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AN EXAMPLE OF THE EFFECT OF SIMULTANEOUS PLANNING OF INTERVENTIONS ON PROXIMATE INFRASTRUCTURE NETWORKS

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Abstract: 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 of one network that are geographically close to each other are combined. They can be reduced even further if interventions on objects of multiple networks that are close to each other can be combined. In this paper, the effect of the consideration of the spatial proximity of interventions on objects of single networks and multiple networks on work programs is illustrated using a gas and a sewer network in a small urban area.

1 Introduction

Communities often own multiple infrastructure networks such as water distribution, sewer, gas and electricity networks, and road networks. These networks are one of the main assets but also one of the main cost drivers of municipalities. Therefore, managing these networks in a sustainable and efficient way is important. One part of that task is to combine the maintenance interventions to be executed on the infrastructure into optimal work programs (OWPs). How interventions are combined in WPs can lead to reduced costs (Morcous and Lounis 2005; Arthur et al. 2009; Zayed and 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 another intervention. 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 coordination 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 each network. WP3 is determined taking into consideration the spatial proximity of objects in both networks. 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).

2 Methodology to determine an OWP

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

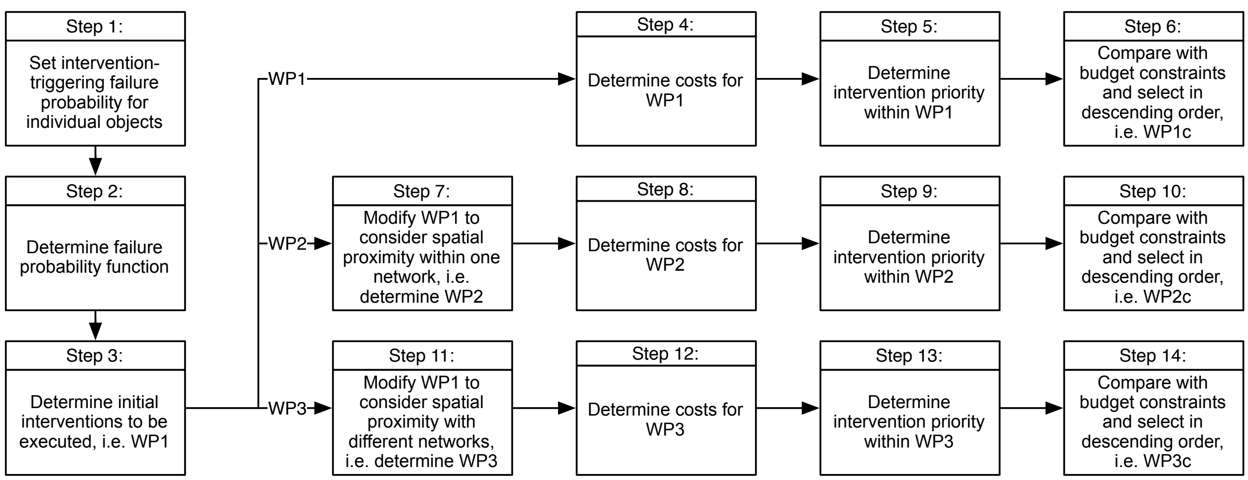

Figure 1: OWP generation steps

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 on one network, he has to proceed through the flowchart until step 10 (WP2/WP2c), whereas if he wants to consider different networks as well, all the steps until step 14 (WP3/WP3c) have to be completed.

2.1 Step 1: Set intervention-triggering failure probability for individual objects

The first step is to define an intervention-triggering (i.e. a critical or maximum acceptable) failure probability. 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:

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

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

2.2 Step 2: Determine failure probability function

The failure probability function $P(t)$ is calculated based on the following modified deterioration function proposed by (Herz 1996), which has been proven suitable to use for calculating the failure probability of pipe networks.

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

with $\alpha\ldots$vector of ageing parameters, $\beta\ldots$vector of transition parameters, $\gamma\ldots$vector of resistance time in condition class, and $H\ldots$Heaviside function[1]

The parameters α, β and γ are estimated by solving the following minimisation problem:

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

under the constraints

[4] $$\frac{\alpha_s+1}{\alpha_s+e^{\beta_s(t-\gamma_s)}} \leq \frac{\alpha_{(s+1)}+1}{\alpha_{(s+1)}+e^{\beta_{(s+1)}(t-\gamma_{(s+1)})}} \ and \quad \alpha_s, \beta_s, \gamma_s \geq 0$$

with $s\ldots$condition state, $F_{s,obs}(t)\ldots$observed relative cumulative frequency of 1 unit of length of network being in condition state s at time t, $\alpha_s\ldots$ a parameter to take into consideration the length of time that the object 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

2.3 Step 3: Determine initial interventions to be executed, i.e. WP1

With the parameter values calculated from Eq.[3] inserted in Eq.[2], the failure probability P_n at each time t for each object n is calculated and compared against the critical failure probability $\bar{P}_n$ (For ease of reading, the index t is omitted). If the failure probability of an object exceeds this critical failure probability, an intervention on this object is included in the WP. For a compact mathematical notation, the Heaviside function can be used:

[5] $$\delta_n = H\left(P_n - \bar{P}_n\right) = H\left(\left(1-\left(\frac{\alpha_n+1}{\alpha_n+e^{\beta_n(t_n-\gamma_n)}}\right)\cdot H\left(t_n-\gamma_n\right)\right)-\bar{P}_n\right)$$

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

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[1] A unary function with $H\left(\left\{x<0\right\}\right)=0$ and $H\left(\left\{x\geq 0\right\}\right)=1$

2.4 Step 4: Determine 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. In this case the costs of WP1 are:

[6] $$C_{WP_1} = \sum_{n=1}^{N} c_n \cdot l_n \cdot \delta_n$$

with $c_n \dots$ unit cost of object n (cost per 1 length unit, including all side costs), $l_n \dots$length of object n, and $C_{WP_1} \dots$ total cost for WP1

2.5 Step 5: Determine intervention priority within WP1

As mentioned in Chapter 1, two cases are compared: one, where there are no restrictions and one where the number of interventions executed is restricted (i.e. having a limited intervention budget). For the former, no priority ranking is needed, as all interventions can be done anyway. 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 as the amount of failure probability exceeding $\bar{P}_n$, thus giving more priority to the pipes with higher excess failure probability. As a network has 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 of different pipe sections. The importance factor is related to the consequences of failure of the pipe. Additionally, the priority is length-weighted.

[7] $$W_n = \frac{(P_n - \bar{P}_n) \cdot l_n \cdot \zeta_n \cdot \delta_n}{\sum_{n=1}^{N} \left((P_n - \bar{P}_n) \cdot l_n \cdot \zeta_n \cdot \delta_n \right)}$$

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

2.6 Step 6: Compare with budget constraints and select in descending order, i.e. WP1c

For WP1 with constraints (WP1c), the interventions in WP1 are added to WP1c starting at the highest priority, until the sum of the costs reaches the budget limitation.

[8] $$\delta_{nc} = \begin{cases} 1 & for\ \delta_n = 1\ and \displaystyle\sum_{n(rank(W_n)=1)}^{n(rank(W_n)=m)} \left(c_n \cdot l_n \cdot \delta_n \right) \leq C_{\lim} \\ 0 & otherwise \end{cases}$$

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

2.7 Step 7: Modify WP1 to consider spatial proximity within one network, i.e. determine WP2

In step 6, which is only applicable for the construction of WP2 and WP3, the spatial proximity of objects that will soon require an intervention is considered. This is done by first assigning each object to a grid cell, as proposed by (R. A. Fenner, L. Sweeting 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. The impacts (or costs) associated with an excavation are assigned directly to each grid cell. The grid cells in which interventions to be executed are given by:

[9] $$\Delta_{i,j}\begin{cases}\Delta_{i,j}=1\Leftrightarrow & \exists\delta_{n_{i,j}}>0\\ \Delta_{i,j}=0\Leftrightarrow & \nexists\delta_{n_{i,j}}>0\end{cases} with \begin{cases}\delta_n=1\ and\ \delta_{k\neq n}=1\Leftrightarrow & \exists\, n\ \left|\left\{P_n(t)\geq\overline{P_n}\wedge P_{k\neq n}(t)\geq P_n^*\right\}\right.\forall n,k\in G_{i,j}\\ \delta_n=0\ and\ \delta_{k\neq n}=0 & otherwise\end{cases}$$

with $i\ldots$ x-coordinate of grid cell, $j\ldots$ y-coordinate of grid cell, $G_{i,j}\ldots$ grid cell with coordinates (i,j), $\Delta_{i,j}\ldots$ binary variable indicating inclusion of grid cell $G_{i,j}$ in WP2 (1=yes, 0=no), $n,k\ldots$objects of one network, $n_{i,j}\ldots$ objects in grid cell with coordinates (i,j), $\delta_k\ldots$ binary variable indicating inclusion of object k in WP2, and $P_n^*\ldots$ threshold failure probability.

or in words:

For all grid cells, that contain at least one (1) object that will have an intervention, mark this grid cell and set all other objects in this cell to "intervention" if they exceed a certain threshold failure probability"

2.8 Step 8: Determine costs for WP2

It is assumed for this example that all interventions in one grid cell are executed at the same time, and that the setup costs (construction site setup, traffic rerouting, excavation etc.) are the same for each grid cell. In this case the costs of WP2 are:

[10] $$C_{WP_2}=\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\Delta_{i,j}\cdot\left(c_g+\sum_{n_{i,j}}c_n^*\cdot l_n\cdot\delta_n\right)\right)$$

with $c_g\ldots$setup costs per grid cell, $c_n^*\ldots$unit cost of object n (cost per 1 length unit, without setup costs), and $C_{WP_2}\ldots$ total cost for WP2

2.9 Step 9: Determine intervention priority within WP2

For the case when constraints are imposed, a priority ranking is calculated. Differently from WP1, the priority is now grid-based. It is calculated as the priority-, length- and importance-weighted normalized sum of all objects in the respective grid cell.

[11] $$W_{G_{i,j}}=\Delta_{i,j}\cdot\frac{\sum_{n_{i,j}}\left((P_n-\bar{P}_n)\cdot l_n\cdot\zeta_n\cdot\delta_n\right)}{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n_{i,j}}\left((P_n-\bar{P}_n)\cdot l_n\cdot\zeta_n\cdot\delta_n\right)}$$

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

2.10 Step 10: Compare with budget constraints and select in descending order, i.e. WP2c

For WP2 with constraints (WP2c), the grid cells with their selected objects from WP2 are added to WP2c starting at the highest priority, until the sum of the costs reaches the budget limitation.

[12] $$\Delta_{i,j}^c=\begin{cases}1 & for\ \Delta_{i,j}=1\ and \displaystyle\sum_{\{i,j\}\left(rank(W_{G_{i,j}})=1\right)}^{\{i,j\}\left(rank(W_{G_{i,j}})=m\right)}\left(\left(c_g+\sum_{n_{i,j}}c_n^*\cdot l_n\cdot\delta_n\right)\right)\leq C_{\lim}\\ 0 & otherwise\end{cases}$$

with $\Delta_{i,j}^c\ldots$ binary variable indicating inclusion in WP2c (1=yes, 0=no), $C_{\lim}$º Budget limit

2.11 Step 11: Modify WP1 to consider spatial proximity within different networks, i.e. determine WP3

The calculation is the same as for WP2, except that both networks are being considered simultaneously, i.e. if an intervention is to be done in one grid cell, regardless of which network they are part of, all other objects in that grid cell are compared against the threshold failure probability P^* and selected if they exceed it. The selected cells and objects are then

[13]

$$\Delta_{i,j}\begin{cases}\Delta_{i,j}=1\Leftrightarrow & \exists\left(\delta_{n_{i,j}}>0\vee\delta_{m_{i,j}}>0\right)\\ \Delta_{i,j}=0\Leftrightarrow & \nexists\left(\delta_{n_{i,j}}>0\wedge\delta_{m_{i,j}}>0\right)\end{cases}\ with\begin{cases}\delta_n=1\ and\ \delta_{k\neq n}=1\Leftrightarrow & \exists\, n\left|\left\{P_n(t)\geq\overline{P_n}\wedge P_{k\neq n}(t)\geq P_n^*\right\}\forall n,k\in G_{i,j}\right.\\ \delta_m=1\ and\ \delta_{l\neq m}=1\Leftrightarrow & \exists\, m\left|\left\{P_m(t)\geq\overline{P_m}\wedge P_{l\neq m}(t)\geq P_m^*\right\}\forall m,l\in G_{i,j}\right.\\ \delta_n=1\ and\ \delta_l=1\Leftrightarrow & \exists\, n\left|\left\{P_n(t)\geq\overline{P_n}\wedge P_l(t)\geq P_m^*\right\}\forall n,l\in G_{i,j}\right.\\ \delta_m=1\ and\ \delta_k=1\Leftrightarrow & \exists\, m\left|\left\{P_m(t)\geq\overline{P_m}\wedge P_k(t)\geq P_k^*\right\}\forall m,k\in G_{i,j}\right.\\ \delta_n,\delta_m,\delta_k,\delta_l=0 & otherwise\end{cases}$$

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 failure probability.

2.12 Step 12: Determine costs for WP3

The costs for this work program can be calculated from a modified version of Eq.[10] as:

[14]
$$C_{WP_3}=\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\Delta_{i,j}\cdot\left(c_g+\sum_{n_{i,j}}c_n^*\cdot l_n\cdot\delta_n+\sum_{m_{i,j}}c_m^*\cdot l_m\cdot\delta_m\right)\right)$$

2.13 Step 13: Determine intervention priority within WP3

Similar to Step 9, the priority of intervention is calculated from a modified version of Eq.[11] as:

[15]
$$W_{G_{i,j}}=\Delta_{i,j}\cdot\frac{\sum_{n_{i,j}}\left((P_n-\bar{P}_n)\cdot l_n\cdot\zeta_n\cdot\delta_n\right)+\sum_{m_{i,j}}\left((P_m-\bar{P}_m)\cdot l_m\cdot\zeta_m\cdot\delta_m\right)}{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\sum_{n_{i,j}}\left((P_n-\bar{P}_n)\cdot l_n\cdot\zeta_n\cdot\delta_n\right)+\sum_{m_{i,j}}\left((P_m-\bar{P}_m)\cdot l_m\cdot\zeta_m\cdot\delta_m\right)\right)}$$

For WP3 with constraints (WP3c), the grid cells with their selected objects from WP2 are added to WP3c starting at the highest priority, until the sum of the costs reaches the budget limitation.

[16]
$$\Delta_{i,j}^c=\begin{cases}1 & for\ \Delta_{i,j}=1\ and\ \sum_{\{i,j\}\left(rank(W_{G_{i,j}})=1\right)}^{\{i,j\}\left(rank(W_{G_{i,j}})=m\right)}\left(c_g+\sum_{n_{i,j}}c_n^*\cdot l_n\cdot\delta_n+\sum_{m_{i,j}}c_m^*\cdot l_m\cdot\delta_m\right)\leq C_{\lim}\\ 0 & otherwise\end{cases}$$

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 2 and 3. 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.

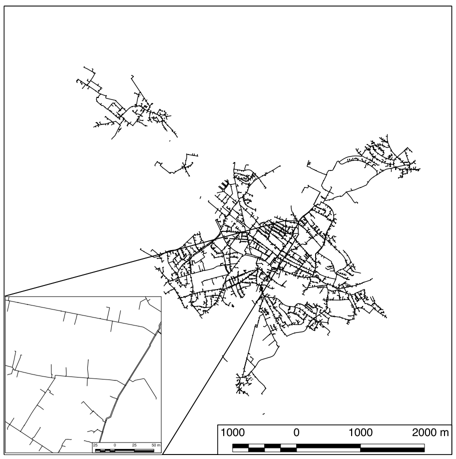

Figure 2: gas network

Figure 3: sewer network

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 5 condition states (Table 1). It was assumed that an intervention is needed in the gas network when a pipe reaches condition state "defunct" and in the sewer network when a pipe reaches condition state 4. Table 1 shows the actual network condition state distribution.

Table 1: Actual network condition state distribution

Network type	Number of condition states used	Condition state distribution 1 (good)	2 (fair)	3 (sufficient)	4 (poor)	5 (defunct)
Gas	2	91.9%	-	-	-	8.1%
Sewer	5	90.7%	7.4%	0.5%	1.1%	0.3%

3.2 Step 1: Set intervention-triggering failure probability

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

Table 2: Assumed values

Variable	Description	Value	Unit
$\bar{P}$	Trigger failure probability for single objects	0.025	[-]
P^*	Trigger failure probability for neighbouring objects	0.020	[-]
ζ	Importance factor	1.0	[-]
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	45'000	[MU]

3.3 Step 2: Determine failure probability function

The failure probability functions were determined using Eq. [3], with the values of the parameters given in Table 3.

Table 3: Estimated failure prob. function parameters

Parameter	Gas network	Sewer network
α	13.69	163.2
β	7.94e-3	3.28e-2
γ	1.44	34.1

3.4 Steps 3-6

Using Eq. [5]ff. the WPs 1-3 were be calculated. Table 4 shows these for the selected network section, Figures 4 to 6 show the selected pipes on a map.

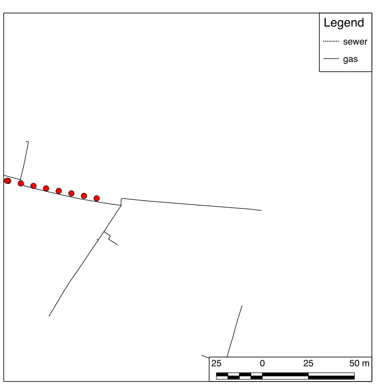

Figure 4: WP1

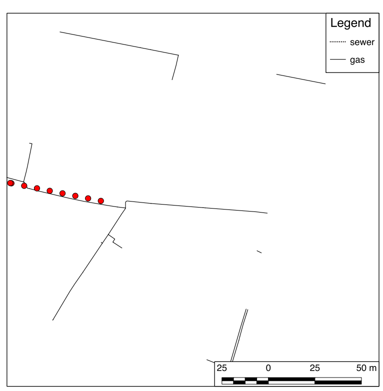

Figure 5: WP 2

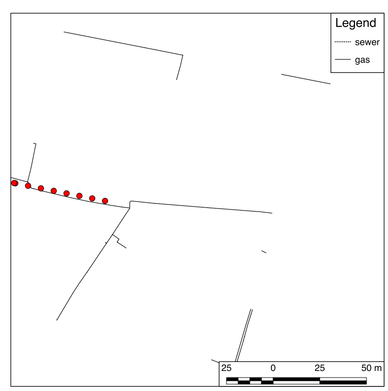

Figure 6: WP 3

Table 4: Work Programs for the selected sector

							WP1		WP2		WP3	
Pipe ID	Cell ID	Age	Failure Prob.	Length	CS	CS removed	Rank	Cost	Rank	Cost	Rank	Cost
G0002C8E	66-59	52	3.28%	43.51	5	218	1	10'878	1	6'527	2	6'527
G0001F51	64-58	76	5.96%	4.39	5	22	2	1'098	3	659	4	659
G00025BC	65-59	60	3.90%	6.01	5	30	3	1'503	4	902	1	902
G000260D	66-58	46	2.83%	18.76	5	94	4	4'689	5	2813	5	2813
G000042E	67-60	46	2.83%	13.59	5	68	5	3'397	2	2038	3	2'038
G0002D10	66-59	44	2.69%	22.36	5	112	6	5'590	1	3354	2	3'354
G00024A5	65-59	43	2.61%	34.20	5	171	7	8'551	4	5130	1	5'130
G00024E8	66-59	52	3.28%	4.81	5	24	8	1'203	1	722	2	722
G00024D1	65-59	60	3.90%	2.12	5	11	9	531	4	319	1	319
G0002E42	65-59	44	2.69%	14.26	5	71	10	3'565	4	2139	1	2'139
G000245C	66-59	52	3.28%	2.52	5	13	11	629	1	378	2	378
G0000CCC	65-59	60	3.90%	0.40	5	2	12	100	4	60	1	60
G0002414	66-59	43	2.61%	2.65	5	13	13	663	1	398	2	398
G00021DF	64-58	37	2.19%	6.16	5	31	-	-	3	924	4	924
G00022EF	64-58	37	2.19%	17.64	5	88	-	-	3	2646	4	2'646
G0000BBB	65-59	35	2.06%	1.49	5	7	-	-	4	223	1	223
G00027EA	65-59	35	2.06%	12.01	5	60	-	-	4	1801	1	1'801
G00023EC	67-60	40	2.40%	43.90	5	220	-	-	2	6585	3	6'585
S0099622	65-59	104	5.24%	29.86	4	119	1	12'440	1	7464	1	7'464
Affected cells							-	-	5+1	9'000	5	7'500
Sum (MU)								54'838		54'082		52'582
CSs removed								952		1'373		1'373
MU/CS								57.6		39.4		38.3

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 5) that in WP1, only the objects that exceed the critical failure probability (13 gas pipes, 1 sewer pipe) are selected. With the budget constraint (gray background), only 7 objects (6 gas pipes, 1 sewer pipe) are selected. By ignoring all the other network objects, this WP includes interventions on the smallest number of objects (14), has the highest total costs (54'838), removes the least number of CSs (952) and has the least effective CS removal (57.6 MU/CS).

WP2 adds 5 more gas pipes to the object list. Additionally the priority rank and the costs change. The different priority originates in a shift from an object-based to a grid-based strategy. Therefore, objects in the same grid get the same priority rank. In total, 5 cells of the gas network and 1 cell of the sewer network are affected by interventions. WP2 includes interventions on the largest number of objects (19), has medium total costs (54'082), removes the largest number of CSs (1'373) and has a medium effective CS removal (39.4 MU/CS).

WP3 is almost identical to WP2, with the difference that the gas and the sewer network are regarded as one single entity instead of two. As there are both gas and sewer interventions in cell 65-59, the setup costs can be reduced by combining them. Therefore the total cost of WP3 is the lowest. Additionally, the priority of the grid cells change, so that grid cell 64-58 is excluded from the constrained WP, and exchanged for grid cell 65-59. WP3 includes interventions on the largest number of objects (19), has the lowest total costs (52'582), removes the highest number of CSs (1'373) and has the most effective CS removal (38.3 MU/CS).

4 Conclusions and further work

In this article it has been demonstrated, that the explicit consideration of multiple networks can lead to more cost efficient interventions i.e. through the cost per added condition state.

It has also 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. This is especially true in the when budget constraints are imposed. It is, therefore, crucial to consider these proximity effects in the planning of work programs on 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 generate optimal work programs, in order to fill the demonstrated gap. This includes taking into consideration other types of interactions between networks, e.g. the fact that the excavation of one pipe may result in damage to another pipe. It also includes developing algorithms that will allow the development of work programs on much larger infrastructure networks. Additionally, effort will be spent on refining the expected lifetime calculations when there is more data available, estimating the calculation of work programs over multiple time period, and optimizing the consideration of different intervention types and costs respectively.

5 References

Arthur, S, H Crow, L Pedezert, and N Karikas. 2009. "The Holistic Prioritisation of Proactive Sewer Maintenance." *Water Science and Technology* 59 (7): 1385–96.

Herz, Raimund. 1996. "Dégradation et Renouvellement Des Infrastructures." *Un Modèle de Survie Par Cohorte*: 21–36.

Liu, Min, and Dan M. Frangopol. 2004. "Optimal Bridge Maintenance Planning Based on Probabilistic Performance Prediction." *Engineering Structures* 26 (7): 991–1002.

Morcous, G., and Z. Lounis. 2005. "Maintenance Optimization of Infrastructure Networks Using Genetic Algorithms." *Automation in Construction* 14 (1): 129–42.

R. A. Fenner, L. Sweeting, M. J. Marriott. 2000. "A New Approach for Directing Proactive Sewer Maintenance." *Proceedings of the ICE - Water and Maritime Engineering* 142 (Volume 142, Issue 2): 67–77(10).

Zayed, Tarek, and Elsayed Mohamed. 2013. "Budget Allocation and Rehabilitation Plans for Water Systems Using Simulation Approach." *Tunnelling and Underground Space Technology* 36 (0): 34–45.