Intervention Grouping Strategy for Multi-component Interconnected Systems

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Intervention grouping strategy for multi-component interconnected systems: a scalable optimization approach

Omar Kammouh
Department of Multi-Actor Systems, Faculty of Technology, Policy, and Management, Delft University of Technology, The Netherlands, E-mail: o.kammouh@tudelft.nl

Ahmadreza Marandi
Department of Industrial Engineering and Innovation Sciences Eindhoven University of Technology, the Netherlands, E-mail: a.marandi@tue.nl

Claudia Fecarotti
Department of Industrial Engineering and Innovation Sciences Eindhoven University of Technology, Eindhoven, the Netherlands, E-mail: c.fecarotti@tue.nl

The well-being of modern societies depends on the functioning of their infrastructure networks. During their service lives, infrastructure networks are subject to different stresses (e.g., deterioration, hazards, etc.). Interventions are performed to ensure the continuous fulfillment of the infrastructure's functional goals. To guarantee a high level of infrastructure availability and serviceability with minimal intervention costs, preventive intervention planning is essential.

Finding the optimal grouping strategy of intervention activities is an NP-hard problem that is well studied in the literature and for which various economic models and optimization approaches are proposed. This research focuses on a new efficient optimization model to cope with the intervention grouping problem of interconnected multi-component systems. We propose a scalable two-step intervention grouping model based on a clustering technique. The clustering technique is formulated using Integer Linear Programing, which guarantees the convergence to global optimal solutions of the considered problem. The proposed optimization model can account for the interactions between multiple infrastructure networks and the impact on multiple stakeholders (e.g., society and infrastructure operators). The model can also accommodate different types of intervention, such as maintenance, removal, and upgrading.

We show the performance of the proposed model using a demonstrative example. Results reveal a substantial reduction in net costs. In addition, the optimal intervention plan obtained in the analysis shows repetitive patterns, which indicates that a rolling horizon strategy could be adopted so that the analysis is only performed for a short time horizon.

Keywords: infrastructure, optimization, intervention, maintenance, interdependency, intervention management.

1. Introduction

Infrastructure networks continuously degrade due to their excessive use. Degradation of infrastructure networks ultimately leads to failure, which affects the service quality and causes safety issues and physical damages. Interventions, such as maintenance and renovations, are executed to ensure a continuous fulfillment of the infrastructure's functional goals and quality of service (e.g., water protection, traffic flow, etc.). To increase infrastructure availability while minimizing maintenance costs, a shift from a corrective to a preventive maintenance approach is needed (Adey et al. 2020).

Unlike corrective maintenance, preventive maintenance allows maintenance activities to be adequately planned, thus facilitating the optimal grouping of maintenance activities. Intervention grouping can be highly advantageous in complex multi-component systems, such as interconnected infrastructure networks. It enables set-up costs to be shared and the frequency of scheduled and unscheduled downs to be reduced. However, there can also be negative economic consequences due to the increased frequency of implementing some activities or the waste of remaining useful life if preventive thresholds for components replacement are not optimized (Moinian et al. 2017).

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 various contexts that indicate that these costs must be massive, stressing the need for a more integrative approach to infrastructure intervention.

The existing literature on intervention planning and optimization shows a growing interest in 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 simultaneously (e.g., set-up 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 when deterioration modeling is based on expert judgment rather than statistical data analysis. Do et al. (2015) presented a stationary grouping strategy for maintenance activities of complex systems whose components are classified into series and parallel. 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 use a genetic algorithm 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.

The main shortcomings that exist in the literature on intervention planning are:

1- The available approaches are not explicitly designed for complex interconnected systems. This means that interdependency between multiple systems is not properly tackled.

2-These approaches are based on nonlinear models, which are computationally expensive and do not guarantee scalability.

The primary goal of this paper is to cover the shortcomings in existing scientific literature by introducing a scalable integrative multi-system optimization model for infrastructure interventions in which multiple infrastructure networks and stakeholders can be reflected. The work introduced here extends previous work on intervention planning and optimization in (Kammouh et al. 2021; Kammouh et al. 2020).

The remainder of the paper is organized as follows. Section 2 introduces the developed intervention planning approach. Section 3 presents the optimization model. Section 4 presents a numerical example to illustrate the applicability of the proposed optimization model. Finally, conclusions are drawn in Section 5.

2. Multi-system intervention planning for interdependent infrastructures

This section presents the proposed intervention planning approach for interdependent infrastructure networks. We start by introducing the concept, followed by the benefits that can be attained by applying this concept, and finally the modelling approach that we use to model the infrastructure networks and their interdependencies.

2.1 Concept and approach

The intervention optimization model introduced here aims at planning the required intervention activities such that disrupted services are minimized and so are the incurred cost and users' discomfort. The applicability of the model is not limited to maintenance planning but also accommodates other types of intervention activities, such as upgrading and removal. In addition, the model is multi-system, which allows considering multiple infrastructure networks in the analysis. The intervention planning model introduced in this paper can be divided into three steps.

The first step is to classify the intervention types into central and non-central interventions. Central interventions are those that must occur at a pre-established time moment, and neither delay nor advance is possible. They are usually implemented with a fixed frequency due to their dominant time-dependent nature. This time interval represents the time between two interventions of the same type; for instance, the time between an intervention on a road section and the following intervention on the same road section. The non-central intervention types are condition-based interventions and can be scheduled during the planned closures of the central interventions.

The second step is to cluster intervention activities. This is done by grouping the non-central interventions with the initially planned central interventions while respecting some predefined individual constraints, such as the time interval between two successive interventions of the same type. The first two steps are illustrated in Figure 1, where intervention type A is central and intervention type B is non-central. Interventions of type A are fixed at predefined time slots. Interventions of type B are executed together with interventions of the Type A. It is important to note that an additional intervention of type B was created to avoid increased failure risk of the underlying object.

The third and final step is to optimize for the intervention program (i.e., intervention plan) that meets the conditions initially set. In this work, the optimization objective is to reduce the net cost of executing the interventions. The net cost is divided into three parts; the first part is direct preventive intervention cost, the second part is the set-up cost, and the third part is the system interruption cost (see Section 2.2 for more information). Implementing multiple interventions at the same time signifies reduced service interruption and reduced set-up costs.

2.2. Financial and societal effect of grouping intervention activities

Grouping intervention activities result in broad economic and societal benefits. There are three elements that contribute towards the net cost of an intervention plan:

1- Direct preventive intervention cost, which constitutes all costs that are directly linked to the intervention activity (e.g., replacement parts, specialized crew, etc.)
2- Set-up cost, which constitutes generic costs needed to execute an intervention but can be shared by several intervention activities (e.g., cost of crew traveling, excavation, scaffolding, etc.)
3- System interruption cost, which constitutes the negative effect due to object (i.e., component of a network) unavailability when the object is under maintenance or replacement (e.g., extra travel time due to road disruption, low water pressure, etc.).

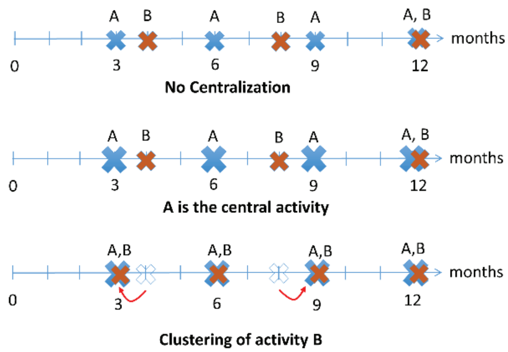

Figure 1. Centralizing and Clustering of interventions.

Grouping intervention activities is performed with the objective of minimizing the net cost. It is not unusual that the direct intervention costs are increased in the optimal intervention plan due to more frequent intervention execution. In this case, the global benefits achieved by the intervention grouping will be due to less system interruption and set-up costs. Note that the service's interruption cost must be monetized to be able to combine it with the intervention cost. Several comprehensive methods on how to monetize the impact of service interruption have been recently introduced (Adey et al. 2020; Kerwin and Adey 2020).

2.3. Multi-system modeling approach

In the context of this paper, the words *system* and *network* are used interchangeably. Every network is composed of multiple objects, such as road sections, water pipes, bridge, etc. An object (*obj* in Figure 2) is considered a part of a major infrastructure network (*Net*). Two adjacent network sections or objects with different essential features represent two different objects. An operator is the manager of an infrastructure network, who can be responsible for one or multiple networks. Each operator is assumed to be responsible for their networks' intervention and service interruption costs. An intervention type (*Int*) is an intervention on one or more objects. Intervention types belong to the same group (*Grp*) if they can share set-up costs.

Figure 2 shows the hierarchical relationships between operators, infrastructure networks, objects, intervention types, and intervention groups. The proposed approach takes into consideration the interaction among different objects. Considering the interaction among objects is especially important when tackling interconnected infrastructure networks run by multiple operators. For a single network, there is always dependency between the performance of the network and its objects (i.e., executing an intervention on a major object might require a temporary suspension of a part of or the whole network). When tackling multiple networks, the loss of performance of an object within a network could or could not affect an object within another network. Therefore, the relationships among the objects across the networks should be considered.

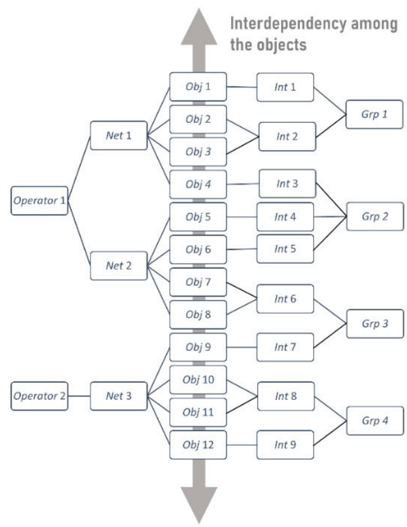

Figure 2 Relationships between operators, infrastructure networks (*Net*), objects (*Obj*), and intervention types (*Int*).

In this paper, we model the relations between the different elements using adjacency matrices. A similar approach has been adopted in (Cimellaro et al. 2016; Kammouh and Cimellaro 2018; Kammouh et al. 2018) to model the interdependency among the resilience indicators at the community scale. The relations between the objects are represented using the Interaction Matrix (IM). Eq. (1) is an interaction matrix of a set of N objects, where $\boldsymbol{I}_{N\times N}$ is a square matrix whose components, the so-called interaction coefficients $\left[I_{i,j}\right]=[0,1]$, determine if object j interacts with object i. If $I_{i,j}=0$ then object j does not affect the functionality of object i, whereas $I_{i,j}=1$ implies the contrary. $I_{i,j}$ can take values between 0 and 1 (e.g., 0.5) which implies a partial dependency between objects I and j. Consequently, the diagonal terms of IM are equal to 1. $\boldsymbol{I}_{N\times N}$ can be asymmetric as a result of the non-reciprocal interaction behaviour between the objects. The values of the interaction coefficients can be obtained from experts judgment.

$$\boldsymbol{I}_{N\times N}=[I_{i,j}]=\begin{bmatrix} I_{1,1} & \cdots & I_{1,N} \\ \vdots & \ddots & \vdots \\ I_{N,1} & \cdots & I_{N,N} \end{bmatrix}, \qquad (1)$$

where $N\in\mathbb{N}^{+}$ is the number of objects.

The relations between the intervention types and the objects are captured using the relation matrix $\boldsymbol{R}_{N\times K}$. Eq. (2) is a relation matrix whose components $\left[R_{j,k}\right]\in\{0,1\}$ indicate upon which objects the intervention types intervene. The component $R_{j,k}$ takes the value 1 if intervention type *k* affects object *j*, and 0 otherwise.

$$\boldsymbol{R}_{N\times K}=[R_{j,k}]=\begin{bmatrix} R_{1,1} & \dots & R_{1,K} \\ \vdots & \ddots & \vdots \\ R_{N,1} & \dots & R_{N,K} \end{bmatrix}, \quad (2)$$

where $K\in\mathbb{N}^+$ is the number of intervention types,

Finally, $\boldsymbol{G}_{E\times K}$ in Eq.(3) is a relation matrix whose components $\left[G_{e,k}\right]\in\{0,1\}$ indicate the intervention groups to which the intervention types belong. The component $G_{e,k}$ takes the value 1 if intervention type *k* belong to group *e*, and 0 otherwise.

$$\boldsymbol{G}_{E\times K}=[G_{e,k}]=\begin{bmatrix} G_{1,1} & \dots & G_{1,K} \\ \vdots & \ddots & \vdots \\ G_{E,1} & \dots & G_{E,K} \end{bmatrix}, \quad (3)$$

where $E\in\mathbb{N}^+$ is the number of intervention groups.

3. Mathematical optimization with intervention grouping

This section presents the mathematical formulation of the proposed intervention optimization model. We adopt a bottom-up approach where we first (stage 1) determine a tentative intervention planning for each individual object separately based on a block replacement policy with minimal repair. Then (stage 2), based on these tentative plannings, we aim at optimizing the intervention program for the entire network by grouping interventions.

3.1 Stage 1: tentative intervention scheduling for individual objects

To come up with a tentative intervention plan for each individual object, we adopt the block replacement policy with minimal repair. The object is preventively maintained at fixed time intervals; the preventive action brings the object to a "as good as new" condition. If a failure occurs between two consecutive preventive actions, then the object is repaired to "as bad as old" conditions, namely to the conditions right before failure. The optimal intervention interval is then obtained by minimizing the long-run expected intervention costs. This tentative planning is a periodic intervention optimized for each object independently. The objects are assumed to degrade according to a Weibull distribution with a scale parameter $\alpha_k > 0$, and a shape parameter $\beta_k > 0$. The optimal replacement interval for a block replacement policy with minimal repair is given by:

$$T_{opt,k}=\alpha_k\sqrt[\beta_k]{\frac{C_k^{prev}}{C_k^{corr}(\beta_k-1)}}, \quad (4)$$

where α_k, $\beta_k\in\mathbb{R}^+$ are the scale and shape parameters, respectively, of objects targeted by intervention type *k*. We assume that objects targeted by the same intervention type share similar characteristics (e.g., degrade similarly). If the objects do not share similar characteristics, they should not be included under the same intervention type. $C_k^{prev}\in\mathbb{R}^+$ is the cost of performing preventive intervention on the objects targeted by intervention type *k* and $C_k^{corr}\in\mathbb{R}^+$ is the cost of performing corrective intervention on the objects targeted by intervention type *k* (see Vu et al. (2014) for more details).

3.2 Stage 2: optimal intervention scheduling for the global system

The global optimization problem introduced here aims at scheduling interventions for each object such that the net intervention cost, including the direct intervention costs and the compound costs of service interruption, is minimum. The optimization problem is a multi-integer linear programming problem, which is mathematically expressed as follows:

$$\underset{M,U,V}{Min}\ (C_{tot}^{prev}+U_{tot}-S_{tot}), \quad (5)$$

where C_{tot}^{prev} is the total cost of interventions, given by:

$$C_{tot}^{prev}=\sum_{t=1}^{T}\boldsymbol{C}_{1\times K}^{prev}\times\boldsymbol{M}_{K\times T}^{t}, \quad (6)$$

where $T\in\mathbb{N}^+$ is the number of time steps considered in the analysis, $\boldsymbol{C}_{1\times K}^{prev}$ is a vector of preventive intervention costs whose components $\left[C_k^{prev}\right]\in\mathbb{R}^+$ indicate the costs of performing the preventive interventions with $k=1,2,...K$, and $\boldsymbol{M}_{K\times T}^{t}$ is the t^{th} column of the matrix $\boldsymbol{M}_{K\times T}$ whose components $\left[M_{k,t}\right]\in\{0,1\}$ indicate whether intervention type *k* is conducted (=1) or not (=0) at time step *t*; and U_{tot} is the total service interruption cost caused by the interventions:

$$U_{tot}=\sum_{t=1}^{T}\boldsymbol{C}_{1\times N}^{shut}\times\boldsymbol{U}_{N\times T}, \quad (7)$$

where $\boldsymbol{C}_{1\times N}^{shut}$ is vector of service interruption costs whose components $\left[C_j^{shut}\right]\in\mathbb{R}^+$, with $j=1,2,...,N$, indicate the costs of suspending the objects, $\boldsymbol{U}_{N\times T}$ is a matrix whose components $\left[U_{i,t}\right]\in\{0,1\}$ indicate which objects are directly or indirectly affected by at least one intervention activity at a given time step. The component $U_{i,t}$ takes the value 1 if object

i is directly or indirectly affected by at least one intervention activity at time step t, and 0 otherwise; and S_{tot} is the total set-up costs of the interventions:

$$S_{tot} = \sum_{t=1}^{T} \boldsymbol{C}_{1\times E}^{setup} \times \boldsymbol{V}_{E\times T} \ , \tag{8}$$

where $\boldsymbol{C}_{1\times E}^{setup}$ is vector of set-up costs whose components $\left[C_e^{setup}\right] \in \mathbb{R}^+$, with $e = 1,2,...,E$, indicate the set-up costs of the intervention groups, $\boldsymbol{V}_{E\times T}$ matrix whose components $\left[V_{e,t}\right] \in \{0,1\}$ indicate the groups of intervention types that contain at least one intervention activity that is executed at a given time step. The component $V_{e,t}$ takes the value 1 if group of activities e contains at least one intervention activity that is executed at time step t, and 0 otherwise.

The first constraint set in Eq. (9) restricts any two successive interventions of type k to have at least a time interval equal to $T_{min,k}$, where $T_{\min,k} \in \mathbb{N}^+$ is the minimum number of time steps between two successive interventions of type k.

$$0 \le \sum_{t}^{t+T_{\min,k}-1} M_{k,t} \le 1$$
$$for \quad \forall k = 1,2,...,K, \quad \forall t = 1,2,...,T - T_{\min,k} + 1 \, . \tag{9}$$

The second constraint set in Eq. (10) restricts any two successive interventions of type k to have a time interval not larger than $T_{opt,k}$., where $T_{opt,k} \in \mathbb{N}^+$ is the maximum number of time steps between two successive interventions of intervention type k:

$$\sum_{t}^{t+T_{opt,k}-1} M_{k,t} \ge 1$$
$$for \quad \forall k = 1,2,...,K, \quad \forall t = 1,2,...,T - T_{opt,k} + 1 \, . \tag{10}$$

The third constraint in Eq. (11) helps avoid double-counting of interruption costs; That is, if an object is directly or indirectly affected by more than one intervention activity, its service interruption cost will only be considered once.

$$\sum_{j=1}^{N} \sum_{k=1}^{K} [I_{i,j}][R_{j,k}][M_{k,t}] \le \delta_1 \times [U_{i,t}]$$
$$for \quad \forall i = 1,2,...,N, \quad \forall t = 1,2,...,T \, . \tag{11}$$

The last constraint in Eq. (12) helps avoid double-counting of set-up costs; That is, if two or more intervention activities belonging to a specific group are executed at the same time step, the corresponding set-up cost will only be considered once.

$$\sum_{k=1}^{K} [G_{e,k}][M_{k,t}] \le \delta_2 \times \left[V_{g,t}\right]$$
$$for \quad \forall e = 1,2,...,E, \quad \forall t = 1,2,...,T \, , \tag{12}$$

where δ_1 and δ_2 are two numbers to prevent infeasible solutions such that:

$$\delta_1 = N \times K \, , \tag{13}$$

$$\delta_2 = K \, . \tag{14}$$

4. Demonstrative example

The purpose of this section is to demonstrate the applicability of the proposed intervention planning model with an illustrative example of a small infrastructure network. A description of the network is first given then the results of the optimization model are presented

4.1. Example description and modeling

The illustrative example presented in this section demonstrates the applicability of the introduced planning model. The network consists of three individual infrastructure systems: a water network, a highway network, and a railway network. These networks are operated by independent operators: water network operator (referred to as W), highway operator (referred to as H), and railway operator (referred to as R).

A top view of the analyzed infrastructure networks is shown in Figure 3, along with some intervention types (indicated by *Int*) that are to be planned. As shown in the figure, the objects intersect at different locations. These intersections imply interdependency among the objects so that an intervention on one object can cause the unavailability of the intersecting objects. The costs incurred per time unit due to the unavailability of each object are listed in Table 1. These costs are required to estimate U_{tot}. The unavailability cost occurs every time an object is directly or indirectly affected by one of the intervention types. These interactions among the objects, which are necessary to feed the interaction matrix, are also listed in the table. The relations between the objects are mathematically represented using Eq. (15).

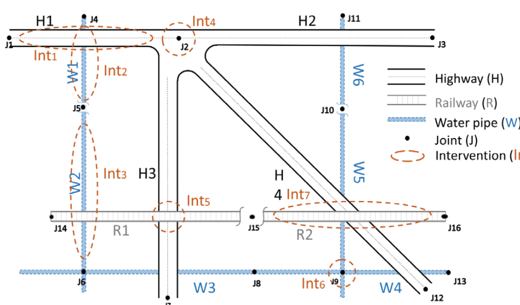

Figure 3. Infrastructure networks with preventive intervention types to be planned

As shown in Figure 3, seven preventive intervention types are to be planned. The interventions target different objects at different locations. The intervention types 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 $T_{min,k}$ and $T_{\hat{o}pt\_k}$, respectively. Column 5 shows the cost of executing each intervention type, which is required to calculate C_{tot}^{prev} . Table 2 also includes a list of objects that are affected by the interventions. Interventions can directly affect multiple objects at the same time. For example, Int5 is an intervention on the crossing joint of highway H3 and railway R1. Hence, two objects are affected by this intervention. In this case, two operators are liable for the cost of interventions (i.e., operators H and R). The relations between the intervention types and the objects, which are derived from Table 2, are represented by the relation matrix $\boldsymbol{R}_{N\times K}$ in Eq. (16) which indicates upon which object i each activity type k intervenes.

Finally, Table 3 clusters the intervention types under groups. Interventions that are in the same group share the set-up cost if they are executed at the same time. The relations between the interventions and the groups are mathematically represented using Eq. (17). The shared set-up cost in Table 3 is required to estimate S_{tot}.

Table 1 Data of the analyzed objects.

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

Table 2 Description of the intervention types.

Intervent-ion type and index (k)	Description	Objects directly affected (i)	$[T_{min,k}, T_{\hat{o}pt\_k}]$ (time steps)	Intervention cost per time unit (monetary unit/time step)
Int1 (1)	Intervention on highway H1	7	[1, 5]	5,000
Int2 (2)	Intervention on water pipe W1	1	[1, 6]	2,500
Int3 (3)	Intervention on water pipe W2	2	[1, 6]	4,000
Int4 (4)	Intervention on the highway intersection J2	7, 8, 9, 10	[1, 4]	4,500
Int5 (5)	Intervention on the crossing joint of the highway H3 and railway R1	9, 11	[1, 5]	3,000
Int6 (6)	Intervention on water joint J9	3, 4, 5	[1, 6]	5,500
Int7 (7)	Intervention on the railway R2	12	[1, 4]	3,000

Table 3 Intervention groups and set-up costs.

Intervention group	Index (g)	Intervention types included in the group	*Shared set-up cost (monetary unit)*
G1	1	Int2, Int3	700
G2	2	Int1, Int4	550
G3	3	Int5, Int7	800
G4	4	Int6	640

$$\boldsymbol{I}_{N\times N}=[I_{ij}]=\begin{bmatrix} & W1 & W2 & W3 & W4 & W5 & W6 & H1 & H2 & H3 & H4 & R1 & R2 \\ W1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ W2 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ W3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ W4 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ W5 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ W6 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ H1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ H2 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ H3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ H4 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ R1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ R2 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}, \tag{15}$$

$$\boldsymbol{R}_{N\times K}=[r_{j,k}]=\begin{bmatrix} & Int1 & Int2 & Int3 & Int4 & Int5 & Int6 & Int7 \\ W1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ W2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ W3 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ W4 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ W5 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ W6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ H1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ H2 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ H3 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ H4 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ R1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ R2 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \tag{16}$$

$$\boldsymbol{G}_{E\times K}=[G_{e,k}]=\begin{bmatrix} & Int1 & Int2 & Int3 & Int4 & Int5 & Int6 & Int7 \\ G1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ G2 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ G3 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ G4 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}. \tag{17}$$

4.2. Results

Figure 4 shows the optimal intervention plan of the intervention types for a period of 30 time steps. The vertical axis on the left is the cumulative cost and the vertical axis on the right shows the different intervention types that are to be planned. Every row on the graph (i.e., a set of bars with same colour) represents the intervention plan of one intervention type. Every bar is an execution an intervention type. From the figure, we can recognize patterns and fixed frequencies of interventions (i.e., every intervention type is executed every fixed number of time steps). This indicates that a rolling horizon strategy could be adopted so that the analysis is only performed for a short horizon.

The cumulative costs of preventive interventions (referred to as f_1 in Figure 4), the cumulative set-up cost (f_2), the cumulative cost of service interruption (f_3), and the cumulative total cost are plotted on the same graph. It is clear that the service interruption cost makes up most of the total cost. Therefore, there is an opportunity to reduce the cost by better arranging the interventions, even if the arrangement does not yield the least number of interventions.

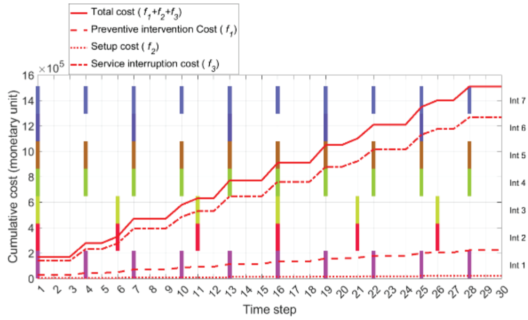

Figure 4. Optimal intervention plan with the corresponding cumulative incurred cost for T = 30 time steps

To analyse the cost-benefit, the optimal intervention program is compared to an intervention program in which the number of interventions is minimum (Figure 5). The latter implies minimum intervention cost for the operator, and thus it is usually assumed among operators (Adey et al. 2020). In such an intervention program, the time between two successive interventions of the same type is equivalent to T_{opt_k}. Herein, this intervention program is referred to as *individual* intervention program. The individual intervention program occurs when every operator individually plans their interventions with no regard to other operators' intervention programs, overlooking the service interruption their interventions would cause to other networks. In real life, this is usually the case because there is indeed minimal or no communication among the infrastructure operators in this regard. From Figure 5, the total cost resulting from the optimal program is 17% less than the individual program.

To verify the scalability characteristic of the optimization model, the model performance is studied here. The objective is to identify and capture the computational complexity due to increasing the number of variables. To do so, repeated optimization runs with different numbers of variables have been carried out.

Figure 6 shows a linear relationship between the computation time and the number of time steps considered in the analysis. The computation time is proportional to the number of time steps.

Similarly, the relationship between the computational time and the number of intervention types considered is studied. Repeated optimization runs with different numbers of intervention types have been carried out. The results of the analysis are presented in Figure 7 showing a linear trend between the two the optimization time and the number of time steps. This suggests that the proposed optimization problem is easily scalable. This is a significant advantage because it allows for long-term intervention planning of systems with many objects.

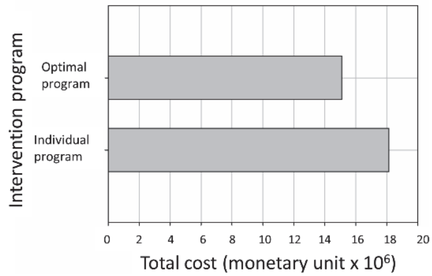

Figure 5 Total costs comparison between the individual and optimal intervention programs

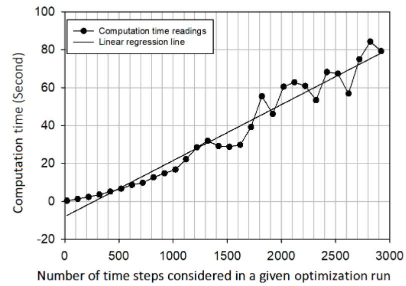

Figure 6 computation time of different optimization runs with varying time steps

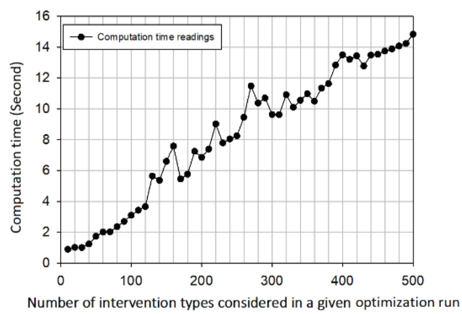

Figure 7 Computation time of different optimization runs with varying number of intervention types

5. Conclusions

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

This paper introduced a multi-system optimization model for infrastructure intervention planning. The proposed model can consider the interactions between multiple infrastructure networks and multiple stakeholders (e.g., society and infrastructure operators), and can accommodate different types of interventions, such as maintenance, removal, and upgrading.

It has been shown that finding the optimal arrangement of interventions may significantly reduce the net costs, which is divided into (indirect) service unavailability cost and (direct) intervention and set-up costs. The decrease in cost is mainly due to reduced service unavailability and set-up costs.

The proposed optimization problem is simple and easily scalable. The computation time consumed by the optimization problem is roughly proportional to the number of variables, unlike other published algorithms where the simulation time increases exponentially by increasing the number of variables. This is a significant advantage because it allows for intervention planning of networks with many objects accounting for the interdependencies among them.

It should be noted that uncertainties may affect the planning. For example, interventions that are planned at a certain time step could be delayed. In this case, the whole planned could be impacted. Therefore, in case the planning is no longer feasible, a new planning should be proactively run given the new input.

The results should motivate 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 aims to account for the complex structure of dependence among infrastructures.

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References

Adey, B., Burkhalter, M., and Martani, C. (2020). "Defining road service to facilitate road infrastructure asset management." *Infrastructure Asset Management*, 7(4), 240-255, 10.1680/jinam.18.00045.

Chalabi, N., Dahane, M., Beldjilali, B., and Neki, A. (2016). "Optimisation of preventive maintenance grouping strategy for multi-component series systems: Particle swarm based approach." *Computers Industrial Engineering*, 102, 440-451,

Cimellaro, G. P., Zamani-Noori, A., Kammouh, O., Terzic, V., and Mahin, S. A. (2016). "Resilience of Critical Structures, Infrastructure, and Communities." Pacific Earthquake Engineering Research Center (PEER), Berkeley, California.

Dekker, R. h. (1995). "Integrating optimisation, priority setting, planning and combining of maintenance activities." *European Journal of Operational Researc*, 82(2), 225-240,

Dekkert, R., Smit, A., and Losekoot, J. (1991). "Combining maintenance activities in an operational planning phase: a set-partitioning approach." *IMA Journal of Management Mathematics*, 3(4), 315-331,

Do, P., Vu, H. C., Barros, A., and Bérenguer, C. (2015). "Maintenance grouping for multi-component systems with availability constraints and limited maintenance teams." *Reliability Engineering System Safety*, 142, 56-67,

Kammouh, O., and Cimellaro, G. P. (2018). "PEOPLES: a tool to measure community resilience." Proceedings of 2018 Structures Congress (SEI2018), J. G. Soules, ed., ASCE-American Society of Civil Engineering, Fort Worth, Texas. April 19–21, 2018, 161 - 171.

Kammouh, O., Nogal, M., Binnekamp, R., and Wolfert, A. R. M. R. (2021). "Multi-system intervention optimization for interdependent infrastructure." *Automation in Construction*, 127, 103698, https://doi.org/10.1016/j.autcon.2021.103698.

Kammouh, O., Nogal, M., Bruijne, M. D., Binnekamp, R., and Wolfert, A. R. M. (2020). "Interdependent Infrastructure Interventions Optimization: An Integrative Systems Thinking Approach." 30th European Safety and Reliability Conference, ESREL 2020 and 15th Probabilistic Safety Assessment and Management Conference, PSAM 2020, 1175-1182.

Kammouh, O., Noori, A. Z., Taurino, V., Mahin, S. A., and Cimellaro, G. P. (2018). "Deterministic and fuzzy-based methods to evaluate community resilience." *Earthquake Engineering and Engineering Vibration*, 17(2), 261-275, 10.1007/s11803-018-0440-2.

Kerwin, S., and Adey, B. T. (2020). "Optimal Intervention Planning: A Bottom-Up Approach to Renewing Aging Water Infrastructure." *Journal of Water Resources Planning and Management*, 146(7), 04020044, 10.1061/(asce)wr.1943-5452.0001217.

Moinian, F., Sabouhi, H., Hushmand, J., Hallaj, A., Khaledi, H., Mohammadpour, M., and Management. (2017). "Gas turbine preventive maintenance optimization using genetic algorithm." *International Journal of System Assurance Engineering*, 8(3), 594-601,

Vu, H. C., Do, P., Barros, A., and Bérenguer, C. (2014). "Maintenance grouping strategy for multi-component systems with dynamic contexts." *Reliability Engineering System Safety*, 132, 233-249, 10.1016/j.ress.2014.08.002.