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Temporal Coordination of Urban Infrastructure Construction Activities

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Abstract: The challenges facing aging urban infrastructure systems require a more holistic and comprehensive approach to their management. The large number of urban infrastructure renewal activities occurring in cities throughout the world leads to social, economic and environmental impacts on the communities in its vicinity. As such, a coordinated effort is required to streamline these activities. This paper presents a framework to enable temporal (time-based) coordination of water, sewer and road intervention activities. Intervention activities include routine maintenance, renewal, and replacement of physical assets. The coordination framework considers 1) Life-cycle costs, 2) Infrastructure level-of-service, and 3) Risk exposure to system operators. The model enables infrastructure asset managers to trade-off options of delaying versus bringing forward intervention activities of one system in order to be executed in conjunction with another co-located system in the right-of-way. The framework relies on a combination of meta-heuristics and goal-based optimization. In order to demonstrate the applicability of the framework, a case study for a major infrastructure corridor in Cairo, Egypt is taken as an example. Results show that the framework can be scaled-up to include other infrastructure systems located in the right-of-way like electricity, gas and telecom, provided that information can be shared among these entities.

1 Introduction

Aging infrastructure systems around the world have led to a plethora of problems for the communities they serve and are placing tremendous pressure on governments responsible for their operation. Sudden system failures, deteriorating level of service (LOS), and requirements for increased spending by governments have led to the adoption of Asset Management (AM) as a core business practice within organizations that own and operate infrastructure systems. Existing trends towards urbanization are creating unique challenges for infrastructure asset managers. According to the UNFPA (United Nations Population Fund, the world is undergoing the largest wave of urban growth in history. In 2008, for the first time in history, more than half of the world's population was living in towns and cities. By 2030 this number will swell to almost 5 billion, with urban growth concentrated in Africa and Asia (UNFPA, 2007). The large number of collocated urban infrastructure systems is requiring asset managers to take a more holistic approach in asset management decision making. A typical urban right-of-way will typically include a minimum of five and may include up to 10 different infrastructure systems that are owned and operated by as many entities. Each one of these systems has a unique useful life, deterioration mechanism, maintenance schedule, and rehabilitation/replacement method. More importantly, they are managed by entities that take decisions within a silo and are reluctant to share information and coordinate their actions.

As a result, communities are suffering from the lack of proper coordination of infrastructure intervention activities. It has been argued that proper coordination of infrastructure intervention activities can lead to the following benefits:

1- Minimizing community disruption by construction activities through the spatial and/or temporal grouping of construction works at one time.
2- Optimizing overall objectives of infrastructure management (minimizing life cycle cost, risk exposure and maximizing level of service) across various infrastructure systems rather than making decisions that are sub-optimal when considering each system separately.
3- More efficient tendering of construction works.
4- Ability to package construction works in larger projects that can attract more contractors. This is especially relevant with small communities that want to attract contractors from larger urban centers (Amador and Magnuson, 2011).

Previous research on infrastructure construction coordination is somewhat limited and there is still a significant opportunity to provide more effective decision-making and optimization frameworks. Amador and Magnuson (2011) presented a case study for spatial and temporal optimization of infrastructure rehabilitation using heuristic simulation. They compared their results to traditional, single system life cycle cost optimization methods. Islam and Moselhi (2012) developed a spatial analysis model to determine the extent of spatial interdependence of co-located infrastructure systems using GIS. The proposed technique was used to quantify the extent of spatial overlap between two asset classes in order to determine the most suitable intervention based on the asset driving the rehabilitation decision. Coordination of works among single systems and consideration of economics of scale of water distribution system renewal was considered by Kleiner et al (2010). Their model utilized multi-objective genetic algorithms to develop optimal renewal strategies for a water supply network considering the possibility to spatially group adjacent renewal work into single packages during construction and subsequently decrease the number of construction activities taking place.

This paper focuses on the temporal coordination problem of co-located infrastructure systems. The proposed approach considers economic, risk and LOS triggers for intervention within a single system. A goal optimization approach is used to undertake a trade-off between delaying or brining forward construction activities of any system on the objectives (and constraints) of other co-located systems.

2 Framework for Temporal Modeling

Based on an analysis of cost and performance for a particular infrastructure system, the framework considers that there is an optimal time to intervene based on cost, risk and LOS considerations. As such the variables TIC_i, TIR_i and TIL_i are the optimal times for infrastructure intervention for system i considering life cycle cost, risk exposure and minimum acceptable LOS, respectively. TIC_i can be obtained from life cycle cost analysis that considers the impact of decreasing ownership and increasing operating and maintenance costs for an asset. TIL_i and TIR can be obtained from deterioration model for an asset as found in the literature and the cost of expected maintenance and rehabilitation throughout the asset lifecycle (Abaza, 2004). These points in time can be considered an optimal point to intervene in order to minimize LCC, minimize risk exposure or prevent deviation from a minimum acceptable LOS standard. It is most often the case that $TIC_i \neq TIR_i \neq TIL_i$ which requires asset managers to undergo a trade-off between these three objectives. It has also been noticed that for most civil infrastructure systems that have extended useful lives, small deviations around TIC_i usually do not result in a significant impact on the objective being attained (Osman, 2007). This suggests that optimal intervention strategies will be governed more by risk exposure and LOS. In a general form, the overall shape of the objective function for LCC, Risk and LOS can be described by the functions $C_i(t)$, $R_i(t)$, and $L_i(t)$ respectively for any infrastructure system i as shown in Figure 1.

At the beginning of the asset life, the cost function C(t) decreases over time as the capital cost of the asset is distributed over a longer period of time, as shown in Figure 1(a). Increasing maintenance and operation expenses towards the end of the asset service life causes to total LCC to subsequently increase. Asset level of service will tend to decrease over time as the asset ages. This deterioration can be manifested in a deteriorating ride quality for a pavement or increasing pipe breakage rates and water outages for a water supply network. Based on community-driven Minimum Acceptable Level of Service (MALOS), an optimal time to intervention TIL_i can be determined based on the shape of $L_i(t)$ as shown in Figure 1(b). Risk exposure can be represented by the probability of sudden asset failure. According to reliability theory, a bath-tub shaped curve has been found to be a reasonable representation of infrastructure asset failure rate. Figure 1 shows the typical shape of the tail end of this curve. Based on the Maximum Acceptable Risk Exposure (MARE) set by system operators, the optimal intervention time based on risk TIR_i can be determined based on the shape of $R_i(t)$ in figure 1(c).The level of MARE will usually depend on the criticality rating (consequence of failure) of an individual asset.

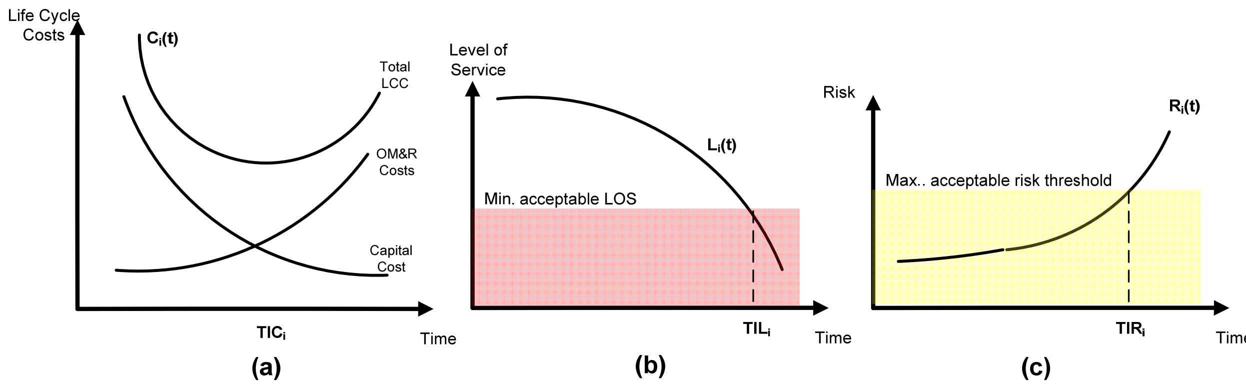

Figure 1 Optimal intervention points based on LCC, LOS and risk for a single system

The framework assumes that the asset manager responsible for undertaking an intervention will select an intervention time ITi for system i that will result in an attained life cycle cost objective of $C(IT)_i$, risk exposure $R(IT)_i$ and $L(IT)_i$. In order to include the impact of temporal grouping and the subsequent decrease in disruption due to construction works, three possible coordination scenarios are possible:

No coordination: In this case the intervention time is based on the optimal intervention for each infrastructure system separately. As such, $\forall i\ ITi \neq ITi$ .This case will result in the most disruption. In a case with roads, water and sewer which will result in three disruptive activities.
Partial coordination: In this case the intervention time of at least two systems is taken to be equal while the intervention time for the other systems is not. As such, $\exists i\ ITi = ITi$. For example in a system for roads water and sewer, a partial coordination strategy could have the road and water rehabilitation taking place concurrently while the sewer rehabilitation taking place separately. In this case we will encounter only two disruptive activities.
Full coordination: In this case the intervention time for all systems is taken equal. As such, $\forall i\ ITi = ITi$. This case will result in the least disruption. In a case with roads, water and sewer which will result in only one disruptive activity.

As such, in a case where we have a total of *n* co-located infrastructure services within the right-of-way, and intervention coordination is being considered, full coordination will result in one disruption, no coordination will result in *n* disruptions and partial coordination will result in *d* disruptions where $1 \leq d \leq n$.

2.1 Single-system heuristic

Before considering the case of multiple systems, a single system heuristic is developed to trade-off intervention triggers for cost, risk and LOS.Based on the sequence of optimal intervention times TIC, TIR and TIL a total of six possibilities can be enumerated. These possibilities are combined to form three cases as shown in Table 1.

Table 1 Cases of optimal intervention times

Case	Description	Action and Consequence
A - Cost First	$TIC_i, \leq TIR_i \leq TIL_i$ *or* $TIC_i, \leq TIL_i \leq TIR_i$	Intervene at $IT_i = TIC_i$. This is an optimal scenario from the perspective of the asset manager. This will result in the least possible LCC while achieving: 1) LOS that is better than the allowable minimum and 2) Risk exposure that has not yet crossed the threshold.
B - Risk First	$TIR_i, \leq TIC_i \leq TIL_i$ *or* $TIR_i, \leq TIL_i \leq TIC_i$	Intervene at $IT_i = TIR_i$. This is a sub-optimal scenario from the perspective of the asset manager. Intervention will result in 1) LOS that is better that the allowable minimum, 2) LCC that is higher than the least possible that can be attained. In this case the community will have to pay more for acceptable risk exposure.
C - LOS First	$TIL_i, \leq TIC_i \leq TIR_i$ *or* $TIL_i, \leq TIR_i \leq TIC_i$	Intervene at $IT_i = TIL_i$. This is a sub-optimal scenario from the perspective of the asset manager. Intervention will result in 1) Risk exposure that has not yet crossed the threshold, 2) LCC that is higher than the least possible that can be attained. In this case the community will have to pay more in order to attain the LOS that it has set as an acceptable minimum.

It is noted that the first case is an optimal strategy from the perspective of the asset manager. Undertaking the intervention at time $IT_i = TIC_i$will result in all objectives of LCC, risk and LOS being fully attained. A tangible example of such cases can be seen in the operations of a water supply network. An example for case 'B' is critical water infrastructure that is known to have significant consequences of failure (e.g. large transmission mains or pipes along critical city corridors). These assets will typically have an optimal intervention time based on risk of operations that will usually precede the optimal cost or LOS intervention points. That is, from a purely economic point of view, asset managers would prefer to delay any rehabilitation.When considering their risk exposure, early intervention is the most suitable course of action. An example for case 'C' is low criticality water pipes (e.g. small diameter distribution piping along quiet residential streets). These assets have a low consequence of failure and a run-to-failure mode of operation is the most suitable policy. From a purely economic perspective it may be more favourable to delay asset rehabilitation and continue to repair upon failure. From a LOS perspective the frequency of service interruptions may be unacceptable to customers and a decision to replace based on LOS standards may be taken (that is, TIL will precede both TIC and TIR).

For the second and third case the asset manager is faced with a trade-off between two objectives. In the second case the trade-off is between risk and cost and communities must ask themselves "Are we willing to pay a premium for reduced risk exposure?" In the third case the trade-off is between LOS and cost and communities are faced with the dilemma "Should we pay more for an improved LOS?" In cases (B) and (C) the cost premium (CP) is calculated as the difference between the LCC at time of intervention and the optimal time of intervention.

[1] $CP_i = C_i(IT_i) – C_i(TIC_i)$

In cases A and B, the community will receive a LOS value-added (LVA) which is calculated as the difference between the LOS at time of intervention and the minimum acceptable LOS:

[2] $LVA_i = L_i(IT_i) – L_i(TIL_i)$

In cases A and C, the community will receive a risk value-added (RVA) which is calculated as the difference between the risk exposure at time of intervention and the maximum acceptable risk threshold:

[3] $RVA_i = R_i(IT_i) – R_i(TIL_i)$

2.2 Model assumptions

The model is governed by the following assumptions:

1- All intervention types have the same extent of disruption per unit time. This assumption would have to be revisited in order to account for some trenchless technologies that are commonly used for buried infrastructure.
2- All intervention types will result in the asset returning to a pristine condition state. This assumption neglects many pavement intervention types like non-structural overlays, crack seals and fog seals that target specific pavement distresses and do not result in an asset in 'excellent' condition state.
3- Currently the model does not consider maintenance activities. Scope is focused on infrastructure rehabilitation and/or replacement.
4- Asset deterioration, probability of failure and life cycle cost profiles are required to be known and they are considered to be fully deterministic.
5- Determining system adjacency (spatial coordination) is beyond the scope of the model.

The single-system heuristic and assumptions are extended to include coordination of multiple spatially adjacent infrastructure systems.

2.3 Considering multiple systems

Dealing with multiple systems will require an optimization approach due to the relatively large search space. Considering n adjacent systems with possible coordination options and an analysis window of t years will yield a total of n * n^t possible solutions. As such this research utilizes goal optimization approach for finding the optimal intervention time considering various infrastructure coordination options.
In order to determine the optimal intervention time for *n* adjacent infrastructure systems, it is assumed that the overall life cycle cost considering decreasing ownership and increasing operating costs over time for *n* infrastructure systems is a summation of individual LCC profiles and is represented by *C(t)*

$$[4] C(t) = \sum_{i=1}^{n} C_i(t)$$

Via differentiation, the minimum total LCC can be found. Let TIC be the optimal time for intervention in order to minimize the total LCC for all system (i.e. the time at which $\frac{dC}{dt} = 0$).

Undertaking an intervention at any time before or after time TIC will result in a cost premium being paid. This cost premium represents a penalty that will be paid by system operators due to not undertaking an intervention at its optimal time based on cost. This cost premium at any time t can be calculated as:

$$[5]\ CP(t) = C(t) - C(TIC)$$

When multiple systems are considered, the heuristic approach described in the previous section can no longer be applied. An optimization approach is utilized such that overall cost, risk, LOS, and public disruption due to construction activities are optimized. Goal optimization principles are used to structure the optimization problem such that it is sought to minimize deviations from set goals.The goal optimization formulation is able to consider multiple, conflicting and incommensurableobjectives, which is the case with LOS, Risk and LCC (Schniederjans, 1995).

Goal optimization, sometimes referred to as goal programming (GP) is a mathematical optimization technique, quite similar to linear programming, although it has the capability to handle several conflicting goals (Lee &Nwak 1999). In GP terminology, a set of goals, Gi, where i=1, 2, 3, …, n, need to be achieved simultaneously. The objective function is then formulated to minimize the sum of deviations from these prescribed goal values. A GP objective function generally has the following form (Schniederjans, 1995):

$$[6] Min\ Z = \sum_{i=1}^{n} w_{kl}\, p_k (d_i^- + d_i^+)$$

Where *Z* is the minimized value of the sum of all negative deviations (d_i^-) and positive deviations (d_i^+) for a set of *n* goals. All terms denoted by d_i in the equation are referred to as the "*Deviational Variables*." If goals have different priorities, they are each ranked by a *Priority Factor* (p_k). The deviational variables within each priority level are differentiated using the *Deferential Weights* (w_{kl}). One of the interesting characteristics of GP is that there are no decision variables in the objective function. GP relates the objective function with the decision variables using *Goal Constraints*. Based on the formulation of the problem's constraints (goal to be attained), a deviational variable *di* is introduced into the constraint and the objective function.

In order to combine multiple objectives, a percentile ranking approach is taken by calculating the percentage deviation from a goal rather that the absolute deviation. These goals include:

1- Deviation below minimum acceptable level of service standards (MALOS) that can occur when an intervention is delayed in order to group a project and undertake corridor rehabilitation. This deviation will only occur in case the intervention time t is selected after the optimal intervention time based on LOS (TIL_i)

$$[7] d_1^- = \frac{\sum_{i=1}^{n} L_i(TIL_i) - L_i(t)}{\sum_{i=1}^{n} L_i(TIL_i)}$$

2- Deviation above a risk threshold that can occur when an intervention is delayed in order to group a project and undertake corridor rehabilitation. This deviation will only occur in case the intervention time t is selected after the optimal intervention time based on risk exposure(TIR_i)

$$[8] d_2^+ = \frac{\sum_{i=1}^{n} R_i(t) - R_i(TIR_i)}{\sum_{i=1}^{n} R_i(TIR_i)}$$

3- Deviation below a LOS value-added that could have been achieved in case of single system decision making (using the heuristic approach described in the previous section). In essence this can be considered a lost opportunity for improved LOS that could have been achieved had the system rehabilitation decision not considered coordination with other system. This deviation will only be calculated for systems in cases A and B.

$$[9] d_3^- = \frac{\sum_{i=1}^{n} LVA_i - L_i(t)}{\sum_{i=1}^{n} LVA_i}$$

4- Deviation below a RVA that could have been achieved in case of single system decision making (using the heuristic approach described in the previous section). In essence this can be considered a lost opportunity for reduced risk exposure that could have been achieved had the system rehabilitation decision not considered coordination with other system. This deviation will only be calculated for systems in cases A and C.

$$[10] d_4^- = \frac{\sum_{i=1}^{n} RVA_i - R_i(t)}{\sum_{i=1}^{n} RVA_i}$$

5- Overall cost premium due to deviation from the minimum possible LCC for all systems. This is the total deviation from the minimum possible LCC for all systems combined.

$$[11] d_5^+ = \frac{\sum_{i=1}^{n} \mathrm{C_i(t)} - \mathrm{C_i}(TIC)}{\sum_{i=1}^{n} \mathrm{C_i(TIC)}}$$

The aforementioned positive and negative deviation variables are summed together using non-pre-emptive goal optimization by assigning a relative weight to each deviation variable. These deviation variables represent the importance of various objectives (LCC, risk, and LOS).

$$[12] Min(Z) = w_1 d_1^- + w_2 d_2^+ + w_3 d_3^- + w_4 d_4^- + w_5 d_5^+$$

The following section presents a case study that will illustrate how the aforementioned framework can be applied to three infrastructure systems.

3 Case Study: Salah Salem Corridor

In order to demonstrate the functionality of the coordination framework, a case study for a main urban road corridor in Cairo, Egypt is used. The Salah Salem corridor is a major urban arterial road in Cairo that links the northern and southern areas of the city and is a major route linking Cairo International Airport. A two kilometre stretch of the road was selected for analysis. The corridor houses two main sewer collectors, a 600mm and a 900mm vitrified clay pipe in the median of the road as well as two 300mm asbestos cement water pipes in the right and left edges of the road as shown in
Figure 2.

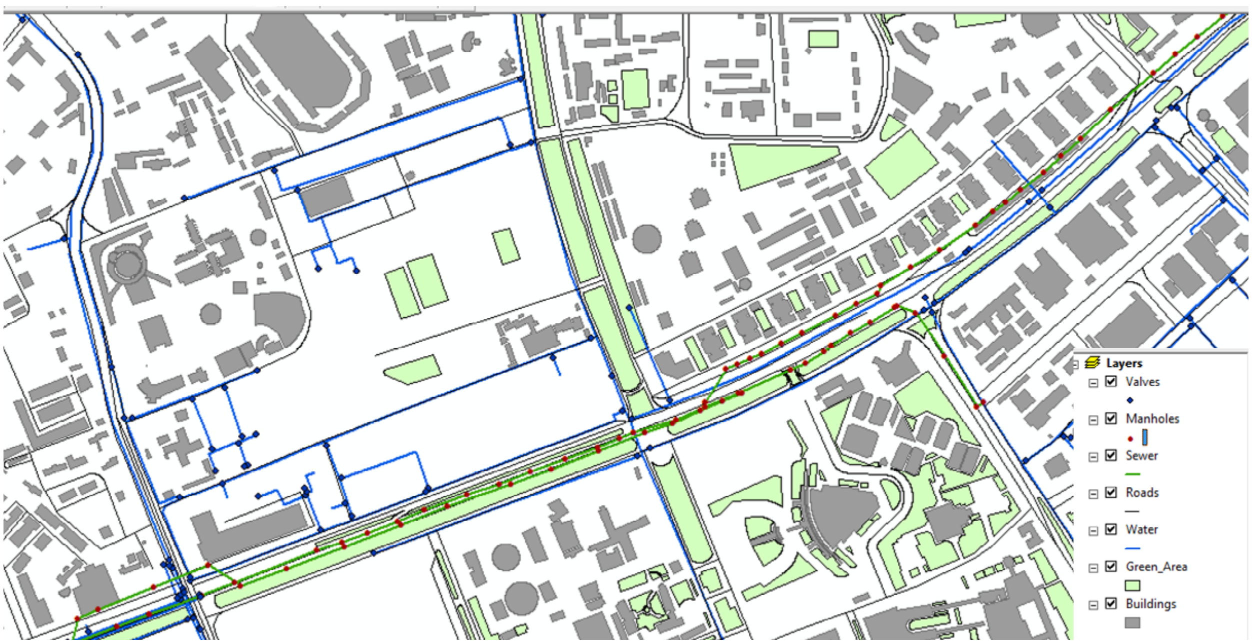

Figure 2 Road, water and sewer infrastructure along the Salah Salem corridor in Cairo

Date of construction, condition assessment information, and the date of last major road rehabilitation was used to construct curves for LOS, risk exposure and life cycle costs.

Using the single system heuristic discussed in section 2.2, optimal time to interventions were determined based on the acceptable thresholds for MALOS, MARE and MLCC as shown in Table 2. These threshold were determined based on 1) Meetings with system operators, 2) Hydraulic model information, and 3) Criticality consequence of failure modeling. Due to the important nature of the road as a major arterial street with significant traffic volumes and lack of alternate routes, the MALOS was taken to be 35% for roads as opposed to 20% for water and sewer system respectively. Minimum acceptable risk exposure (probability of failures) for sewers and roads were taken at 3.2% and 3.5% respectively.

Based on these thresholds, optimal interventions times were determined to be 2020, 2014 and 2021 for roads, water and sewer systems. In the case of roads, intervention was driven by cost due to ability to undertake a cost-effective treatment in 2016 rather than postpone the intervention and undertake costly road rehabilitation. In the case of sewer, intervention was driven by risk exposure due to the high consequence of asset failure both on road operations and the system itself (Case B). In the case of water infrastructure, intervention was driven by LOS due to the high break rates that were occurring on the asbestos cement pipe and the subsequent water outages and repairs that were required. Based on this single-system heuristic, the optimal intervention time is 2016, 2017, and 2021 for road, water, and sewer systems respectively. It is evident that grouping the road and water rehabilitation is a logical decision. In this case the asset manager is faced with two options: 1) Undertake sewer rehabilitation in 2021 and group water and road rehabilitation in 2016 or 2) Group all systems sometime during 2016-2021.

Table 2 Optimal intervention times based on single system heuristic

	Road	Water	Sewer
TIL	2020	2017	2026
TIR	2040	2018	2021
TIC	2016	2043	2043
IT	2016	2017	2021
Case	A	C	B

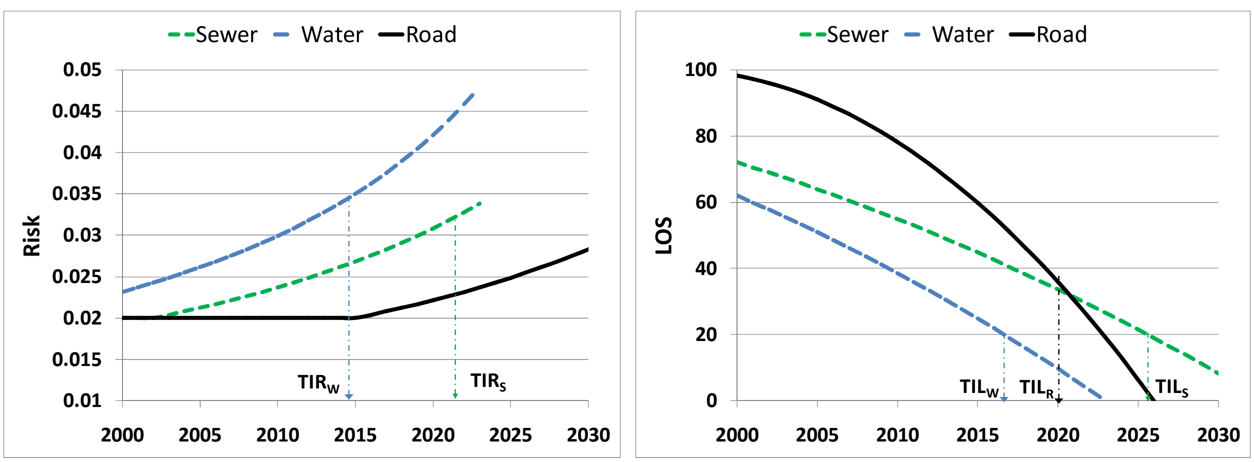

Figure 3 Optimal intervention times based on risk exposure and LOS for separate systems

It will be assumed that the second option is followed and a full-scale coordination will be adopted. In order to transition to the multi-system optimization, a search window spanning the maximum and minimum intervention times is used. In this case the optimal intervention time spans 2016-2021.

The goal optimization was run with equal weights for all deviation variables and the results are summarized in Table 3. Based on the model assumptions delaying the intervention will generally result in a worse outcome. As such the optimal intervention is to coordinate all construction activities in 2016. This will result in no deviation in risk or LOS but will lead to the highest possible cost premium of 104,000 EGP

(~ USD 17,000). In addition to this overall general conclusion, specific conclusions for each system and objective include:

1- Delaying the intervention will not result in any deviations for the sewer system as its optimal intervention time is 2021.
2- Delaying the intervention will not lead to any deviations below minimum acceptable level of service (MALOS) standards for roads or sewer as their optimal intervention times based on LOS are 2020 and 2026 respectively. A delayed intervention will lead to deviation below MALOS standards for water services that reach 67% below standard by 2021.
3- Delaying the intervention will lead to a deviation from the value-added in level of service for roads that could have been achieved if road rehabilitation took place during 2016 as recommended by the single-system heuristic. No such deviations will occur for water or sewer.
4- Delaying the intervention after 2018 will result in a positive deviation above the maximum allowable risk exposure (MARE) for the water system that reaches a total of 9.8% by 2021. No such deviations will occur for road or sewer networks as their optimal intervention times based on risk are 2040 and 2021 respectively.
5- Delaying the intervention will lead to a deviation from the value-added in risk exposure for roads and water that could have been achieved if rehabilitation took place during 2016 as recommended by the single-system heuristic. No such deviations will occur for the sewer system.
6- A 30% decrease in the total cost premium for all systems will be encountered if the intervention is delayed from 2016 to 2021. Taking a single system view, delaying water and sewer interventions is advantageous while delaying road intervention will cost more.

Table 3 Results of the goal optimization algorithm

Intervention Year		2016	2017	2018	2019	2020	2021
DEV(MALOS)	Roads	0.00%	0.00%	0.00%	0.00%	0.00%	12.70%
	Water	0.00%	5.00%	20.14%	35.56%	51.25%	67.22%
	Sewer	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
d_4^- DEV(VALOS)	Roads	0.00%	22.16%	45.41%	69.73%	95.14%	100.00%
	Water	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Sewer	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
d_3^+ DEV(MARE)	Roads	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Water	0.00%	0.00%	0.00%	1.23%	5.33%	9.77%
	Sewer	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
d_4^- DEV(VARISK)	Roads	0.00%	2.12%	4.33%	6.64%	9.04%	11.55%
	Water	0.00%	35.03%	72.65%	100.00%	100.00%	100.00%
	Sewer	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cost Premium (x1000 EGP)	Roads	2.5	3.6	4.9	6.4	8.1	10.0
	Water	28.9	25.6	22.5	19.6	16.9	14.4
	Sewer	72.9	67.6	62.5	57.6	52.9	48.4
	Total	104.3	96.8	89.9	83.6	77.9	72.8
Overall goal	Z	2.04%	4.20%	7.18%	9.96%	12.10%	14.45%

4 Summary and Conclusions

The majority of existing infrastructure asset management frameworks in the literature has focused on the development of decision-frameworks for single system optimization. Spatial adjacencies and physical independencies have motivated some researchers to take a more holistic view in considering infrastructure intervention options for co-located systems. As such, this paper presents a temporal coordination algorithm that can be used to undertake 'corridor rehabilitation' decisions. The framework combines a heuristic approach for single-system tradeoffs between level of service, risk exposure and life cycle cost. At the multiple-system level a non-pre-emptive goal optimization procedure is developed to undertake a trade-off between bringing forward versus delaying infrastructure intervention activities. The developed framework allows decision makers to quantify the impact of their coordination decisions on increased risk exposure and reduced level of service. This framework can be used to assess infrastructure coordination options in urban areas that have a large number of infrastructure systems within the right-of-way. The use of the heuristic approach significantly reduces the search space and allows for the framework to be scaled up to include more than three infrastructure systems.

Future work is underway to address some of the model limitations through extending the framework by 1) including the effect of routine maintenance activities, 2) Quantifying the disruption caused by construction activities based on the extent and duration of construction work and including that in the optimization model, and 3) Undertaking trade-off between partial and full coordination options.

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