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Interdependent Infrastructure Interventions Optimization: an Integrative Systems Thinking Approach

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Abstract: Despite widespread attention for the governance of infrastructures and improvements of the way infrastructure assets are maintained, the interdependency of infrastructures is not often considered from a systemic maintenance and renovation perspective. In this context, the issue of unforeseen intervention delays is of particular relevance because its impact on cost and hindrance might be too costly for infrastructure operators. Building upon the 3C concept (Centralize, Cluster, and Calculate) for intervention scheduling and optimization, this paper investigates the effect of unforeseen intervention delays on the intervention costs and the corresponding closure cost of the affected interdependent systems. A stochastic approach has been proposed to deal with the uncertainty of such delays. Uncertain intervention times are combined by Monte Carlo simulations to obtain the probabilistic distribution of the total cost at the end of the timeline of an intervention program affecting multiple interdependent infrastructures. Also, the change in the statistical deviation over time of the total cost with respect to the planned (optimal) cost during the entire program is obtained. This analysis yields interesting conclusions, such as the need for specific mitigation plans conducted during the course of the program to reduce the cost generated by the cumulative delays, and the need for enhanced communication between infrastructure managers, which could bring significant (economic) benefits to all stakeholders by jointly planning their intervention activities.

Keywords: infrastructure, optimization, intervention, maintenance, unforeseen delay, interdependent systems, intervention management.

1. Introduction

Despite widespread attention for the governance of infrastructures and improvements of the way infrastructure assets are maintained, much of these efforts have taken place in infrastructure industries and their specific engineering disciplines. The interdependency of infrastructures is not often considered from a systemic maintenance and renovation perspective. However, given the increased awareness of the vulnerabilities of our interdependent infrastructures fed by incidents and disturbances, there is an increasing need for a more systemic maintenance and renovation perspective in the design and management of interdependent infrastructures which requires intense collaboration between infrastructure operators.

In this context, the Design to Manage Interconnected Infrastructures (D-to-MII) project seeks to develop guidelines and an asset management framework to help Dutch infrastructure owners to manage responsive innovation for next-generation infrastructure assets.

The existing literature on intervention optimization shows a growing interest for

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approaches to minimize the intervention cost. Dekkert et al. (1991) proposed a dynamic grouping algorithm to reduce the intervention cost. Cost reduction is mainly due to the activities that can be shared when multiple interventions are scheduled at the same time (e.g., setup cost). Their approach was applied to optimize 16 maintenance activities and the results showed a decrease in the total cost. Dekker (1995) developed a framework that covers several optimization models in a uniform model. The introduced model can help in setting up an elicitation procedure especially in the case when deterioration modelling is based on expert judgment rather than on statistical data analysis. Do et al. (2015) presented a stationary grouping strategy for maintenance activities of complex systems whose components are classified in series and parallel components. Both preventive and corrective maintenance activities are considered. Chalabi et al. (2016) presented a two-objective optimization model to minimize the cost of preventive maintenance while improving the system's availability. To do so, the authors considered the positive economic dependence among the maintenance activities. Moinian et al. (2017) point out the necessity of having an assistive tool to help decision-makers with their infrastructural intervention-related decisions. They introduced a genetic-algorithm driven approach to optimize the maintenance of infrastructure. The objective of the optimization problem is to find the optimal balance between the maintenance costs and the downtime cost while restricting the availability of the system to a predefined level. The introduced approach was applied to a gas turbine case study to prove the improvements in cost and downtime.

Previous works have addressed the concept of intervention optimization from different perspectives; however, the issue of interdependencies among systems is rarely tackled. Kammouh et al. (2020) propose addressing the interdependencies within and across infrastructure systems using the so-called interaction matrix (IM). IM considers the effect of executing a set of intervention activities on the different interdependent systems (more information will follow in Section 3.2).

In a context of interdependent infrastructure systems, the issue of unforeseen intervention delays is particularly relevant because of its impact on cost and hindrance that might be too costly for infrastructure operators; therefore, uncertainty analysis taking into account unforeseen intervention delays could help the identification of the risk associated with adopting a certain intervention plan.

Building on the novel 3C concept for intervention scheduling and optimization proposed by Kammouh et al. (2020), this paper investigates the effect of unforeseen intervention delays on the total cost. A statistical approach has been proposed to deal with the uncertainty of such delays. Uncertain intervention times are combined by Monte Carlo simulations to obtain the probabilistic distribution of the total cost at the end of the timeline of an intervention program affecting multiple interdependent infrastructures. Also, the change in the statistical deviation over time of the total cost with respect to the planned (optimal) cost during the entire program is obtained. This analysis yields interesting conclusions, such as the need for specific mitigation plans that help to make low-risk decisions during the course of the program.

The remaining document is organized as follows. Section 2 discusses the need for an integrative approach for intervention optimization. Section 3 reviews the 3C-concept approach for optimizing intervention activities considering the interaction among systems. Section 4 is dedicated to analysing the impact of unforeseen intervention delays using an example. Finally, conclusions are drawn in Section 5.

2. The need for an integrative approach

Current efforts in the field of intervention optimization are project-based and not aligned across various infrastructures. Although data regarding the potential (societal) costs of the lack of optimization are missing, ample anecdotal examples exist in the context of the D-to-MII project that indicate that these costs must be massive, and stress the need for a more integrative approach to infrastructure maintenance.

For example, two different road infrastructure owners in the Netherlands (Rijkswaterstaat and the city of Rotterdam) only became aware by chance that both of them were scheduling a major road-connection for long-term maintenance. Similarly, the Dutch rail network owner ProRail initially had scheduled major maintenance during the holidays to the one railway track feeding into Schiphol airport. However, this is actually the busiest period of the year for the airport operator. Although the impact in terms of extended deference from maintenance was not known in both instances, it is known that increasingly and seemingly conflicting interests can increase maintenance costs as well as potentially affect safety.

Another example relates to a road bridge across a major shipping artery in the Rotterdam Harbor. The road bridge is due for replacement. The Port of Rotterdam, from the perspective of shipping, would like to make use of the opportunity to raise the height of the bridge to allow higher vessels to sail underneath the bridge. However, next to the road bridge lies a railway bridge which, according to the railway network owner, is not due for replacement until 2030. Currently, infrastructure owners are struggling in the timely identification of these issues and the resolution of these problems.

3. Multi-system intervention planning for interdependent infrastructure

3.1 The 3C concept

The 3C concept, where 3C stands for Centralize, Cluster, and Calculate, is an approach proposed by Kammouh et al. (2020) to plan and optimize intervention activities of interdependent infrastructure. The optimization problem aims to plan the required intervention activities such that disrupted services are minimized and so are the incurred cost and users' discomfort. Their work is not limited to maintenance planning, but also accommodates other types of intervention activities, such as upgrading and removal. In addition, the approach is multi-system, which allows considering multiple infrastructure systems in the analysis.

The starting point to realize the 3C concept is to consider all potential intervention activities of each infrastructure system from their individual engineering asset intervention timeline (activity, frequency, time, cost, hindrance). The first step is to centralize the principle activities that have a given and dominant time-dependent repetitive nature. Centralizing an activity implies a defined execution frequency of that activity by allowing no execution flexibility. The second step is to cluster other condition-based activities into these time slots by shifting these activities either forward or backwards while respecting some predefined individual constraints, such as the minimum and the maximum time between two successive interventions. Therefore, every activity type is assigned two values, $G_{min,k}$ and $G_{max,k}$, which are the minimum and the maximum time gap between two successive interventions of activity type k. The centralization of activities in the first step is done by setting $G_{min,k} = G_{max,k}$. The centralizing and clustering steps are illustrated in Fig. 1.

The final step is to calculate or optimize on quality of service parameters, such as cost and hindrance. The optimization problem, which is described in Kammouh et al. (2020), results in an intervention plan where the total intervention cost is minimized.

The total intervention cost is divided into two terms, the cost of executing the intervention activities, f_1, and the closure cost of the system, f_2. The first term is the sum of the cost of intervention activities while the second term considers the closure cost of every system or subsystem interrupted by an intervention activity, where a subsystem is considered as a part of a major infrastructure system. This is where it can be more beneficial to group intervention activities rather than executing them separately. For example, if two intervention activities affect the same subsystem then, executing the intervention activities at the same time would limit the hindrance of the system, and thus the closure cost. Therefore, the second term of cost includes a variable that accounts for the relations between the intervention activities and the subsystems (*relation matrix,* ***R***) and another variable that accounts for the interdependencies among the subsystems (*interdependency matrix,* ***IM***), which is further explained in the next section.

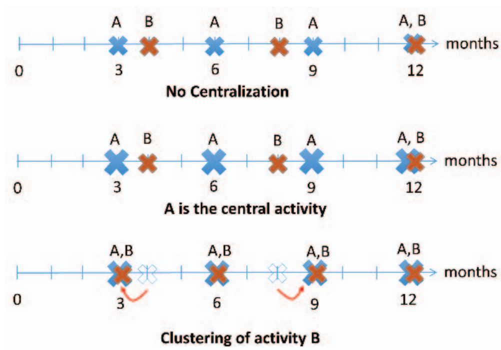

Fig. 1. Centralizing and Clustering of intervention activities.

3.2 Infrastructure interdependency analysis

Infrastructure interdependency is becoming an emerging topic in the field of asset management and resilience engineering. In the literature, when modelling infrastructure performance, most of these interdependencies tend to be ignored. The physical-type interdependency is what seems to be tackled the most by the researchers. This is due to the complexity of including all forms of interdependencies in the analysis. Ignoring part or all of these interdependencies could potentially result in an unrealistic model that does not represent the real behaviour of the system.

Modelling interdependency needs to be simple and scalable, otherwise, it would not be promoted for industrial use. It should not be very data-intensive or require complicated and high-level computational tools, because this will just make it practically unusable. Besides, interdependencies identification should accommodate easy input identification and must be easily definable and systematic.

To achieve that, identifying the different interdependency types needs to be done. This can help in treating every type separately and avoid possible overlap and ambiguity. Five types of interdependencies can be identified:

- Functional/logical: two infrastructures are logically interdependent if the state of the first depends on the state of the other through a mechanism that is not a physical, cyber, or geographic.
- Geographical: infrastructures are geographically interdependent if a local event, such as a maintenance activity, can create state changes in all of them. A geographic interdependency occurs when elements of multiple infrastructures are in close spatial proximity.
- Cyber/Informational: an infrastructure has a cyber-interdependency if its state depends on information transmitted through the information infrastructure.
- Physical: two infrastructures are physically interdependent if the state of each is dependent on the material output(s) of the other. As its name implies, a physical interdependency arises from a physical linkage between the inputs and outputs of two agents:
- Temporal: intervention on one component can be done only after the intervention on another component.

The first four types were identified in (Rinaldi et al. 2001), while the temporal-type interdependency is here proposed to model temporal restrictions. In the context of this paper, the interdependency types are to be seen from an infrastructure intervention point of view. Every interdependency type can be represented using a matrix, hereafter referred to as the *interaction matrix* (IM). IM defines the interactions of subsystems within systems and across systems. Eq. (1) is an IM of a set of N subsystems, where $\boldsymbol{I}$ is a square matrix whose components, the so-called interaction coefficients $I_{ij}=\{0,1\}$ determine if a subsystem i interacts with subsystem j. $I_{ij}=0$ means that subsystem i does not affect the functionality of subsystem j, whereas $I_{ij}=1$ implies the contrary. Consequently, the diagonal terms of IM are $I_{ij}=1$ and $\boldsymbol{I}$ can be asymmetric.

$$\boldsymbol{I}=[I_{ij}]=\begin{bmatrix} I_{11} & \cdots & I_{1N} \\ \vdots & \ddots & \vdots \\ I_{N1} & \cdots & I_{NN} \end{bmatrix} \quad (1)$$

A similar approach has been adopted in (Kammouh and Cimellaro 2018; Kammouh et al. 2018) to model the interdependency among the resilience indicators at the community scale. To give an example, three interdependent components are assumed belonging to different infrastructure systems, a road, a railway, and a buried water pipe (Fig. 2). The systems are further divided into sub-systems to account for the geographical and functional interdependencies. For example, an intervention on the water pipe can affect the highway or the railway systems depending on the location of the intervention. Therefore, the water pipe is divided into two subsystems. This division is only a functional division. The IM of the network in Fig. 2 is given as follows:

$$\boldsymbol{I}=\begin{bmatrix} I_{11} & I_{12} & I_{13} & I_{14} & I_{15} & I_{16} \\ I_{21} & I_{22} & I_{23} & I_{24} & I_{25} & I_{26} \\ I_{31} & I_{32} & I_{33} & I_{34} & I_{35} & I_{36} \\ I_{41} & I_{42} & I_{43} & I_{44} & I_{45} & I_{46} \\ I_{51} & I_{52} & I_{53} & I_{54} & I_{55} & I_{56} \\ I_{61} & I_{62} & I_{63} & I_{64} & I_{65} & I_{66} \end{bmatrix}=\begin{bmatrix} \mathbf{1} & \mathbf{1} & 0 & 0 & \mathbf{1} & 0 \\ \mathbf{1} & \mathbf{1} & 0 & \mathbf{1} & 0 & 0 \\ 0 & 0 & \mathbf{1} & \mathbf{1} & 0 & \mathbf{1} \\ 0 & 0 & \mathbf{1} & \mathbf{1} & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathbf{1} & \mathbf{1} \\ 0 & 0 & \mathbf{1} & 0 & \mathbf{1} & \mathbf{1} \end{bmatrix} \quad (2)$$

It is important to note the functional dependence between the subsystems of the same system; for instance, the water pipes SS1 and SS2. Hence, the interaction coefficients of these subsystems I_{12} and I_{21} are set 1 because it is assumed that the disruption of a pipe section affects the functionality of the other pipe section.

Once the interdependency matrices are obtained, they are integrated into the optimization phase of the 3C-concept approach to account for these interdependencies. This allows considering the interaction among the components within and across infrastructure systems.

In this manner, the structure of interdependencies is introduced in the mathematical formulation proposed by (Kammouh et al. 2020) to define the optimal intervention strategy based on the 3C concept. The following section will show an illustrative example of the application of the 3C-concept approach.

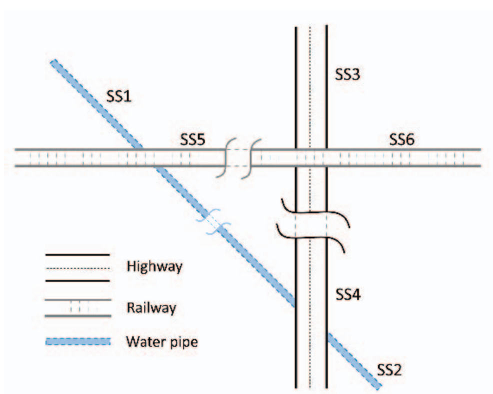

Fig. 2. Example of multi-system component interaction

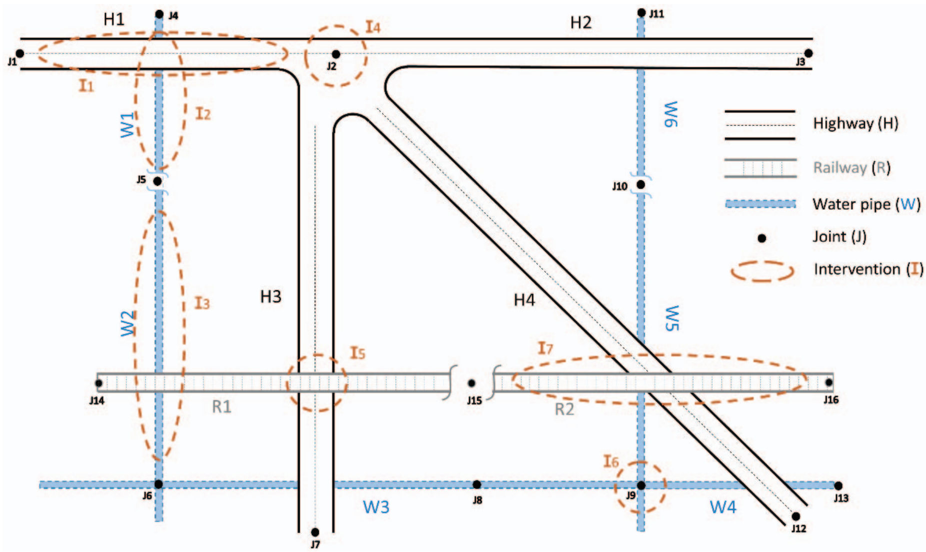

Fig. 3. Infrastructure systems with preventive intervention activities to be planned.

3.3. Optimal scheduling: an illustrative example

The illustrative example demonstrates the applicability of the 3C-concept approach and it serves as the input for the next section. The network consists of three infrastructure systems: water network, highway, and railway. These systems are operated by independent operators: water network operator (W), highway operator (H), and railway operator (R).

A top view of the analysed infrastructure systems is shown in Fig. 3 along with some intervention activities that are to be planned. As shown in the figure, the subsystems intersect at different locations. These intersections imply interdependency among the subsystems in such a way that an intervention on one subsystem can cause the closure to the intersecting subs-systems. Closure of a subsystem incurs a subsystem closure cost. Table 1 lists the analysed subsystems with their closure cost per time unit, which is required to estimate f_2. The closure cost occurs every time a subsystem is directly or indirectly affected by one of the intervention activities. These interactions among the subsystems, which are necessary to feed the interaction matrix, IM, are also listed in the table. In this example, only functional, geometrical, and physical interdependencies are considered. The IM is constructed following Section 3.2.

Table 1 Data of the analysed subsystems.

Sub-system	Index (i)	Closure cost per time unit (monetary unit/month)	Interaction with other subsystems (i)
W1	1	25,000	2 (W2), 7 (H1)
W2	2	12,500	1 (W1), 11 (R1)
W3	3	20,000	9 (H3)
W4	4	22,500	10 (H4)
W5	5	15,000	6 (W6), 10 (H4), 12 (R2)
W6	6	27,500	5 (W5), 8 (H2)
H1	7	15,000	-
H2	8	25,000	-
H3	9	12,500	11 (R1)
H4	10	20,000	12 (R2)
R1	11	22,500	9 (H3), 12 (R2)
R2	12	15,000	10 (H4), 11 (R1)

Table 2 Description of intervention activities.

Intervent-ion activity type and index (k)	Description	Subsystems directly affected (i)	$G_{min,k}$ $G_{max,k}$ (months)	Intervention cost per time unit (monetary unit/month)
I1 (1)	Intervention on highway H1	7 (H1)	3,5	5,000
I2 (2)	Intervention on water pipe W1	1 (W1)	2,6	2,500
I3 (3)	Intervention on water pipe W2	2 (W2)	4,6	4,000
I4 (4)	Intervention on the highway intersection J2	7, 8, 9, 10 (H1, H2, H3, H4)	3,4	4,500
I5 (5)	Intervention on the crossing joint of the highway H3 and railway R1	9, 11 (H3, R1)	2,5	3,000
I6 (6)	Intervention on water joint J9	3, 4, 5 (W1, W2, W3)	4,6	5,500
I7 (7)	Intervention on the railway R2	12 (R2)	2	3,000

As shown in Fig. 3, seven preventive intervention activities are to be planned. The intervention activities target different subsystems at different locations. Interventions activities with their descriptions are listed in Table 2.

Information about the interventions' occurrence frequency is also presented. Interventions can be performed with minimum and maximum time gaps $G_{min,k}$ and $G_{max,k}$, respectively. Column 7 shows the cost of executing the intervention activity, which is required to calculate f_1. This cost may include the cost of replacement parts, mobilizing resources, etc. Table 2 also includes a list of subsystems that are affected by the intervention activities. Interventions can directly affect multiple subsystems at the same time. For example, I5 is an intervention on the crossing joint of the highway H3 and railway R1. Hence, two subsystems are affected by this intervention. In this case, two operators are liable for the cost of intervention activity (i.e., operators H and R). The relations between the intervention activities and the subsystems, which are derived from Table 2, are represented by the relation matrix **R** in Eq. (3) which indicates upon which subsystem i each activity type k intervenes.

$$\boldsymbol{R} = [r_{i,k}] = \begin{bmatrix} 0 & \mathbf{1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \mathbf{1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathbf{1} & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathbf{1} & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathbf{1} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{1} & 0 & 0 & \mathbf{1} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathbf{1} & \mathbf{1} & 0 & 0 \\ 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathbf{1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{1} \end{bmatrix} \quad (3)$$

Fig. 4 shows the results of the optimal arrangement of intervention activities for a timeline of 18 months. Every row on the graph represents the distribution of one intervention type. It is assumed here that every intervention activity is completed during a single time interval. As can be seen, no pattern could be identified for the distributions of the seven interventions. The cumulative costs of intervention activities f_1, the cumulative cost of systems' interruption (closure cost), f_2, and the cumulative total cost are plotted on the same graph. The total cost obtained is 1,170,000 monetary units. It is clear that the closure cost makes up most of the total cost. Therefore, it is easy to reduce the cost by better arranging the intervention activities, even if the arrangement does not yield the least number of activities.

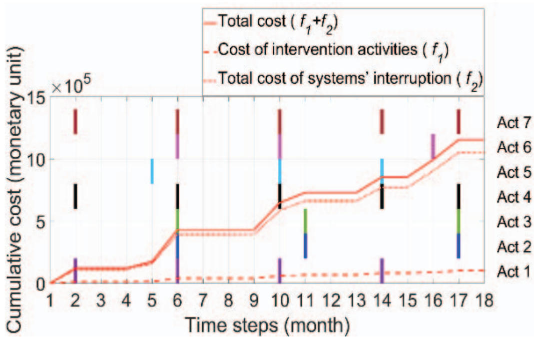

Fig. 4. Optimized arrangement of intervention activities with the corresponding cumulative incurred cost for a timeline of 18 months.

The optimal distribution of intervention activities is compared to the distribution for which the number of intervention activities is minimum. This particular distribution implies minimum intervention cost for the operator and thus it is usually assumed among operators. In this paper, this distribution is referred to as *individual* distribution. The individual distribution of intervention activities occurs when every operator individually plans their intervention activities with no regard to other operators' intervention plans, overlooking the system closure their interventions would cause to other systems. The total cost that would be resulted from the individual distribution of intervention activities is 1,567,500 monetary units. Therefore, the cost-saving by adopting the optimal plan is 397,500 monetary units (25%). This saving is the result of the optimal arrangement of intervention activities. (Kammouh et al. 2020).

4. Consequences of delayed maintenance

There are two types of interventions: preventive and corrective. The first is planned while the other is conducted when a failure takes place. Because it is planned, preventive intervention is associated with occurrence uncertainty (or delay probability). An intervention activity may be executed after the scheduled date because of unexpected circumstances, such as resources deficiency or extreme weather conditions on the date of intervention. In this section, this type of uncertainty is studied by analysing the consequences of unforeseen intervention delay. Every intervention activity is assigned an occurrence probability distribution that provides the likelihood of the activity being executed at the planned interval as well as the likelihood of having a delay. For the sake of simplicity and without any loss of generality, the probability distribution of occurrence of each activity is assumed to follow a geometric distribution *Geom*(p), where the parameter p is the success probability, which is in our case the probability of activity execution in the assigned month. This parameter is based on the maximum possible delay of the programmed activity of type k, which is one-time step less than the gap between the potentially delayed activity and the next activity (Fig. 5). It is assumed here that a delay of one activity does not affect other activities; that is, there is not a re-schedule of the rest of the activities if a delay occurs.

The Monte Carlo technique is used to investigate the impact of unforeseen intervention delays on the total intervention costs. A total number of 2000 simulations has been conducted to obtain the deviation of the total cost with respect to the optimal cost when there are no delays.

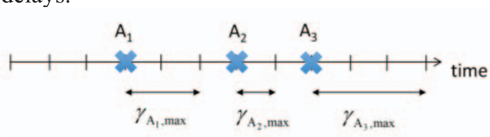

Fig. 5. Maximum delay ($\gamma^k_{j,\max}$) considered for every programmed activity of type k.

Given that the optimal plan has been defined for a specific timeline, 18 months in this case, it is expected that a delay would always increase the cost obtained from the optimal plan at T=18 months; however, there are some cases where the total cost is lower. This is because some of the restrictions initially set to obtain the optimal plan are violated. For example, the gap between two activities of the same type might exceed the maximum allowed gap (G_{max}). Therefore, the new plan could be more economical than the optimal plan. This comes at the cost of a high risk of failure since the gap between two successive activities is higher than the maximum allowed gap.

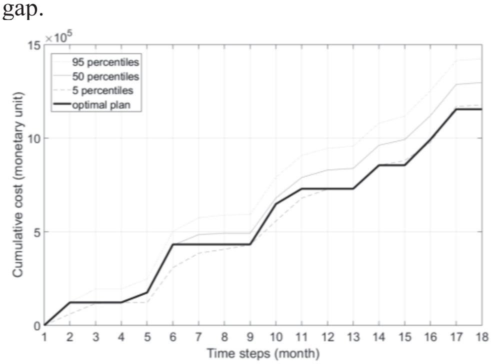

Fig. 6. The 5th, 50th and 95th percentiles of the cumulative cost over time assuming unforeseen delays.

Fig. 6 shows the 5th, 50th, and 95th percentiles of the cumulative cost distribution assuming the unforeseen delays for each time step. These are compared to the optimal plan. The optimal plan without considering uncertainty yields a total cost lower than the 95th percentile. Therefore, the occurrence of a delay is very impactful to the total intervention cost, given that the total cost corresponding to the 95, 50, and 5 percentile curves are 24%, 12%, and 2% higher than that of the optimal plan. Hence, overlooking this uncertainty leads to high impact. It is also noted how some delays might cumulate a total cost smaller than the one corresponding to the optimal program before month 13, however, these strategies become more expensive than the optimal one as the end of the timeline is approaching.

Fig. 7 shows the probability distribution function (PDF) of the total intervention cost at T=18 months assuming unforeseen delays. The Gamma distribution has been used to model the observed data. The parameters have been obtained using the maximum likelihood estimation method (MLE) (a=296 and b=4382.5).

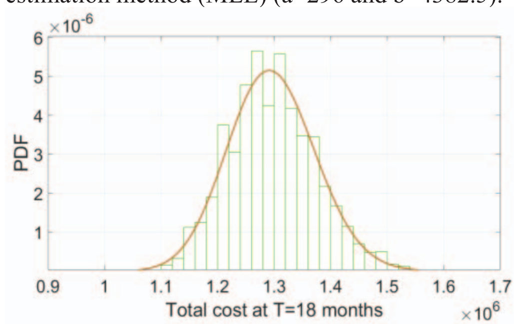

Fig. 7. Probability distribution function of the total cost at T=18 months assuming unforeseen delays.

5. Conclusions

The challenges that interdependent infrastructures pose to the operators of these infrastructures are numerous. Developing tools to help the managing of maintenance and renovation activities in a systemic and collaborative manner has been identified as a priority need for operators.

In this context, this paper studies the impact of unforeseen delays in a multi-system intervention planning for interdependent infrastructure. The optimal planning has been obtained based on the mathematical framework proposed by Kammouh et al (2020), which considers the physical, geographical, and functional interdependencies across infrastructure systems. The uncertainty of executing each intervention activity at their planned time interval is combined to obtain the probability distribution function of the total cost due to the unforeseen delays at the end of the timeline. An intervention planning application for three interdependent infrastructure systems is introduced as an illustration.

It can be concluded that the economic impact due to unforeseen intervention delays is significant. The cost is very sensitive to the execution time such that a small shift in the execution time of one of the activities is capable of producing a considerable cost increase. Given that unforeseen delays cannot be avoided, this work highlights the need for specific mitigation strategies to make low-risk decisions during the course of the intervention program.

The results encourage infrastructure managers to enhance communication between each other regarding their intervention planning as this could bring significant benefits to all stakeholders by jointly planning their intervention activities. Future work is aimed at developing the mitigation strategies accounting for the complex structure of dependence among infrastructures.

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