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Modelling the long-term sustainability impacts of coordination policies for urban infrastructure rehabilitation

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ABSTRACT

Due to structural and hydraulic deterioration, urban water pipe networks have annual rehabilitation needs. Worldwide, these needs are often significantly larger than the actual amount of rehabilitation being performed, leading to increased risks of serious failures, lower performance and a growing techno-financial burden for future generations. It is well accepted that, in order to limit the multiple impacts of utility works in the urban environment, rehabilitation projects should be coordinated between water, transport, energy and telecommunication infrastructures. In practice, such coordination means that public utilities must rehabilitate assets earlier or later than technically needed, in order to engage in joint projects in which digging and resurfacing expenditures are shared. Hence, at the municipal scale, such coordination influences two variables that are key to strategic decision support: average costs (€/metre) for asset rehabilitation, and the service lifetimes of those assets. However, current models for strategic asset management do not enable practitioners to estimate how changes in the coordination process may influence the long-term financial and environmental impacts of infrastructure rehabilitation. The present study aimed at addressing this methodological gap by introducing the concept of a coordination window that quantifies to what extent utilities compromise asset rehabilitation times in order to join multi-utility projects. An algorithm for modelling the influence of the coordination window size on long-term sustainability costs is presented and applied to one Swedish municipality. The results suggested that total capital costs and carbon emissions can be lowered by 34% and 16% with a coordination window of 35 and 25 year, in comparison to the no-coordination case.

1. Introduction

Despite their criticality for human welfare and development, municipal infrastructures such as drinking water, sewers and road networks have been shown worldwide to be in poor condition (Berger et al., 2016; Wall and Rust, 2017; Sakai et al., 2020; ASCE, 2021) and to suffer from insufficient reinvestment. This underlines the need for water and road utilities to step up their pro-active rehabilitation efforts and thereby prevent levels of service deteriorating and operational expenditures increasing. Water utilities are under pressure to meet rehabilitation needs in a cost-effective manner as they also have to finance adaptations to climate change, urban population growth and tighter environmental regulations. For example, it has been estimated that all EU countries but Germany need to increase annual expenditures for water supply and sanitations by at least 25% to comply with the current water directives (OECD, 2020). At the same time, utilities must decrease the external consequences of successive excavation activities as these affect numerous external actors and may also hinder the implementation of rehabilitation projects. These external consequences include disturbance to traffic and local businesses as well damage to adjacent infrastructure and the local environment (e.g. trees). To address these challenges and the problem of ageing municipal infrastructures two complementary strategies can be identified: the implementation of infrastructure asset management (Marlow, Beale and Burn, 2010) and coordination of rehabilitation efforts between utilities.

Infrastructure asset management for water utilities has been organised into three aligned decision levels (Alegre et al., 2013). Work at the strategic level includes setting target renewal rates for the entire infrastructure and securing the corresponding reinvestment budget with a time horizon of 10 to 20 years. The tactical level often refers to the

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production of 3-to-5-year plans through which rehabilitation projects are prioritized, typically taking a risk-based approach. The focus at that level is generally to maximize network improvement with the available reinvestment budget. The operational level deals with project implementation on a 1–2 years time horizon, including choice of rehabilitation methods and spatial and temporal coordination of building activities, possibly with other utilities. The ability to address multi-utility coordination is important at all three decision levels of water infrastructure asset management. In particular, coordination of rehabilitation works between utilities has an influence on the quantities evaluated at the strategic level, including the yearly capital expenditure required to meet the renewal needs of urban water pipe networks. This is because coordination can reduce rehabilitation costs (€/metre) through, for example, shared excavations and repaving expenditures but may also shorten or extend asset service lives. This is a consequence of the "problems of scale" defined by Daulat et al. (2022) as one of the seven challenges in practicing integrated multi-infrastructure asset management. Integration of multi-utility coordination in the water infrastructure asset management process has mostly been addressed in scientific studies at the tactical decision level. For example, studies by Carey and Lueke (2013), Osman (2015), Tscheikner-Gratl et al. (2016), Abu-Samra et al. (2020) and Shahata et al. (2022) focus on optimized scheduling and prioritization of rehabilitation interventions, with the general aim of making the best use of available re-investment budgets. Integration of multi-utility coordination at the strategic level has been partly addressed by Bruaset et al. (2018) who estimated total reinvestment costs over a 15 year period for the drinking water and sewer pipe networks of Trondheim municipality in Norway. The authors considered different scenarios with regards to multi-utility coordination and use of trenchless technologies. However, the coordination process was assumed to be systematic (i.e. rehabilitation of an asset triggers rehabilitation of the adjacent assets, independent of their conditions), which did not allow for modelling different levels of coordination. Earlier, Malm et al. (2013) estimated the capital costs of meeting the long term renewal needs of both sewer and water pipe networks in Sweden, using cohort survival functions calibrated with historical decommissioning data, This approach assumes a "same as in the past" scenario (Large et al., 2015) when it comes to rehabilitation performed for other reasons than deterioration, including coordination between utilities. The study presented in this paper aimed at increasing the currently limited knowledge and availability of tools for assessing the long-term (>30 years) effects of multi-utility coordinated rehabilitation on strategic asset management metrics. The objectives of the study were:

- To develop an algorithm, modelling the influence of multi-utility coordination on the long-term costs of pipe and road network rehabilitation.
- To apply the algorithm to a case study to compare different coordination policies in terms of long-term sustainability costs and identify possible optimal coordination levels, and
- To assess the importance of the inter-infrastructure spatial correlation of asset lifetimes as a modelling parameter.

2. Method

2.1. Defining and quantifying the concept of coordination

Coordination can have different meanings depending on which aspect of integrated multi-infrastructure asset management (Daulat et al., 2022) is being discussed. In this study, coordination was identified where adjacent infrastructure assets (e.g. pipes, pavement) were rehabilitated earlier or later than the end of their functional lives, in order to carry out works on multiple assets within a single project. The end of an asset's *functional life* was defined as the point in time when the asset reaches an unacceptable level of performance or risk, due to deterioration, and therefore needs to be rehabilitated. Thresholds for unacceptable performance or risk levels may be organisation- and time-dependent (Bruaset et al., 2017). The concept of adjacency between assets was determined by the observation that the digging required to rehabilitate these assets individually would involve partly or fully excavating the same soil masses.

Modelling the influence of coordination on long-term rehabilitation costs requires that coordination is quantified. This was achieved by introducing the concept of a coordination window. As presented in Fig. 1, the coordination window starts when one asset needs rehabilitation and is extended a given number of years, τ, into the future. This period represents the criteria for coordination, meaning that adjacent assets (i.e. those in the same street segment) whose end of functional life (circles in Fig. 1) falls within the coordination window are rehabilitated together in a joined multi-infrastructure project (vertically aligned crosses in Fig. 1). A pro-active asset management approach was assumed, meaning that the joint rehabilitation project would take place at the beginning of the coordination window. This implies that asset rehabilitations are performed, at a maximum, τ years earlier than needed.

The variable τ was used as a quantitative metric of the intensity of the coordination process occurring in infrastructure asset rehabilitation. If $\tau=0$, adjacent assets are rehabilitated in joint projects only if they reach the end of their functional lives at the same time, leading to mostly single-utility projects, i.e. no coordination. If $\tau=\infty$, adjacent assets are always rehabilitated in multi-utility projects, i.e. there is systematic coordination. In this paper, τ is interchangeably referred to as the size of the coordination window or the level of coordination. The coordination model was developed on the basis of τ being constant throughout the simulation period.

2.2. Choice of the deterioration model

The cohort survival approach was selected to model infrastructure asset deterioration in the algorithm developed, providing the predictions of remaining functional lifetimes needed to implement the concept of a coordination window. Cohort survival is a probabilistic single-variate (Kleiner and Rajani, 2001) modelling approach which has been applied mainly to drinking water (Herz, 1996; Malm et al., 2012; Large et al., 2015; Bruaset et al., 2017) and sewer pipe networks (Baur and Herz, 2002; Duchesne et al., 2013; Malm et al., 2013). No theoretical or practical obstacles to using this approach for other networked infrastructure were found in the literature. The approach consists of organizing assets into groups (cohorts) that are homogeneous with regard to their deterioration behaviour (Herz, 1996). The approach is well suited to making long term predictions of rehabilitation needs at the network level and has a relatively low data requirement. It does not take into account spatial co-variates with the intention of making predictions for single assets. The minimum data requirement is so-called survival functions for each cohort as well as the network age and cohort distribution expressed in installed kilometres of pipe/road installed per decade and cohort type. The survival functions can be based on any statistical distribution (e.g. Herz, Weibull) that is appropriate to the observations used in its calibration. If the purpose is to forecast replacement needs (as in this study), these observations should normally be a dataset of times, or time periods, at which assets have reached the end of their functional life, i.e. need replacement due to unacceptable levels of performance (e.g. excessive frequency of leakage for a drinking water pipe, high groundwater infiltration rate for a sewer pipe) or risk (e.g. poor structural condition for a critical sewer pipe). For sewer networks, the calibration of survival curves capturing pipe deterioration is currently limited by the fact that CCTV inspection, which is by far the most common inspection method, has many flaws in assessing structural integrity and water tightness. Other methods are under development and are expected to be mature within 2–10 years (Tscheikner-Gratl et al., 2020).

The choice of using a cohort survival model was motivated by the

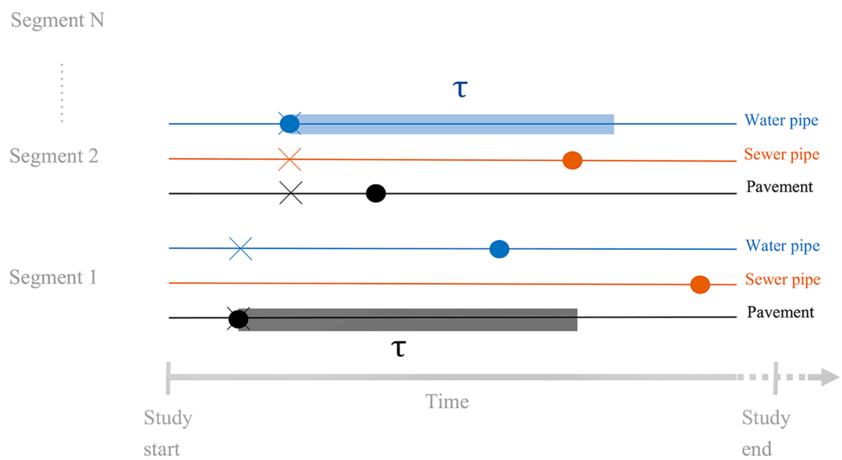

Fig. 1. Illustration of the concept of coordination window for the rehabilitation of a fictitious street network of N segments served by a water pipe, sewer and pavement. Circles represent the end of functional life of an asset, i.e. the point when rehabilitation is needed, while crosses represent the actual time of rehabilitation. τ refers to the duration of the coordination window expressed in years.

availability of data for such models in a Scandinavian context, as they are commonly used for estimating rehabilitation needs at the strategical level for both sewer and drinking water networks. The developed coordination model is however compatible with other survival model, for example the ones that have been previously developed for sewer networks (Laakso et al., 2019). The coordination model may also be used with failure prediction models, which are more common for drinking water networks (Scheidegger et al., 2015), by assuming that the end of functional life corresponds to a failure probability threshold.

2.3. Level of aggregation of the infrastructure inventories

The coordination model was developed on the assumption that an integrated asset inventory would be available as input data. The integrated asset inventory is more detailed than the conventional data requirement of cohort survival models and refers to a list of segments with the following attributes: segment length, installation years for each infrastructure concerned and cohort type for each infrastructure concerned. As mentioned in section 2.2, the age distribution in installed km per decade and cohort type is sufficient to run a cohort survival model for a single infrastructure. However, the study of a coordination scenario requires knowledge of the inter-infrastructure spatial combination of one of the outputs of cohort survival models, namely remaining lifetimes. Hence, the inter-infrastructure spatial combination of cohort survival model inputs (installation years and cohort types) was identified as a necessary input to the coordination model that was developed. One way to summarize this information is to use combined multi-infrastructure cohorts but these can be too numerous to be practical to consider: 3 infrastructures and 5 cohorts leads to 125 combined cohorts. Moreover, adjacent assets from different infrastructures do not necessarily have the same installation year, leading to even more combinations to express the asset inventories in a summarized way. This motivated the choice to use a detailed integrated asset inventory: GIS information about whole pipe/road networks is becoming increasingly available and quick to process thanks to improved computing power. An example of integrated asset inventory is presented in Table 1. The coordination model was developed to process input data at segment level, but not to make predictions at that level as this would constitute tactical asset management. The detailed asset inventory was used as a structure to sample lifetimes and derive aggregated information at the network level concerning the strategic implications of different coordination strategies.

A segment (see above) contains adjacent assets and is sometimes referred to as either a street segment if it contains a road or otherwise a trench segment. The criteria used to define segments were that they should be short enough to contain no more than one cohort type and one installation year per infrastructure.

2.4. Lifetime sampling strategy

The survival function (S) of a given cohort is directly related to the cumulative distribution function (F) of its assets' lifetime distribution through the relation $S = 1\text{-F}$. Cumulative distribution functions can be used to generate random numbers according to given distributions by using inverse transform sampling (Devroye and Devroye, 1986). Therefore, inverse transform sampling was used in the coordination model to assign a functional lifetime to all infrastructure assets, based on the expected lifetime distribution within each cohort. This involved first assigning to the assets a random number X from a uniform distribution in the range [0,1], and then computing $F^{-1}(X)$ to obtain the corresponding lifetime. Different uniform distributions were used for each infrastructure type. Special attention was given to how correlated these distributions were, as described in section 2.5 below.

2.5. Accounting for inter-infrastructure spatial correlation of asset lifetimes

The Cholesky decomposition (Cholesky, 2005) was identified as a suitable method to account for the inter-infrastructure correlation of asset lifetimes in the coordination model. It is the simplest method that was found in the literature that generates sets of normally distributed random numbers with given correlation coefficients between these sets (Burgess, 2022). The matrix R was defined as an input modelling parameter, with $\rho_{i,j}$ referring to the Pearson coefficient between the asset

Table 1
Example of an aggregated infrastructure inventory.

Segment ID	Segment length [m]	Installation year, water pipe	Cohort water pipe	Installation year, sewer	Cohort sewer	Installation year, road	Cohort road
1	48	1930	Grey iron <1950	1930	Concrete <1950	1965	<1000 v./day
2	56	1990	PVC >1970	1955	Concrete >1950	1990	<1000 v./day
…	…	…	…	…	…	…	…

lifetimes of infrastructure i and infrastructure j. The model followed a routine to:

1) Generate, for each infrastructure, a normal distribution in the range [0;1] with as many elements as there are street segments.
2) Use the Cholesky decomposition to generate a new set of normal distributions, correlated according to matrix R.
3) Apply the cumulative distribution function of the normal distributions to obtain uniform distributions in the range [0,1], also correlated according to the R matrix.

$$R = (\rho_{i,j})_{1<i<I,1<j<I}$$

2.6. Definition of model outputs

The following quantities are needed in order to compare coordination polices and evaluate their implications for infrastructure owners:

- -Length (i.e. meters of) of rehabilitation action performed per year. A rehabilitation action corresponds to a combination of adjacent assets being rehabilitated (examples: rehabilitation of drinking water pipe and pavement, rehabilitation of sewer and pavement, etc.). The number of possible rehabilitation actions A is related to the number of studied infrastructures I, with the equation $A = 2^I - 1$.
- Sustainability costs per year (e.g. capital costs, greenhouse gases emissions), obtained by multiplying per year length of rehabilitation performed action by the user-defined unit costs of these actions.
- Rehabilitation rate per year by infrastructure type, expressed as a percentage.
- Under-utilization ratio per year by infrastructure type. This is the average ratio between asset age at time of rehabilitation and the asset's functional lifetime.

The structure of the coordination model developed implies that the result from one simulation is based on only one possible set of assigned asset lifetimes compatible with the input cohort survival functions and the inter-infrastructure correlation matrix R. To obtain results with a decision-making value, the model was programmed to run numerous simulations and plot the average value and 95% confidence interval of the output quantities for each year of the simulation period. The number of simulations to be performed should be increased incrementally in order to narrow confidence intervals until the comparison between coordination policies is deemed to be meaningful.

2.7. Application to the case study of Luleå

2.7.1. Integrated asset inventory

The comparative coordination study focused on the sewer, drinking water distribution and road infrastructure of the municipality of Luleå in Sweden. In January 2021 the population of Luleå municipality serviced by the public water utility was 66,700 inhabitants. Asset inventories of the three infrastructures were retrieved in GIS format from the water utility and the Swedish Transport Administration website. An integrated asset inventory was produced by processing the GIS layers of the three infrastructures with the buffering and spatial join functions of the open source software QGIS. A 6-metre-wide buffer was created along each sewer pipes to determine if there was an adjacent drinking water pipe and to read its attributes. The inventory comprised 3469 residential street segments with an average length of 50.7 m, for a total length of 176 km. This corresponded to 39% of the total street length of Luleå municipality. The attributes of the segments were:

- Length.
- Installation year of drinking water pipe.
- Material of drinking water pipe.
- Installation year of sewer pipe.
- Material of sewer pipe.
- Installation year of the road subbase.

All segments corresponded to residential streets with average daily traffic of less than 1000 vehicles The inventory was limited to such streets because they were considered to be the most suitable for coordinated infrastructure renewal projects in the chosen municipality. A large proportion of residential streets in Luleå municipality lacks both an engineered subbase layer and a functioning drainage solution. Improving the status of these roads therefore requires excavation works which could be performed in coordination with open-cut pipe replacement operations. On the other hand, condition improvement operations on larger roads more commonly consists of replacing the asphalt top layer, making them less suited for coordination with open-cut pipe replacement projects.

2.7.2. Survival functions

The cohort survival functions estimated by Malm et al. (2013) were used for the water and sewer pipes in the asset inventory for Luleå. These curves are described by Herz survival functions (Herz, 1996) on the basis of three parameters:

- T_{100} the time after installation when 100% of the asset cohort remain functional.
- T_{50} the time after installation when 50% of the asset cohort remain functional.
- T_{10} the time after installation when 10% of the asset cohort remain functional.

The survival functions were determined based on decommissioning data from Gothenburg, Stockholm and several Norwegian municipalities (Malm et al., 2013). They do not capture only the deterioration behaviour of the different cohorts but also the fact that pipes were replaced for adapting hydraulic capacity or due to external factors (e.g. coordination), to an unspecified extent. It is a limitation of this case study, as the MURM prototype requires that the input survival functions represent the deterioration of the assets. A method to obtain such curves is described in section 4.3.

Lifetime estimates for road subbase layers are scarce in the literature. For the case of Luleå, a review of amortization periods used by Swedish municipalities for road subbase layers was performed. This found an average value of 80 years. This figure was used as the parameter T_{50} for the road subbase. Values of 50 and 110 years were assumed for the T100 and T10 parameters (±30 years). All the survival curves used for the case study of Luleå are presented in Fig. 2.

The survival curves "Water - PE and ductile iron, after 1980 and "Sewer – Plastic" were used for water and sewer pipes rehabilitated with the digging method (pipe replacement). For pipes rehabilitated with structural trenchless methods, the survival curves proposed by Bruaset et al. (2018) were applied.

2.7.3. Unit costs of actions

The economic cost, global warming potential (GWP) and excavation need for each combination of rehabilitation actions are presented in Table 2. The assumed rehabilitation methods (digging or trenchless) are also given for each infrastructure. Note that a trenchless approach is assumed for rehabilitation of pipes without road rehabilitation. This is because, due to installation depth and trench width, changing urban water pipes with the open-cut method in Luleå cannot be performed without changing the road layers.

Economic costs for open-cut rehabilitations were derived from completed projects within the municipality of Luleå. For the trenchless methods, the costs were derived from completed projects in Stockholm municipality, as there was insufficient data available for the

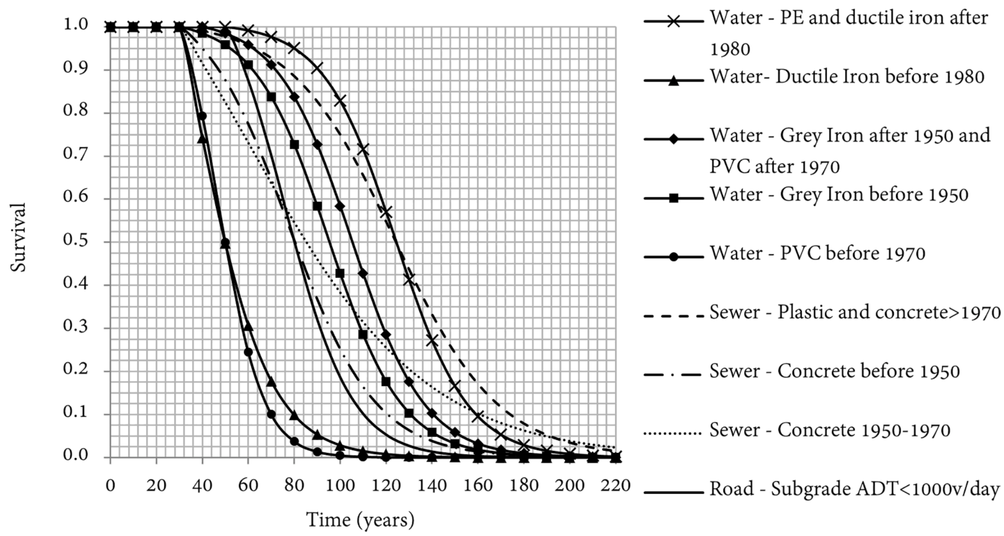

Fig. 2. Survival curves used in the case study of Luleå for the different water pipe, sewer pipe and road subbase cohorts.

Table 2
Estimated economic cost, global warming potential, excavation need and rehabilitation method for different combinations of rehabilitation actions. Case study of residential streets in Luleå, Sweden.

Water pipe	Sewer pipe	Road	Economic cost (Euro/m)	GWP ($kgCO_2eq/m$)	Excavation need (m^3/m)	Rehabilitation method
Yes	Yes	Yes	1300	77	8.8	Digging
Yes	Yes	No	1700	24	0.6	Trenchless
Yes	No	Yes	1000	57	7	Digging
Yes	No	No	1300	9	0.6	Trenchless
No	Yes	Yes	900	56	5	Trenchless (sewer) + digging (road)
No	Yes	No	400	15	0	Trenchless
No	No	Yes	500	41	5	Digging

municipality of Luleå. The Cured-In-Placed Pipe (CIPP) relining method was assumed for the trenchless rehabilitation of sewers while pipe bursting was assumed for drinking water pipes.

Global Warming Potential and excavation needs for the open-cut operations were obtained from Pericault et al. (2018). For the CIPP method values were obtained from Ariaratnam and Sihabuddin (2009). For the pipe bursting method values were obtained from Kaushal and Najafi (2020).

2.7.4. Comparison of coordination policies

Three coordination policies involving the rehabilitation of urban water pipes and road subbase in the residential streets of Luleå municipality were compared: one policy with no coordination (coordination window of 1 year), another with an optimized coordination level and a third policy with extensive coordination (coordination window of 100 years). For the optimized coordination scenario, the model was run for sizes of coordination window varying from 1 to 100 years and total costs over the period 2020–2120 were computed. The optimized coordination window was chosen based on the point where the weighed sum of total capital cost, global warming potential and excavated volume was lowest, with all three factors given equal weight. When computing the weighed sum, total costs values (capital cost, global warming potential, excavation need over the period 2020–2120) were first divided by the value obtained for the case of no coordination (τ=0).

The python codes for the MURM and MURP modules adapted for the case study of Luleå and the headers of the different input tables are published on the Zenodo repository with the following DOI: 10.5281/zenodo.7118609.

2.7.5. Sensitivity analysis

An analysis was performed to assess the sensitivity of the optimized coordination window to changes in input parameters. The following changes in input parameters were tested:

- Change from middle to upper and lower bounds of the ranges of survival times proposed by Malm et al. (2013) for drinking water and sewer pipe cohorts. Changes in similar proportion were applied to the survival times of road subbase. These changes are summarized in Table 3, alongside the initial survival times.
- 50% decrease, 25% decrease, 25% increase and 50% increase in economic cost and global warming potential per metre of the different rehabilitation actions.
- 25% decrease and 50% decrease in excavation needs per metre for the open-cut rehabilitation actions. Increase in excavation needs were not tested as the values used for Luleå are high in comparison to other European cities due to deep frost-free line for pipes installation (2.5 m) and thick road subbase for frost heave protection (1 m).
- 50% increase in the weights given to economic, environmental, and social costs when optimizing the coordination window.

The optimization of the coordination window size (τ) was repeated for each change in parameter value. This resulted in 32 optimizations corresponding to 640 simulations, as one optimization required 20 simulations (τ values from 0 to 100 year with a 5-year time step) The optimized τ values and corresponding reductions/increases in total costs were saved for comparison.

3. Results

3.1. Multi-utility rehabilitation modeller (MURM) and planner (MURP)

The infrastructure coordination model developed in this study

Table 3
Initial, pessimistic (-) and optimistic (+) survival times used for drinking water pipes, sewer pipes and road subbase cohorts.

Cohort	Years after installation								
	100% Survival			Survival 50%			Survival 10%		
	Initial	–	+	Initial	–	+	Initial	–	+
Water - PE and ductile iron >1980	50	40	60	125	110	140	160	140	180
Water - Grey iron <1950	30	20	40	95	80	110	130	110	150
Water - Grey iron >1950 and PVC>1970	40	30	50	105	90	120	140	120	160
Water- Ductile iron <1980	30	20	40	50	40	60	80	60	100
Water - PVC <1970	30	20	40	50	40	60	70	60	80
Sewer - Plastic and concrete >1970	30	20	40	125	100	150	175	150	200
Sewer - Concrete <1950	30	20	40	80	60	100	120	90	150
Sewer - Concrete 1950–1970	30	20	40	85	60	110	160	140	180
Road - Subgrade ADT<1000v/day	50	40	60	80	65	95	110	90	130

consisted of a Python program structured in two modules. The MURM (Multi-Utility Rehabilitation Modeller) module computes model outputs for one set of input modelling parameters (τ, R, ρt) and one sampling of asset lifetimes. The different computing steps of the MURM module are shown in a flowchart (Fig. 3). Using the MURM module with other deterioration models would imply discarding the part of the flowchart leading to interface 1. The deterioration model would need to feed the computing step "coordinated renewal modelling" with the estimated end of functional life of the infrastructures for all studied segments. MURP enables up to three sets of modelling parameters to be compared by running the MURM module a user-defined number of times for each set of parameters and plotting the corresponding average values and confidence intervals of the model outputs in line charts.

3.2. Case study of Luleå residential streets

3.2.1. Influence of coordination window size and inter-infrastructure lifetime correlation on total sustainability costs

Fig. 4 shows the influence of the size of the coordination window (τ) on capital costs, global warming potential and excavated volume *accumulated over the period 2020–2120*. These accumulated costs are also referred to as total sustainability costs. The relationships between τ and total costs represented in Fig. 4 were computed assuming a low (ρ=0.1), moderate (ρ=0.5) and high (ρ=0.9) correlation of asset lifetimes between infrastructures.

Total capital expenditures (Fig. 4a) were highest (425 million €) for a coordination window size τ of 0 year (i.e. a policy of no coordination). Increasing τ up to 35 or 40 years was found to decrease capital expenditure by up to 34% or 29% depending on the inter-infrastructure correlation of asset lifetimes (ρ=0.9 or 0.1). Increasing the coordination window size further, to beyond 40 years, was found to moderately increase the total capital cost (Fig. 4a) although the latter remained lower than with a policy of no coordination (τ=0 years). For example, for ρ=0.5, a τ value of 100 years, corresponding to a policy of extensive coordination, resulted in a total capital cost of 319 million €, a 25% reduction on the no-coordination policy (τ=0 years). Total global warming potential (Fig. 4b) reached a minimum of 13,000 tons of CO_2 equivalent for a coordination window size τ of 25 years, representing a 16% reduction on the 16,000 thousand tons of CO_2 equivalent emitted with the no-coordination policy. For τ values greater than 25 years, total global warming potential increased. Additionally, τ values larger than 60 years resulted in a higher global warming potential than if no coordination took place (τ=0 years). Total excavated volume (4c) was consistently found to increase, from 1.25 to 2.15 million cubic meters, as the coordination window increased from 0 to 100 years. This is because, in this case study, single utility (i.e. uncoordinated) replacement of pipes was assumed to be carried out using trenchless methods. The rate of increase was higher in the range 0–40 years than for τ values of more than 40 years.

The inter-infrastructure spatial correlation of asset lifetimes (ρ) was found to have a somewhat positive effect on total capital cost reductions. This effect was most noticeable for a τ value of 30 years, where increasing ρ from 0.1 to 0.9 was found to reduce total capital costs by 11%. The influence of ρ on total global warming potential and total excavation was very limited with changes of at most 4% and 2% observed for a τ value of 100 years. A possible explanation for this is the differences in survival functions between the different infrastructure cohorts. This leads to lifetime underutilization even under the beneficial scenario of ρ=0.9 under which short lived sewer pipes are adjacent to short lived drinking water pipes and situated under short lived road subbases, as "short lived" has different meaning among the infrastructures in terms of functional lifetimes.

3.2.2. Yearly sustainability costs, renewal rates and under-utilization ratios

Fig. 6 shows the modelled yearly capital costs, global warming potential and excavated volume associated with the renewal of drinking water, sewer and road infrastructures in the residential streets of Luleå in Sweden. The results are shown for three policies: no coordination (blue curve, τ=0 years), optimized coordination (orange curve, τ=20 years) and extensive coordination (green curve, τ=100 years). For each curve, the bold line represents the average of 30 simulations and the area surrounding the bold line represents the corresponding 95% confidence interval. Results are shown for 30 simulations because standard deviation of the different yearly costs were stable when increasing the number of simulations beyond 30. An example of this is shown in Fig. 5 for capital costs. The inter-infrastructure lifetime correlation coefficient ρ was set to 0.5 (moderate correlation) between all three infrastructures. The τ value for the optimized coordination policy (20 years) was selected based on the relationships shown in Fig. 4 and according to the method described in section 2.7. This policy resulted in differences of −22% in total capital costs, −14% in total global warming potential and +19% in total excavated volume, over the period 2020–2120, compared to the no-coordination policy.

The policy of no-coordination (Fig. 6a, blue curve) resulted in relatively low levels of reinvestment (4.4 ± 0.4 million € per year) over the period 2020–2170. On the other hand, extensive coordination (Fig. 6a, green curve) led to high initial capital costs of 5.8 million € per year steadily decreasing to 2.1 million € per year by the 2065 and later remaining in the range 2.7 ± 0.5 million € per year. The optimized coordination policy (Fig. 6a, orange curve) showed similar variation but within a narrower range of capital cost values. It led to 5.2 million € per year of reinvestment at the beginning of the simulation period, sharply decreasing to 2.8 million € per year by 2035 and remaining in the range 3.2 ± 0.4 million € per year beyond this.

Greenhouse gas emissions were also relatively stable over time under the no-coordination policy (Fig. 6b, blue curve). These emissions corresponded to global warming potential values in the range 150±25 tons CO_2 equivalent per year. Extensive coordination (Fig. 6b, green curve) led to much higher emissions of 340 tons CO_2 equivalent per year at the beginning of the simulation period with a decreasing trend up to 2070

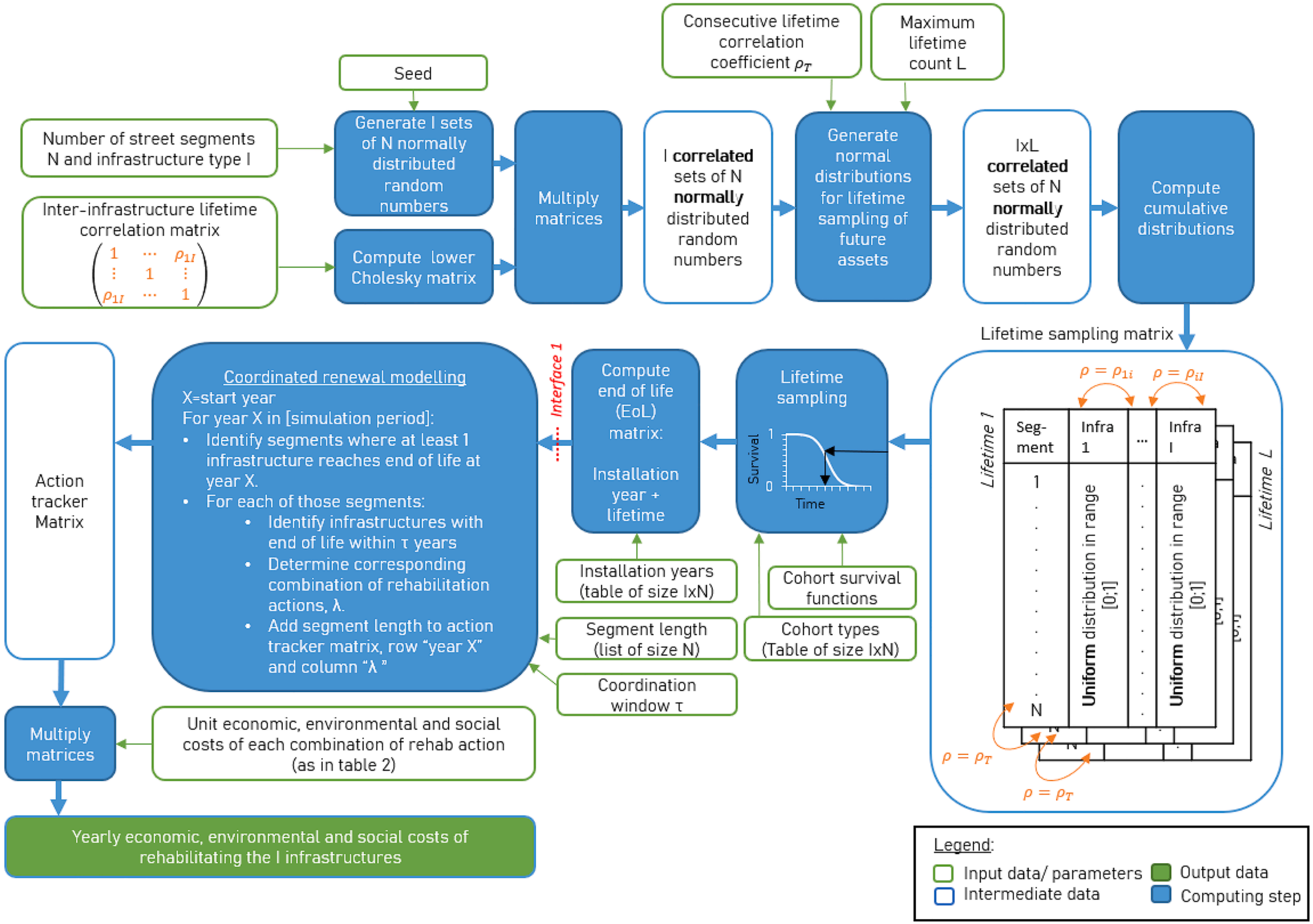

Fig. 3. Flowchart of the developed Multi-Utility Rehabilitation Modeller (MURM).

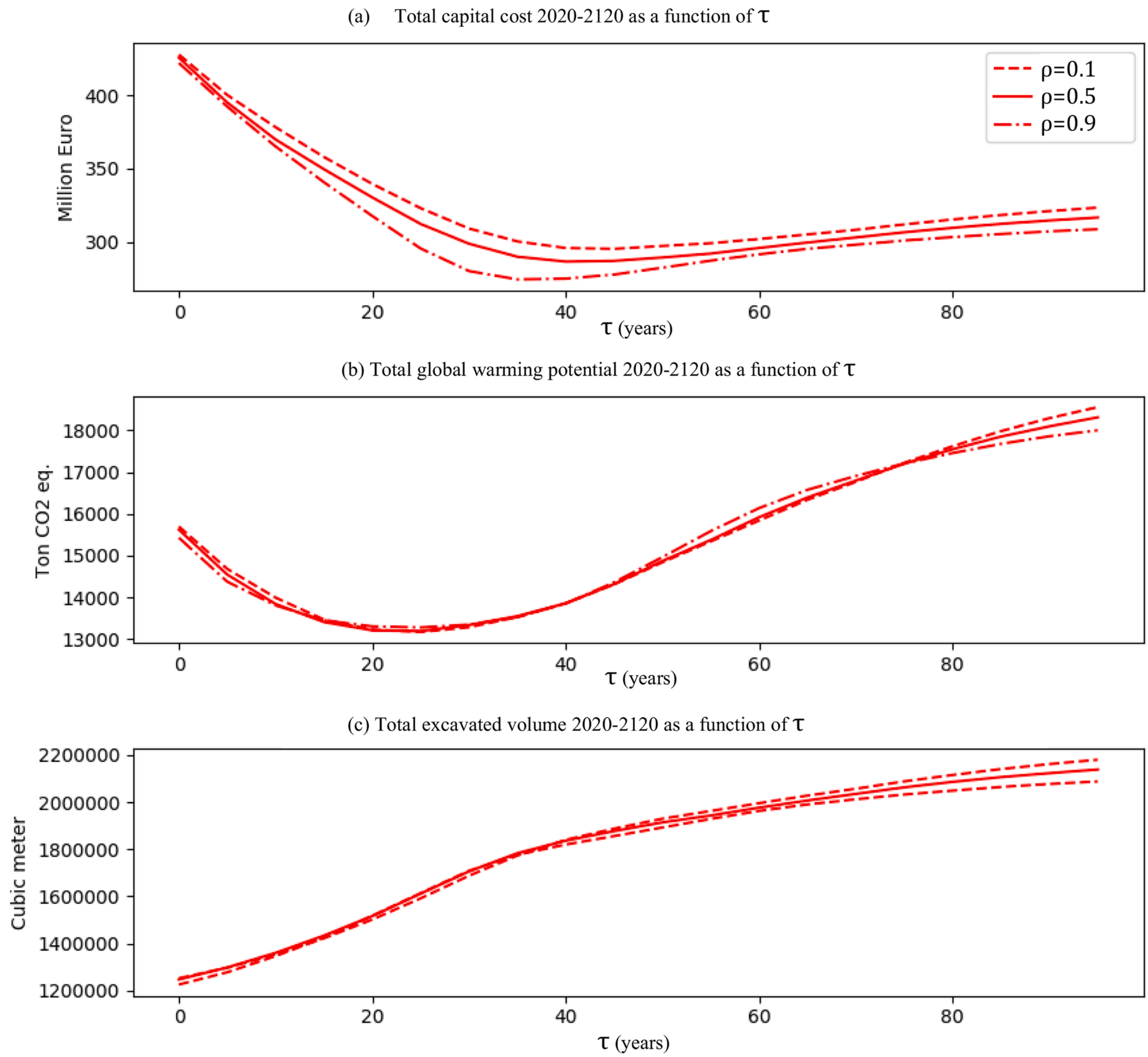

Fig. 4. Influence of the size of the coordination window, τ, on accumulated sustainability costs for the period 2020–2120. The costs relate to the renewal of the water, sewer and road infrastructures in the residential streets of Luleå municipality, Sweden. ρ refers to the inter-infrastructure Pearson correlation coefficient of lifetime distributions.

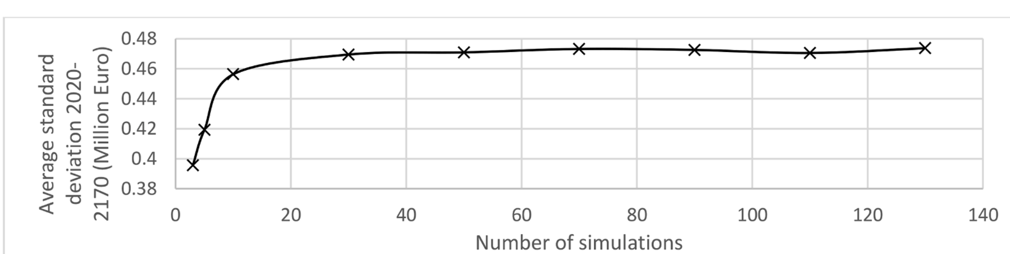

Fig. 5. Average of the standard deviations obtained for capital costs for the 150 years of the simulation period, as a function of the number of simulations.

and levels similar to the no-coordination policy (150±25 tons CO_2 equivalent per year) beyond that. Optimized coordination (Fig. 6c, orange curve) also resulted in high initial greenhouse gases emissions (250 tons CO_2 equivalent per year) but with a sharp decrease to 120 tons CO_2 equivalent per year by 2035 and beyond, which is lower than the levels achieved by the other two policies.

As with capital costs and global warming potential, excavated volumes (Fig, 6c) were initially high for the extensive (green curve) and optimized (orange curve) coordination policies and decreased at different rates to more stable levels. However, they both resulted in more excavation volume per year than with the no-coordination policy (blue curve) thoughout the 2020–2170 period. This is because low coordination resulted in more single-pipe rehabiliation projects, which were assumed to be perfomed with trenchless methods (i.e. no or very

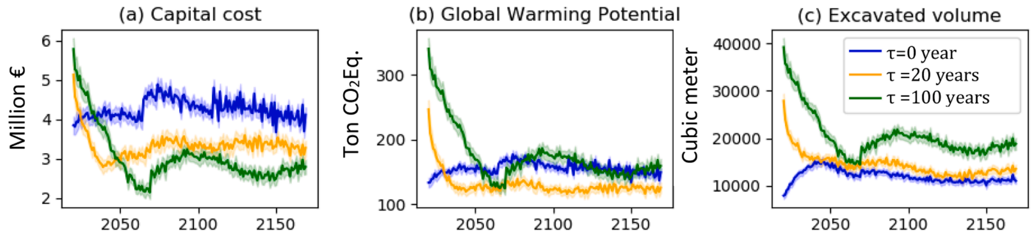

Fig. 6. Yearly capital costs (a), Global Warming Potential (b) and excavation volume (c) for the renewal of water, sewer and road infrastructure in the residential streets of Luleå, Sweden over the period 2020–2170. Blue curve was estimated for a coordination window of 0 years (no coordination), orange for 20 years (optimized coordination) and green for 100 years (extensive coordination).

low excavation needed per metre of rehabiliated pipe). However, after 2035 the excess excavation volume associated with the optimized co-ordination policy was only 20% greater than the level expected under the no-coordination policy.

Fig. 7 presents the implications of the different coordination policies for each infrastructure in terms of renewal rate (i.e. renewed pipe length divided by total network length) achieved via coordinated open-cut projects (a-c), renewal rate achieved via trenchless or single-utility projects (d-f) and under-utilization ratios (g-i). The total renewal rate of an infrastructure is the sum of the renewal rate achieved via coordinated open-cut projects and the renewal rate achieved via trenchless methods.

In this case study, the policy of no-coordination (τ=0) implied no open-cut projects for rehabilitating water or sewer pipes and no road subgrade replacement projects in coordination with pipe replacement, as shown by the blue curves in Fig. 7a, b and c. With τ=0, the renewal of infrastructures was achieved entirely with trenchless and "road-alone" projects at renewal rates varying within the ranges 1.05±0.25% (water, Fig. 7d), 1 ± 0.3% (sewer, Fig. 7e) and 1.15±0.25% (road, Fig. 7f) during the period 2020–2170. These renewal rates followed the actual renewal need of the three infrastructures through "just on time" asset rehabilitation. This is illustrated by the under-utilization plots (Fig. 7g–i) showing null values for the τ=0 policy (blue curves) throughout the simulation period.

The policy of extensive coordination (τ=100 years, green curves) showed the opposite to the no-coordination policy, with asset rehabilitation achieved only through open-cut coordinated projects (Fig. 7a–c), with negligible application of trenchless technologies and road-alone rehabilitation projects (Fig. 7d–f). The renewal rates of the three infrastructures were equal during the entire simulation period as the rehabilitation of an asset from one infrastructure systematically triggered rehabilitation of the adjacent assets from the two other infrastructures. Initially, these rates were particularly high at 2.6% but then decreased to 0.9% by 2065 and varied within the range 1.2 ± 0.2% later on. These values did not reflect the renewal needs of the three infrastructures as assets were rehabilitated not only based on their condition but also for coordination reasons. This is reflected in the under-utilization ratios which are not null for this policy (Fig. 7g–I,

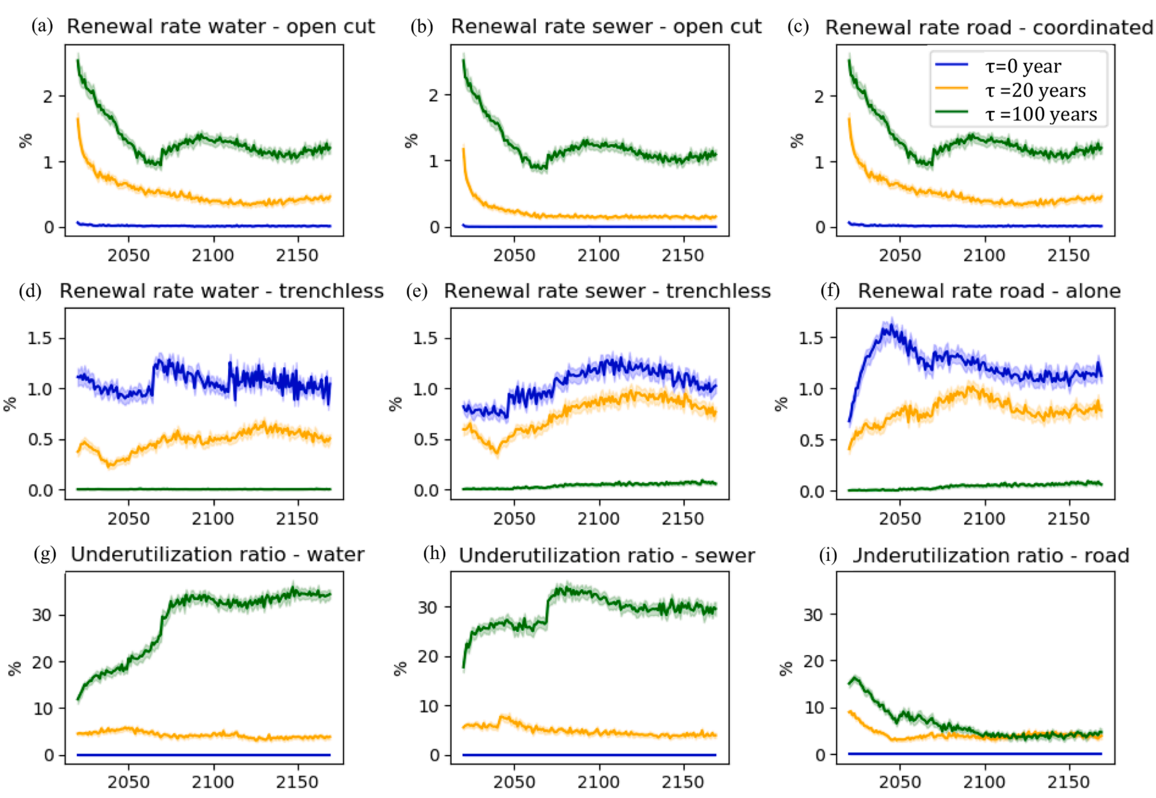

Fig. 7. Yearly renewal rates (a-f) and underutilization ratios (g-i) for the renewal of water, sewer and road infrastructure in the residential streets of Luleå, Sweden over the period 2020–2170. Underutilization ratio represents the average percentage of lifetime unused for the assets replaced that year. The blue curve was estimated for a coordination window of 0 years (no coordination), orange for 20 years (optimized coordination) and green for 100 years (extensive coordination).

green curves). Under utilization of assets was not the same across the three networks. In the simulation it increased from 12% and 17% to 35% and 30% for the drinking water and sewer networks while for the road infrastructure it decreased from 15% to 4%.

The optimized coordination policy (Fig. 7, orange curves) resulted in both open-cut and trenchless methods being employed to renew the piped infrastructures. The rate of renewal of the drinking water pipe network with open-cut projects had an initial value of 1.6% (Fig. 7a) and gradually decreased to remain in the range 0.4 ± 0.1% by 2060 and beyond. With trenchless methods, this rate fell within the range 0.4 ± 0.15% before 2060 and 0.5 ± 0.1% after that date. For the sewer network, renewal with open-cut methods had an initial value of 1.2% and gradually decreased to 0.15% by 2060 and beyond, while with trenchless methods this rate was within the range 0.5 ± 0.2% before 2060 and 0.8 ± 0.1% later on. The road infrastructure was renewed both in coordination with pipe rehabilitation (Fig. 7c, orange curve) and in individual projects (Fig. 7f, orange curve). With the optimimized policy, under-utilization ratios (Fig. 7g–i, orange curves) were considerably lower and more balanced than with the extensive coordination policy (green curve). The lifetimes of renewed drinking water and sewer pipes were under-utilized by about 5% thoughout the simulation period (Fig. 7g,h, orange curves). For the road subbases, the underutilization ratio (Fig. 6i, orange curve) had an initial value of 10% but then decreased to 0.4% from 2050 onwards.

3.2.3. Sensitivity analysis

The results of the sensitivity analysis are presented in Table 4. The optimized coordination window (τ) proved relatively robust to single changes of parameters values (i.e. changing value of one parameter at a time). The largest change in optimized tau value was observed when the digging costs were decrease by 50% or when the weight of the economic costs was increased by 50%. This increased the optimized coordination window by 10 years, from 15 to 25 years. Note that in the original analysis the optimized value obtained for τ with the initial parameter set was 20 years while in Table 4 this value is 15 years. This is because only multiple of 10 years were considered for τ in the original analysis. In the sensitivity analysis a refined time step of 5 years was used in the optimization.

The differences in total sustainability costs between the optimized coordination window and the case of no coordination were considerably affected by some of the changes in input parameters. For example, when decreasing digging cost by 50%, the reduction in total capital costs was of 43%, in comparison to 18% in the initial optimization. The reduction in total global warming potential changed from 14% to 27% when decreasing the global warming potential per metre of open-cut rehabilitation by 50%. The excess excavation need in comparison to the no

Table 4
Sensitivity of the optimized tau value and corresponding total costs to changes in input parameters and optimization weights. The variation in functional lifetimes corresponding to the + and – signs are described in Table 3.

Parameter variations			Optimization	Capital costs 2020-2120		GWP 2020-2120		Excavation 2020-2120	
			Optimized τ *(years)*	Difference from τ=0	Value *(10^6 Euro)*	Diffrence from τ=0	Value *(Ton CO_2 eq.)*	Difference from τ=0	Value *(10^6 m^3)*
Initial set			15	-18%	350	-14%	13405	15%	1.43
Functional lifetimes	Water	+	20	-20%	317	-17%	12228	19%	1.46
		-	15	-19%	367	-12%	14480	18%	1.49
	Sewer	+	20	-24%	313	-14%	12896	20%	1.49
		-	10	-12%	387	-12%	14124	10%	1.37
	Road	+	15	-16%	340	-13%	12744	16%	1.19
		-	20	-24%	346	-17%	14175	20%	1.85
Economic costs per meter	Water (pipe bursting)	+50%	20	-30%	380	-15%	13206	22%	1.52
		+25%	20	-27%	355	-15%	13206	22%	1.52
		-25%	15	-13%	316	-14%	13405	15%	1.43
		-50%	10	-5%	288	-11%	13838	9%	1.36
	Sewer (cure-in-place pipe)	+50%	15	-18%	376	-14%	13405	15%	1.43
		+25%	15	-18%	363	-14%	13405	15%	1.43
		-25%	15	-18%	336	-14%	13405	15%	1.43
		-50%	15	-17%	323	-14%	13405	15%	1.43
	Road, Road+Water, Road+Water+Sewer (open-cut, digging)	+50%	10	-8%	443	-11%	13838	9%	1.36
		+25%	15	-14%	390	-14%	13405	15%	1.43
		-25%	20	-28%	285	-15%	13206	22%	1.52
		-50%	25	-43%	211	-16%	13188	29%	1.61
Glocal Warming Potential per meter	Water (pipe bursting)	+50%	15	-18%	350	-15%	14126	15%	1.43
		+25%	15	-18%	350	-15%	13766	15%	1.43
		-25%	15	-18%	350	-14%	13044	15%	1.43
		-50%	15	-18%	350	-13%	12683	15%	1.43
	Sewer (cure-in-place pipe)	+50%	20	-22%	330	-21%	14603	22%	1.52
		+25%	15	-18%	350	-17%	14222	15%	1.43
		-25%	15	-18%	350	-11%	12592	15%	1.43
		-50%	10	-13%	370	-7%	11872	9%	1.36
	Road, Road+Water, Road+Water+Sewer (dig)	+50%	15	-18%	350	-9%	17759	15%	1.43
		+25%	15	-18%	350	-11%	15583	15%	1.43
		-25%	20	-22%	330	-20%	10922	22%	1.52
		-50%	20	-22%	330	-27%	8636	22%	1.52
Excavation need per meter	Road, Road+Water, Road+Water+Sewer (dig)	-25%	15	-18%	350	-14%	13405	13%	1.09
		-50%	20	-22%	330	-15%	13206	15%	0.78
Optimization weights	Economic	+50%	25	-27%	312	-16%	13188	29%	1.61
	Environmental	+50%	20	-22%	330	-25%	13206	22%	1.52
	social	+50%	10	-13%	370	-11%	13838	9%	1.36

coordination case changed from 15% to 29% when increasing by 50% the weight of economic costs in the optimization process.

4. Discussion

4.1. Renewal coordination: long-term impacts and strategic implications

This study confirms and illustrates the intuitive hypothesis that coordinating infrastructure renewal too little or too much can both be sub-optimal due to, respectively, missed opportunities for cost-sharing or underutilizing the lifetimes of particular assets. Application of the coordination model to the case study of Luleå showed that total capital cost and global warming potential could be minimized by using a coordination window, τ, of 35 and 25 years, respectively. The results from applying the coordination model also showed that deviation from these values (e.g. 10 or 50 years) would result in substantially higher total costs for the municipality. These results suggest that it is beneficial for a municipality to have control over the τ parameter by pro-actively choosing and implementing a coordination policy in light of its long-term strategic implications. Treating coordination as a purely operational, project-specific matter, i.e. not having a specific coordination policy in place, is likely to result in sub-optimal levels of coordination and cost more overall. This study showed that the capital cost reduction obtained by optimizing coordination was 34% over a 100 year period. This differs considerably from the 11% to 7% reductions found by other studies (Carey and Lueke, 2013) and (Abu-Samra et al., 2020) where coordination was optimized at the tactical decision level. One possible reason for these differences is that pipes in Luleå are installed at a minimum depth of 2.5 m to protect them from ground frost, leading to large excavation volumes per pipe replaced, and consequently more potential for savings through cost sharing than in other locations. A second possible reason for the large savings found in this study is that the option of using either open-cut or trenchless methods was considered in the optimization process. This option can lead to more cost-efficient scenarios than when only the open-cut method is considered, but it has the drawback of assuming that trenchless methods can be used for any pipe replacement project, which is not always valid, for example where pipes suffer from an uneven slope profile or where pipe diameter needs to be increased.

The results also indicate that coordinating the rehabilitation of multiple adjacent infrastructures can lead to higher sustainability costs in the shorter- to mid-terms but still yield long term benefits. For example, the optimized policy (orange curve in Fig. 6a-b) implied higher yearly capital costs and carbon emissions than the no-coordination policy (blue curve) during the first 10 years of the simulation but was cheaper and less carbon intensive from a 100 year perspective (Fig. 4a–b). This was due to future costly replacement of individual assets (e.g. sewer pipes) being avoided by replacing the asset earlier in joint projects with other infrastructures (e.g. road and/or drinking water). This highlights the need for a long-term approach when studying the benefits of coordinated asset rehabilitation, hence its relevance to the strategic decision level. Incurring high short-term capital costs may be unrealistic because they require prohibitively sharp increases in investment budgets and customer fees. There may also be insufficient in-house staff and contractors to carry out rehabilitation projects at the rate that a more coordinated approach would entail. Besides, excessive carbon emissions in the short term may not be desirable, even if in the long run there are greater savings, as climate studies have shown the need to reduce carbon emissions drastically and urgently (IPCC, 2022). Keeping short-term costs at acceptable levels is therefore a criterion that should be considered when identifying the ideal size of a coordination window, in addition to minimizing sustainability costs accumulated in the long term. This could be addressed by studying coordination policies where the size of the coordination window increases progressively during the first 10–20 years of the simulation period.

For the case study of Luleå where the rehabilitation of individual pipes without road subbase replacement was assumed to be carried out using trenchless methods, the size of the coordination window influenced the yearly ratios of rehabilitation that would be performed with open-cut versus no-dig methods. This finding is significant for the water utility in terms of ensuring that contractors and in-house capacity with the right competence is available. The optimized coordination policy (orange curve, Fig 7.a,b,d,e) involved a significant share of trenchless rehabilitation throughout the simulation period, particularly after 2060 when approximately half of the water pipes and 80% of the sewer pipes would be rehabilitated using trenchless methods. In an economic sustainability study in Trondheim Norway, Bruaset et al. (2018) found that a scenario under which 100% of pipe rehabilitation was performed by open-cut methods in coordination with the drinking water, sewer and road networks would be preferable, closely followed by the same scenario but with 50% of rehabilitations performed with no-dig methods. Amongst several other factors the overall pipe age and material distribution in that setting could explain the differences between Bruaset et al. (2018)'s findings and the present study. In particular, Bruaset et al. (2018) assumed a 50% ratio between structural and non-structural no-dig methods and focused on the cost borne by the water utility, while the present study considered only structural no-dig rehabilitation and looked at the total cost for water, sewer and road infrastructure rehabilitation.

This study of different coordination policies has highlighted differences between the infrastructures in terms of asset lifetime underutilization (Fig. 7g–i). With an extensive coordination policy, road lifetimes were underutilized to a lesser extent than urban water pipes. This can be explained by the shorter functional lifetimes assumed for road subbase than for the largest pipe cohorts in Luleå municipality (see Fig. 2), meaning that road sections triggered coordinated rehabilitation projects more often than urban water pipes did. This is because the concept of a coordination window applied through the present Multi-Utility Rehabilitation Model (MURM) implies that the asset which is in need of rehabilitation first initiates the coordinated project. In the case of Luleå, asset lifetime underutilization was relatively balanced between the infrastructures when applying the optimized coordination policy, but there is no reason to expect similar results in other contexts as balancing lifetime underutilization was not a specified objective when optimizing the size of the coordination window. Insight into asset lifetime underutilization may be particularly important to establishing cost-sharing principles between utility owners, as a given coordination policy may trigger re-investment in the infrastructure to a greater extent and/or sooner in one utility than another.

The influence of the inter-infrastructure spatial correlation of asset lifetimes (ρ) on total sustainability costs (Fig. 4) of at most 11% for capital costs and 4% for the other costs appears to be limited compared to the uncertainties inherent in estimating asset lifetimes and the evolution of unit rehabilitation costs in the future. This suggests that estimating the ρ parameter is not essential to studying the long-term effects of coordination policies.

4.2. Generalizability

The age distributions of Luleå's drinking water pipe networks is similar to the Swedish average for suburban and middle-to-small municipalities, as seen in Fig. 8. The same is true of sewer pipes when comparing the age distribution of Luleå to the Swedish average as provided by the Swedish water association (Svenskt Vatten, 2021). This study therefore appears to be representative of the Swedish context in terms of pipe network rehabilitation need. However, pipe networks in other countries may have significantly different age distributions due, for example, to reconstruction efforts after World War II or different historical trends in urban development.

In this study, the rehabilitation of drinking water and/or sewer pipe without replacement of the road subbase was assumed to be performed using trenchless methods. This is because in Luleå the replacement of

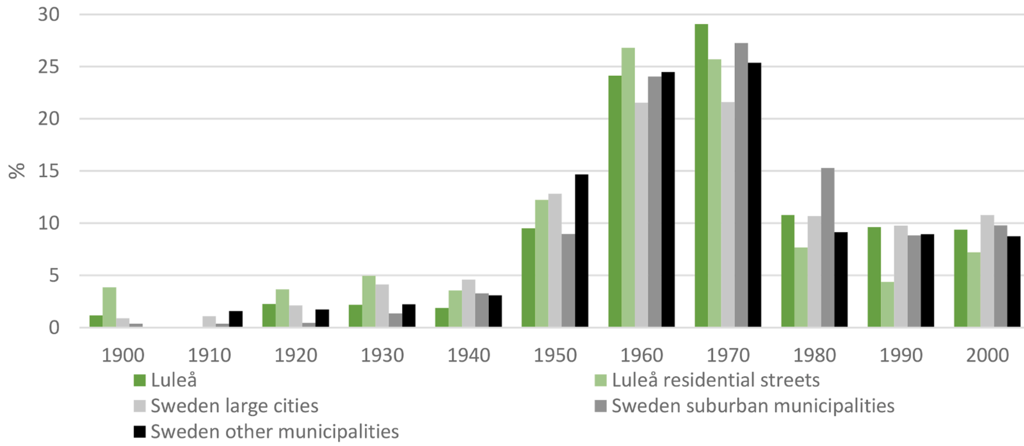

Fig. 8. Share of drinking water pipe length per installation decade for Luleå and Sweden as provided the Swedish water association (Svenskt Vatten, 2021).

urban water pipes by digging normally requires 2.5–3 m deep trenches with a top width of 4–6 m. A new road subbase and bitumen layer is therefore laid whenever open-cut pipe replacement is carried out, although it may be financed by the water utility if the road utility does not decide to join the rehabilitation project. Further, the rehabilitation of only sewer pipes and the road subbase was assumed to involve relining of the sewer and digging for the road subbase. This is because open-cut replacement of the sewer pipe without changing the drinking water pipe is highly impractical and risks damaging the latter. It is therefore avoided by the water utility which manages both networks.

These factors mean the results of the case study cannot be generalized to municipalities where open-cut replacement of individual pipes is common and implies partial excavation and restoration of the road width. This is a rather common practice in the rest of Europe where pipes are laid at a more shallow depth (due to shallower frost depth) and/or the different infrastructures are separately owned. The comparison of coordination policies in such contexts could be performed with the MURM model and may show higher costs for low coordination levels than in the present study, as there would be an increased probability of re-excavating the same soil masses and resurfacing the same road sections within short time frames.

4.3. Usability

Putting into practice the concepts of a coordination window and coordination policy options presented here requires the participation of the different utilities at the strategic, tactical and operational decision levels. Most negotiation and decision making would take place at the strategic level where infrastructure owners could meet twice to create the coordination policy. The first meeting would entail seeking agreement on the action types and costs matrix (as in Table 2), the time horizons on which to evaluate the coordination policies, and how to weight the sustainability costs against each other. Before the second meeting, infrastructure owners would have to provide input data to the MURM and MURP modules, including the survival functions that should be calibrated on local data to increase accuracy. A first important aspect in the calibration stage is to determine the levels of service or levels of risk that represent the threshold at which a pipe reaches the end of its functional life. A second important aspect is to correct for the left truncation and right censoring biases in the survival data, using for example the Kaplan-Meier method. The second meeting would take place once the coordination policies (different tau values) have been evaluated with the MURM and MURP modules. In this meeting, stakeholders would have to agree on which coordination policy they deem most beneficial for the municipality as a whole. The choice would have to be made in light of the implications of the coordination policy for each infrastructure in terms of rehabilitation rates (as in Fig. 7a–f) and capital costs. This is to ensure that the infrastructure owners can allocate the necessary budget and secure sufficient staff to implement the coordination policy. Estimation of capital costs per infrastructure would need to include a cost sharing scheme in the MURM model, which was outside the scope of the present study. The two meetings at the strategic level and the data gathering and modelling work could be organized by one of the infrastructure owners, a third party representing the general interest of the municipality (e.g. employee of the town hall) or a consulting firm with the relevant competencies in multi-utility asset management. The coordination policy should be revised on a timeline that is relevant to strategic asset management, for example 10 years (Alegre et al., 2013).

Coordination of rehabilitation works would be guided at the tactical level by the coordination policy, i.e. the agreed coordination window size. This implies that each utility would make their own 3–5 years list of projects, having identified which of its assets are in need of rehabilitation, prioritized for example on the basis of risk. When a utility (e.g. drinking water) communicates its prioritized projects to the other infrastructure managers (e.g. sewer, road), the latter would have to justify whether their assets situated in the affected infrastructure corridors have a high or low probability of operating at acceptable risk and performance levels for longer than the agreed τ-value (e.g. 30 years). On this basis they would decline or accept joining the relevant rehabilitation projects. In this way, applying the coordination policy as defined in this study would not involve performing an integrated prioritization or optimization of rehabilitation projects at the tactical decision level, as proposed for example by Tscheikner et al. (2016) or Carey and Lueke (2013). This is because the development of the coordination policy (choice of coordination window size) at the strategic level relies on the assumption that each utility a) meets their own short-term rehabilitation needs (tactical time horizon of 3–5 years) and b) joins rehabilitation projects initiated by other utilities if it contributes to meeting future rehabilitation needs within the timeframe of the coordination window (e.g. 30 years). At the operational level, the participation of the different utilities in implementing the chosen coordination approach would consist of continuously documenting replaced assets, actual τ-values and actual costs through a database which is accessible to stakeholders at the tactical and strategic decision levels. In this way, deviations from the agreed tau-value and expected sustainability costs can be taken into account when applying and revising the coordination policy.

4.4. Limitations and potential

Sustainability cost predictions were made in this study using a time horizon of over 100 years. This creates significant uncertainties due to expected technological developments in rehabilitation methods (e.g. use of electrical excavator, advances in trenchless technologies and asphalt production) which are likely to affect the economic costs and global warming potential per metre of rehabilitated pipes and roads. Besides the sensitivity analysis performed in this study, it would be preferable to estimate the uncertainties associated to each input parameter and evaluated their joined effect on result uncertainties. Changes in functional requirements may also occur during the coming 100 years, for example concerning source separation of wastewater and adaptation of residential streets to pedestrian and bike traffic. Such changes may be drivers of asset replacement, but they are not accounted for in the present modelling approach. More generally, use of the model in its current state is limited to areas characterized by street segments where asset rehabilitation is driven by deterioration. Areas where hydraulics or traffic capacity increase are likely to drive rehabilitation would have to be analysed separately. Another limitation of the model is that predictions can only be based on a given rehabilitation need per asset cohort, described by survival functions calibrated for a target performance or risk level. The model does not estimate decrease of performance levels (leakage or infiltration and inflow rate) associated with coordination policies where asset rehabilitations may be delayed beyond the end of the functional lifetimes of relevant assets. Excavation volume was used as an indicator of the external consequences of excavation (e.g. disturbances to traffic) in the case study. This is another limitation of this study as a given excavation size can disturb traffic in different ways depending on its location. External consequences are also connected to the time of interventions which are a function of not only the excavation volume but also other parameters such soil type, pipe diameter, etc.

Results which are more valuable for practitioners could be obtained with the present coordination model (MURM and MURP modules) by adding modules allowing it to: i) predict economic cost per utility with a cost sharing scheme, ii) account for inflation and discount rates in economic calculations, iii) include a minimum length for rehabilitation projects; iv) account for uncertainties in cohort survival functions, v) use multi-variate asset deterioration models, or vi) use model coordination policies where the coordination window size depends on the infrastructure initiating the rehabilitation project.

5. Conclusion

A modelling approach was developed to quantify the influence of multi-utility coordination on the overall long-term costs of water, sewer and road network rehabilitation. The concept of a coordination window size was introduced as part of the model, and this appears to be a useful parameter in accounting for the impact of coordinated rehabilitation projects on shortening the lifetime of infrastructure assets. The study highlights the so far poorly employed value of considering and leveraging multi-utility coordination at the strategic decision level where long-term financing of infrastructure rehabilitation is addressed. Similar studies on other municipalities, which consider the uncertainties in survival functions and rehabilitation costs (€/metre), are needed before any generalizable quantifications of the benefits of multi-utility rehabilitation can be made.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Youen Pericault reports a relationship with Luleå Kommun (Water utility) that includes: employment. Youen Pericault reports a relationship with Luleå Miljöresurs AB (water utility) that includes: employment.

Data availability

Data will be made available on request.

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