Consideration of Increased Failure Probabilities due to Interventions on Multiple Networks

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One task of city engineers is to plan the execution of interventions on infrastructure to ensure that it provides an adequate level of service. The execution of each intervention, however, results in negative impacts, such as the costs to the owner and increased travel time for users due to traffic perturbations. These negative impacts can be reduced if interventions on objects that are geographically close to each other are combined. However, due to this closeness, there is a non-negligible probability of damaging other infrastructures during an intervention. In this paper, the effect of the consideration of the spatial proximity of interventions on objects of multiple networks, with and without damage risk consideration, on work programs is illustrated using a gas and a sewer network in a small urban area.

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1 Introduction

Communities often own multiple infrastructure networks such as water distribution, sewer, gas and electricity networks, and road networks. These networks are some of their assets but also some of their main cost drivers. One part of that task is to determine the interventions to be executed in a relatively short time period that minimize negative impacts, i.e. the optimal work program (OWP). How interventions are combined in WPs can lead to significant reductions in negative impacts. (Arthur, Crow, Pedezert, u. Karikas, 2009; Morcous u. Lounis, 2005; Zayed u. Mohamed, 2013)

The starting point for the construction of WPs for proximate networks is normally the determination of the interventions to be executed on the individual objects within each single network. This initial WP is then adjusted to take into consideration other interventions that could be executed on other objects within the same network, e.g. interventions that may be planned in 5 years but would be less expensive in combination with other interventions. This is usually done by having the responsible engineers meet and discuss possible combinations of interventions. Once the interventions have been planned for multiple objects within each individual network, the managers of the other networks are informed of the planned interventions. This leads to further discussions and tweaking of the WP for each network so that a final WP is generated for the proximate networks. It is expected that this process, although an improvement on one where no coordination occurs, could be improved further.

One of the challenges of determining OWPs for proximate networks is that they are often modelled differently. This difference comes principally from whether or not they are affected by sudden (latent) or gradual (manifest) processes. Gas networks, for example, are principally affected by sudden processes (due to the limited inspection possibilities), whereas sewers are affected by gradual (i.e. observable) processes. In the former, the pipes are considered to be in one of two states, i.e. operational and non-operational, and in the latter, the pipes are considered to be in multiple condition states, whereas perhaps only the last condition state is one in which an inadequate level of service is provided.

In this paper, the potential reduction of the negative impacts related to WPs through improved co-ordination of interventions in WPs is investigated. This is done by determining three WPs for a gas and a sewer network in a small urban area. WP1 is determined taking into consideration only the objects on each network. WP2 is determined taking into consideration the spatial proximity of objects within both networks, albeit without accounting for the increased damage risk during interventions. WP3 is determined taking into consideration the spatial proximity as well as the resulting risk increase in the probability of damaging objects in the other network when an intervention on one network is executed. The WPs are compared for two cases: 1) where there are no restrictions on the number of interventions and 2) where there are certain restrictions on the number of interventions to be executed (i.e. a limited intervention budget). The work presented in this paper builds on that presented in (Kielhauser et al., 2014).

2 Methodology to determine an OWP

The intervention strategy used to generate the WPs is based on a maximal acceptable annual failure probability, i.e. when a failure probability of a specific value is reached an intervention is executed. The steps to determine the six WPs are shown in Figure 1. Each WP is generated for one time interval (1 year). To be able to see the effects of an imposed budget constraint, a priority ranking is calculated to determine the interventions executed.

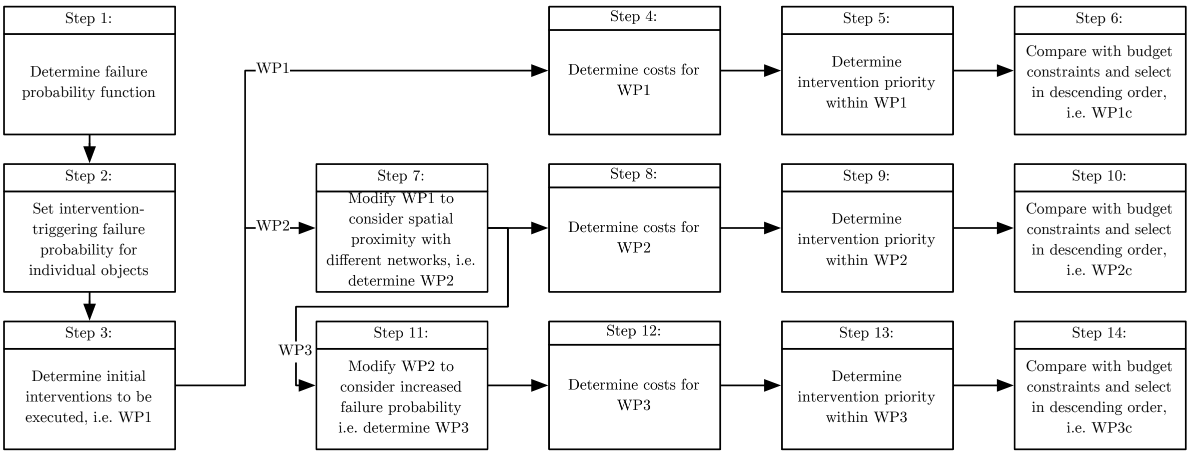


Figure 1: OWP generation steps

As can be seen from Fig. 1 there are three sequential WPs in the methodology. In many practical cases, managers select WP1/WP1c only. In other words, they stop after step 6. If a manager also considers the spatial proximity, he has to proceed through the flowchart until step 10 (WP2/WP2c), whereas if he wants to consider the damage risk as well, all the steps until step 14 (WP3/WP3c) have to be completed.

2.1 Step 1: Failure probability function

As a matter of fact, the types of models used for manifest (i.e. observable) and sudden (i.e. non-observable) deterioration are different for different infrastructure systems. For example, the Weibull model or the Herz model can be used to compute the failure probability of gas pipes, whereas the Markov model can be used for deterioration prediction of road sections and bridges. The choice of model for each system greatly depends on 1) the system failure[1] type, i.e. whether the system fails binary, step-wise or gradually, and 2) the availability of data.

2.1.1 Models used for binary system failure

Many objects in infrastructure systems can be described as binary objects. For example, a gas pipe can be considered to be in one of two states (e.g. operational / non-operational). For those objects, some examples of the types of probabilistic models that can be used to calculate the failure probability given the historical data are, Poisson, Weibull, Gamma, and Herz.

2.1.2 Models used for gradual or multiple state system failure

Other objects, such as those in road networks, for example road sections, bridges, and tunnels, might be better described as a multiple state object. For example, a road can be described as being in one of 5 discrete condition states (CSs), where each CS can be linked to a reduced functionality. In such situations, Markov or Herz type models, or any of the model types used for the binary object can be used to estimate the probability of passing from one condition state to another.

2.2 Step 2: Intervention-triggering failure probability

The second step is to define an intervention-triggering (i.e. a critical or maximum acceptable) probability of *failure to provide an acceptable level of service (FLOS).*

Determining this probability is a management decision, which depends on the amount of risk the infrastructure manager is willing to take. Once determined the basic intervention strategy is then:

$$\forall n \in N \begin{cases} P_n(t) < \bar{P}_n & \textit{do nothing} \\ P_n(t) \geq \bar{P}_n & \textit{do intervention} \end{cases} \tag{1}$$

with $t\ldots$age, $n\ldots$object, $N\ldots$all objects, $P_n(t)\ldots$FLOS probability for object n at age t, and$\bar{P}_n\ldots$ acceptable FLOS probability of object n.

2.3 Step 3: WP1: interventions to be executed

Here, the FLOS probability P_n at each time t for each object n is calculated and compared against the critical FLOS probability $\bar{P}_n$ (For ease of reading, the index t is omitted). If the FLOS probability of an object exceeds this critical FLOS probability, an intervention on this object is included in the WP. For a compact mathematical notation, the Heaviside function[2] can be used:

[1] in this context: loss of functionality for which it is designed

[2] Multiple definitions for this function exist. In this paper, the following definition is used: $H(x < 0) = 0,\ H(x \geq 0 = 1)$

$$\delta_n = H\left(P_n - \bar{P}_n\right) \tag{2}$$

with $\delta_n \ldots$ binary variable indicating inclusion in WP1 (1=yes, 0=no). WP1 consists of all the initially determined interventions.

2.4 Step 4: Costs for WP1

It is assumed for this example that all interventions are executed at separate times even if they are planned in one time interval, e.g. intervention 1 in month 1 of year 1 and intervention 2 in month 2 of year 1. In this case the costs of WP1 are:

$$C_{WP_1} = \sum_{n=1}^{N} c_n \cdot u_n \cdot \delta_n \tag{3}$$

with $c_n \ldots$ unit cost of object n (e.g. per m, per m^2, etc.) , $u_n \ldots$ amount of units of object n (e.g. length, area, etc.), and $C_{WP_1} \ldots$ total cost for WP1

2.5 Step 5: Intervention priority within WP1

As mentioned in Section 1, two cases are compared: one, where there are no restrictions and one where the number of interventions executed is restricted due to having a limited intervention budget. For the former, no priority ranking is needed, as all interventions can be done. For the latter however, a priority ranking is needed in order to select the interventions to be executed from WP1 if not all can be executed. The priority is defined using three components:

- Excess FLOS probability $\left(P_n - \bar{P}_n\right)$: The portion of the probability of FLOS that is above the acceptable probability of FLOS, which allows for a more equal comparison of objects with different acceptable probabilities of FLOS than if the probability of FLOS itself was used.
- Object size u_n: the larger the object is (length, area, etc.), the more weight is put on it, to reflect that the consequences of FLOS would increase with the size of the object
- Network importance ζ_n: As network objects have different hierarchical levels (i.e. levels of importance), an importance factor ζ_n is added to be able to discern between these different importance levels. This importance factor is a proxy of th siz-inependent consequences of FLOS of theobject.

Eq. 4 allows the calculation of the excess FLOS probability, that is size- and importance-weighted as well as normalised, so that all weights add up to 1:

$$W_n = \frac{\left(P_n - \bar{P}_n\right) \cdot u_n \cdot \zeta_n \cdot \delta_n}{\sum\limits_{n=1}^{N} \left(\left(P_n - \bar{P}_n\right) \cdot u_n \cdot \zeta_n \cdot \delta_n\right)} \tag{4}$$

with $W_n \ldots$ Priority for object n (value increases with increasing priority), and $\zeta_n \ldots$importance factor of object n.

From there, the rank r_n of an object can be calculated in a way that the object with the highest priority gets rank 1, the object with the second-highest priority gets rank 2, and so forth:

$$r_n = rank\left(sort\left(W_n \,|\, desc.\right)\right) \tag{5}$$

2.6 Step 6: WP1c: Budget constraints

WP1 with constraints (WP1c) is constructed out of WP1: The objects in WP1 (i.e. where $\delta_n = 1$) are added to WP1c (i.e. $\delta_{nc} = 1$) starting at the object with the highest priority (n where $r_n = 1$), then (n where $r_n = 2, 3, ...$ etc.) until the sum of the costs reaches the budget limit C_{lim}:

$$\delta_{nc} = \begin{cases} 1 & for\, \delta_n = 1 \;and\; \sum_{n(r_n=1)}^{n(r_n=N)} (c_n \cdot u_n \cdot \delta_n) \leq C_{lim} \\ 0 & otherwise \end{cases} \tag{6}$$

with $\delta_{nc} \ldots$ binary variable indicating inclusion in WP1c (1=yes, 0=no), $C_{\text{lim}} \ldots$ Budget limit.

2.7 Step 7: WP2: Spatial proximity consideration

In this step, in addition to $\bar{P}$, another value of probability, P^* is defined. It represents the threshold FLOS probability where one object can undergo an intervention, i.e. an object that does not have a probability of FLOS over the acceptable level but willin the near future. The idea is to take into consideration that the reduced cost of executing the intervention on this object together with an intervention on a nearby object will at least offset the additional cost expected due to executing the intervention earlier than required.

This is done by first assigning each object to a grid cell, as proposed by (R. A. Fenner, 2000) who proposed a GIS-based model to calculate critical grid squares and used algorithms to predict the likelihood of sewer failure in each square, based on past failure events. Threshold failure probabilities are then set for all objects that will trigger interventions if another object nearby is to have an intervention, where nearby is defined as being in the same grid cell.

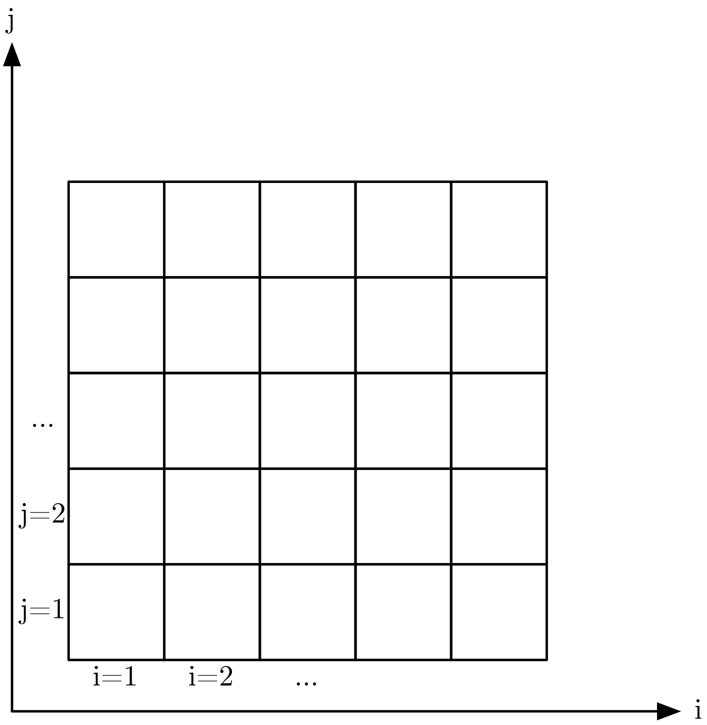


Figure 2: Definition of grid cells

The osts associated with the execution of an intervention are assigned directly to each grid cell. The grid cells in which interventions to be executed are given by:

$$\Delta_{i,j} \begin{cases} \Delta_{i,j} = 1 \Leftrightarrow & \exists \left(\delta_{n_{i,j}} = 1 \vee \delta_{m_{i,j}} = 1\right) \\ \Delta_{i,j} = 0 \Leftrightarrow & \nexists \left(\delta_{n_{i,j}} = 1 \vee \delta_{m_{i,j}} = 1\right) \end{cases} \tag{7}$$

with

$$\begin{aligned}
\delta_n = 1\, and\, \delta_{k\neq n} = 1 \quad = 1\, and\, \delta_{k\neq n} = 1 &\Leftrightarrow \quad \exists\, n \,|\, \left\{P_n\,(t) \geq \bar{P}_n \wedge P_{k\neq n}\,(t) \geq P_k^*\right\} \forall n, k \in G_{i,j} && (8)\\
\delta_m = 1\, and\, \delta_{l\neq m} = 1 &\Leftrightarrow \quad \exists\, m \,|\, \left\{P_m\,(t) \geq \bar{P}_m \wedge P_{l\neq m}\,(t) \geq P_l^*\right\} \forall m, l \in G_{i,j} && (9)\\
\delta_n = 1\, and\, \delta_l = 1 &\Leftrightarrow \quad \exists\, n \,|\, \left\{P_n\,(t) \geq \bar{P}_n \wedge P_l\,(t) \geq P_l^*\right\} \forall n, l \in G_{i,j} && (10)\\
\delta_m = 1\, and\, \delta_k = 1 &\Leftrightarrow \quad \exists\, m \,|\, \left\{P_m\,(t) \geq \bar{P}_m \wedge P_k\,(t) \geq P_k^*\right\} \forall m, k \in G_{i,j} && (11)\\
\delta_n, \delta_m, \delta_k, \delta_l = 0 & \qquad otherwise && (12)
\end{aligned}$$

with $n, k\ldots$objects of network A, $m, l\ldots$objects of network B,$n_{i,j}, m_{i,j}\ldots$ objects of network A resp. B in grid cell with coordinates (i, j), $\delta_k, \delta_l\ldots$ binary variable indicating inclusion of object k resp. l in WP3, and $P_n^*, P_m^*\ldots$ threshold FLOS probability.

In words, Eq. 7 means: In grid cell $G_{i,j}$ an interventionis executed ($\Delta_{i,j} = 1$) if there is an intervention to be executed on at least one object of network A ($\delta_{n_{i,j}} = 1$) or network B ($\delta_{m_{i,j}} = 1$). The objects are selected by the following rules:

Eq. 8: If there is at least one object of network A with intervention ($\delta_n = 1$) in grid cell $G_{i,j}$, look for other objects of network A in the same grid cell (δ_k) with a FLOS probability $P_k(t)$, that exceed the threshold FLOS probability P_k^* and set this δ_k to 1

Eq. 9: If there is at least one object of network B with intervention ($\delta_m = 1$) in grid cell $G_{i,j}$, look for other objects of network B in the same grid cell (δ_l) with a FLOS probability $P_l(t)$, that exceed the threshold FLOS probability P_l^* and set this δ_l to 1

Eq. 10: If there is at least one object of network A with intervention ($\delta_n = 1$) in grid cell $G_{i,j}$, look for other objects of network B in the same grid cell (δ_l) with a FLOS probability $P_l(t)$, that exceed the threshold FLOS probability P_l^* and set this δ_l to 1

Eq. 11: If there is at least one object of network B with intervention ($\delta_m = 1$) in grid cell $G_{i,j}$, look for other objects of network A in the same grid cell (δ_k) with a FLOS probability $P_k(t)$, that exceed the threshold FLOS probability P_k^* and set this δ_k to 1

Eq. 12: otherwise, select no objects

2.8 Step 8: Total expected costs for WP2

The total expected cost of WP2 is then defined as the sum of the setup cost for executing all interventions in grid square $G_{i,j}$ ($c_{G_{i,j}}$) and the unit costs without setup costs for each bject of network A resp. B times its size ($c_n^* \cdot u_n$) resp. ($c_m^* \cdot u_m$). As the costs only apply, if an intervention is xecuted, the terms are multiplied by the respective binary selection variable ($\delta_n, \delta_m, \Delta_{i,j}$).

$$C_{WP_2} = \sum_{i=1}^{I}\sum_{j=1}^{J}\left(\Delta_{i,j} \cdot \left(c_{G_{i,j}} + \sum_{n_{i,j}} c_n^* \cdot u_n \cdot \delta_n + \sum_{m_{i,j}} c_m^* \cdot u_m \cdot \delta_m\right)\right) \tag{13}$$

2.9 Step 9: Intervention priority within WP2

For WP2, the priority is defined for every grid cell, using the following components:

- Excess FLOS probability $\left(P_n - \bar{P}_n\right)$, $\left(P_m - \bar{P}_m\right)$: As the FLOS probability below the critical level (even if it is above the threshold level) is seen as acceptable, only the portion of the FLOS probability that exceeds the critical level is used.

- Object size u_n: the larger the object is (length, area, etc.), the more weight is put on it
- Network importance ζ_n: As network objects have different hierarchical levels (i.e. levels of importance), an importance factor ζ_n is added to be able to discern between these different importance levels. This importance factor is related to the consequences of FLOS of the network element.

The excess FLOS probability for each object of both networks A and B in grid cell $G_{i,j}$ is then summed up and normalised:

$$W_{G_{i,j}} = \Delta_{i,j} \cdot \frac{\sum\limits_{n_{i,j}} \left((P_n - \bar{P}_n) \cdot u_n \cdot \zeta_n \cdot \delta_n\right) + \sum\limits_{m_{i,j}} \left((P_m - \bar{P}_m) \cdot u_m \cdot \zeta_m \cdot \delta_m\right)}{\sum\limits_{i=1}^{I} \sum\limits_{j=1}^{J} \left(\sum\limits_{n_{i,j}} \left((P_n - \bar{P}_n) \cdot u_n \cdot \zeta_n \cdot \delta_n\right) + \sum\limits_{m_{i,j}} \left((P_m - \bar{P}_m) \cdot u_m \cdot \zeta_m \cdot \delta_m\right) \right)} \tag{14}$$

with $W_{G_{i,j}} \ldots$ Priority for grid cell $G_{i,j}$, value increases with increasing priority.

From there, the rank $r_{G_{i,j}}$ of a grid cell can be calculated:

$$r_{G_{i,j}} = rank\left(sort\left(W_{G_{i,j}} \,|\, desc.\right)\right) \tag{15}$$

This results in the grid cell with the highest priority $W_{G_{i,j}}$ having the lowest rank $r_{G_{i,j}}$.

2.10 Step 10: WP2c: budget constraints

WP2 with constraints (WP2c) is constructed out of WP2: The grid cells in WP2 (i.e. where $\Delta_{i,j} = 1$) are added to WP1c (i.e. $\Delta^c_{i,j} = 1$) starting at the grid cell with the highest priority (n where $r_{G_{i,j}} = 1$), then (n where $r_{G_{i,j}} = 2, 3, \ldots$ etc.) until the sum of the costs reaches the budget limit C_{lim}:

$$\Delta^c_{i,j} = \begin{cases} 1 & for\, \Delta_{i,j} = 1 \;and\; \sum_{G_{i,j}\left(r_{G_{i,j}}=1\right)}^{G_{i,j}\left(r_{G_{i,j}}=N\right)} \left(c_{G_{i,j}} + \sum\limits_{n_{i,j}} c^*_n \cdot u_n \cdot \delta_n + \sum\limits_{m_{i,j}} c^*_m \cdot u_m \cdot \delta_m \right) \leq C_{lim} \\ 0 & otherwise \end{cases} \tag{16}$$

with $\Delta^c_{i,j} \ldots$ binary variable indicating inclusion in WP2c (1=yes, 0=no), $C_{\mathrm{lim}} \ldots$ Budget limit.

2.11 Step 11: WP3: increased failure probability consideration

During the execution of interventions, there is a non-neglible probability that the construction work will result indamage to other nearby objects in other networks. These damages can be separated into groups: 1) Direct damage due to construction work self, for example the excavator inadvertently hitting another pipe and 2) Indirect damage due the perturbation of the nearby soil, for example additional settling due to insufficient compaction.

For the former, the previous existing FLOS probability is irrelevant; the result (a destroyed pipe) will be the same, whether the pipe was old or new. Therefore this type of damage is not regarded in this study. For the latter however, the change of soil conditions imposes additional stress on the material over the longterm, thus affecting (and possibly increasing) the FLOS probability. To account for this increased probability of FLOS, Eq. 10 and 11 are adapted:

$$\Delta_{i,j} \begin{cases} \Delta_{i,j} = 1 \Leftrightarrow & \exists \left(\delta_{n_{i,j}} > 0 \vee \delta_{m_{i,j}} > 0\right) \\ \Delta_{i,j} = 0 \Leftrightarrow & \nexists \left(\delta_{n_{i,j}} > 0 \vee \delta_{m_{i,j}} > 0\right) \end{cases} \tag{17}$$

with

$$\delta_n = 1\, and\, \delta_{k\neq n} = 1 \quad and\, \delta_{k\neq n} = 1 \Leftrightarrow \quad \delta_{k\neq n} = 1 \Leftrightarrow \exists\, n \,|\, \left\{P_n\left(t\right) \geq \bar{P}_n \wedge P_{k\neq n}\left(t\right) \geq P_k^*\right\} \forall n,k \in G_{i,j} \tag{18}$$

$$\delta_m = 1\, and\, \delta_{l\neq m} = 1 \quad and\, \delta_{l\neq m} = 1 \Leftrightarrow \quad \delta_{l\neq m} = 1 \Leftrightarrow \exists\, m \,|\, \left\{P_m\left(t\right) \geq \bar{P}_m \wedge P_{l\neq m}\left(t\right) \geq P_l^*\right\} \forall m,l \in G_{i,j} \tag{19}$$

$$\delta_n = 1\, and\, \delta_l = 1 \quad and\, \delta_l = 1 \Leftrightarrow \quad \delta_l = 1 \Leftrightarrow \exists\, n \,|\, \left\{P_n\left(t\right) \geq \bar{P}_n \wedge P_l\left(t\right)\cdot\xi \geq P_l^*\right\} \forall n,l \in G_{i,j} \tag{20}$$

$$\delta_m = 1\, and\, \delta_k = 1 \quad and\, \delta_k = 1 \Leftrightarrow \quad \delta_k = 1 \Leftrightarrow \exists\, m \,|\, \left\{P_m\left(t\right) \geq \bar{P}_m \wedge P_k\left(t\right)\cdot\xi \geq P_k^*\right\} \forall m,k \in G_{i,j} \tag{21}$$

$$\delta_n, \delta_m, \delta_k, \delta_l = 0 \qquad otherwise \tag{22}$$

where ξ denotes the increasing factor.

The changed equations now can be used to select objects by the following rules:

Eq. 20: If there is at least one object of network A with intervention ($\delta_n = 1$) in grid cell $G_{i,j}$, look for objects of network B in the same grid cell (δ_l) with an increased FLOS probability $P_l(t)\cdot\xi$, that exceed the threshold FLOS probability P_l^* and set this δ_l to 1

Eq. 21: If there is at least one object of network B with intervention ($\delta_m = 1$) in grid cell $G_{i,j}$, look for objects of network A in the same grid cell (δ_k) with an increased FLOS probability $P_k(t)\cdot\xi$, that exceed the threshold FLOS probability P_k^* and set this δ_k to 1

2.12 Step 12: Costs for WP3

The costs for WP3 are calculated according to Eq. 13:

$$C_{WP_3} = \sum_{i=1}^{I}\sum_{j=1}^{J}\left(\Delta_{i,j}\cdot\left(c_{G_{i,j}} + \sum_{n_{i,j}} c_n^*\cdot u_n\cdot\delta_n + \sum_{m_{i,j}} c_m^*\cdot u_m\cdot\delta_m + \sum_{k_{i,j}} c_k^*\cdot u_k\cdot\delta_k + \sum_{l_{i,j}} c_l^*\cdot u_l\cdot\delta_l\right)\right) \tag{23}$$

2.13 Step 13: Intervention priority within WP3

The intervention priority for WP3 is calculated according to Eq. 14:

$$W_{G_{i,j}} = \Delta_{i,j}\cdot\frac{\sum\limits_{n_{i,j}}\left((P_n-\bar{P}_n)\cdot l_n\cdot\zeta_n\cdot\delta_n\right) + \sum\limits_{m_{i,j}}\left((P_m-\bar{P}_m)\cdot l_m\cdot\zeta_m\cdot\delta_m\right)}{\sum\limits_{i=1}^{I}\sum\limits_{j=1}^{J}\left(\sum\limits_{n_{i,j}}\left((P_n-\bar{P}_n)\cdot l_n\cdot\zeta_n\cdot\delta_n\right) + \sum\limits_{m_{i,j}}\left((P_m-\bar{P}_m)\cdot l_m\cdot\zeta_m\cdot\delta_m\right)\right)} \tag{24}$$

Still, the intervention priority only depends on the excess FLOS probability of the objects that exceed the acceptable level and not the specific level defined in each of the above described situations.

From there, the rank $r_{G_{i,j}}$ of a grid cell can be calculated:

$$r_{G_{i,j}} = rank\left(sort\left(W_{G_{i,j}}\,|\,desc.\right)\right) \tag{25}$$

This results in the grid cell with the highest priority $W_{G_{i,j}}$ having the lowest rank $r_{G_{i,j}}$.

2.14 Step 14: WP3c: Budget constraints

The selection for WP3c is done according to Eq. 16:

$$\Delta_{i,j}^c = \begin{cases} 1 & for\,\Delta_{i,j} = 1\ and\ \sum_{G_{i,j}\left(r_{G_{i,j}}=1\right)}^{G_{i,j}\left(r_{G_{i,j}}=N\right)}\left(c_{G_{i,j}} + \sum\limits_{n_{i,j}} c_n^*\cdot u_n\cdot\delta_n + \sum\limits_{m_{i,j}} c_m^*\cdot u_m\cdot\delta_m + \sum\limits_{k_{i,j}} c_k^*\cdot u_k\cdot\delta_k + \sum\limits_{l_{i,j}} c_l^*\cdot u_l\cdot\delta_l\right) \leq C_{lim} \\ 0 & otherwise \end{cases} \tag{26}$$

3 Case Study

3.1 General

The methodology described in section 2 was used to determine OWPs for both a sewer and a gas distribution network of a city with a population of ca. 30'000 and a population density of ca.1'000 people per sq. km. The network maps are shown in Figures 3(a) and 3(b) . To be able to directly compare the different WPs, a small sector (200m by 200m) is selected. The WPs were generated in a case where there was no budget constraint and a case where there was a budget constraint that affected the number of interventions that could be executed.

(a) gas network (b) sewer network

Figure 3: network maps

The pipes in the gas network were considered to be in one of 2 condition states, operational and not operational, the pipes in the sewer network were considered to be in one of five condition states (Table 1). It was assumed that an intervention is to be executed on a pipein the gas network when it reaches the non-operational condition stat and on a pipe in the sewer network whenit reaches condition state 4. Table 1 shows the percentage of length of pipe in each.

Table 1: Actual network condition state distribution

Network type	Number of condition states	Condition state distribution 1	2	3	4	5
Gas	2	91.9%	-	-	-	8.1%
Sewer	5	90.7%	7.4%	0.5%	1.1%	0.3%

3.2 Step 1: Determine failure probability function

The FLOS probability for each objinthe gas networkand in the sewer networkis calclated usingthe failure probability function $P(t)$ proposed by Herz (1996), which has been proven suitable to use for calculating the failure probability of pipe networks with both binary and step-wise deterioration modelling.

$$P(t) = 1 - \left(\frac{\alpha + 1}{\alpha + e^{\beta(t-\gamma)}} \right) \cdot H\left(t - \gamma\right) \tag{27}$$

with $\alpha\ldots$vector of ageing parameters, $\beta\ldots$vector of transition parameters, $\gamma\ldots$vector of resistance time in condition class.

To be able to generate meaningful data, the whole network (shown in Fig. 3) is used to estimate the function parameters α, β and γ. This is done by solving the following minimisation problem:

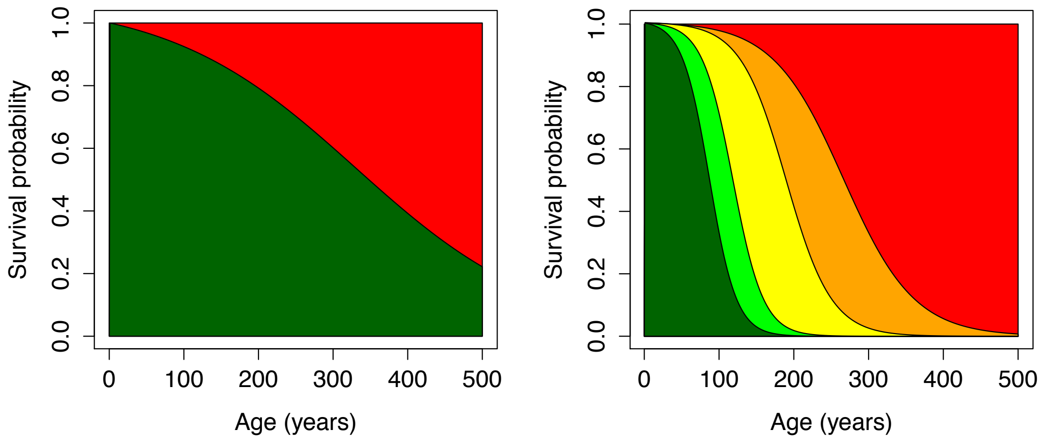
$$\sum_{t=0}^{T} \sum_{s=1}^{S} \left| F_{s,obs}(t) - \frac{\alpha_s + 1}{\alpha_s + e^{\beta_s(t-\gamma_s)}} \right| = min! \tag{28}$$

under the constraints

$$\frac{\alpha_s + 1}{\alpha_s + e^{\beta_s(t-\gamma_s)}} \leq \frac{\alpha_{(s+1)} + 1}{\alpha_{(s+1)} + e^{\beta_{(s+1)}(t-\gamma_{(s+1)})}} \;\; and \;\; \alpha, \beta_s, \gamma_s \geq 0 \tag{29}$$

with $s\ldots$condition state, $F_{s,obs}(t)\ldots$observed relative cumulative frequency of 1 unit of length of pipe being in condition state s at time t, $\alpha_s\ldots$ a parameter to take into consideration the length of time that the pipe has been in condition state s, $\beta_s\ldots$transition parameter for condition state s, and $\gamma_s\ldots$resistance time in condition state s.

This gives the deterioration functions shown in Fig. 4 as well as their parameters, shown in Tbl. 2. As mentioned in Section 3.1, a sewer pipe needs to be replaced if it reaches CS4.



(a) Gas network

(b) Sewer network

Figure 4: Deterioration functions

Table 2: Estimated failure/transition prob. function parameters, used values with grey cell colour

Parameter	Gas network	Sewer network			
	$1 \rightarrow 5$	$1 \rightarrow 2$	$2 \rightarrow 3$	$3 \rightarrow 4$	$4 \rightarrow 5$
α	13.69	82.19	149.33	163.2	124.36
β	7.94e-3	5.51e-2	4.88e-2	3.28e-2	2.12e-2
γ	1.44	7.11	15.7	34.1	38.4

As can be seen from 4, the average length of time until the condition reaches a state where an intervention is required for pipes in both networks (e.g. the survival probability = 0.5) is very long (~350y for the gas network ~200y for the sewer network). Using this age directly would imply that a 50% probability of FLOS is acceptable. However, if the impacts of actual FLOS, (in the best case local service interruptions in an object is just unuseable, in the worst case loss of life if there is an explosive failure of a gas pipe) are taken into consideration, the acceptable probabilities of FLOS are in reality likely to be very small. For example, the failure of agas pipe, can result in numerous fatalities(Stephens, Leewis, u. Moore, 2002), a broken sewer can contaminate the drinking water supply. For this reason, it was decided to choose the value of the intervention-triggering FLOS probability $\bar{P}$ to be 0.025 for gas the network and 0.02 for the sewage network. Similarly, the values of P^* are 0.02 and 0.015, respectively.

3.3 Step 2: Set intervention-triggering failure probability

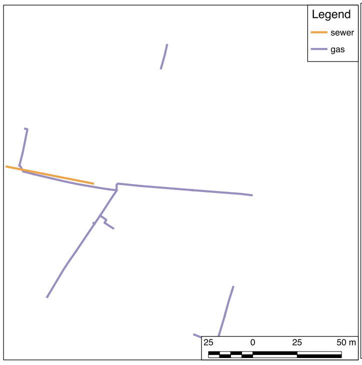
The following intervention-triggering FLOS probabilities and factor values have been assumed:

Table 3: Assumed values

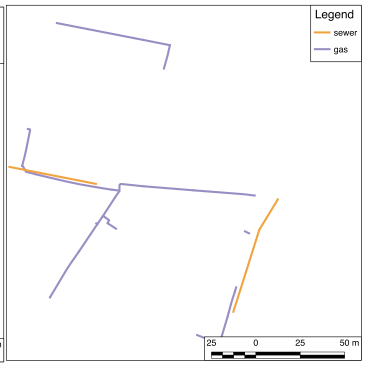
Variable	Description	Value		Unit
		gas	sewer	
$\bar{P}$	Trigger FLOS probability for single objects	0.025	0.020	[-]
P^*	Trigger FLOS probability for neighbouring objects	0.013	0.005	[-]
ζ	Importance factor	1.0	1.0	[-]
ξ	Increasing factor	1.6	1.6	[-]
c_n	Gas pipe intervention cost incl. setup cost	250	–	[MU]
c_n^*	Gas pipe intervention cost excl. setup cost	150	–	[MU]
c_m	Sewer pipe intervention cost incl. setup cost	–	350	[MU]
c_m^*	Sewer pipe intervention cost excl. setup cost	–	250	[MU]
c_g	Grid cell setup cost	1'500		[MU]
C_{lim}	Budget constraint	65'000		[MU]

3.4 Steps 3-6

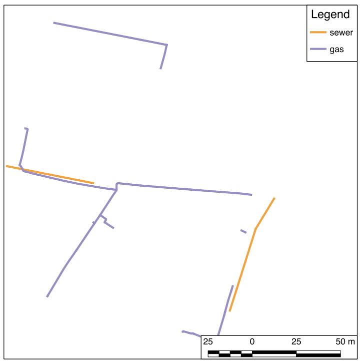
Using Eq. 2ff. the WPs 1-3 were be calculated. Table 4 shows these for the selected network section, Figures 5(a) to 5(c) show the selected pipes on a map.



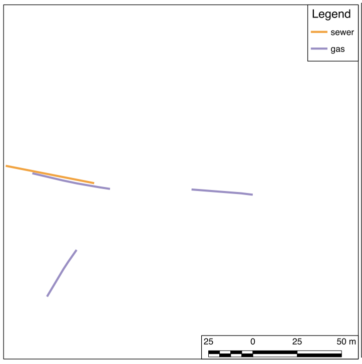
(a) WP1



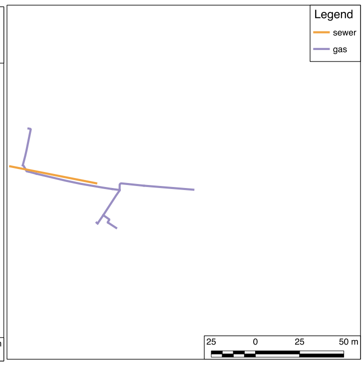
(b) WP2



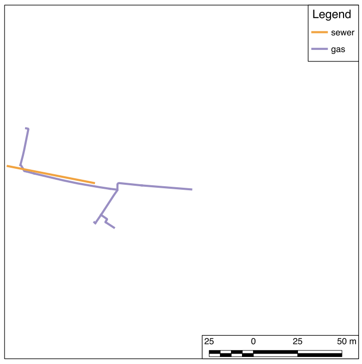
(c) WP3



(d) WP1c



(e) WP2c



(f) WP3c

Figure 5: Work programs

Table 4: Work Programs for the selected sector

Pipe ID	Cell ID	Age	FLOS Prob.	Length	CS	CS removed	WP1 Rank	Cost	WP2 Rank	Cost	WP3 Rank	Cost
G0002C8E	66-62	52	3.28%	43.5	5	217.6	1	10'878	2	6'527	2	6'527
G0002340	68-61	46	2.83%	33.5	5	167.3	2	8'364	3	5'018	3	5'018
G000245B	66-60	46	2.83%	30.0	5	150.0	3	7'501	6	4'501	6	4'501
G0002470	67-61	46	2.83%	28.1	5	140.4	4	7'019	4	4'211	4	4'211
G0002405	67-61	76	5.24%	5.5	5	27.7	5	1'385	4	831	4	831
G000260D	66-61	46	2.83%	18.8	5	93.8	6	4'689	7	2'813	7	2'813
G0002D10	66-62	44	2.69%	22.4	5	111.8	7	5'590	2	3'354	2	3'354
G000243B	67-61	46	2.83%	17.1	5	85.5	8	4'277	4	2'566	4	2'566
G000252D	67-61	46	2.83%	17.0	5	85.0	9	4'252	4	2'551	4	2'551
G000042E	67-63	46	2.83%	13.6	5	67.9	10	3'397	8	2'038	8	2'038
G0002600	68-60	45	2.76%	16.0	5	80.0	11	4'001	5	2'401	5	2'401
G00024E8	66-62	52	3.28%	4.8	5	24.1	12	1'203	2	722	2	722
G00022F4	68-60	45	2.76%	13.5	5	67.5	13	3'376	5	2'025	5	2'025
G00022A9	67-61	52	3.28%	4.3	5	21.7	14	1'083	4	650	4	650
G0001FFE	68-60	45	2.76%	12.8	5	63.9	15	3'193	5	1'916	5	1'916
G0002488	67-61	46	2.83%	6.4	5	32.2	16	1'611	4	967	4	967
G000260E	67-61	76	5.24%	0.7	5	3.7	17	187	4	112	4	112
G000245C	66-62	52	3.28%	2.5	5	12.6	18	629	2	378	2	378
G0002879	67-61	46	2.83%	5.7	5	28.4	19	1'419	4	851	4	851
G0002EC8	68-60	45	2.76%	2.3	5	11.7	20	584	5	350	5	350
G00020D3	68-60	45	2.76%	2.1	5	10.3	21	515	5	309	5	309
G0002DD9	68-61	46	2.83%	1.1	5	5.7	22	286	3	171	3	171
G0002414	66-62	43	2.61%	2.7	5	13.3	23	663	2	398	2	398
G00022C9	66-60	46	2.83%	0.3	5	1.7	24	85	6	51	6	51
G0001420	66-60	24	1.34%	1.4	1	1.4			6	209	6	209
G0002220	68-61	26	1.46%	9.7	1	9.7			3	1'460	3	1'460
G0002235	66-60	24	1.34%	0.1	1	0.1			6	22	6	22
G0002257	68-60	28	1.59%	6.8	1	6.8			5	1'024	5	1'024
G0002260	66-60	24	1.34%	9.9	1	9.9			6	1'482	6	1'482
G000229E	66-60	24	1.34%	14.1	1	14.1			6	2'109	6	2'109
G00022E8	68-61	38	2.26%	2.5	1	2.5			3	376	3	376
G0002321	66-60	24	1.34%	16.3	1	16.3			6	2'449	6	2'449
G0002322	66-60	24	1.34%	8.3	1	8.3			6	1'247	6	1'247
G00023EC	67-63	40	2.40%	43.9	1	43.9			8	6'585	8	6'585
G00023FF	66-60	24	1.34%	7.3	1	7.3			6	1'097	6	1'097
G0002464	66-60	24	1.34%	1.7	1	1.7			6	248	6	248
G00024AB	66-60	24	1.34%	17.8	1	17.8			6	2'666	6	2'666
G00024DC	67-63	40	2.40%	15.3	1	15.3			8	2'298	8	2'298
G00024FA	66-60	24	1.34%	7.7	1	7.7			6	1'155	6	1'155
G00026C1	67-63	40	2.40%	5.6	1	5.6			8	844	8	844
G00027A4	68-61	26	1.46%	0.3	1	0.3			3	40	3	40
G0002AA5	66-60	24	1.34%	7.7	1	7.7			6	1'149	6	1'149
G0002D00	66-60	24	1.34%	19.2	1	19.2			6	2'879	6	2'879
G0002EF5	68-60	25	1.40%	0.6	1	0.6			5	96	5	96
G0002105	68-61	20	1.09%	4.7	1	4.7					3	700
G00021A7	68-61	19	1.03%	21.2	1	21.2					3	3'176
G00021FD	68-61	20	1.09%	1.0	1	1.0					3	152
G000229F	68-61	20	1.09%	0.2	1	0.2					3	37
G0002341	68-60	20	1.15%	9.5	1	9.5					5	1'420
G00023B8	67-63	17	0.91%	12.2	1	12.2					8	1'831
G0002455	67-61	22	1.21%	0.3	1	0.3					4	52
G0002489	67-61	17	0.91%	0.1	1	0.1					4	15
G00027A6	66-61	17	0.91%	7.2	1	7.2					7	1'078
G0002878	67-61	22	1.21%	3.7	1	3.7					4	555
S009961B	66-62	79	2.01%	49.6	4	198.5	1	17'371	2	12'408	2	12'408
S009A097	68-61	79	2.01%	35.8	4	143.2	2	12'530	3	8'950	3	8'950
S013D2B8	69-62	79	2.01%	28.8	4	115.1	3	10'070	1	7'193	1	7'193
S013D2B9	69-62	79	2.01%	28.8	4	115.1	4	10'070	1	7'193	1	7'193
S013D2A5	69-62	79	2.01%	28.8	4	115.1	5	10'070	1	7'193	1	7'193
S013D2AF	69-62	79	2.01%	28.8	4	115.1	6	10'070	1	7'193	1	7'193
S0099C02	69-62	79	2.01%	27.3	4	109.0	7	9'538	1	6'813	1	6'813
S009961A	68-61	79	2.01%	20.1	4	80.3	8	7'028	3	5'020	3	5'020
S0099F9E	68-60	79	2.01%	12.6	4	50.2	9	4'396	5	3'140	5	3'140
S0099CA7	68-60	51	0.45%	55.0	4	220.1					5	13'755
S009A29A	67-63	51	0.45%	6.9	4	27.6					8	1'728
S009A29B	67-63	51	0.45%	7.6	4	30.5					8	1'905
S013529E	69-62	47	0.32%	27.2	4	108.7					1	6'793
S01728B3	66-60	47	0.32%	96.8	4	387.3					6	24'208
Affected Cells							-	-	8	12'000	8	12'000
Sum (MU)								167'328		152'247		209'652
CSs removed								2'565		2'762		3'596
MU/CS								65		55		58

3.5 Comparison

The WPs are compared through the pipes that are to have an intervention, the amount of money spent on these interventions, and the amount of improvement to the network, measured as the number of CSs removed and cost of removing one CS-unit as MU/CS.

It can be seen (Table 4) that in WP1, only the objects that exceed the critical FLOS probability (14 gas pipes, 9 sewer pipes) are selected. With the budget constraint (grey background), only 8 objects (7 gas pipes, 1 sewer pipe) are selected. By ignoring all the other objects, this WP includes interventions on the smallest number of objects (23), has the medium total costs (167'328), removes the least number of CSs (2'565) and has the least efficient CS removal (65 MU/CS).

WP2 adds 20 more gas pipes to the object list. Additionally the priority rank and the costs change. The different priority originates from the shift from an object-based to a grid-based strategy. Therefore, objects in the same grid receive the same rank. In total, 8 cells are to have interventions. WP2 includes interventions on 43 objects, has the lowest total costs (152'247), removes a medium number of CSs (2'762) and has the most efficient CS removal (55 MU/CS).

WP3 adds 10 more gas pipes and 5 more sewer pipes to the object list (in total 58 objects). The priority ranking is identical to WP2, as only the pipes exceeding the critical FLOS probability (and not the threshold FLOS probability) are taken into consideration for the priority ranking. WP3 has the highest total costs (209'652), removes the highest number of CSs (3'596) and has a medium effecient CS removal (58 MU/CS).

However, the impression that WP2 is the best, may be misleading. In fact, it cannot be said by comparing the total costs of the WPs because they include different pipes and different amounts of pipes. Although more is being done now (WP2 and WP3 in contrast to WP1), and one might expect that this will lead to reduced costs in the future, it can not be said without further analysis.

When comparing the WPs with constraints (grey background), one notices that the interventions should be executed on different objects. In WP1, the focus is put on individual objects, so only the objects with the highest FLOS probabilities are candidates for interventions. In WP2 the focus shifts from objects to locations. Therefore the locations with the most critical pipes (cells 69-62 and 66-62) receive the highest priority - which accounts for the spatial dimension of infrastructure networks. In WP3 the additional increase in FLOS probability of nearby objects is taken into consideration, which will result in an even longer time until another intervention in the grid cell is required.

4 Conclusions and further work

In this article it has been demonstrated, that the consideration of multiple networks may mean a change in the pipes to be included in the work program when compared to the situation where multiple networks are not considered, especially when there are budget constraints. It is, therefore, crucial to consider these proximity effects in the planning of work programs on multiple networks if it is desired to maintain them for the least amount of money.

The next steps in this research are the refinement of the methods to take into consideration the long term effect of work programs in the determination of the optimal work programs. This includes taking into consideration other types of interactions between networks, such as the consideration of non-location based interactions like functional interaction, e.g. consequences on the water distribution network during interventions on the sewer network. It also includes developing algorithms that will allow the development of work programs on much larger infrastructure networks, as with increased size and number of considered networks, these problems suffer from dimensional explosion, i.e. exponentially increasing computation time. Additionally, effort will be spent on improved estimation of the FLOS probabilities when there is more data available, estimating the work programs over multiple time periods, and taking into consideration different intervention types and different cost type.

By making these processes automated and linked to the database (including GIS-data) with the data from all networks, a global network simulation tool can be developed that allows future predictions of the network behaviour and the suggested interventions, which is the ideal starting point for advanced optimisation tools to generate more efficient community management.

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