventive maintenance at Startpunt instead of at bin location is the improved quality of preventive maintenance. According to the estimations of mechanics, the underground bins are as good as new after they are treated at Startpunt. This is better than in the current situation since the on-site preventive maintenance is not as thorough as it could be at Startpunt.

2.4.2 Constraints of the desired situations

The most important constraint is the working capacity of Startpunt. Since the employees are being taught and still going to school, the working hours are restricted to school hours and holidays. In addition, the capacity is influenced by the number of newly arriving employees who need more instructions at the beginning of their period of employment and can work more independently and faster towards the end of their employment period.

Another constraint to the current situation is that not all frameworks of the underground bins are the same. This means that not all containers are interchangeable as described in the advantages in section 2.3.1. It is unsure when all frameworks will be uniform and a way should be found to deal with this problem.

It is also necessary that a bin for a certain waste stream is replaced by a bin of the same waste stream. So another constraint for the desired situation is that there are sufficient bins of all waste streams in stock to replace bins in the street that need washing, lubrication and inspection.

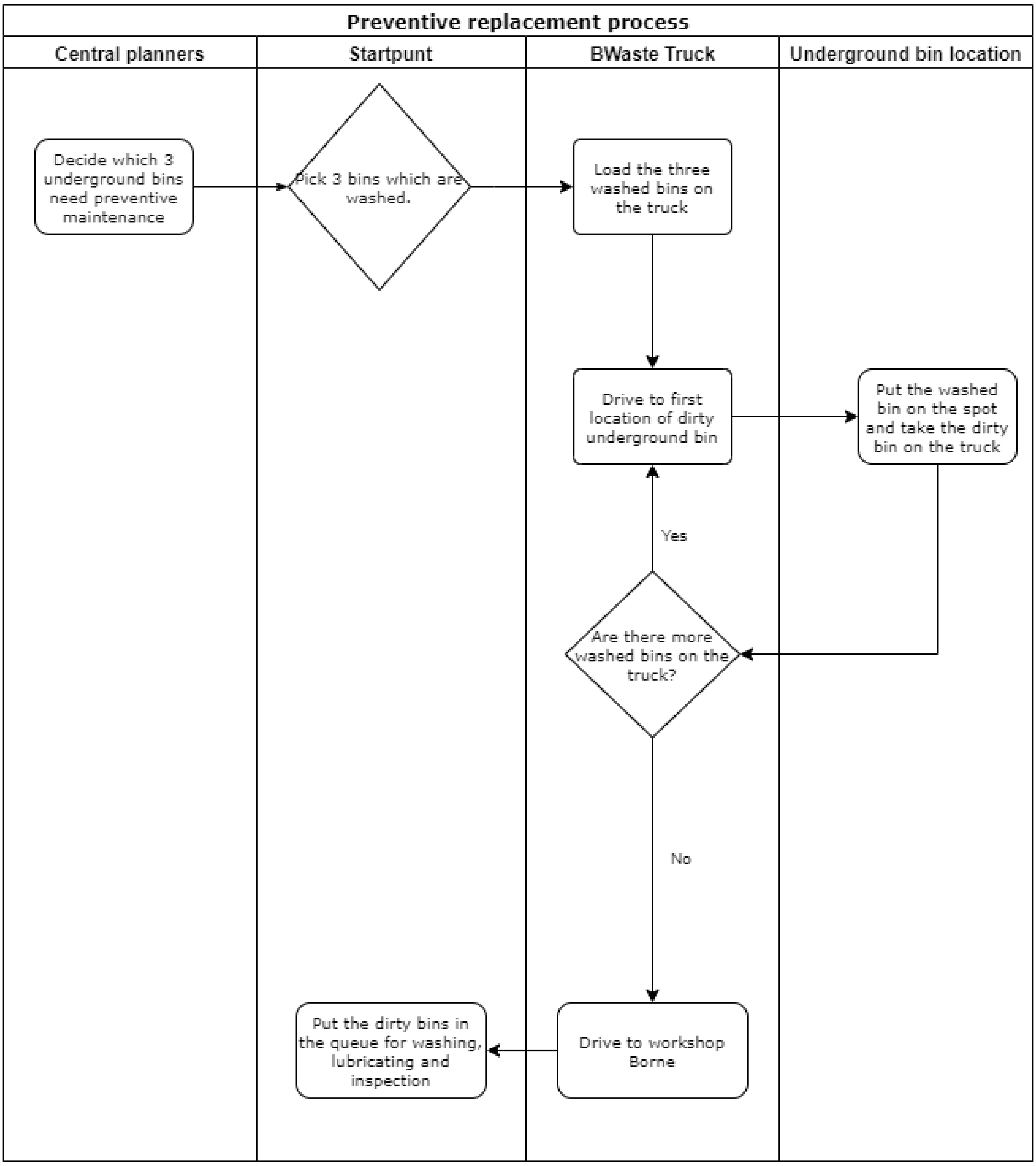

Figure 7, Process of bin replacement for preventive maintenance at Startpunt

Figure 7 shows the process to replace underground bins by a clean and repaired bin and to take the old bin to the workshop for preventive maintenance treatment (washing, inspection and lubrication). The flow chart shows how three washed bins are loaded on a truck that drives to bins that need preventive maintenance. Old bins are replaced with new ones. This can be done for three bins in one trip, since three bins is the carrying capacity of the truck. The old bins are brought to the workshop for preventive maintenance treatment and then stocked to replace bins on the street later.

2.5 Washing, lubrication and inspection at Startpunt

Chapter 1 mentioned the great social value of Startpunt. This section elaborates on this social value and explains the preventive maintenance actions in the form of washing, lubrication and inspection which are going to be carried out by the employees of Startpunt. Insourcing the process of washing, lubrication and inspection to Borne is a way to ensure that there is enough work at Startpunt to warrant capacity for the working and learning environment.

At Startpunt employees work from October up to and including July for four days a week. The fifth day is reserved for theoretic and practical schooling. The area of the workshop is designed in such a way that there is enough space to store the underground bins. The underground bins come (partly) filled with garbage from the street in batches of at most three bins because of the truck capacity. The bins arrive only on days that the truck is hired, this day we label transportation day. Theoretically the truck can be hired any working day, but this would involve high costs because of daily payment for truck rent.

The bins must be emptied from garbage before they treatment at the workshop. Emptying a bin is done with a crane and a garbage truck which is open on top. After bins are emptied, the crane puts them on a tilting frame, because the bins can only be moved horizontally with a forklift.

There is a special part of the terrain reserved for washing with a high-pressure cleaner. Washing a bin is one of the least time-consuming activities of the process. The capacity of the wash area in bins per hour is much larger than the capacity of the rest of the process. After washing bins are stored and it is assessed which treatments are needed. Some bins might be in a very good state and need only penetrating oil, while other bins might need a new layer of paint or need to be welded.

After the additional treatment, bins are lubricated with penetrating oil and a final inspection follows. Bins are inspected by using a checklist and then brought to the done bin’s storage. From this storage, bins can be taken immediately to put on the streets. Figure 8 shows a flowchart of the process described above.

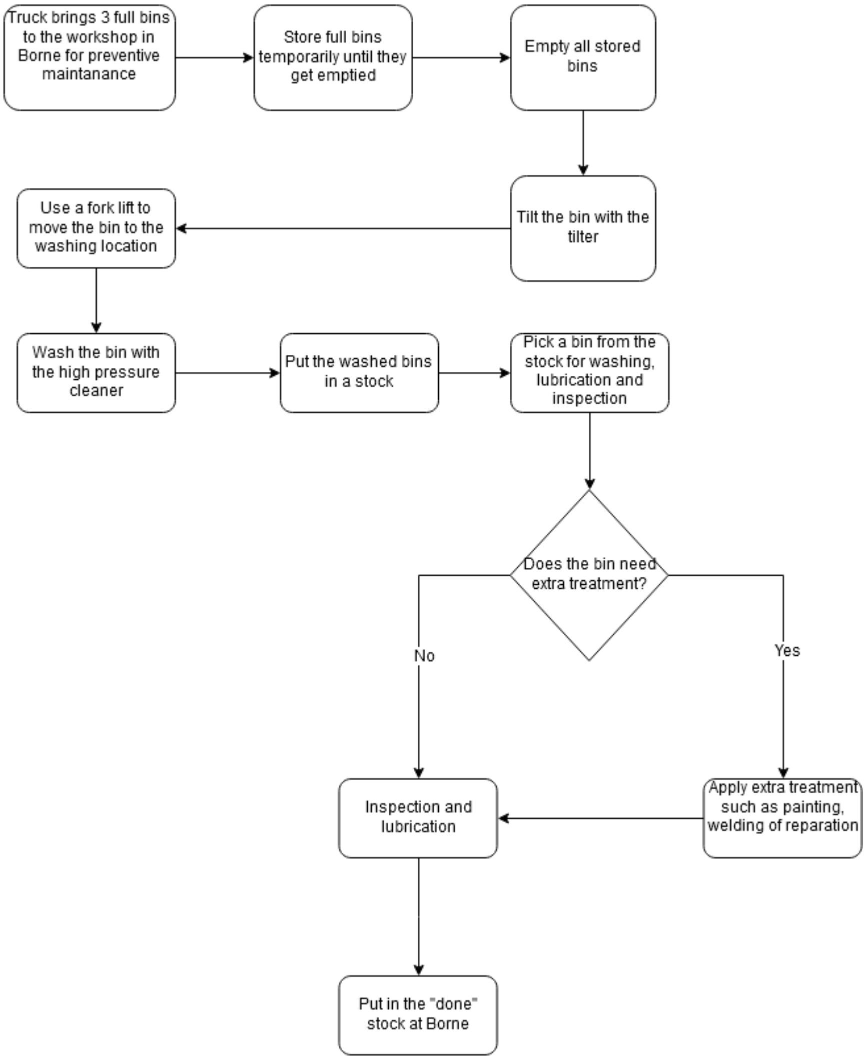

Figure 8 Desired process of washing, lubrication and inspection at Startpunt

2.6 Case Hengelo

The underground bins in Hengelo provide the case study for this research. The management of Twente Milieu has decided to start insourcing the preventive maintenance activities on the underground bins in the municipality Hengelo. This means that the underground bins in Hengelo are the first ones to be brought to Startpunt. For all other municipalities, the preventive maintenance activities will still be outsourced in the near future. There are several practical reasons to start in Hengelo:

- Hengelo has the newest bins with mostly the same frameworks, thus allowing to locate all bins at each bin location. This makes the start of the implementation logistically easier.

- The number of bins in Hengelo is large enough to ensure sufficient work for Startpunt and to test the effectiveness of insourcing preventive maintenance. On the other hand, the number of bins is probably acceptable so that Startpunt can handle the workload.

- Hengelo is closer to Borne than Enschede, the second-best option regarding the interchangeability of underground bins.

- The municipality of Hengelo is willing to cooperate in this process.

2.7 Conclusions

The first conclusion is that the current method of preventive maintenance has too many black box features for Twente Milieu. An external company is hired to clean the underground bins and reports on issues with underground bins lack sufficient detail. Secondly, all corrective repairs carried out by Twente Milieu themselves, so the technical knowledge is available. Thirdly, there is a project at Startpunt to facilitate the educational process of the employees to instruct them how to wash, lubricate and inspect the underground bins. This possibly results in better maintenance compared to the preventive maintenance by BWaste.

Our quantitative assessment of the corrective maintenance actions leads to the following conclusions. Corrective maintenance actions take so long or have such a large impact on the state of the underground bin that it is possibly better to get the bin inside and carry out the preventive maintenance (washing, lubricating and inspection). This additionally saves corrective maintenance trips to underground bin locations.

Twente Milieu has proposed the desired situation for the preventive maintenance, so in section 2.4 and 2.5 elaborate on the requirements for the desired situation. The advantages of insourcing preventive maintenance relate to a higher quality of the underground bins and to the efficiency gains in the overall process.

The main constraint for the idea to interchange bins at pit location is the type of framework and the concerned types of waste streams. Availability of several types of bins in stock is required. The second constraint concerns the working capacity of Startpunt. Section 2.5 presented the necessary steps in the process of washing, lubricating and inspection.

The next chapter provides a review of literature topics useful for the transition from the current to the desired situation. From the ideas in literature, a model is designed to optimize the maintenance policy at Twente Milieu.

3. Literature review on maintenance methods

This chapter reviews literature on maintenance optimization and the role of simulation studies. Section 3.1 elaborates on different maintenance strategies that can be applied. Section 3.2 explains what theoretical distributions are used to model maintenance activities. Section 3.3 introduces the concept of opportunistic maintenance. The sections 3.4 to 3.6 elaborate on discrete event simulation. The advantages, conceptual model and experimental design are discussed. At the end of the chapter, section 3.7 summarizes the findings in literature that are relevant to this research.

3.1 Maintenance methods

Many industries depend on the availability of high-value capital assets to provide services (Driessen, Aarts, Houtum, Rustenburg, & Huisman, 2010). Downtime of these assets results in, amongst others, revenues, customer dissatisfaction and public safety hazards. The consequences of downtime are costly. In the case of underground bins, the three mentioned consequences occur for Twente Milieu. Because the capital assets are essential to the operational processes of Twente Milieu, downtime needs to be minimized. The downtime is divided into two parts, diagnosis and maintenance time and delay caused by unavailable resources for diagnosis and maintenance (Driessen, Aarts, Houtum, Rustenburg, & Huisman, 2010). The availability of spare parts directly influences the possibility of delay for preventive and corrective maintenance.

Driessen considers an asset base where the demand for maintenance activities is large enough to guarantee a constant demand over time (Driessen, Aarts, Houtum, Rustenburg, & Huisman, 2010). This corresponds with the desired situation at Twente Milieu, where all underground bins in Twente should be timely maintained, which can be considered a constant demand. Maintenance is carried out according to a planning that distinguishes three types of maintenance:

Preventive maintenance is conducted in order to prevent failure in the future. This maintenance is usually planned in advance and is conducted in a time frame planned in advance, although rescheduling is possible. Inspection is an additional part of preventive maintenance but might also be conducted separately.

Corrective maintenance is conducted after a failure has occurred. This means that this type of maintenance is usually unplanned, since occurring failures are unforeseen. The time that elapses between the failure and the moment the asset is repaired is downtime. For Twente Milieu, this is the time where the mentioned drawbacks of downtime occur.

Modificative maintenance is conducted to improve the performance of capital assets. This maintenance can be planned to fit other maintenance schedules so that the necessary resources are available. Modificative maintenance is outside the scope of this research and not discussed in detail.

3.1.1 Preventive maintenance concepts

This section we describe several concepts to determine the interval between two preventive maintenance actions. In literature we found four concepts which we will elaborate on since they might be applicable to the desired situation at Twente Milieu. These concepts are time-based, usage-based, usage-severity-based and condition-based maintenance.

Time-based maintenance

Time-based maintenance is also called periodic based maintenance. This is a traditional way of maintenance where the end of life of an asset is estimated. A periodic replacement or preventive maintenance is planned after a predetermined period of time (T) or corrective maintenance is carried out after a failure of the unit. The state of the unit is considered to be as good as new after corrective or preventive maintenance. Using such a replacement strategy implies the assumption that the failure rate is predictable (Ahmad & Kamaruddin, 2012). This assumption is based on the bathtub curve as presented in figure 9. In this bathtub curve we can see that in the beginning of the lifetime, the failure rate decreases until it has a failure rate that is constant until the wear out starts at the end of the operating lifetime.

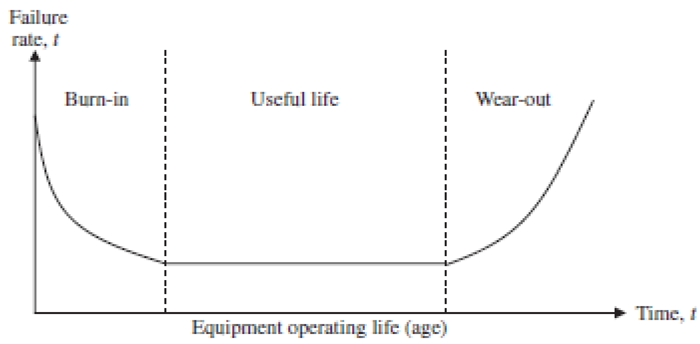

Figure 9 Bathtub curve

The cost function that comes with a time-based maintenance policy per cycle is split up in two types of costs. Firstly, the costs for corrective maintenance C_c when the unit breaks down. Secondly, the costs for preventive maintenance C_p when the unit reaches time T, where $C_p < C_c$. The cost function is:

$$g(T) = \frac{C_c * F(T) + (1 - F(T)) * C_p}{\int_0^T (1 - F(t))dt} \qquad (1)$$

Where F is the life time distribution of the unit. Minimizing this function leads to an optimal period until maintenance (T*).

Usage-based maintenance

Applying usage-based maintenance reduces conservatism which characterizes time-based maintenance. With usage-based maintenance the scheduling of maintenance activities and intervals is based on the actual usage of the system (Tinga, 2010). However, measuring operating hours as usage might not be accurate because of varying impact on life consumption during operating hours. For this reason, a more sophisticated usage-based method, which is called usage-severity-based maintenance (Tinga, 2010) is additionally considered.

Usage-severity-based maintenance

To make distinction between the different usage hours, the variation in use indicators need to be monitored. This can be done by parameters such as power settings, rotational speed or other performance indicators (Tinga, 2010). In addition, the relation between the usage and the life consumption must be known. Monitoring usage reduces uncertainty and consequently the variability in the lifetime distribution. Figure 10 shows how the lifetime distribution changes and the service time increases when including failure probabilities in the planning of maintenance.

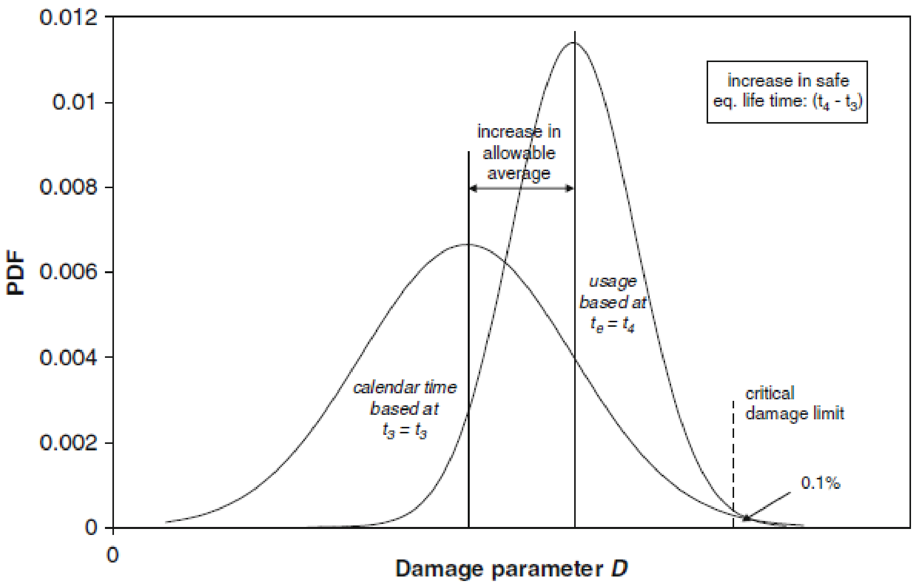

Figure 10 Time based vs usage based life time distribution

Condition-based maintenance

A fourth maintenance strategy is the condition-based maintenance (CBM). CBM was introduced to maximize the effectiveness of preventive maintenance (Ahmad & Kamaruddin, 2012). The difference compared to time-based maintenance is that the lifetime is measured in its operation condition instead of in years. This operation condition can be monitored by certain parameters such as vibration, temperature and contaminants (Ahmad & Kamaruddin, 2012). The most important part of CBM is, periodically or continuously, monitoring the condition of the asset (Ahmad & Kamaruddin, 2012). Mostly, failures in assets are preceded by signs or indications that such a failure will occur (Bloch & Geitner, 1983).

3.2 Failure distributions

Maintenance planning requires insight in failure distributions. Failure distributions in reliability studies are only for t > 0, hence instead of a normal distribution, with t going from -∞ to ∞ , the three most commonly used distributions used for corrective planning are Exponential E(λ), Weibull (β, λ) and Gamma (*k*, λ) (Gertsbakh, 2000).

In the theoretical distribution, T is the first time to failure given that a system starts operating at time t = 0 (Heijden M. v., 2018). Then a cumulative probability distribution is F(t) = P(T≤t) and the probability density function is the derivative of the cumulative probability distribution namely f(t) = F'(t). Next, a survival function (R(t)) is given by $\bar{F}(t)$ which is 1 - F(t). To conclude, the failure rate function z(t) is given by $z(t) = \frac{f(t)}{R(t)}$. The failure rate can be interpreted as proneness to failure at time t (Heijden M. v., 2018).

Exponential distribution

For the exponential distribution the failure rate is characterized as constant. This means that the failure rate is not time dependent and that failures occur randomly. An exponential distribution is characterized with the following probability density function:

$$f(t) = \frac{e^{-t/\eta}}{\eta} \qquad (2)$$

The constant failure rate is expressed only by a parameter η:

$$z(t) = \frac{1}{\eta} \qquad (3)$$

Weibull distribution

The Weibull distribution, with two or three parameters, is commonly used in reliability engineering. The two-parameter Weibull distribution consists of a shape parameter (β) and a scale parameter (η). From the shape parameter, one can see if the failure rate is decreasing (β < 1), constant (β = 1) or increasing (β > 1) (Schenkelberg, 2019). In the 3-parameter Weibull distribution a failure free period is taken into account. In that case, it is assumed that the system cannot break down in certain periods of its lifetime.

The probability density function of the Weibull distribution is given by the function:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} * e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (4)$$

The integral of this function F(t) is:

$$1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (5)$$

The survival function of the Weibull distribution is described by the following equation which is the complement of the cumulative distribution function $\bar{F}(t) = 1 - F(t)$ which is:

$$\bar{F}(t) = 1 - \left(1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}\right) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (6)$$

These formulas lead to a failure rate function:

$$z(t) = \frac{f(t)}{R(t)} = \frac{\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} * e^{-\left(\frac{t}{\eta}\right)^{\beta}}}{e^{-\left(\frac{t}{\eta}\right)^{\beta}}} = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \qquad (7)$$

When β is equal to 1, the failure rate function of the Weibull distribution is exactly the same as the failure rate function of the exponential distribution, namely 1/η.

To estimate the parameters of the failure rate distribution, the least mean square regression method is used. This method is described by van der Heijden (Heijden M. v., 2018) in the slides of reliability engineering and maintenance management at the University of Twente. This method is effective only when enough failure data is available. The least mean square regression method to estimate the parameters in the Weibull distribution is based on the times between failures of different components. The survival function

$$\bar{F}(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (8)$$

can be rewritten as:

$$Ln\left(Ln\left(\frac{1}{\bar{F}(t)}\right)\right) = \beta(\ln(t) - \ln(\eta)) \qquad (9)$$

By applying linear regression with the dependent variables y(t) on the left-hand side and ln(t) equals x(t) on the right-hand side, we can find the slope and the intercept with the y-axis. The slope of the regression line is parameter β and the intercept with the y-axis (C) can be used to calculate η by the following formula:

$$\eta = e^{-C/\beta} \qquad (10)$$

The goodness of fit is quantified by the coefficient of determination (R^2) (Kvalseth, 1985). In a linear regression model, the value of R^2 is always be between 0 and 1. If the value is 0, there is no better fit than a line through the mean of all points. This means that Y cannot be predicted by X. On the other hand, when the value of R^2 is exactly 1, all data points lie on the curve and knowing the value of X, gives the value of Y automatically (GraphPad Software, 1995). So, the closer the value of R^2 to 1, the better the fit of the linear regression model.

The estimations for the parameter β are important for maintenance planning. The value of β indicates the cost effectiveness of preventive maintenance with β equal to or smaller than 1 indicating that preventive maintenance is not cost effective, and with β larger than 1 pointing to a situation that the asset wears out over time and it is cost effective to carry out preventive maintenance. (Abernethy, 2004). This is only true for cases where the costs for corrective maintenance are higher than the costs for preventive maintenance.

Chi square test

The Chi-square test of independence is one of the most useful statistical techniques for testing hypotheses with nominal variables (McHugh, 2015). The Chi-square test is used to find whether the observed value differ significantly from expected value (Statistics Solutions, 2019). The term goodness of fit is a measure how a theoretical distribution fits an empirical distribution. The sample data is divided over a certain amount of intervals. The number of data points from the data set that belong to one interval is compared to the theoretical expected number of data points in the according interval.

The Chi-square test does not only provide information on significance but can also tell which categories are accountable for the difference. Secondly the variables should be mutually exclusive and independent from each other.

The null hypothesis for the Chi-square goodness of fit test assumes that there is no significant difference between the observed and the expected value. The alternative hypothesis is that there is a significant difference between the observed and expected value (Statistics Solutions, 2019). The Chi-square value is the sum of the squared difference of the expected and the observed number per category:

$$\chi^2 = \frac{(O-E)^2}{E} \qquad (11)$$

Where O is the observed number in one category and E is the expected number in the same category.

This formula is applied to every category of the data set and the sum of these values is the total value of the Chi-squares:

$$\sum \chi^2 \qquad (12)$$

This value is compared to a table value in order to test the null hypothesis. In case the Chi-square value is higher than the table value, the null-hypothesis is rejected, thus concluding that there is a significant difference between the empirical distribution and the theoretical distribution. However, when the Chi-square value is smaller than the table value, the conclusion is that there is no significant difference between the empirical and the theoretical distribution.

The selection of table values depends on the degrees of freedom and the level of significance. The degrees of freedom are dependent on the number of rows and columns in the table. The number of rows is equal to the number of categories. The number of columns is equal to the number of distributions you are comparing (Statistics Solutions, 2019). To conclude, the number of degrees of freedom is (# of rows - 1)(# of columns - 1). A typical value for the level of significance is 0.05.

3.3 Opportunistic maintenance

Most conventional maintenance strategies are purely corrective or time-scheduled (Thomas, Levrat, & Iung, 2008). Thomas suggests to move from a more traditional maintenance towards condition based maintenance where maintenance is only carried out when a certain level of deterioration occurs (Thomas, Levrat, & Iung, 2008). Anticipation allows to carry out maintenance not only in response to a failure but also for opportunistic reasons. The key for opportunistic maintenance is to answer the following questions: When to carry out a maintenance action? What components should benefit from a preventive maintenance action? What components should benefit first? (Thomas, Levrat, & Iung, 2008).

Initially, opportunistic maintenance, was considered as an opportunity if preventive maintenance can be combined with corrective maintenance in order to make the set-up costs decrease. (Thomas, Levrat, & Iung, 2008). In later studies by Radner and Jorgenson, opportunistic maintenance was considered to be to opportunity to replace non-monitored components in combination with the monitored components (Radnar & Jorgensen, 1963). The aim of these policies is to minimize for example set up costs or production losses. From this we define an opportunity as a period during which maintenance can be carried out without loss or negative impact on production.

3.4 Discrete event simulation

In this section we will look into the literature of a very common simulation study approach, namely discrete event simulation.

Discrete event simulation is used for modelling queuing systems. Entities flow between activities that are separated by queues. These queues appear when entities flow into the queue faster with a higher rate than they flow out of the queue (Robinson, Simulation the Practice of Model Development and Use, 2014).

Advantage of a simulation study over real-life experiments

Stewart Robinson describes the advantages of a simulation study over experimenting in a real system. Although some points that are raised by Robinson seem straightforward, it is good to emphasize the main advantages of a simulation study: (Robinson, Simulation the Practice of Model Development and Use, 2014).

Costs. It can be costly to set up experiments in a real system. This would interrupt day-to-day activities if one wants to try new things.

Time. It will be very time-consuming to change the experimental factors in a real system. Besides, it will take a lot of time until the effects of the experimental factors will be reflected in the real system. The results of a simulation study can be obtained in a timespan of minutes to hours.

Control of the experimental conditions. In a real system, it is hard to compare experiments. The most obvious reason is that some real life situations only occur once, so an experiment can only be executed once. But there are also other factors that cannot be controlled in real systems, which makes it hard to look at the effect of other parameters.

The real system does not exist. If the real system does not exist yet, it is better to build a simulation model first to conduct experiments on beforehand, instead of building a series of alternative real systems.

Fostering creativity. In a simulation study, out of the box ideas can be tested and improved in an environment that is free of risk.

Advantages of a simulation study over other modelling approaches

Besides the advantages of a simulation study over real system experiments, Robinson points out two advantages of simulation studies over other modelling approaches (Robinson, Simulation the Practice of Model Development and Use, 2014).

Variability. The main advantage of a simulation study is that it is capable of perfectly modelling variability in a system. If a system is subject to a significant level of variability, a simulation study makes it possible to predict the performance of a system and the influence of the experimental factors. Robinson illustrates this with an example of failing machines which are analytically taken into account by averaging the failures with the process times, but can be modelled much more detailed with a simulation study (Robinson, Simulation the Practice of Model Development and Use, 2014).

Transparency. In order to show the results to a manager, a set of mathematical equations in a spreadsheet might not be easy to understand or believe the results. A simulation study is appealing since it is more intuitive to understand.

Disadvantages of a simulation study

Stewart Robinson also describes some disadvantages of a simulation study, which are good to mention to give the simulation study a broader context.

Expensive. Simulation software is usually expensive and the price can even get higher when external consultants have to be hired to develop the simulation model.

Data hungry. In order to create a simulation model that is a good representation of the real system, a lot of data is needed. It might be the case that the data is not directly available and must be processed first.

Requires expertise. Conducting a simulation study demands more than just programming skills. The modeller should also have skills in conceptual modelling, statistics and validation. This expertise is not always available at the company.

Over confidence. There is a danger that all the results that a simulation study shows are considered to be right. When interpreting the results of a model, one should take into account underlying simplifications and assumptions.

3.5 Conceptual model

Before we start building a simulation model, we must design a conceptual model. The conceptual model is defined as a non-software-specific description of the computer simulation model that includes the objectives, inputs, outputs, content, assumption and simplifications of the model (Robinson, Brooks, Kotiadis, & Zee, 2010).

- Following this definition, we will make a conceptual model that describes the simulated model of the maintenance strategy for underground bins at Twente Milieu. The main reasons for making a conceptual model according to Robinson et al are (Robinson, Brooks, Kotiadis, & Zee, 2010) are i) to minimize incompleteness; ii) to warrant the credibility of the model, iii) to provide a basis for the validation and verification of the model; and iv) act as independent verification if that is required.

In his book "Simulation, the practice of model development" Stewart Robinson gives a framework for the development of the conceptual model (Robinson, Simulation the Practice of Model Development and Use, 2014). This framework consists of the following five key activities: i) understanding the problem, ii) determining the modelling and project objectives, iii) identifying the model outputs, iv) identifying the model inputs, and v) determining the content (scope, assumptions and simplifications).

3.6 Experimentation

Reliable experiments require an adequate the set-up. This section explains two important factors of a simulation study, namely the warm-up period and the number of replications.

Warm-up period

A simulation model defines experiments for which input values can be altered. The result of every simulation will give the KPI's related to the input values of that experiment. In this way, the influence of different input variables parameters on the costs for the maintenance strategy is assessed. For carrying out the experiments, a warm-up period and a run length for the simulation study are required.

The warm-up period is a way to deal with the initialization bias of a simulation model (Robinson, Simulation the Practice of Model Development and Use, 2014). The warm-up period should be long enough to ensure that the model is in a realistic condition before extracting results and drawing conclusions. The bias comes from the fact that the simulation model starts with an empty system with commonly unrealistic conditions. According to Robinson, there are two main ways to determine the warm-up period, namely the graphical method and the marginal standard error rule (MSER).

Robinson describes the MSER method to determine the warm-up period for experiments. The aim of the MSER is to minimize the width of the confidence interval of the mean of the simulation output after the initial transient data (Robinson, Simulation the Practice of Model Development and Use, 2014).

The MSER method uses the following formula to determine the number of days after which the warm-up period ends:

$$MSER(d) = \frac{1}{(m-d)^2} \sum_{i=d+1}^{m} \left(Y_i - \bar{Y}(m,d)\right)^2 \qquad (13)$$

Where *d* is the proposed warm-up period, *m* is the number of observations in the simulation output data and $\bar{Y}(m,d)$ is the mean of the observations from Y_{d+1} to Y_m.

Number of replications

To perform a proper simulation study, we also need to determine the number of replications per experiment. If we carry out multiple replications for the same experiment, the stream of random numbers changes per experiment, resulting in a better estimate of the mean performance (Robinson, Simulation the Practice of Model Development and Use, 2014). Robinson states that a rule of thumb by Law and McComas asks for three to five replications per experiment. Robinson additionally explains a technique to determine the number of replications by using the confidence interval of the mean value per experiment (Robinson, Simulation the Practice of Model Development and Use, 2014). The idea behind this method is that the narrower the confidence interval, the more precise the estimate of the mean value is.

The technique starts by carrying out a lot of replications of one experiment and choose one KPI to analyse. We take the mean value of this KPI for every replication. Then we compute a cumulative mean and standard deviation over the performed replications. With these values we can compute a confidence interval which narrows with every replication that is added. The formula for the confidence interval is:

$$CI = \bar{X} \pm t_{n-1,\propto/2} \frac{S}{\sqrt{n}} \qquad (14)$$

Where $\bar{X}$ is the mean of the replications, *n* is the number of replications, α is the confidence level and S is the standard deviation of the output of the replications. The level of significance is set to 95%. The deviation of the confidence interval is how wide one half of the confidence interval is compared of the value of the mean. We want the deviation to be lower than 2.5% before we take the corresponding number of replications.

3.7 Relevance to this research

Several ideas from literature described in this chapter are applicable to our research for Twente Milieu. Distinction is made between preventive, corrective and opportunistic maintenance. Especially for underground bins where customers notice directly when the bin does not function properly and stay behind with their garbage, it is important to guarantee a certain uptime for the underground bins. Preventive maintenance (Section 3.1.1) improves uptime.

In order to carry out preventive maintenance, a certain preventive maintenance interval must be chosen. Especially intervals based on usage-severity or on fixed time periods look promising. Usage-severity based maintenance would take into account the usage of the bins by customers, before it undergoes a preventive maintenance treatment of washing and lubrication. In addition, time-based maintenance is investigated because of requirements set by the municipalities and Twente Milieu themselves.

The modelling of a maintenance policy (Section 3.2) requires statistical techniques to determine failure rate distributions and to compare empirical distributions with theoretical distributions. The relationship between time to failure, survival rate and failure rate is quantified. The Weibull distribution and the exponential distribution are commonly used distributions for maintenance management. Then we elaborated on the theoretical parameters for these distributions and identified linear regression as an adequate method to determine the parameters of empirical distributions.

Another important maintenance strategy is opportunistic maintenance (Section 3.3). Because the first and second line maintenance teams of Twente Milieu drive around the streets to carry out corrective repairs, it might gain efficiency if underground bins that need corrective repair are brought to Startpunt for preventive maintenance instead and be repaired correctively at Startpunt at the same time. In the section 4.1 this will be referred to as corrective replacement. The findings on opportunistic maintenance, worked out by Thomas et al (Thomas, Levrat, & Iung, 2008), are used to develop such a strategy for Twente Milieu.

Section 3.4 elaborated on discrete event simulation, a main ingredient for empirical modelling. The theory behind simulation studies and the advantages and disadvantages of different simulation studies lead to the conclusion that discrete event simulation can be used to catch the variability that an analytical model cannot catch. Before starting a simulation study, a conceptual model (section 3.5) needs to be created to define the objective, input, output, scope and simplifications of the simulation study.

4. Modelling approach

Chapter 4 describes the models that are used to analyse maintenance methods for the underground bins. Section 4.1 describes maintenance methods that are carried out at Twente Milieu. Section 4.2 describes the research outline of the next sections. Section 4.3 describes the way to find an optimal preventive maintenance interval by using a cost function. Section 4.4 elaborates on optimizing a maintenance policy by carrying out a discrete event simulation study. Section 4.5 describes the conclusions that we draw from chapter 4.

4.1 Maintenance methods

The next part of this research considers four types of maintenance: corrective repair on the bin site or at Startpunt (corrective replacement), and preventive maintenance for age-based reasons or for opportunistic reasons:

Corrective repair on the bin site: This maintenance method is currently applied. After a notification of a failed bin, the second line mechanics drive to the bin site and repair the bin.

Corrective replacement with repair at Startpunt: This maintenance method is added to the desired situation. Failing bins on the street are replaced by an available bin from the stock at Startpunt, the latter bins are as good as new. The failing bin is transported to Startpunt where it is repaired and given a treatment of washing, lubrication and inspection. After this maintenance treatment, the bin is as good as new and stocked at Startpunt.

Age-based preventive maintenance: This preventive maintenance method uses a preventive maintenance interval that is based on findings in literature. An active bin is replaced after a certain period called the preventive maintenance interval with an as good as new bin from Startpunt. The bin from the street is transported to Startpunt to get washed, lubricated and inspected.

Opportunistic preventive maintenance: Opportunistic maintenance as described in the literature section 3.3 is intended increase the performance of the maintenance strategy. The idea is to use the failure of a bin as an opportunity to carry out preventive maintenance to another active bin in the same neighbourhood. This maintenance method comes with a certain threshold to prevent that the time interval between two preventive maintenance instances does not become too small.

Figure 11 shows a tree diagram of how the maintenance methods relate to each other.

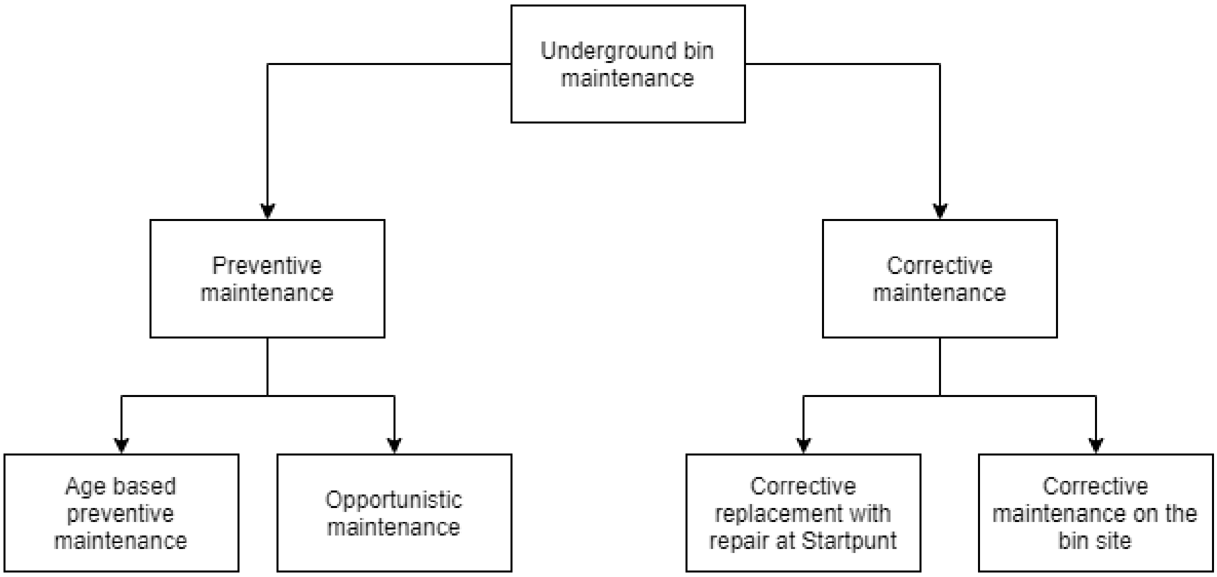

Figure 11 Types of maintenance

These four maintenance methods come with different costs since the nature of the repair differs.

Costs for downtime: Both corrective repair on the bin site and corrective replacement account for downtime, so the costs for downtime must be taken into account for each maintenance method in response to the failure of a bin.

Fees of the mechanics: The corrective repair at the bin site is carried out by the second line mechanics who have a higher hourly fee than the Startpunt mechanics, who carry out the other three maintenance methods at Startpunt.

Transportation costs: The three maintenance methods with preventive maintenance or repair at Startpunt come with transportation costs from the bin site to Startpunt. The transportation costs for the second line mechanics from bin to bin are included in the hourly fee.

4.2 Research outline

The effects of the four types of maintenance we defined in the previous section must be examined in order to determine an effective preventive maintenance strategy for Twente Milieu. We start by analysing the cost function in formula 1 which we found in literature. This cost function leads to an optimal preventive maintenance interval. The cost function incorporates only two out of four maintenance methods from figure 11. Namely (i) corrective repair at the bin site and (ii) age based preventive maintenance.

After analysing the cost function, we can incorporate the other two maintenance methods from figure 11 (i) corrective replacement and (ii) opportunistic preventive maintenance in a discrete event simulation model. This model analyses the performance of the maintenance methods in terms of costs, downtime of underground bins and number of corrective repairs by second line mechanics. Due to the ability of a simulation model to make decisions based on events, we expect to improve the performance of the maintenance planning model.

In order to see how reliable the results are, we end the numerical analysis with a sensitivity analysis. After the two numerical analyses, we can draw conclusions about the effectiveness of maintenance policies and if Twente Milieu should implement the proposed policies.

4.3 Age-based maintenance

In maintenance engineering, the optimal preventive maintenance interval for an underground bin can be determined analytically by using the cost function G(t) based on the failure distribution as described in section 3.1.1 (formula 1). The optimal interval is dependent on the failure distribution, the costs of corrective maintenance and the costs of preventive maintenance. The maintenance methods that are included in this study are (i) corrective repair on the bin site and (ii) preventive maintenance at Startpunt. The costs of random breakdowns leading to unforeseen downtime are important because of lost revenue and customer dissatisfaction and can be included in the corrective maintenance costs.

The cost function G(T) defines the cost per period of time, given a certain preventive maintenance interval. The cost function from chapter 3.1.1 (formula 1) is:

$$g(T) = \frac{C_c * F(T) + \left(1 - F(T)\right) * C_p}{\int_0^T \left(1 - F(t)\right) dt}$$

F(t) is the cumulative distribution function for lifetime T. The numerator concerns the expected costs per cycle and the denominator contains the expected cycle length. The expected values are dependent on the lifetime distribution determined by the mean time to failure (MTTF) of the underground bins.

To determine the optimal preventive maintenance interval analytically, we evaluate the cost function g(T) for every T in days. Typically these kind of figures will present a given T for which the costs per unit of time are the lowest.

Before computing such a graph, the failure distribution needs to be determined. Section 5.1 elaborates on the processing of the failure data to find a failure rate distribution F(t).

4.4 Discrete event simulation

The age based maintenance model compares the effectiveness of two of the four described maintenance methods, corrective repair at the bin site and preventive maintenance of washing, lubrication and inspection at Startpunt. The other two described maintenance methods, corrective replacement and opportunistic maintenance policies, can also add effectiveness to the maintenance strategy but are not taken into account in the maintenance planning model with the cost function. The cost function model does not include all variability needed for this research and the maintenance methods opportunistic maintenance and corrective replacement require more variability and decisions based on events than the cost function model can give.

Another shortcoming of the cost function model is that it does not include the capacity of Startpunt. The cost function results in a strict preventive maintenance interval minimizing the maintenance costs per day. Such a strict maintenance interval implies that all bins should be replaced by a new bin at the same moment, which is not feasible.

For the latter reasons, the simulation study incorporates the four described maintenance methods, takes into account capacity issues and adds more variability to the model.

4.4.1 Opportunistic maintenance in the simulation model

Section 2.3 showed that most of the underground bins are inspected at least once a year. This would imply that opportunistic maintenance policies as described in section 3.4 gain efficiency in the maintenance process. In section 3.4 we described an opportunity as a repair of one component that creates an opportunity to carry out preventive maintenance on other components. Using this opportunity would combine two types of maintenance thus decrease the set up costs. Opportunistic maintenance in this study requires a different analysis because we do not consider different components of one underground bin. However, we will still call it opportunistic maintenance since a failure of an underground bin gives the opportunity to carry out preventive maintenance at Startpunt.

The idea is the following: Twente Milieu seeks to give a preventive maintenance treatment to all underground bins with a regular interval. Such a regular interval depends on the planning of using the available capacity at Startpunt. On beforehand, specific active underground bins are selected to be replaced by fully repaired underground bins. The number of bins depends on the specified interval and the available capacity at Startpunt. In case other non-functioning bins need to be repaired Twente Milieu needs to deviate from the initial maintenance planning and leave one of the pre-selected non-failing underground bins active and replace the one that has just failed instead. Consequently, the second line mechanics do not have to go to the failed underground bin for corrective repair, since the bin will be repaired in combination with the rest of the washing, lubrication and inspection treatment at Startpunt. In the long run, this should save time and labour for the second line mechanics.

4.4.2 Conceptual model

The five key activities for conceptual modelling as described in section 3.6.2 will be discussed and elaborated on in the following sections. The five key activities are (i) understanding the problem, (ii) setting the objective, (iii) choosing inputs, (iv) selecting outputs, and (v) setting the scope.

Understanding the problem

The main problem description has been given in section 2.4 to 2.6 where the desired situation by Twente Milieu concerning washing, lubrication and inspection is explained. Twente Milieu seeks to optimize the maintenance of underground bins by combining maintenance on site (in the streets) and at the workshops. The envisaged planning should combine the time-based preventive maintenance with corrective maintenance at the workshops. A key issue insufficient capacity at Startpunt to carry out preventive maintenance for all underground bins at the same time. Besides this, the analytical model as described in section 4.1 and 4.2 does not catch all variability that a discrete event simulation study can include. Variability is important because of the model simulation of it and the subsequent simulation of the decision taken based on variable actions in the model. For example, the simulation model allows making decisions after a failure occurs. These decisions are possibly based on many factors such as the last maintenance instance and the available stock of bins. Such a decision cannot fully be analysed by a time-based preventive maintenance model.

Objective

According to Robinson (date), it is vital that the objectives of the model are known before making a conceptual model, because without clear objectives it is not possible to create a simplification of reality. In this case, the objective of the simulation model is to design a method to give all underground bins the necessary maintenance treatments, corrective when they break down and preventive when with a certain maintenance interval by minimizing the costs. In addition to this objective, the workload at Startpunt needs to be evenly spread over the available capacity thus minimizing the total maintenance costs for the full maintenance method.

This objective is measurable and data on selected KPI’s in the simulation model are available.

This objective is achievable with the simulation model in this study that incorporates different variables and the relationship between these variables.

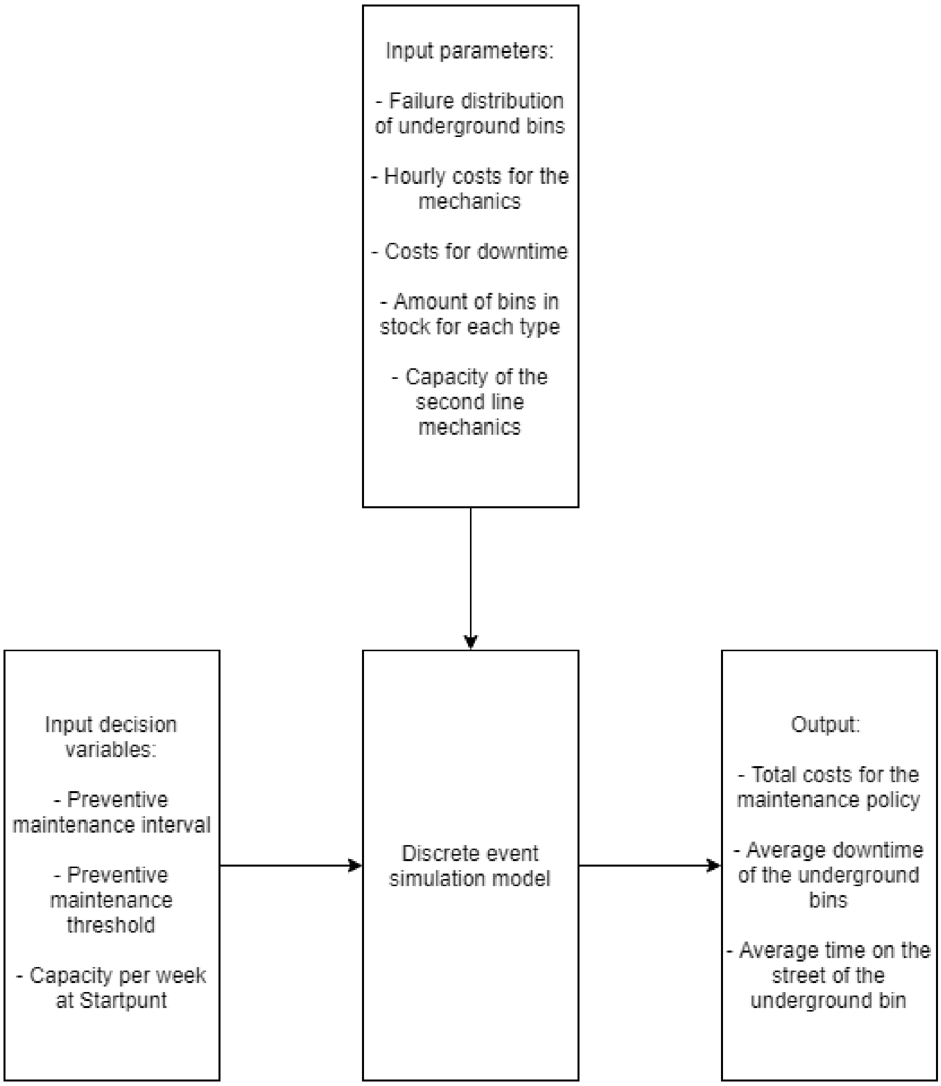

Figure 12 Black box model of the discrete event simulation study

Input parameters

The inputs are the experimental factors that are adjusted in order to achieve the models objectives. For Twente Milieu, the inputs are the interval for preventive maintenance, the time the bins are allowed to go to Startpunt before the time of preventive maintenance (preventive maintenance threshold) and the capacity for repairs of underground bins including washing, lubrication and inspection at Startpunt. The interpretation of the preventive maintenance threshold is given in figure 13.

Figure 12 shows a box model with the decision variables on input on the left-hand side. The box on the top shows the input parameters that are the same for each experiment. The box on the right-hand side shows the output variables of the simulation model, based on which we can compare different experiments.

In section 2.4 we explained that the capacity of Startpunt is limited, so the model uses a minimum time a bin has to be on the street before it can go back to Startpunt at a failure. For this, the variable 'preventive maintenance threshold' is introduced. This variable indicates the time a failing bin is allowed to go to Startpunt for maintenance actions before regular replacement time is reached. This has influence on the opportunistic maintenance strategy since this strategy takes into account failures that occur before the moment of scheduled preventive maintenance. In figure 13 the period after the preventive maintenance threshold is indicated at the left-hand side.

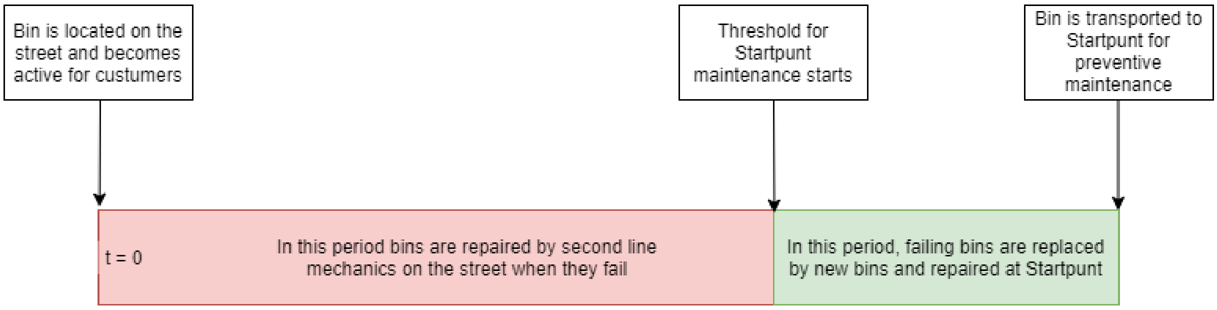

Figure 13 explanation of threshold for preventive maintenance

Besides the experimental factors, the settings that are kept constant in experiments are also part of the simulation model input. These settings include the number of bins on the street and the failure rate distribution of these bins. The failure rate distribution is the same as used in the analytical model (Section 4.2.). Since not all failures are mechanical failures there should be a distribution that decides if the failure is mechanical and can be resolved at Startpunt.

Since all bins periodically need preventive maintenance, the simulation model should follow a planning to process all bins at the right time. But this production scheme is not rigid. During the simulation study, events can take place that change the production scheme for preventive maintenance. To take these events into account, the conceptual process model depicts the events and actions taken based on an event. An example of such an adaptive production planning is that a failure of an underground bin can result in either a maintenance treatment at Startpunt or on the bin site. If the broken bin is repaired at Startpunt, the bin gets an additional treatment of washing, lubrication and inspection which is preventive maintenance. The decision to transport the broken bins to Startpunt changes the schedule.

The decisions included in the simulation are shown in the flowcharts in appendix A and B. The decision process starts when a bin fails (Appendix A). The decision on second-line mechanics or repair at Startpunt is made by the maintenance engineer. A flow chart of the decision by the maintenance engineer is shown in appendix B.

Outputs

The output of the model is defined by Robinson (Robinson, Brooks, Kotiadis, & Zee, 2010) as the statistics that tell us if the objective has been reached. If the objective has not been reached, the output should also show why the objective has not been reached. The main output for this study's model is the costs per year for the entire maintenance plan carried out by Twente Milieu.

The costs of the output include:

- the costs for all maintenance actions both preventive and corrective,
- the costs for each day that a bin is unavailable,
- the purchase costs for each bin in the system,
- the costs for hiring the truck to transport underground bins from the street to Startpunt.

The actual costs for maintenance actions are different from the analytical model in a few ways. Firstly, a broken bin that is repaired at Startpunt for the costs of preventive maintenance has been broken on the street as well, so the costs for downtime have been added to the repair at Startpunt. These costs for downtime have been determined to €100,- for every day a bin is unavailable. Since this is a rough estimation, we will test the sensitivity of the maintenance strategy to the costs for downtime.

The transportation costs, which were a rough estimation in the maintenance planning model as well, can be better specified based on available exact data on how many bins are transported to Startpunt with driving costs of €1000,- a day.

The workload at Startpunt is also a model output that is important for Twente Milieu. The model output should give the number of bins that is processed at Startpunt per week. The capacity at Startpunt is one of the main reasons the simulation model is built, since not all bins can get preventive maintenance at the same time.

The number of maintenance actions by the second line mechanics is also a model output. The number of corrective repairs on bin site that they perform is also important. We expect that number to decrease since more maintenance activities are taken over by the mechanics at Startpunt who perform the washing, lubrication and inspection treatment together with the repair of a broken bin if that happens.

The average amount of days that a bin is unavailable is also a measurable KPI in the simulation model.

Lastly we determine the average time on the street of an underground bin and the standard deviation of this average. This measure indicates whether bins are given preventive maintenance frequently enough (on average).

Scope

The scope defines the possibilities and limitations of the simulation model.

The scope of the simulation is the combination of second line repair jobs and preventive maintenance jobs carried out at Startpunt. We decided to leave out the corrective maintenance jobs by first line mechanics since these jobs differ too much from the maintenance jobs that can be done by mechanics at Startpunt.

The decision to leave out the first line is also due to the computed failure rate which was exponential distributed. According to the literature (Heijden M. v., 2018) a beta value of approximately 1 does not support a preventive maintenance strategy.

4.4.3 Assumptions, simplifications and verification

To make a modelled representation of the reality, assumptions and simplifications are necessary. This section explains which assumptions were made in this simulation study.

Driving time between bins on the street is not taken into account: In the real life situation it is useful to transport bins from the street to Startpunt which are close to each other. However, if we only consider the municipality Hengelo, there are a lot of underground bins which are relatively close to each other. In addition, the mechanics of Twente Milieu use route optimizing software. The shortest routes between the bins cannot be included in the simulation model because of programming limitation. Driving time is included in the capacity of bin transportation on one day.

All underground bins have the same failure rate distribution: This assumption is justified by the fact that all underground bins have the same mechanical structure. The only possible difference is that the bins for residual waste have electronics inside to register cards from customers. The failures concerning the electronics are resolved by the first line mechanics and are beyond the scope of our research.

After corrective repair and preventive maintenance the failure rate starts again: In the simulation model we assume that a broken bins are adequately repaired and mechanics also verify the state of other components of the underground bin.

The exact process times at Startpunt are not taken into account: The process times at Startpunt for washing, lubrication and inspection are not taken into account in the simulation models. This would require data on the repair time per failure mode. This data is not available because these kind of repairs are not carried out at Startpunt yet. The main implication of the lack of this data is that the stock of underground bins cannot depend on the lead times in Startpunt. This issue is resolved by setting the capacity of Startpunt of as an input variable for the model.

Lastly, to verify the model we check if the model follows logic reasoning, and the debugging tools by Siemens Plant Simulation are used. By means of this tool each bin that fails is being traced. It is checked what happens when the method of repair is decided by the model, either at Startpunt or by the second line mechanics. And a last check verifies whether the model adds the right numbers to the KPI tables and information tables. From extensive debugging, it follows that the model follows the intended logic.

4.5 Conclusions of the modelling approach

Sections 4.1 to 4.4 describe a manner in which we can build models to analyse proposed maintenance policies at Twente Milieu. Section 4.1 elaborated on four maintenance methods that should be incorporated in the models. We concluded that these four methods are (i) corrective repair at the bin site, (ii) corrective replacement of failing bins, (iii) age-based preventive maintenance and (iv) opportunistic maintenance.

Section 4.3 describes how we can set up a maintenance planning model based on the cost function (Formula 1). The advantage of using this method is that with little computation time we can find an optimal preventive maintenance interval for underground bins. The drawbacks are that there are only two out of four maintenance methods involved, corrective repair at the bin site and preventive maintenance at Startpunt.

Section 4.4 shows the conceptual model for a discrete event simulation study to analyse the proposed maintenance strategies. The main advantage of carrying out a simulation study is the inclusion of extra variability, the opportunity to respond to events and incorporation the four maintenance methods from section 4.1.

The next section elaborates on the numerical analysis of both the time-based preventive maintenance model and the discrete event simulation study.

5. Numerical analysis

Section 5 elaborates on the numerical analysis of the cost function model and the discrete event simulation model. The goal in chapter 5 is to analyse several maintenance policies and find a way to optimize maintenance. Section 5.1 shows the failure distribution based on failure data. Section 5.2 describes the implementation of the failure distribution in the cost function in order to find the optimal preventive maintenance interval. Section 5.3 shows how the implementation of the same failure distribution in the discrete event simulation model. Section 5.4 validates the simulation model with the reality. Section 5.5 describes the sensitivity analysis to test the robustness of the results. Section 5.6 summarizes the results from the numerical analysis.

5.1 Failure data

The failure rate distribution of underground bins is necessary to design an analytical model and to find the optimal preventive maintenance interval as described in section 3.2.1. This section describes the methodology to collect and process the data.

5.1.1 Method of data gathering

Twente Milieu stores data in an online ERP system Wincar (Twente Milieu, 2015). Maintenance jobs performed on any vehicle, underground bin or other appliance are registered in this system. As a result, a lot of data is available on the frequency of visits to the bins by mechanics and for what reason.

The data provides insight in the failure distribution of underground bins. Some choices and assumptions on data selection are necessary. In the current situation practically only corrective repairs are carried out by Twente Milieu. The only policy on preventive maintenance is the outsourced washing, which is not taken into account in this study. This means that the data is based on the failures and therefore suitable for a failure distribution analysis; there is no interference of preventive maintenance.

Because the maintenance plan in this study concerns the underground bins in Hengelo, the corrective maintenance data are on this municipality. The data include the maintenance jobs by the first line and second line mechanics. The data is available from end 2013 and is still updated since corrective maintenance is continued. This study uses the data of 2016 – 2018 on the corrective maintenance activities by Twente Milieu. These last three years the number of underground bins in Hengelo has increased. This means that the last three years provide sufficient data points that adequately take into account the increased pressure on underground bin of the last years. The data of 2019 will be used to validate the model afterwards.

One assumption we have to make because of the data availability is that the time of maintenance is the moment of failure. This is not the real-life scenario since there is some elapsed between the moment the failure occurs and the moment Twente Milieu is notified. There is also some elapsed time between Twente Milieu is notified and the moment of maintenance, but there is only data available of the moment of maintenance. However, the difference between failure and repair is a matter of a few hours to a few days. That is on a negligible scale compared to a life time of months to years, which justifies this assumption for the time of failures.

An additional assumption is that each underground bin has the same failure rate. This assumption is justified by the fact that the system and components of the underground bins are almost identical. This means that the failure data of all bins apply to the failure distribution of a single bin. Consequently, it is possible to use the general failure distribution to define an optimal preventive maintenance interval for a single bin.

The relevant data available from Wincar concerns: unique number of the underground bin, date of maintenance and executing mechanic (first of second line). There are two relevant failure types are distinguished. Firstly the failures where the first line mechanics are summoned to execute corrective repairs, and secondly the failure where the second line mechanics are summoned to execute the corrective repairs. The nature of both types of failure differs, because the first line mechanics usually repair bins that fail because of getting stuck or because of electrical trouble. Second line mechanics carry out repairs to mechanical failures in the inside structure of the underground bin. Probably the first line failures have more of a random nature (customer actions) and second line failures have a nature that is more time dependant. Due to these differences in nature, both failure types likely have a different failure distribution. Note also that the failures that are repaired by first line mechanics are also failures that are more easily repaired on the bin site. The electronic parts and the input shaft are easily reachable from outside the bin by opening the underground bin. The second line failures are also repairable on the bin site, but require more work.

5.1.2 Life time distributions

The time between failures can be obtained by extracting all dates an underground bin has been visited from the total table. Then by sorting them in ascending order and subtracting two consecutive maintenance dates, we find the number of days between two maintenance activities. Based on our assumption, this can be seen as a time to failure for an underground bin. By doing this for all underground bins in Hengelo for the years 2016 to 2018, we have a large data set to find a failure distribution.

This sequence of actions results in a list of times to failure for each of the two relevant failure types (i) first line and (ii) second line. The times to failure of the underground bins are presented in figure 14 and 15. The number of bins is based on the rule of thumb for histograms where the number of bins is the square root of the sample size. Clearly the histograms for first line failures follow the indicators of an exponential distribution.

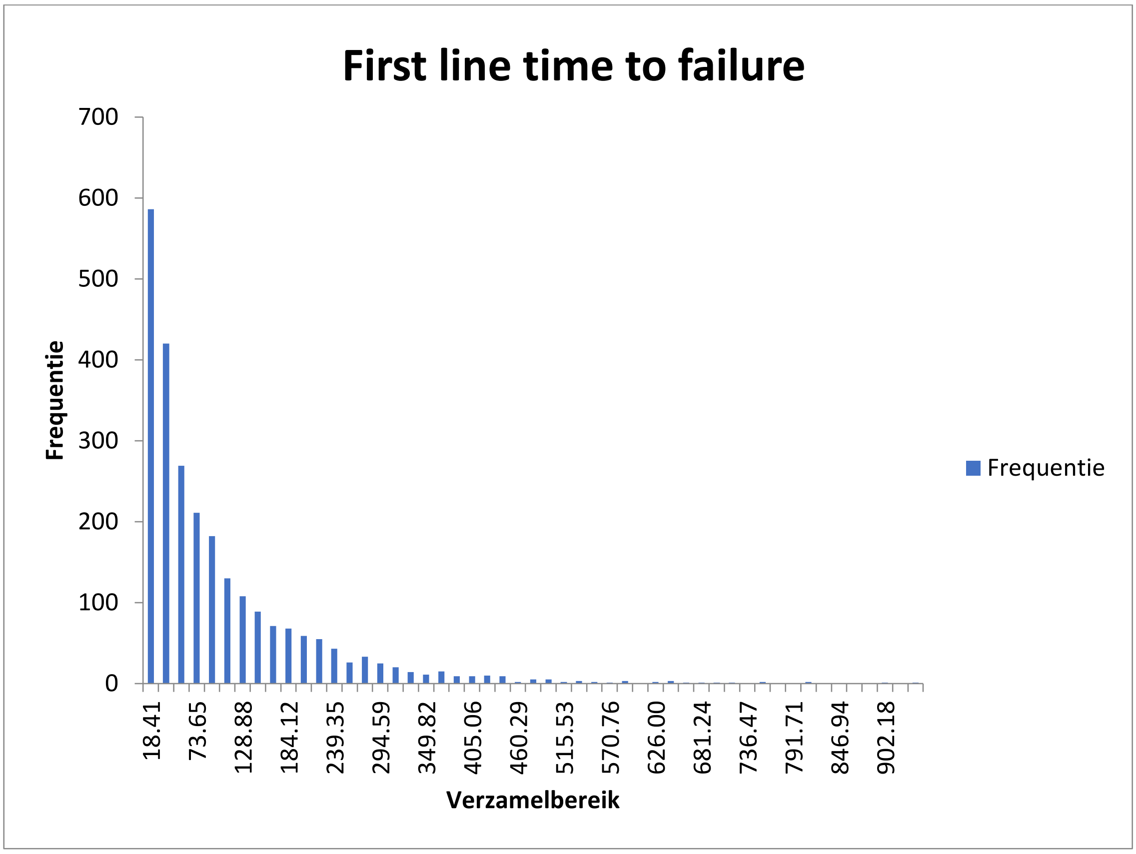

Figure 14 Histogram of times to failure of first line failures

Figure 15 Histogram of times to failure of second line failures

However, the failure rate function for second line failures seems to be distributed according to a Weibull distribution. As we described in section 3.3, is the Weibull distribution commonly used in maintenance management. For this empirical distribution the parameters η and β, are estimated in order to fit a Weibull distribution. We use the least mean square regression method described in section 3.3

We start ordering the times to failure in non-decreasing order in such a way that $X_1 \leq X_2 \ldots \leq X_n$. After that, we calculate the natural logarithm of each time to failure, which can be seen as the x(t) of the linear function we want to find. Then we calculate$1 - \hat{F}(X_i)$, we use $\frac{i-0.5}{n}$ as proposed by van der Heijden (Heijden M. v., 2018).

The linear regression function provides a variable coefficient for the two datasets. The variable coefficient of ln(t) gives the estimated value of beta. Based on the histograms in figure 14 and 15 it is expected that the beta value of the first line failure rate is close to one. If that is the case, the Weibull distribution would approach the exponential distribution and this is in accordance with the histograms. We expect the value of the beta of the second line failure to be larger than 1 since there are indications in the histogram that the failures are Weibull distributed.

Table 3 Parameters of failure rate distributions

Failure/parameter	β	C	η	R^2
First line	0.997	-4.4276	84.95781	0.969
Second line	1.280	-6.85303	211.6387	0.995

Table 3 shows the results of the least mean square regression. The hypotheses about the beta are confirmed by the analysis. This means that the failure rate of first line failures is exponentially distributed and random. The second line failure distribution shows the characteristics of a Weibull distribution with wear out property. The failure rate is higher than 1, so a preventive maintenance policy can be useful. The first check to quantify the goodness of fit is given by the R^2 value that is the outcome of the regression analysis. We show the values of R^2 in table 3 as well. Al values of R^2 are very close to one, which is an indication the X is a good predictor for Y. The empirical distributions should be tested to the theoretical Weibull distribution with the parameters β = 1.28 and η = 211.64.

For this, the Chi-square test we compute the expected number of data points in on bin for the theoretical distribution. The number of bins is determined by the rule of thumb that the number of bins is the square root of the number of data points ($\sqrt{n}$) which is $\sqrt{397} = 19.9$ thus 19 bins. So, we want to see how much the empirical distribution differs from the theoretical distribution. The number of bins is determined the measure is the difference between the two bins squared divided by the expected number of data points in a bin. The results are shown in the table in appendix C.

The degrees of freedom for this Chi-square test are calculated as: (19-1)*(2-1) = 18 and the significance is 0.05 which means a probability of 1 - 0.05 = 0.95. The Chi-square table value 28.87 and thus the value of the Chi-square test (19.86) is lower than the table value. This means that we can conclude that the empirical data does not differ from the theoretical Weibull distribution (β = 1.28 and η = 211.64) with a level of significance of 0.05.

From the Chi-square test we conclude that the failure distribution for the second line failures are Weibull distributed with a level of confidence of 95%. The value of confidence is high enough to use the Weibull distribution in the numerical analysis that we will carry out in section 5.2 and the discrete event simulation study in section 5.3.

5.1.3 Discussion on data analysis

The parameter estimations are according to our estimations. The fact that the first line failures are exponentially distributed is expected because a large part of the failures for the first line is due to garbage bags that get stuck in the underground bin. These failures are not time dependant since they randomly happen, for example when someone drops a bag that is too large. Many other first line repairs are due to vandalism or abuse of the underground bins, which also randomly occur.

The repairs which are carried out by the second line are because of failures of parts that are not reachable for customers, and therefore they are not subject to human actions and consequently subject to elapsed time. From this perspective the Weibull distributed failure rate with the wear out property since $\beta > 1$ was expectable. According to literature, this indicates that preventive maintenance can be an effective policy. We study this in section 5.2, where we add the costs for maintenance actions to the research.

5.2 Numerical analysis for time-based preventive maintenance

This section shows calculations for the optimal preventive maintenance interval based on the cost function as described in literature section 3.1 and based on the failure distribution presented in in section 5.1. In section 5.2.1 we will define the costs for maintenance actions at Twente Milieu to analyse the cost total cost function.

5.2.1 Costs for preventive and corrective maintenance

In the previous section, we described the failure distribution for underground bins. The failure distribution for second line failures seems to be suitable for a preventive maintenance policy, since the Weibull distribution has a beta value that is higher than 1, which is in accordance with values in literature (Heijden M. v., 2018). According to van der Heijden, a second criterion for a suitable time-based preventive maintenance policy is that preventive maintenance is cheaper than corrective maintenance. The cost estimations should show if that is the case and provides information on the influence of the costs on the optimal preventive maintenance interval (Heijden M. v., 2018).

Only the second line failures follow a Weibull distribution, an optimal preventive maintenance interval based on the second line failure rate is computed. These failures are time dependent, unlike the first line failures, and thus suitable for a time based preventive maintenance policy.

The failure rate distribution in section 5.1 is used to compute the graph for expected maintenance costs per period of time. Prior to the calculation of the costs per period of time, the costs for both corrective and preventive maintenance need to be defined.

The estimation of the costs for maintenance are based on the data at Twente Milieu. The first estimates are made for corrective maintenance. The internal price Twente Milieu uses is €72,- per hour per mechanic. The second line mechanics are always working together, so their total prices is €144,- per hour. For a working day, Twente Milieu calculates 8 hours. So, for second line maintenance there are daily costs of 1152 per day. Mechanics can handle about 5.5 bins per day. This means that the costs for a corrective maintenance action are estimated at 1152/5.5 ≈ €209,- The €72,- for the mechanics include the costs for the truck they are driving in and all other overhead costs for employing mechanics.

For preventive maintenance variable costs per bin are estimated at €1000,- divided by the number of bins transported on that day plus additional labour costs, which are much lower than for the corrective maintenance because the mechanics are being educated and do drive around. Consequently more bins per day are handled. We estimate the costs of the mechanics at Startpunt on €50,- per bin.

The costs for materials have not been taken into account, since these are about the same for all types of maintenance and are sometimes part of the labour costs. The total costs have been calculated in the table 4.

Table 4 Maintenance costs for the current and proposed maintenance policy

Type of costs	Current preventive maintenance policy	Proposed time-based preventive maintenance policy
Hiring Truck (€)	0	1000 per day
Hiring BWaste for Washing, lubrication and inspection (€)	45 per bin per time	0
Corrective maintenance on the bin location (€)	250 per bin	250 per bin
Preventive maintenance at Startpunt (€)	0	50 per bin
Costs for downtime (€)	100 per day	100 per day

With these costs we can evaluate the costs per unit of time. This is including the estimated number of 20 bins per day, which adds €50,- per bin to the preventive maintenance costs.

Costs for downtime

Section 2.2.3 mentioned the negative consequences of downtime of the underground bins shortly. Although there is lost revenue since people do not pay the €1,20 fee and leave the waste around the bin, a larger loss is in customer experience. Besides, this mess gives negative attention in traditional media and on social media. On the long run, this also encourages other people to leave waste behind without paying. In 2017 the council of Enschede discussed measures to decrease the number of illegally disposed garbage bags. Most of the proposed measures are costly in terms of extra employees, extra IT-systems or surveillance cameras. Because the exact costs for downtime are hard to estimate, we analyse the effect of different cost configurations on the optimal maintenance interval (Figure 16).

Since we see variability in the costs for corrective maintenance (we do not know the exact costs for downtime) and for preventive maintenance (the costs depend on the number of transported bins on one day), we decided to show the impact of the variability on the optimal preventive maintenance interval in the graph in figure 16.

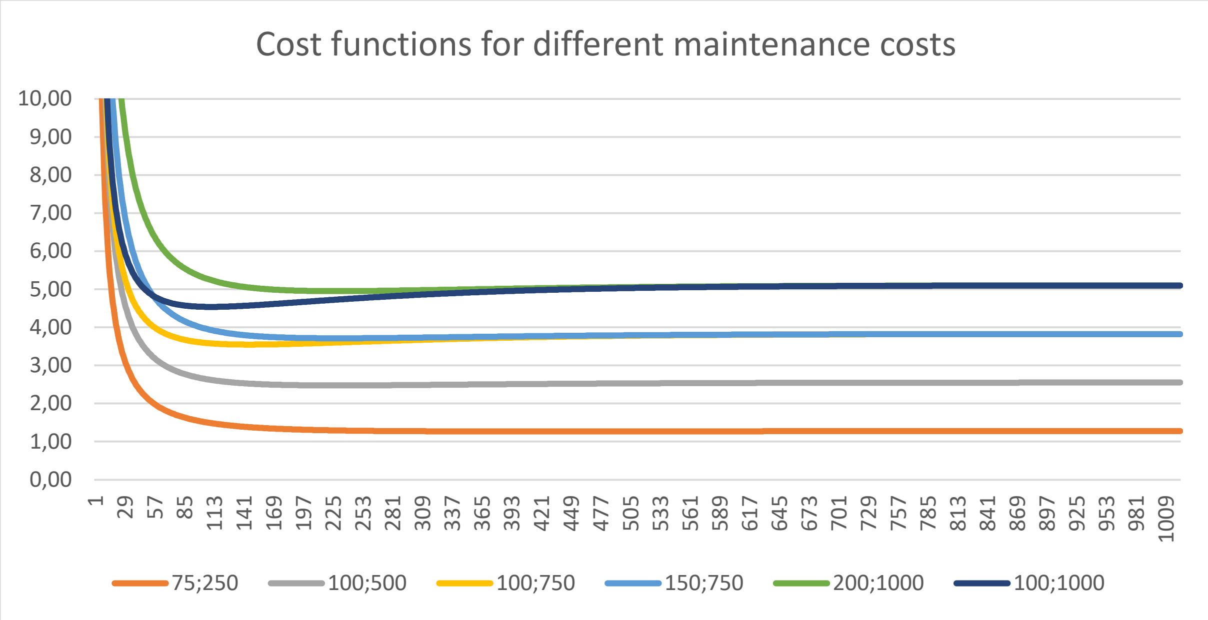

Figure 16 cost function G(T)

Table 5 Optimal maintenance intervals and effectiveness for several cost configurations

Preventive costs in euros (€)	Corrective costs in euros (€)	T* in days	Effectiveness
100	500	240	1.030011079
100	750	165	1.078120782
150	750	240	1.030011079
200	1000	240	1.030011079
100	1000	120	1.123926072

According to the data set and the costs for preventive maintenance and corrective maintenance, the optimal maintenance interval depends on the ratio between the corrective and preventive maintenance costs. This is shown in table 5. The higher the costs of corrective maintenance compared to the costs for preventive maintenance, the shorter the optimal maintenance interval becomes (Figure 16). If the costs of corrective and preventive maintenance are close to each other, a time-based maintenance strategy becomes less effective.

5.2.2 Discussion on maintenance interval

Twente Milieu seeks to give each underground bin a preventive maintenance treatment once a year. The results in table 5 show that that maintenance intervals that become longer (240 days) are less effective. This is due to the relatively low value of beta. The beta value of 1.28 is quite close to 1 which is points to an exponential distribution thus indicating that preventive maintenance might not be very effective.

The uncertainties in the costs for corrective and preventive maintenance make it hard to determine the optimal maintenance interval, however a good indication of the effectiveness of a preventive maintenance interval is visible in figure 16.

For a strict preventive maintenance interval of a specified number of days, the capacity of Twente Milieu is not sufficient to give all underground bins a preventive maintenance treatment within a short time. This means that the preventive maintenance treatment for the underground bins must be spread over a certain period of time, depending on the capacity of transportation and processing of bins. In the research question in section 1.3 we stated that the new preventive maintenance strategy should fit within the financial and working capacity of Twente Milieu.

The last discussion point on the results of the cost function is that it incorporates only preventive maintenance at Startpunt and corrective repairs on the bin site. As we mentioned in section 4.1, there are two other potentially useful maintenance methods that are not taken into account in this maintenance strategy. These methods are corrective replacement and opportunistic maintenance.

Because of the latter reasons, the cost function G(t) is not the best way to determine the interval for preventive maintenance. It is better to combine the costs for preventive maintenance with different parameters such as the capacity of Twente Milieu and different approaches to determine which bins gets preventive maintenance. Therefore a simulation study as described in the literature review section 3.5 is carried out in the next section.

5.3 Numerical analysis for discrete event simulation

This section analyses the results from the simulation model. We start by explaining the KPI's and the experimental design and then present the results of the current situation compared to the simulation model and the improvements that can be achieved by insourcing preventive maintenance. The dashboard of the simulation model is shown in figure 17.

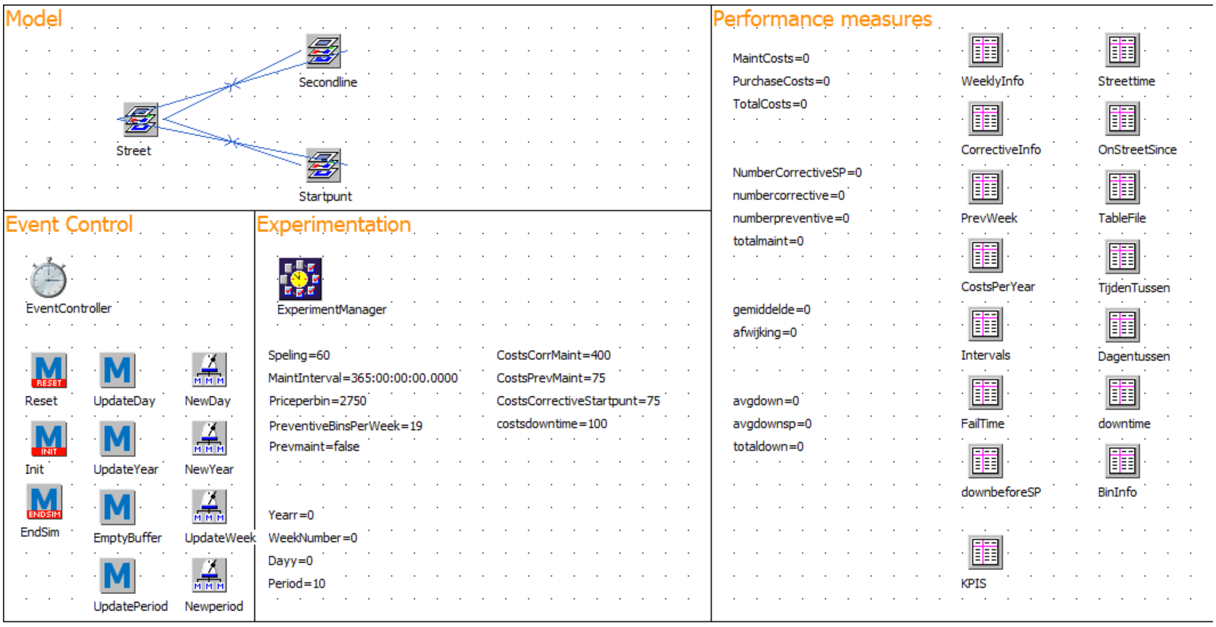

Figure 17, Dashboard of the discrete event simulation model

5.3.1 KPI's

Before we start the numerical analysis we need to have some indication of the performance of the current situation. We acquire this scenario by modelling failures that are repaired on the bin site by the second line mechanics only, as the situation is now. This gives a good indication of the values of the relevant KPI's in the current situation according to the simulation model. We mentioned the KPI's already shortly in the output paragraph in section 5.3: the total costs for the maintenance strategy; the average time a bin is on the street before preventive maintenance at Startpunt; the number of corrective repairs by second line mechanics; and the average downtime of a bin after a breakdown.

The average time on the street is a relevant KPI only if preventive maintenance is included. This KPI, together with the standard deviation of the time on the street, indicates if Twente Milieu is able to give every bin preventive maintenance within the proposed preventive maintenance interval. This KPI gives a useful insight, since it might be necessary to visit a bin location for maintenance as well, for example due to smelly air or failures in the fixed mechanics of the pit.

We expect that the number of maintenance actions increases by applying a preventive maintenance strategy because the underground bins are repaired before the end of their lifetime. On the other hand, this decreases the costs for maintenance since the bins are repaired before they fail and consequently do not lead to negative consequences of failure.

5.3.2 Warm-up period

In order to determine the warm-up period and avoid the initialization bias as described in section 3.6.3, we use a KPI that depends on the emptiness of the system. We choose the number of failing bins per day in the baseline scenario without preventive maintenance. This KPI is subject to the initialization bias because all bins start with the same failure rate and the second line mechanics are directly available to fix it. This is not a realistic situation.

We ran the simulation for 10 years, thus m = 3650. The graph in figure 18 displays the output. In the graph it is not very well visible but on after 16 days of warm-up period, de MSER(*d*) value is minimal. Therefore all information from day 0 to day 16 is excluded in the simulation model. Because the simulation study is non-terminating, we can use any period of days larger than 16 as a warm-up period. With most settings for preventive maintenance interval and the threshold, there is preventive maintenance at Startpunt in the first 20-30 weeks of the first year. In order to overcome this period and for modelling purposes the monitoring of the KPI's starts after year 1.

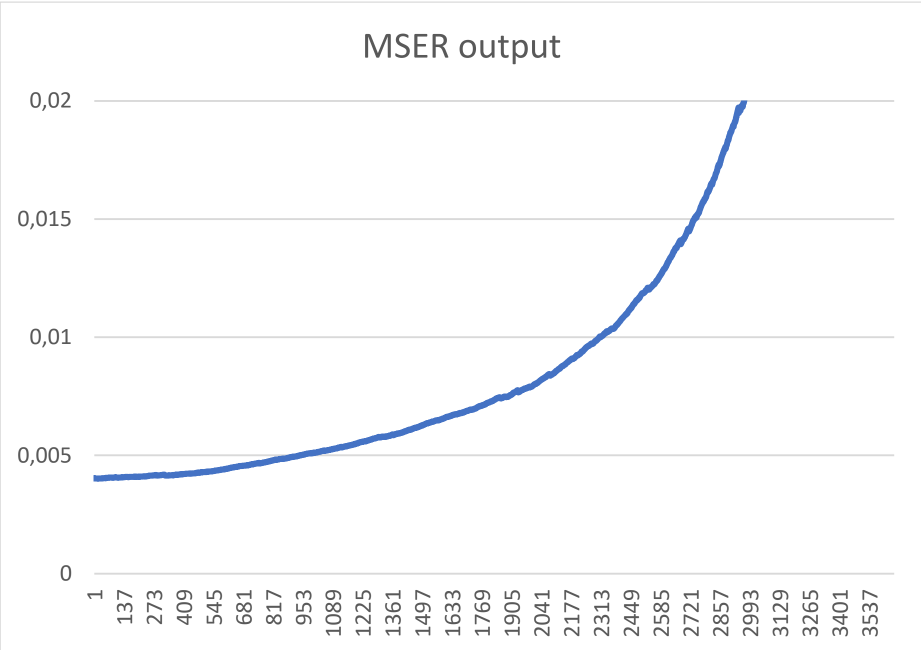

Figure 18 MSER output

The method of confidence intervals (described in section 3.6.3) is used to determine the number of replications per experiment and this number should match the rule of thumb by Law and McConas. The upper and lower bound of the confidence interval are set by formula 14, with the results presented in Table 6.

Table 6 Simulation output to determine number of replications

Replication value maintenance costs (€)	Cumulative mean	Standard deviation	Lower bound	Upper Bound	Deviation (%)

5096000	5096000	N/A	N/A	N/A	N/A
4966500	5031250	52316.12	4089713	5972787	18.71377
5046500	5036333.33	65345.87	4802221	5270445	4.64846
5013000	5030500	54615.32	4916449	5144551	2.267198
4948000	5014000	59986.46	4920230	5107770	1.870172
5031000	5016833.33	54100.52	4946965	5086701	1.392668
5062500	5023357.14	52316.12	4964655	5082059	1.168576
5019500	5022875	48454.51	4974201	5071549	0.969048
5003500	5020722.22	45782.85	4978731	5062713	0.836351

From table 6, it follows that four replications per experiment gives a confidence interval narrower than 2.5% deviation. This fits within the rule of thumb of 3 to 5 replications per experiment.

So the conclusions from this section are that we have a run time of 10 years, with at least 16 days of warm-up period and 4 replications per experiment.

5.3.3 Input variables and hypotheses

Three experimental decision variables in the conceptual model have hypothesised impact on the optimal maintenance strategy.

Maintenance interval. This is the main variable to check how the simulation model fits the maintenance planning model and whether Twente Milieu manages to give each bin a treatment of washing, inspection and lubrication at Startpunt once a year. From numerical analysis of the maintenance planning model in section 5.2, we learned that a maintenance interval of around 200 days is effective in case the difference between corrective and preventive maintenance costs is high.

A large preventive maintenance interval will lead to higher number of corrective repairs, a larger downtime per breakdown but also to less transportation costs and fewer preventive maintenance actions.

Threshold before preventive maintenance. The threshold before preventive maintenance is necessary to improve the maintenance planning with respect to the capacity at Startpunt and to optimize the concept of opportunistic maintenance as introduced in section 3.4. We expect that a higher threshold time results to less corrective repairs on bin site by the second line mechanics, because bins are transported to Startpunt when failing.

Capacity of Startpunt. The main reason to use this decision variable is to check if the proposed maintenance strategy fits the capacity of Twente Milieu. Besides this we can see if having a larger capacity improves the results. This would reduce the number of transportation days from the street to Startpunt, which saves costs from hiring the truck. On the other hand, this variable reduces the influence of the preventive maintenance threshold and the opportunistic maintenance.

5.3.4 Experimental design

The testing of three variables in a broad range in a full factorial experimentation would require too much running time. A full factorial experimental design includes tests of all combinations of input factors in order to see exactly which settings for the input variables gives the best results. Next to that, the full factorial experimental design has to be carried out four times because of required replications. For example, testing the capacity of Startpunt between 12 and 40, the preventive maintenance threshold from 20 days to 80 days with an increment of 10, and the maintenance interval between 300 and 400 days with and increment of 10 would lead to 29*7*11 = 2233 experiments to be carried out in fourfold. With 10 seconds per run, this would require a running time of 25 hours. This phenomenon is described as the problem of combinations by Robinson (Robinson, Simulation the Practice of Model Development and Use, 2014).

We need to define our experiments in such a way that the running time shortened to at most 3 hours, which means about 300 experiments at most.

Therefore we narrow down the range to 13 to 18 bins, a preventive maintenance interval range from 260 to 360 days and just two values for the preventive maintenance threshold, namely 60 and 90. From these experiments we find the influence of the three decision variables on the costs, the average downtime and the number of maintenance activities. Following this set of 132 experiments, we can search in smaller ranges of decision variables. This leads to an adapted search with fewer experiments.

5.3.5 Results

This section compares the results of the modelling of the current situation without preventive maintenance at Startpunt and the desired situation with insourced preventive maintenance. The main reason to model the current situation instead of taking the costs that are made in reality is that we can compare modelled situations. If we would take the costs that are made in reality, the comparison with the outcomes of the simulation model would be less reliable.

Outsourced scenario

In the outsourced scenario generated failures are repaired by second line mechanics. This gives an indication of the performance of the system in the current situation. In this scenario, there is no preventive maintenance and thus the maintenance interval and the preventive maintenance threshold do not matter as input variables.

The output includes the costs for the maintenance strategy, the average downtime after a failure and the number of repairs are taken into account. The average time on the street is not measured, because this is only a measure in the scenario where Twente Milieu carries out the preventive maintenance actions.

For the current situation with outsourced preventive maintenance and corrective repair at the bin site we have the input shown in table 7.

Table 7 Configurations of simulation model to analyse the current situation

Preventive maintenance	False
Costs corrective maintenance	€400
Costs for a day down	€100
Alpha	211.6
Beta	1.28
Warm-up	1 year
Run length	10 years
Number of bins	544

The maintenance costs include the costs for second line mechanics who repair each broken bin on the bin site and the costs for downtime which is set to €100 per day. The costs of purchase and amortization are added to compare scenarios with more bins available for replacement of underground bins. Estimates by Twente Milieu employees result in a price of 2.750 Euro per bin and an amortization period of 15 years. The additional BWaste costs are the costs for outsourcing washing, lubrication and inspection on the bin site, where BWaste charges €85.00 per bin for two maintenance activities in a year). Table 8 provides the results for the baseline scenario with outsourced preventive maintenance on the bin site and corrective repair on the bin site by Twente Milieu mechanics.

Table 8 Results of the current situation analysis

KPI	Simulation outcomes	Per year
Maintenance costs (€)	4844875	€538319.44
Purchase and amortize costs (€)	544*2750= €1496000	1496000/15= €99733
Additional costs BWaste (€)		544*85= €46240
Downtime (days)	1.286	
Total costs (€)		684293,-
Number of corrective maintenance actions	9161	1018

Preventive maintenance at Startpunt

For the simulation study on the effectiveness of preventive maintenance at Startpunt the three input variables mentioned earlier are used: the preventive maintenance interval, the preventive maintenance threshold, and the capacity of bins per week. The objective of the modelling is to minimize the maintenance costs by modifying the input variables. The costs of the preventive maintenance strategy should preferably be lower than the costs of the outsourced scenario in the previous paragraph. Secondly we hope that the outcome of the experiments lowers the average downtime of the underground bins.

In the first experimental design we carried out the experiments as shown in table 9 with a full factorial design. This lead to a total of 11*2*6 = 132 experiments. This number is feasible considering the amount of data generated and the running time. These can be seen as exploratory experiments to investigate the influence of the three input variables.

Table 9 Ranges of experimental factors for simulation model

Variable	Minimum	Maximum	Increment
Maintenance interval (days)	260	360	10
Threshold (days)	60	90	30
Capacity Startpunt (bins per week)	13	18	1

Figure 19 shows the influence of the preventive maintenance interval in days (x-axis) on the annual maintenance costs. The annual costs decrease when the preventive maintenance interval decreases. The main reason for the decreasing costs are the lower fees for the mechanics at Startpunt and the decreased downtime. A short preventive maintenance interval leads to a high pressure on Startpunt due to the ambition to carry out preventive maintenance more often. The drawback of this policy is visible in the average time and the standard deviation of the length of stay on the street before preventive maintenance.

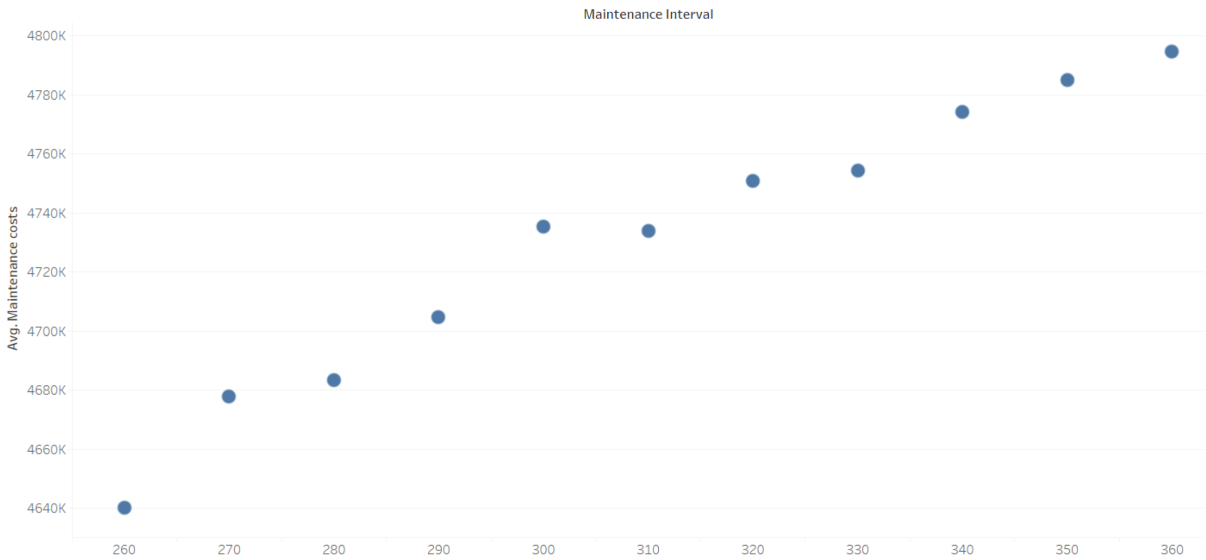

Figure 19 Results of the second simulation run

Next, we look at the influence of the threshold time on the total costs for maintenance. A higher threshold means that it is allowed to treat bins with corrective maintenance at Startpunt shorter after a previous visit to Startpunt. The influence of a higher threshold is that more failures are repaired at Startpunt, since it is allowed earlier, but this also means that broken bins can stay on the street a few days longer because the transport for corrective maintenance at Startpunt is not on a daily basis, in contrast to corrective repair at the bin site. Hence, there is a trade-off between costs for downtime on the street and cheaper labour at Startpunt.

Decreasing the preventive maintenance interval and increasing the threshold leads to a situation where available capacity influences the results. The available capacity allows a certain number of bins per week to be handled at Startpunt. Consequently, the maintenance methods that are carried out at Startpunt shift from preventive maintenance to corrective replacement with repair at Startpunt. The biggest flaw of this policy is the reactive nature which leads to more variability in the time a bin is on the street between two preventive maintenance instances.

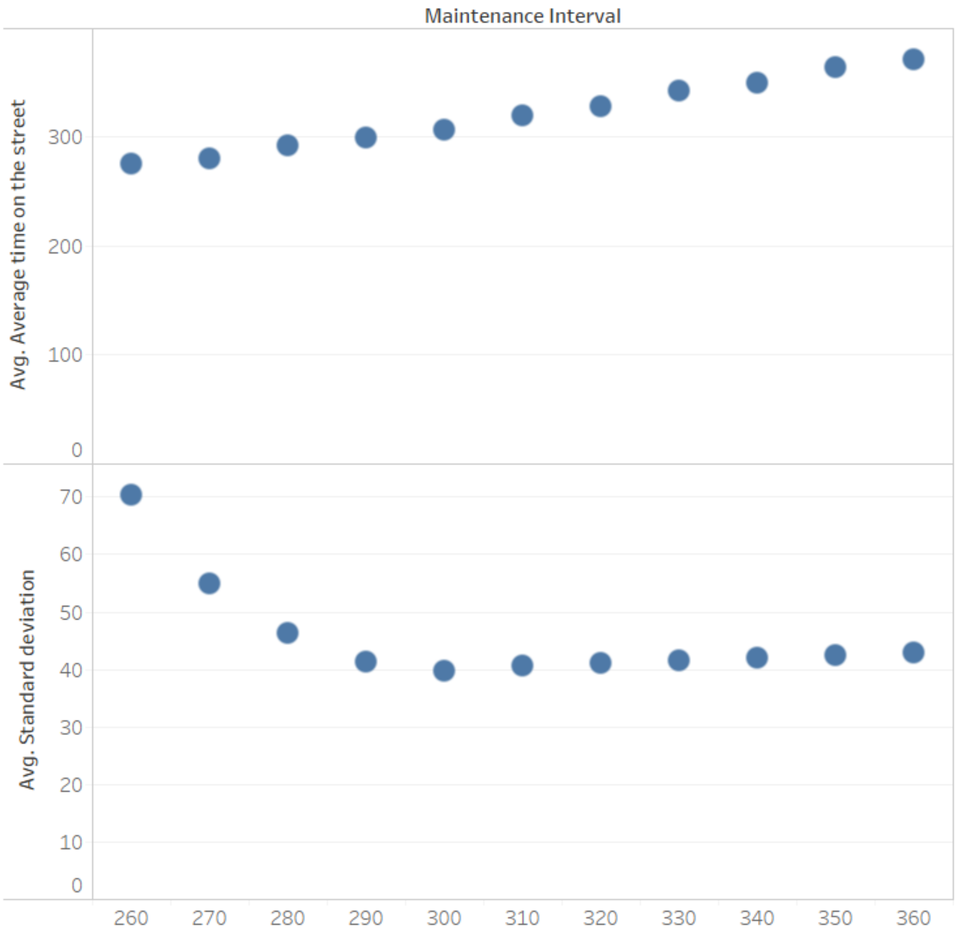

Figure 20 Average time on the street against preventive maintenance interval

The increased variability is demonstrated in figure 20. The figure shows that the average length of stay increases with the increase of the preventive maintenance interval, which is a logical consequence. However, the standard deviation increase with a lower preventive maintenance interval. Figure 20 shows that a preventive maintenance interval of 260 days leads to an average time on the street of 275 days with a standard deviation of 75 days. On the other hand, a preventive maintenance interval of 360 days result in an average time on the street of 371 days with a standard deviation of 40 days.

Lowering the variability

For Twente Milieu it is useful to reduce the variability in the length of stay on the street. The reduction of the variability can lead to a stricter maintenance interval per bin. Initially, Twente Milieu aimed at giving preventive maintenance to each bin at Startpunt once a year.

To examine this option with the simulation model, the maintenance interval is increased to values around 365 days and the weekly capacity at Startpunt is large enough that every bin can be treated at least once. The model objective is to reduce the variability in the length of stay on the street.

Figure 21 shows the results of a set of experiments where the maintenance interval is set to one year. The dots on the graphs represent the average value of five experiments with different threshold values and the weekly capacity depicted on the x-axis. It is noted that an increase in weekly capacity leads to an average time on the street closer to one year. The increase of the weekly capacity does also mean that de standard deviation of the time on the street decreases as expected. The influence of the capacity is according to the expectations, a higher capacity ensures that more bins get preventive maintenance at the right time.

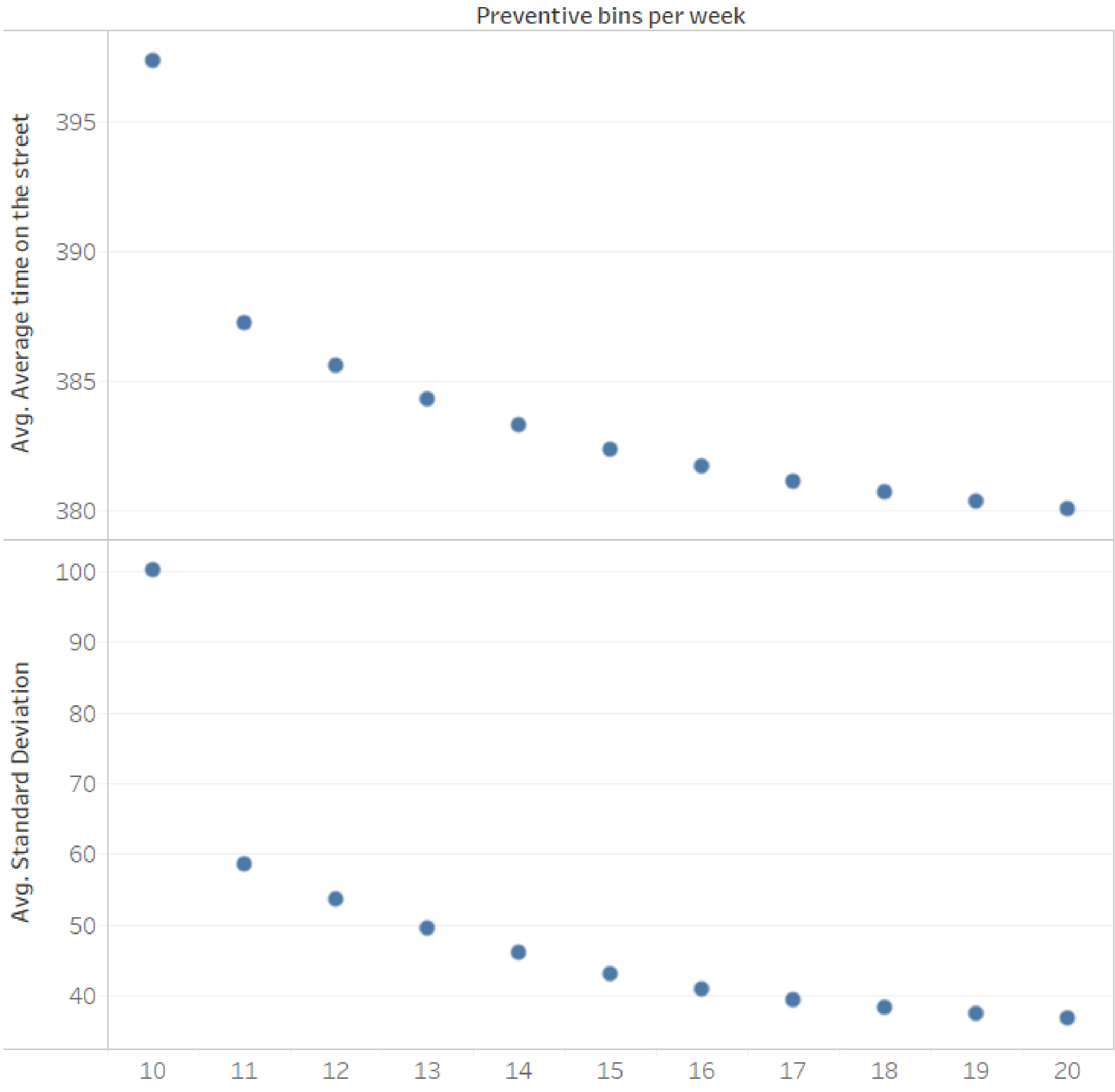

Figure 21 Average time on the street against capacity at Startpunt.

Hence, a higher threshold value and a higher capacity are beneficial to the average time on the street and lower the standard deviation. Consequently, we can take a closer look to the results of individual experiments.

To find a low enough standard deviation, we filter the results in appendix D in such a way that we don't show the weekly capacity of 10, due to the high standard deviation. Then we find the lowest costs at the configurations shown in table 10.

Table 10 optimal configurations according to the objectives of Twente Milieu

Maintenance interval	365
Threshold	60
Capacity per week	19

Table 11 shows the values of the KPI's corresponding to these settings. These values do fit the objectives of Twente Milieu. Namely, the average time on the street before preventive maintenance at Startpunt is just more than 365 days and the standard deviation of 37 days is reasonably low.

Table 11 KPI's at the optimal configurations

KPI	**Simulation outcomes**	**Per year**
Maintenance costs (€)	4797443	533049
Purchase and amortize costs (€)	(544+33)*2750=1504250	1504250/15=100283
Additional costs BWaste (€)		
Downtime (days)	1.07	
Total costs (€)		633332
Number of corrective maintenance actions	8279	920
Average time on the street (days)	378.52	
Standard deviation time on the street (days)	37.33	

Table 12 compares the latter scenario and the current situation with outsourced preventive maintenance. The scenario of using a preventive maintenance interval of one year shows serious improvements on all three KPI's.

Table 12 Comparison between optimal configurations and the scenario with outsourced preventive maintenance

KPI	Outsourced scenario	Averaging a year	Improvement (%)
Yearly costs	684292.78	633332.31	7.45
Average downtime	1.29	1.07	16.75
Corrective maintenance per year	1017.86	920.00	9.61

Implementing a maintenance strategy that combines opportunistic maintenance at Startpunt with corrective replacement, corrective repair at the bin location results in an improvement compared to the scenario with outsourced preventive maintenance and only corrective repair by second line mechanics. The improvements decrease the maintenance costs, decrease the downtime due to failing bins and decrease the number of corrective repairs by second line mechanics.

The proposed maintenance strategy creates work for Startpunt by giving preventive maintenance to each bin in Hengelo on a yearly basis. The extra jobs match the social objective of Twente Milieu to offer social employment combined with education. The saved time for the second line mechanics by the implementation of corrective replacement can be used at other places in the organization. Firstly, there are still seven other municipalities with failing bins that need repair on a daily basis. A higher availability of the second line mechanics will lead to a quicker repair and also a higher uptime of bins in these municipalities. Secondly, their expert knowledge can be used at Startpunt to teach and support the Startpunt mechanics with maintenance actions. The preventive maintenance is about the same for all bins at Startpunt, but the repair of a failing bin requires some extra guidance.

5.4 Validation

This section seeks to validate the results of the discrete event simulation with the real number of failures from the failure data at Twente Milieu. We used the data of the first half of 2019 to see how many failures that are resolved by second line mechanics actually occurred. In the first half of 2019, the second line mechanics repaired 208 bins in Hengelo, this would mean that the total number of failing bins per year lies around 400. The simulation model generates 1018 failures per year (table 8), which is a large overestimation compared to reality.

The influence of this overestimation does not make the results of the simulation study useless. Firstly, the scenario with outsourced preventive maintenance uses the same failure distribution as the new situation, which still shows that using the proposed maintenance strategy leads to an improvement on all three KPI's. Secondly, if it's true that there are fewer failures in real life, Twente Milieu can use a maintenance planning with even less variability or an higher preventive maintenance interval and try to scale up to other municipalities quicker.

To see how the two models used fit together, we validate the results we found in the simulation study with the results of the age-based maintenance policy. From these results, we can conclude that both modelling techniques find an optimal preventive maintenance interval between 160 and 200 days. This means that these models do correspond to each other and justifies the step to extend this research with a discrete event simulation study.

5.5 Sensitivity analysis

We see that the results of the simulation give better results than the maintenance planning model of chapter four and that there are improvements in terms of costs, average downtime and maintenance actions by second line mechanics by insourcing preventive maintenance. However, with such a simulation study, we must be careful with the input parameters. In order to see how robust this solution is and how the parameters such as the failure distribution and input costs influence the outcomes of this simulation study.

First, we consider the failure distribution. From the data at Twente Milieu we found the Weibull distribution with β 1.28 and η 211,6 this results in a mean time to failure of 195 days according to the following formula:

$$E(T) = \eta * \Gamma(1 + \frac{1}{\beta}) \qquad (15) \qquad \text{(Heijden M. v., 2018).}$$

This value might be a bit low, so we see what happens if we increase the value of eta. We expect to have fewer failures thus increasing the preventive maintenance interval.

If the costs for corrective maintenance decrease, the strategy becomes less effective. Similarly, if the costs for downtime decrease, the average downtime accounts for less added costs so in that scenario, the proposed scenario might also lose improvement.

For the sensitivity analysis, we used the settings with the lowest costs, namely the preventive maintenance time of 365 days, a weekly capacity of 19 bins and a preventive maintenance threshold of 60 days.

With these decision variables settled, it is verified if insourcing preventive maintenance would still be useful, although the costs and the failure rate are wrongly estimated.

In figure 22 we see that for all cost configurations the proposed maintenance strategy gains improvement. However 1.26% for the lowest corrective maintenance costs and a downtime cost of €50 per day is not too good. However, for all other cost configurations the improvement percentages are still pretty good.

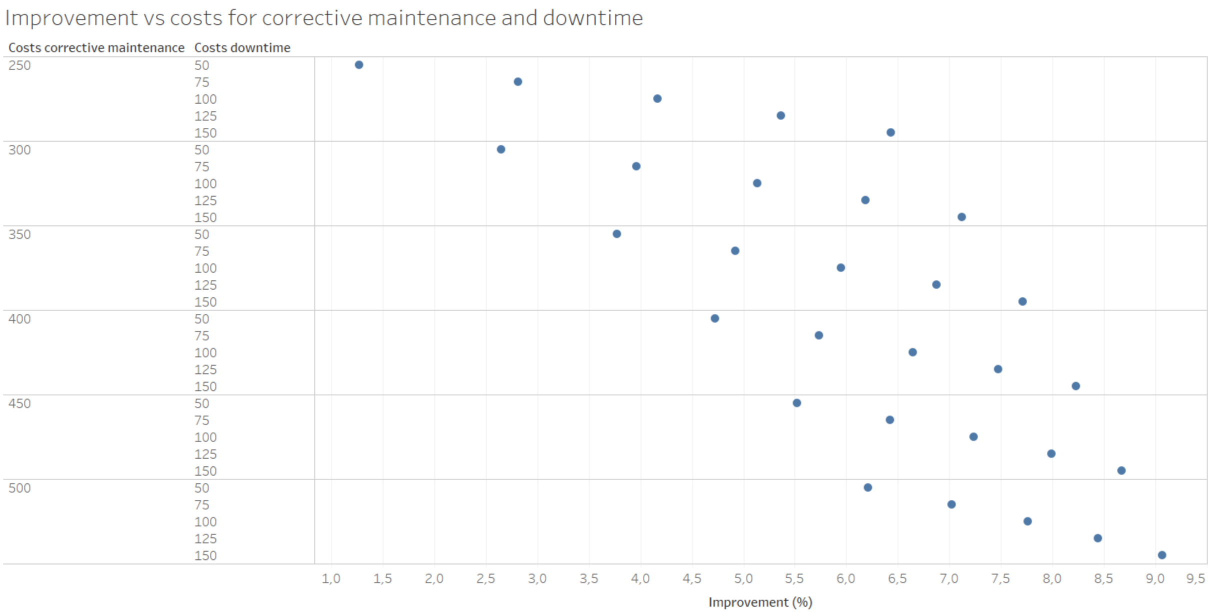

Figure 22 Results of the sensitivity analysis based on different cost parameters

Besides these percentages, it should be realized that the simulation model has not been used to minimize the costs for the maintenance strategy in the sensitivity analysis, so if the cost estimation seems to be too optimistic or too pessimistic, the same simulation model can be used to find an optimal preventive maintenance interval again.

The next thing to check is how sensitive the proposed solution is considering the failure distribution. As we mentioned earlier, we had the feeling that the number of failures is a bit high, so we decided to change the value of eta from 211 days to 250, 300 and 350 days to see the influence on the results of the proposed solution.

Table 13 shows the results for the different values of eta.

Table 13 Results of the sensitivity analysis based on different values for eta

Eta	Outsourced costs per year	Insourced costs per year	Improvement
250	588528.89	559800.69	4.88%
300	509006.67	485838.89	4.55%
350	453203.89	437188.89	3.53%

So with the same settings but with a different value for eta, the KPI's still improve. There is still no optimized maintenance interval in the sensitivity analysis. If new or better failure data becomes available, the simulation model can optimize the preventive maintenance strategy by using the new failure data.

5.6 Conclusions of the numerical analysis

Section 5.2 showed the results of the numerical analysis of the cost function. The cost function of formula 1 is used in literature to find the optimal preventive maintenance interval given the failure distribution and the costs for preventive and corrective maintenance. In this research, the cost function method takes into account two out of four maintenance methods. These are corrective repairs at the bin site and preventive maintenance at Startpunt. The analysis of the cost function results in interesting insights on an effective maintenance interval. Firstly, that a preventive maintenance strategy is effective given the input parameters of the Weibull distribution and the costs for maintenance instances. Secondly, the optimal preventive maintenance interval depends strongly on the ratio of costs for corrective maintenance and preventive maintenance. These results are conforming to the literature findings in chapter 3.

However, implementing a strict preventive maintenance of 260 days directly is practically infeasible for Twente Milieu and does not take into account all four described maintenance policies. Namely (i) corrective repair, (ii) corrective replacement, (iii) age based preventive maintenance and (iv) opportunistic preventive maintenance. Consequently, we extend our research with a discrete event simulation study that gives more insights in the performance of the four maintenance policies, in the decisions that can be made based on events and allows us to introduce corrective replacement and opportunistic preventive maintenance.

The aim of the simulation study is to find a maintenance policy that reduces the maintenance costs, reduces downtime of underground bins and reduces the number of maintenance actions for second line engineers. We use the simulation model to determine the minimum weekly capacity of Startpunt. The simulation model does also show more detailed results for KPI's such as downtime, number of corrective repairs and the average time on the street of underground bins.

The results of the discrete event simulation look very promising. Firstly, implementing a preventive maintenance threshold is the first step to deal with the capacity issues. Such a preventive maintenance threshold is a minimum number of days that a bin should be on the street before it is allowed to go to Startpunt for preventive maintenance. The threshold should prevent that bins get preventive maintenance too often, but should ensure that not all bins arrive at Startpunt at the same time due to a strict preventive maintenance interval. From the results we can see that using a higher threshold results in lower costs for maintenance. Secondly, a smaller preventive maintenance interval additionally leads to lower costs. Both these effects are partly due to the difference in costs between preventive maintenance and corrective maintenance. The results of the simulation study are quite sensitive to the ratio between costs for preventive maintenance and corrective maintenance. The impact of the costs is clearly shown in the sensitivity analysis. If the costs get closer to each other, gains in terms of money of the maintenance strategy decrease. However, there are still gains visible by looking at the downtime and the number of maintenance actions by second line mechanics.

In many configurations with low costs, the undesirable consequence of a high threshold and a small preventive maintenance interval is the big variance in the average time on the street. When the variance of the average time on the street is too high, a strict preventive maintenance schedule cannot be followed, since bins visit Startpunt more irregularly.

In order to decrease the variance in the time on the street, we examined the options with a preventive maintenance interval of one year as desired by Twente Milieu. The goal of the experiments was to lower the variance and apply a more stringent maintenance interval per bin, as initially desired. The main result of having a year as preventive maintenance interval and having enough capacity is that the variance indeed decreases to values of 37 days, with an average number of 370 days on the street.

6. Conclusions and recommendations

In this chapter we will mention the most important conclusions of the research on insourcing preventive maintenance at Twente Milieu. Section 6.2 addresses the steps Twente Milieu should take to implement the proposed maintenance policy. Section 6.3 gives recommendations for further research. To conclude, section 6.4 explains the contribution of our research to literature and practice.

6.1 Conclusions

This research at Twente Milieu aims to insource preventive maintenance treatment of washing, inspection and lubrication of underground bins at Startpunt. In order to reach that goal, we looked at the maintenance data of the first and second line mechanics. We concluded in chapter 2 that many bins were already visited at least once a year, so these visits could be used as opportunities to combine preventive maintenance and corrective maintenance.

From this starting point, we searched into literature to find information on optimizing preventive maintenance, opportunistic maintenance strategies. According to literature, the maintenance policies can be analysed numerically by using the cost function and discrete event simulation.

We found information on how to find an optimal preventive maintenance interval given the costs for preventive and corrective maintenance and a failure distribution. In chapter 4 we conclude that the failures of underground bins are distributed according to a Weibull distribution with a β value 1.28 and a η value 211.6. Secondly, it was hard to estimate the costs for downtime and for corrective maintenance, since the downtime costs are part of the corrective maintenance costs. Besides, it was also hard to estimate the transportation costs which should be included in the preventive maintenance costs. We calculated the optimal preventive maintenance interval and its effectiveness using the cost function G(T), for several cost configurations to see the influence of costs. We conclude that a preventive maintenance policy could be effective for Twente Milieu to lower the maintenance costs, but that minimizing the cost function does not lead to big reductions of the maintenance costs. We can conclude from the maintenance planning model with cost function G(T) (formula 1) that using a preventive maintenance strategy for underground bins leads to slight improvements. Therefore we decided to use a simulation model to seek for more improvements by using different maintenance policies.

In order to introduce more of the real life variability in the maintenance optimization model and to be able to include opportunistic maintenance as described in literature, we decided to create a discrete event simulation model. By means of this simulation study, we concluded that we can lower the costs for maintenance on underground bins in two ways.

We could take the preventive maintenance interval of 240 days that corresponds to the preventive maintenance interval we found by using the cost function in combination with using opportunistic maintenance for failing bins and introducing a preventive maintenance threshold. This approach leads to a lot of corrective replacement since the policy allows bins to be repaired at Startpunt shortly after they are installed on the street. This also means that bins that do not fail stay on the street for a longer time then their preventive maintenance interval due to the lack of capacity at Startpunt. This leads to a high variance in the average time on the street. This variance is undesirable, since Twente Milieu aims to get every bin to Startpunt at least once a year.

We could also increase the preventive maintenance interval to one year to reduce the variance in the time a bin is on the street. These configurations still account for 7.6% cost savings and 16.25% of downtime savings. Secondly setting a larger preventive maintenance interval gives the options to see if an expansion to other municipalities such as Enschede or Borne lies within the opportunities of Twente Milieu.

Both options account for improvements on the costs for the preventive maintenance strategy, reduction of downtime of underground bins and reduction of the number of maintenance actions by second line mechanics. Using a preventive maintenance interval of one year fits better in the practical wishes of Twente Milieu and is less sensitive to overestimations of the costs and the number of failures per year.

6.2 Recommendations for Implementation

As demonstrated in the numerical analysis, insourcing preventive maintenance is an effective strategy for Twente Milieu, to employ Startpunt mechanics and decrease the downtime. This section describes the steps that should be taken to implement the proposed preventive maintenance strategy.

Starting the proposed maintenance strategy has low set up costs, since the right materials are present in the workshop of Startpunt and hiring a truck from BWaste can be done per day that transport is needed. As long as there are repaired bin in stock, the truck can be used for one day to replace a selection of active bins by bins from stock.

The bins that enter Startpunt get preventive maintenance of washing, lubrication, inspection and necessary extra repairs. The first few weeks of implementation must be used to keep track of the number of bins that Startpunt can handle in one week. When Startpunt is (almost) done with handling the bins for one week, other bins must be transported from the street to Startpunt. These bins can be chosen based on the location near a failing bin to reduce travel time (opportunistic maintenance), based on a direct failure (corrective replacement) or based on the current status of the bin obtained from the last round of inspection.

The last time a bin has had preventive maintenance must be stored in Wincar to keep track of the time on the street and when the preventive maintenance interval of one year is approaching.

This information can be used to design a schedule which determines the bins that should get preventive maintenance at the next transportation day. Whenever a bin failure occurs, the maintenance engineer can decide how to repair it. Due to the nature of the failure the second line mechanics need to repair it on bin site, or corrective replacement can be used to repair the broken bin at Startpunt. Reasons for corrective repair can be that the preventive maintenance threshold has not been reached, or the failure cannot be repaired at Startpunt.

We advise to use the full weekly capacity of Startpunt in order to see what the opportunities are to scale up the preventive maintenance area to Hengelo and Enschede, where mainly the same type of underground bins are used. In the first year after implementation the data will show if the quality of the maintenance improves and if the downtime of the underground bins decreases.

6.3 Recommendations for further research

In this section we will address some recommendations for further research.

Update the failure distribution: By treating bins more often at Startpunt, the failure distribution might change. We have this expectations due to interviews with the maintenance engineers. The quality of maintenance at Startpunt with an empty bin and all tools available should be higher than a quick treatment on the street by BWaste. A while after implementation, the change in failure distribution might be visible and could lead to the necessity of a new maintenance policy with different preventive maintenance intervals. Updating the failure distribution, can also lead to a better validated simulation model. This would make the results of the research more reliable.

Add use-based maintenance: We expect that some bins are visited more often by second line mechanics simply because they are used more often by customers because they are located in more densely populated areas of the municipality. It could be interesting to analyse how the usage influences the failure distribution. This could lead to different maintenance strategies for different underground bins. Such an adapted maintenance policy might prevent that bins that are used fewer times get unnecessary maintenance treatments which are costly in terms of working hours and transportation.

Add lead times of the processes at Startpunt: When the processes of Startpunt have started, it is possible to see in what state the bins are transported to Startpunt, what are the main failure modes and how long it takes per failure mode to repair and wash, lubricate and inspect every bin. This will give insight in the lead times for maintenance actions at Startpunt. These lead times can be used to determine the necessary safety stock levels and the number of bins that can be handled in one week.

Add first line failures as opportunities to the model: In this simulation study, only the second line failures have been taken into account as opportunities for corrective replacement. The main reason is that the nature of the first line failures does not seem very suitable for a repair at Startpunt. However, adding the failure distribution for first line failures to the simulation model and see what happens to the performance of the maintenance policy when the first line failures are also used for corrective replacement.

6.4 Contribution to literature and practice

This section describes the contribution of this research to the literature and practice. We showed that the cost function is a useful approach to show the effectiveness of preventive maintenance given a failure distribution. However, in literature this approach is mainly used to find an optimal preventive maintenance interval for large assets, where the maintenance interval can be used. However, implementing the obtained preventive maintenance interval encounters a capacity issue.

The second part of the numerical analysis incorporates the findings from the data analysis in a discrete simulation model to optimize a preventive maintenance strategy based on occurring events. These decisions are based on maintenance methods that are commonly used in literature. However, literature shows a lot of analytical ways to solve the mentioned maintenance models, while this research combines them with discrete event simulation.

The discrete event simulation does also have an additional value to practice, since the simulation study shows how decisions and maintenance strategies influence important KPI's such as downtime and costs of a certain maintenance policy.

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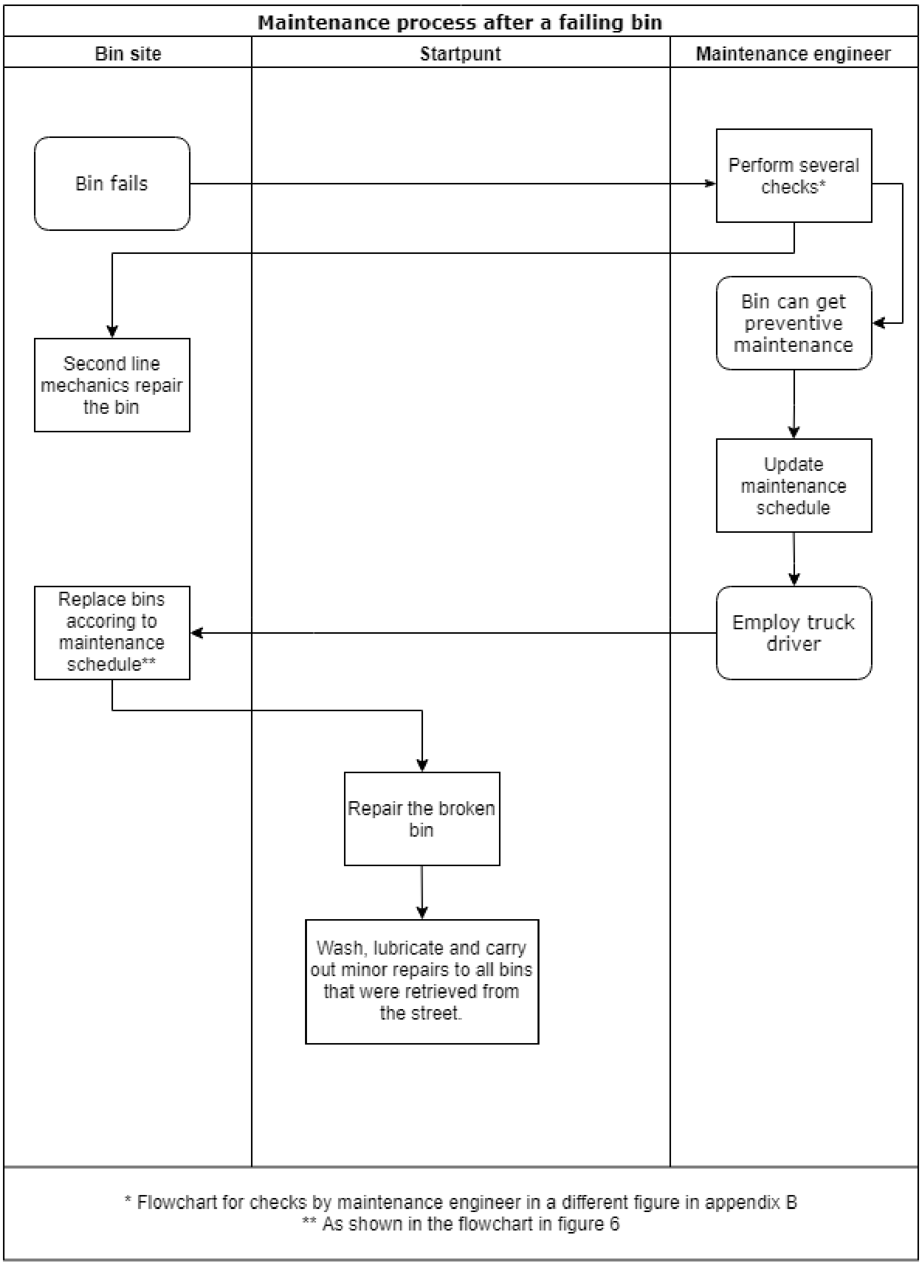
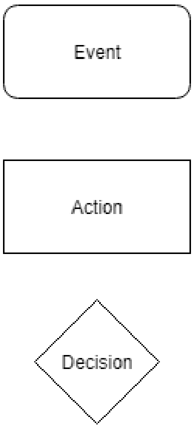
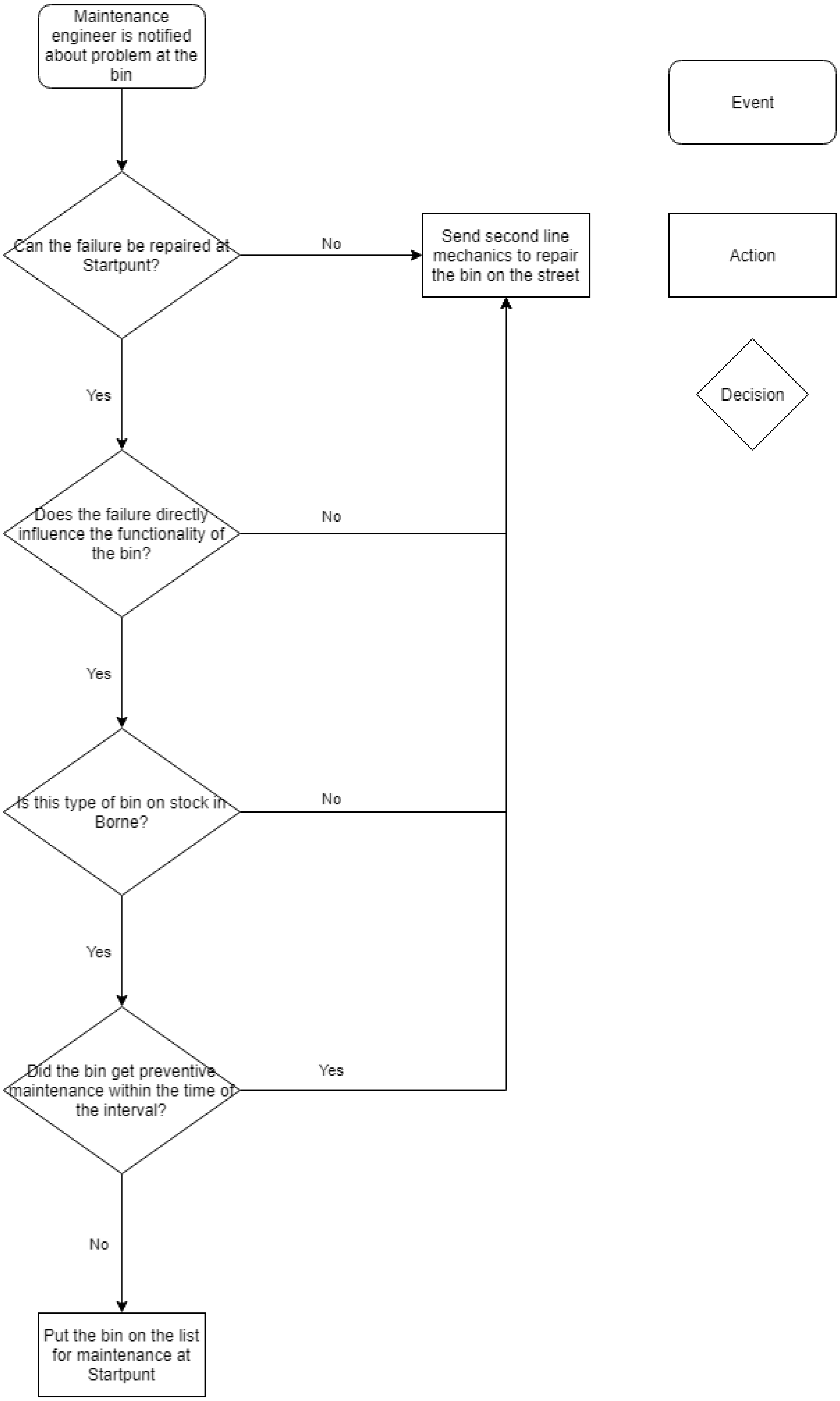
Appendix A Flowchart conceptual model





Appendix B Decision chart maintenance engineer



Appendix C Table of the Chi-square test

Bin max	*Frequency*	*Weibull*	*Expected*	*Error*
43.8	55	0.124704	49.5074	0.609377
87.6	50	0.276311	60.18797	1.724508
131.4	62	0.419206	56.72957	0.489646
175.2	56	0.543972	49.53186	0.844645
219	31	0.648213	41.3836	2.605361
262.8	36	0.732673	33.5306	0.181862
306.6	26	0.79951	26.53462	0.010771
350.4	21	0.851396	20.59869	0.007818
394.2	15	0.891025	15.73249	0.034104
438	14	0.920866	11.84681	0.391347
481.8	10	0.943055	8.809259	0.160952
525.6	4	0.959369	6.476595	0.947029
569.4	4	0.971239	4.712519	0.107731
613.2	6	0.979794	3.396336	1.995993
657	0	0.985905	2.426129	2.426129
700.8	1	0.990235	1.718749	0.300568
744.6	0	0.993278	1.208153	1.208153
788.4	3	0.995401	0.843002	5.519131
832.2	1	0.996873	0.584114	0.296108
				19.86123

Appendix D Simulation results with maintenance interval of 365 days

Exp	root.PreventiveBinsPerWeek	root.Speling	root.MaintCosts	root.TotalCosts	root.numbercorrective	root.totalmaint	root.gemiddelde	root.afwijking	root.totaldown
Exp 06	11	20	4949950	6536700	7971.5	12813.5	388.9329993	60.25894877	1.121381283
Exp 07	11	30	4903543.75	6490293.75	7908.25	12751.5	388.1362851	59.10032337	1.094543342
Exp 08	11	40	4890418.75	6477168.75	7861.25	12708.5	387.3431718	58.38488931	1.098410802
Exp 09	11	50	4879337.5	6466087.5	7850.75	12701.25	386.5325432	57.72197795	1.087242639
Exp 10	11	60	4827312.5	6414062.5	7775.75	12636.25	385.2368847	57.27131805	1.060410701
Exp 11	12	20	4924687.5	6511437.5	7980.25	12851.75	387.2491731	55.11618467	1.111251861
Exp 12	12	30	4913400	6500150	7939.5	12807.5	386.5741678	54.15637779	1.094169503
Exp 13	12	40	4871287.5	6458037.5	7867	12735.5	385.668387	53.48089835	1.079832922
Exp 14	12	50	4885437.5	6472187.5	7858	12727.5	385.002187	52.95984597	1.091246707
Exp 15	12	60	4825618.75	6412368.75	7737.5	12612.75	383.4774993	52.56468864	1.080240995
Exp 16	13	20	4915568.75	6502318.75	7973	12850.25	385.9393137	50.69642564	1.129627838
Exp 17	13	30	4861718.75	6448468.75	7904.5	12774.75	385.2856369	49.84143624	1.092253222
Exp 18	13	40	4867587.5	6454337.5	7882.25	12751.75	384.5266306	49.30301208	1.091992069
Exp 19	13	50	4855643.75	6442393.75	7829	12698.25	383.6872483	48.86748152	1.092185184
Exp 20	13	60	4833350	6420100	7781.25	12662.25	382.2154205	48.64939898	1.07650404

Exp 21	14	20	4891593.75	6478343.75	8000.25	12877.5	384.9002183	47.05018607	1.111969061
Exp 22	14	30	4857975	6444725	7902.75	12773.75	384.2607675	46.3002872	1.11117897
Exp 23	14	40	4858156.25	6444906.25	7879.75	12749.5	383.4667066	45.84865658	1.096105148
Exp 24	14	50	4844200	6430950	7822.5	12694.5	382.7167761	45.50029186	1.090144175
Exp 25	14	60	4819200	6405950	7758.5	12639.5	381.3307603	45.38178694	1.076600444
Exp 26	15	20	4853493.75	6440243.75	7989.75	12867	383.9525899	43.96345803	1.116559659
Exp 27	15	30	4844931.25	6431681.25	7944	12813.75	383.3344415	43.3061135	1.106941662
Exp 28	15	40	4848650	6435400	7888.75	12760.75	382.4943738	42.95101433	1.099258137
Exp 29	15	50	4859175	6445925	7879.25	12750.25	381.869037	42.57230842	1.096219201
Exp 30	15	60	4808250	6395000	7773	12656	380.2005401	42.65879484	1.081537406
Exp 31	16	20	4869193.75	6455943.75	7983.5	12860.75	383.2174168	41.75288948	1.13763798
Exp 32	16	30	4877706.25	6464456.25	7964	12834.75	382.6266819	41.17809153	1.124595059
Exp 33	16	40	4855318.75	6442068.75	7915.75	12786	381.8850853	40.77976056	1.099294098
Exp 34	16	50	4847762.5	6434512.5	7861	12731.5	381.1878972	40.52888267	1.102175527
Exp 35	16	60	4829981.25	6416731.25	7783.75	12665.5	379.6043312	40.66624518	1.094374512
Exp 36	17	20	4872368.75	6459118.75	7976.25	12853.5	382.6522742	40.09578253	1.144340518
Exp 37	17	30	4880231.25	6466981.25	7975.5	12845.25	382.0518987	39.5867646	1.128426131

Exp 38	17	40	4849868.75	6436618.75	7908	12776.25	381.3010152	39.26698837	1.10192749
Exp 39	17	50	4831718.75	6418468.75	7855	12724.25	380.7203083	38.97957885	1.102398755
Exp 40	17	60	4815456.25	6402206.25	7774.75	12656.5	379.0479903	39.18438304	1.082470581
Exp 41	18	20	4888518.75	6475268.75	8033.5	12910.75	382.1399024	38.86531129	1.134608197
Exp 42	18	30	4846087.5	6432837.5	7943.25	12813.75	381.6302241	38.40662281	1.102257325
Exp 43	18	40	4844031.25	6430781.25	7896	12763.75	380.98494	38.07763737	1.106752762
Exp 44	18	50	4834281.25	6421031.25	7850.5	12718.25	380.3156734	37.95718277	1.103594347
Exp 45	18	60	4821000	6407750	7784.75	12667.75	378.7190324	38.19739075	1.083732368
Exp 46	19	20	4865568.75	6452318.75	8008	12885.25	381.7330151	38.00329842	1.122197795
Exp 47	19	30	4870362.5	6457112.5	7968	12838.5	381.2065817	37.59550616	1.117643292
Exp 48	19	40	4854618.75	6441368.75	7917.5	12787.75	380.4850722	37.25266869	1.10488621
Exp 49	19	50	4844443.75	6431193.75	7864.5	12734.75	379.8856291	37.07527076	1.098424201
Exp 50	19	60	4797443.75	6384193.75	7764	12646.25	378.5248891	37.33194704	1.070851883
Exp 51	20	20	4879118.75	6465868.75	8012.75	12890	381.4624548	37.28272415	1.133906837
Exp 52	20	30	4870206.25	6456956.25	7966	12836.75	380.9254191	36.92188618	1.117028944
Exp 53	20	40	4866825	6453575	7894.25	12764.25	380.2221199	36.62098453	1.128481453
Exp 54	20	50	4861306.25	6448056.25	7876	12747.75	379.5838868	36.50876751	1.106695002

Ex p 55	20	60	484228 1.25	642903 1.25	7810.25	12696	378.174 7868	36.672 94022	1.0906 62847