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Mitigation Controller: Adaptive Simulation Approach for Planning Control Measures in Large Construction Projects

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Abstract: Probabilistic Monte Carlo simulations are often used to determine a project's completion time given a required probability level. During project execution, schedule changes negatively affect the probability of meeting the project's completion time. A manual trial and error approach is then conducted to find a set of mitigation measures to again arrive at the required probability level. These are then implemented as scheduled activities. The mitigation controller (MitC) proposed in this paper automates the search for finding the most cost-effective set of mitigation measures using multiobjective linear optimization so that the probability of timely completion remains at the required level. It considers different types of uncertainties and risk events in the probabilistic simulation. Moreover, it removes the fundamental modeling error that exists in the traditional probabilistic approach by incorporating human control and adaptive behavior in the simulation. Its usefulness is demonstrated using an illustrative example derived from a recent Dutch construction project in which delay is not permitted. It is shown that the MitC is capable of identifying the most effective mitigation strategies allowing for substantial cost savings. **DOI: 10.1061/(ASCE)CO.1943-7862.0002126.** *© 2021 American Society of Civil Engineers.*

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Introduction

To maintain a required probability level of meeting the target completion data of a construction project, corrective mitigation measures are normally identified and proposed during the project execution phase (Van Gunsteren et al. 2011). These corrective measures are aimed at shortening and controlling the construction activities so that the project is again back on track so it can be delivered at the target completion time. Several studies focus on identifying these measures (Viswanathan et al. 2020; Olawale and Sun 2010; Fang and Marle 2012; Zhang and Fan 2014; Shrestha and Shrestha 2016). To determine the effect of these identified measures, probabilistic Monte Carlo scheduling is often applied (e.g., Leontaris et al. 2019; Kohli 2017; Harris 2014). Within this approach, different combinations of corrective measures are simulated and calculated until a particular subset meets the required probability for a given target completion time (Karthik et al. 2017; Budruk et al. 2019). This can be considered a cumbersome trial-and-error approach that is highly ineffective, especially within large project schedules.

Another drawback of this approach is that it does not allow for mitigation strategy optimization. This is because standard Monte Carlo (MC) scheduling does not properly model the project management's goal-oriented behavior in which optimization is intuitively carried out by the project manager. That is, the project manager would naturally select only that mitigation strategy (i.e., a combination of measures) that could achieve the requirements of meeting the target completion time. This means that the current MC scheduling contains a fundamental modeling error because it does not reflect human control and adaptive behavior, neither in the overall outcome nor on the iteration level. Applying MC techniques to construction scheduling in itself is not incorrect; however, the way it is used does not fully reflect the construction scheduling mechanism because the human action and mitigation control behavior are not part of the model. This modeling error can be overcome by combining MC with optimization techniques to reflect the real human goal-oriented construction scheduling mechanism. To the best of the authors' knowledge, this application of control concepts is currently not incorporated neither in the industrial tools (e.g., Primavera) nor in the scientific construction scheduling literature. In addition to not reflecting human control behavior, implementing all corrective measures in all MC iterations is overly conservative because it might not be necessary to employ all of the measures in some simulation iterations but only a subset that ensures being on time. Hereby, one can conclude that the current MC approach on selecting the most effective corrective measures to mitigate project delays is inefficient.

Despite the broad utilization of general control concepts in different domains, such as financial planning (i.e., Vasconcellos 1988; Cong 2016), production planning (i.e., Duffie et al. 2014), and manufacturing flows and maintenance planning (i.e., Boukas and Yang 1996), these were not widely used or implemented for controlling construction projects due to their complexity and uniqueness per project (Azimi et al. 2012). Therefore, a methodology and related simulation tool are needed for finding the optimal set of mitigation measures that takes the target completion time as a constraint and a set of mitigation measures as decision variables. The objective is then to find the set of mitigation measures that ensures timely completion at the least amount of costs. On this basis, van Gunsteren developed the concept of mitigation planning on the run,

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which was tested on the Olympic village construction project of the 2016 Olympic Games in Brazil (Doughan et al. 2019). The results of their paper show the benefits of finding and ranking the most cost-effective sets of corrective mitigation measures. However, their optimization model and the program structure diagram of the concept of mitigation planning were lacking traceability; i.e., reproducibility and a clear general mathematical description for broader application were missing. Moreover, they also did not include risk events (foreseen risks for $0 < p < 1$) in their model and only considered uncertainties (known variations for $p = 1$). Last but not least, the focus of their facility application (not infrastructure) was on cost optimization rather than on the general modeling error and its implications on the schedule overdesigning, i.e., for both costs and time, we will show that the classical MC approach is too conservative compared to the approach introduced in this paper.

Hence, based on the preceding shortcomings, this paper introduces the mitigation controller (MitC), a tool that automates and optimizes the delay mitigation process in construction projects. The MitC resolves the aforementioned modeling error within classical MC scheduling by reflecting the human control behavior with the mitigation process. This is done by solving an optimization problem within each iteration of the MC simulation. Moreover, the MitC allows including both risk events and uncertainties on planned activities within the simulation, resulting in an even more accurate model. Finally, the MitC returns a combinatory criticality index for objectively selecting the most effective corrective measures. Results show that the MitC outperforms the classical probabilistic MC because it enables selecting the most time-effective and cost-efficient set of control measures while accounting for the human goal-oriented behavior.

The MitC is targeted as a support tool for project managers in construction scheduling and could be integrated into a later stage within state-of-the-art industrial scheduling software packages. It facilitates the decision-making process on timing and selecting effective control measures, resulting in (1) better cost estimation if used during the tender phase of the project and (2) cost reduction if used during the construction phase. The MitC has been translated into an open-access software tool with a friendly user interface (Kammouh et al. 2021). Both the source code of the MitC version 0.1.1 and the software tool can be downloaded (Kammouh et al. 2021).

Finally, it is important to mention that this paper focuses on infrastructural Design, Build, Finance, and Maintain projects. In DBFM contracts, a delay is not permitted because the financial consequences are extremely high as a result of project financing and guaranteed bullet payments being released only at the completion time.

The remaining document is organized as follows. The next section details the underlying assumptions and considerations behind the MitC, and the section "Implementation of the Mitigation Controller" describes the procedure that makes up the MitC. Section "Demonstrative Example" presents an application of the MitC to a real project and discusses the results and the benefits. Finally, the last two sections include conclusions, limitations, and future MitC developments.

Assumptions and Considerations

This section describes and highlights all assumptions and considerations regarding the different building blocks of the MitC.

Duration Uncertainty of Project Activities

The current state of the art in project planning includes both deterministic and probabilistic approaches. The most common deterministic approach is the critical path method (CPM). In the CPM, the deterministic duration of each activity i, $d_i \in \mathbb{N}^+$, is assumed. This value can be considered as the best guess for the duration of the activity, which is derived from past experience of similar projects. However, over or underestimation of the activities' duration leads to either cost underrun or cost overrun. Therefore, accounting for the uncertainty in activities' duration, the total project duration is necessary to minimize the error margin. In probabilistic project planning, the Program Evaluation and Review Technique (PERT) is the most recognized approach that allows the consideration of uncertainty (Meredith et al. 2017; Del Pico 2013). The PERT distribution is a family of continuous probability distributions defined by the minimum (a), most-likely (b), and maximum (c) values that a random variable can take. It is a transformation of the four-parameter beta distribution with the additional assumption that its expected value is

$$\mu = \frac{a + 4b + c}{6} \tag{1}$$

In this paper, the PERT distribution is adopted. A PERT distribution is built for every project activity, with a probability density function $f(d_i; a, b, c)$. It is noted that the duration obtained with the continuous PERT distribution is transformed into the discrete domain. This is done by rounding the duration obtained to the nearest integer.

Capacity Uncertainty of the Corrective Measures

Similarly, mitigation actions also have uncertainty. In deterministic project control, a corrective measure j is assigned a deterministic value $m_j \in \mathbb{N}^+$ that describes its mitigation capacity. This capacity is the amount of time that the mitigated activity is reduced by incorporating such a measure. To account for this uncertainty, the PERT distribution can also be used. Each corrective measure is given three estimates for its mitigation capacity: minimum, most-likely, and maximum. The three-point estimate is used to build a PERT distribution for every corrective measure with a probability density function $f(m_j; a, b, c)$. Similarly, the capacity obtained with the continuous PERT distribution is transformed into the discrete domain.

Mitigation Costs

Mitigating project delays are associated with a cost that is related to the type of the adopted mitigation strategy. Some mitigation strategies include allocating extra personnel to speed up the execution of certain project activities, while others include injecting extra resources to accelerate the process, such as additional equipment. Each of these strategies is associated with a different cost. Thus, the cost of mitigation can be determined by looking at the type of the adopted mitigation strategy.

Ballesteros-Pérez et al. (2019) suggest that the relationship between the activities and cost is not linear. This also applies to the corrective measures. The mitigation cost is not constant and can depend on the variation in the mitigation capacity of the adopted corrective measure. Because the mitigation capacity can vary, the mitigation cost can also vary. For example, if a corrective measure constitutes allocating an extra workforce to finish a task or renting extra vehicles to speed up the process, then the cost depends on the number of days the extra workforce has worked or the vehicles were rented. However, there exist cases in which the cost is not dependent on the mitigation capacity, such as those with a one-time payment (e.g., buying extra vehicles and tools and paying for a license to work extra hours during the day).

Thus, the mitigation cost is uncertain, and its value is correlated with the mitigation type and the uncertainty of the mitigation capacity. Therefore, the variation in the mitigation cost can be estimated by relating to the mitigation capacity variation and mitigation type, as follows

$$c_{j,\min/\max} = c_{j,l}\left(1 - \frac{m_{j,l} - m_{j,\min/\max}}{m_{j,l}}\eta_j\right) \tag{2}$$

where $c_{j,\min/\max} \in \mathbb{R}^+$ = minimum and maximum mitigation costs that correspond respectively to the minimum and maximum mitigating capacities $m_{j,\min/\max} \in \mathbb{N}^+$ of corrective measure j; $c_{j,l} \in \mathbb{R}^+$ = most-likely mitigation cost that is determined according to the type of corrective measure j and corresponds to the most-likely mitigation capacity $m_{j,l} \in \mathbb{N}^+$; and $\eta_j \in \{[0,1]\}$ = factor that defines the relation between the variation of cost and the variation of the mitigated capacity. In the case in which the cost is independent of the capacity of the mitigation, η is set to zero. In this case, the three estimates will be equal. If, on the contrary, the variation of costs is fully dependent on the variation of mitigation capacity, η is set to 1.

Risk Events

Projects in the execution phase are prone to different types of risk events that can cause a sudden and sometimes long suspension to part or all project activities. They can affect project activities, causing a time lag before or during the execution of the activities. Overlooking such risks leads, in most cases, to failure in meeting the project deadline and/or cost overrun.

Let $D_e \in \mathbb{N}$ be a random variable that denotes the duration of disruption caused by a risk event e. This D_e is characterized by two random variables. The first variable, $X = \{0, 1\}$, represents the occurrence (or nonoccurrence) of the risk event; X is a binary random variable with a Bernoulli distribution that takes the value 1 with probability p_e if the risk event e occurs and the value 0 with probability $q_e = 1 - p_e$ if a risk event does not occur. Therefore, the probability mass function of this distribution, over possible outcomes X, is

$$f(X; p_e) = \begin{cases} q_e = 1 - p_e & \text{if } X = 0 \\ p_e & \text{if } X = 1 \end{cases} \tag{3}$$

The second variable, $D_e^* \in \mathbb{N}$ represents the duration of disruption caused by a risk event e given the occurrence of the risk event (i.e., $X = 1$), that is, $D_e^* = D_e|(X = 1)$. Each risk event is assigned a probability distribution function that determines the probability distribution of each delay amount. The distribution family is chosen according to the risk type. For simplicity, the PERT-distribution approach is also adopted for estimating the risk delay. Every risk event is given three estimates for the delay: minimum, most-likely, and maximum, or a, b and c, respectively. A PERT distribution can then be built for every risk event, with a probability density function $f(d_e^*; a, b, c)$.

Therefore, the random variable D_e can be determined by multiplying the two random variables X and D_e^*, which are statistically independent. That is

$$D_e = XD_e^* \tag{4}$$

and the probability density function of the mixed discrete-continuous distribution of D_e can be written as follows

$$f(d_e; p_e, a, b, c) = \begin{cases} 1 - p_e & \text{if } X = 0 \\ f(d_e^*; a, b, c)p_e & \text{if } X = 1 \end{cases} \tag{5}$$

Because the discrete domain is of interest in this study, the value of d_e is discretized, as discussed previously.

Relation between Activities, Corrective Measures, and Risk Events

In typical project control applications, every activity is assigned a possible corrective measure that can be applied to reduce the duration of the activity and, consequently, the duration of the project. Thus, every corrective measure is coupled with a certain activity. In this paper, the notion of mitigation is generalized in an attempt to break the one-to-one coupling between corrective measures and activities. That is, corrective measures are not necessarily linked to a single activity. Every corrective measure can influence one or more activities at the same time. An example of a corrective measure affecting multiple activities is when renting an extra vehicle to accelerate the execution of multiple activities. The relation between the project activities and the corrective measures are given by a relation matrix with components Eq. (6). The relation parameter $r_{i,j}$ takes the value of 1 when corrective measure j intervenes upon activity i, or 0 otherwise

$$[r_{ij}] = \begin{bmatrix} r_{11} & \cdots & r_{1J} \\ \vdots & \ddots & \vdots \\ r_{I1} & \cdots & r_{IJ} \end{bmatrix} \tag{6}$$

where I = total number of activities; and J = total number of corrective measures.

Similarly, every risk event can cause disruption to one or more activities. The relation parameter $r_{i,e}$ takes the value of 1 when risk event e influences activity i, or 0 otherwise. The corresponding relation matrix is expressed as follows

$$[r_{ie}] = \begin{bmatrix} r_{11} & \cdots & r_{1E} \\ \vdots & \ddots & \vdots \\ r_{I1} & \cdots & r_{IE} \end{bmatrix} \tag{7}$$

where E = total number of potential risk events.

Implementation of the Mitigation Controller

In this section, the procedure that makes up the MitC is described. The essence of the introduced MitC is the ability to account for the uncertainties that govern all variables (i.e., durations, delays, and costs) along with the risk events. This is done by using a Monte Carlo approach that relies on repeated random sampling to capture the stochastic behavior of the combined random variables. The next subsection is dedicated to giving a detailed description of the MitC procedure in a structured manner. This is followed by a formalization of the optimization problem, which is the core of the MitC procedure.

Monte Carlo Simulation (MCS)

This section describes the procedure of the Monte Carlo Simulation (MCS) by means of a flowchart diagram. Fig. 1 shows the main flow of the MitC, where the procedure is divided into concise blocks or steps. The flowchart consists of three main bodies. The first body (Steps 1–3) is related to the network data compilation.

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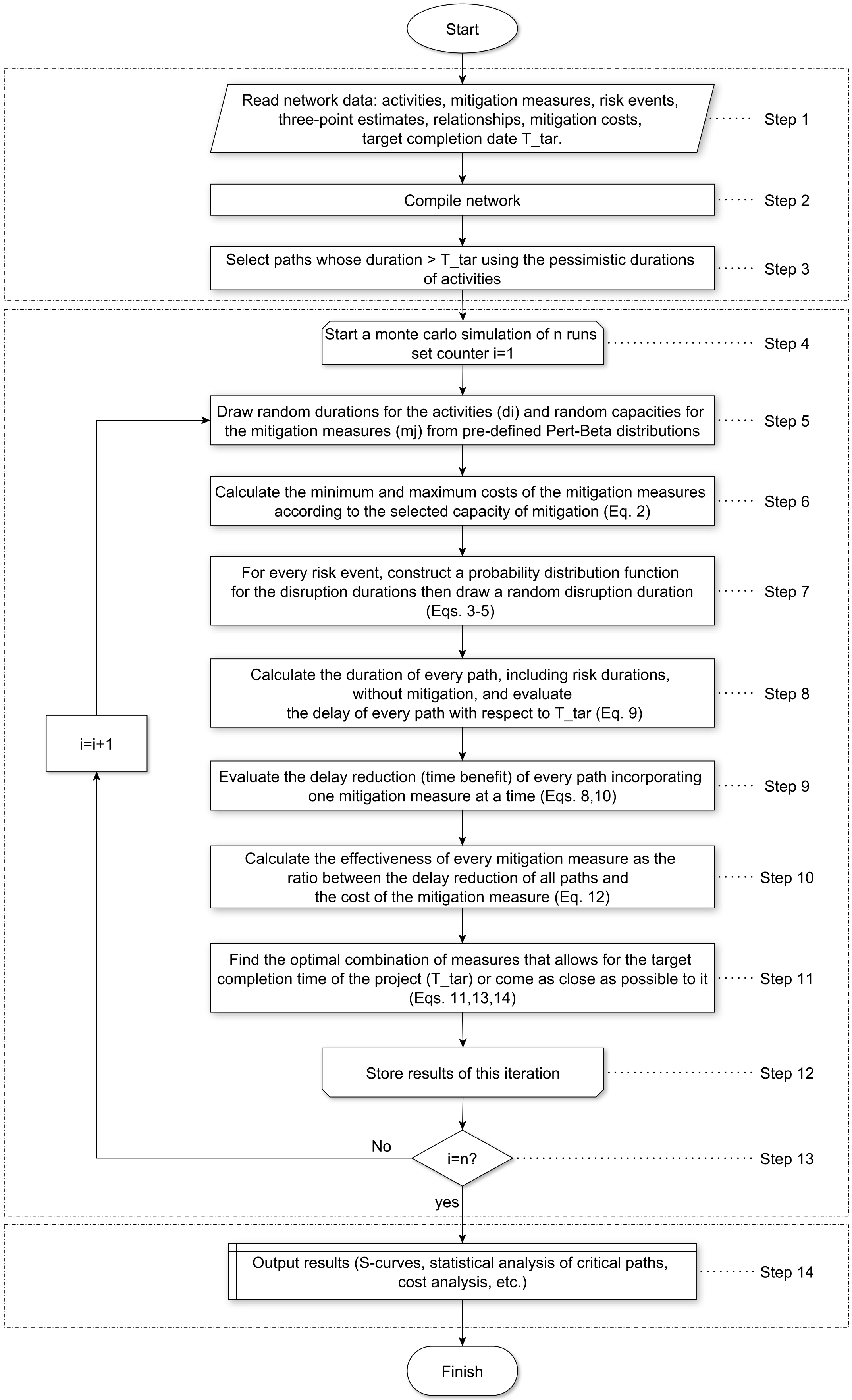

Fig. 1. Flowchart of applying the mitigation controller to a network of activities, incorporating corrective mitigation measures.

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The second body (Steps 4–13) describes the procedure performed in every Monte Carlo iteration, including the optimization problem to obtain the optimum mitigation strategy. In the third body (Step 14), the outputs are collected and analyzed.

In Step 1, the network data is collected and arranged in a machine-readable format. Network data includes the project activities, corrective measures, and risk events, with their corresponding IDs. For every project activity, corrective measure, and risk event, a three-point estimate for the duration, capacity, and disruption duration, respectively, is provided. In addition, the relations between the corrective measures and activity and between the risk events and activities are introduced. For the corrective measures, the most-likely cost of every corrective measure is provided along with the corresponding dependency factor η, which determines to what degree the cost would vary with the variation of the mitigation capacity. For every risk event, the occurrence probability p_e is also needed. Finally, the target completion time of the project T_{tar} is provided. The T_{tar} is the desired project completion duration, which will be pursued by implementing mitigation activities if needed. Therefore, T_{tar} is always equal to or lower than the original completion time of the project T_{org}, which is related to the completion time without mitigation activities. The network is then compiled in Step 2. Network compilation means identifying the project paths with their durations. There are several methods to determine the critical path [see, for instance, the study by Tawanda (2018)]. In this paper, every path is described using a set of activities arranged in chronological order. The duration of the path is thus the summation of the duration of the activities that are on that path, assuming that the activities are of the *finish-to-start* type. For large networks, the number of paths can be large. This can negatively influence the speed of the simulation. Therefore, in Step 3, paths whose *Pessimistic* durations, which are obtained using the *Pessimistic* duration of the individual activities, are less than T_{tar} and are excluded from the analysis. This is justified because these paths will never become critical at any point of the analysis, and so they will not need to be mitigated. By doing so, a smaller set of paths can be obtained. This set is referred to as critical paths subsequently.

In Step 4, the Monte Carlo simulation starts by defining a loop of n iterations and setting the counter i to one. In Step 5, the duration of the activities and the capacities of the corrective measures are randomly drawn from the predefined PERT distributions, which are built using the three-point estimates of activities and corrective measures. In Step 6, using Eq. (2), the minimum and maximum costs of every corrective measure are computed. These costs correspond to the minimum and maximum mitigation capacities. In Step 7, the disruption duration of every risk event is drawn from a predefined distribution, which is constructed using Eqs. (3)–(5). After obtaining a single estimate for the duration of the activities and risk events, the duration of all critical paths is computed (Step 8). The delay of every path with respect to T_{tar} is also computed in Eq. (9). In Step 9, the delay reduction (i.e., time benefit) of every path incorporating one corrective measure at a time is evaluated using Eqs. (8) and (10). This is necessary to distinguish the corrective measures according to their effectiveness, which is computed in Step 10 as the ratio between the delay reduction of all critical paths, obtained in Step 9, and the cost of the corrective measure, using Eq. (12). It is important to note that for a given iteration, the cost of corrective measure, c_j, corresponds to the mitigation capacity, m_j (drawn in Step 5), and is calculated using the trapezoidal linear interpolation method by using the extreme values of mitigation capacities $m_{j,\min/\max}$ and cost $c_{j,\min/\max}$. The optimization problem is carried out in Step 11 using Eqs. (11), (13), and (14), where the optimal combination of measures that allows for the target completion time of the project, T_{tar}, or come as close as possible to it, is obtained. The next section is entirely dedicated to describing the mathematical formulation of the optimization problem. In Step 12, the outputs of the current iteration are stored in the memory. Step 13 is the end of the current simulation iteration, after which the procedure in Steps 5–12 is repeated as long as $i \leq n$. Once the MCS process is completed, the results obtained from every simulation iteration are analyzed in Step 14.

Mathematical Formulation of the Optimization Problem

During the project execution, project managers react to possible delays by applying mitigation measures to reduce the duration of future activities. In the proposed approach, every iteration represents a possible scenario in which the project manager has to react by selecting the optimal mitigation strategy among the existing ones. Thus, by solving an optimization problem within each iteration of the MC simulation, the human factor is modeled. The optimization problem solved at each iteration of MCS aims at selecting the most efficient set of corrective measures that allows for the target completion time of the project. Efficiency in this study is defined in terms of delay reduction with respect to cost. In the case that several sets of corrective measures exhibit the same efficiency, the optimal solution will be the one with the largest time-mitigation capacity. When the existing corrective measures do not allow for the target completion time, the solutions providing the minimum delay will be prioritized.

The optimization problem can be mathematically formalized as follows. Let us assume a set of planned activities $\mathcal{I} = \{1, 2, \ldots, I\}$ that, when combined and connected to one another, yield a set of potential critical paths $\mathcal{K} = \{1, 2, \ldots, K\}$. A potential critical path in this paper is a path whose pessimistic length (i.e., when using the pessimistic durations of the activities) is larger than the target completion time. The relation parameter $p_{k,i}$ takes the value of 1 when activity i is included in the path k, or 0 otherwise. Delays in the planned activities will result in the delay of the duration of the paths with respect to the target completion time of the project, $T_{tar} \in \mathbb{N}^+$. In order to mitigate the individual delay of the activities, a number of corrective measures can be implemented. The set of J existing corrective measures is denoted by $\mathcal{J} = \{1, 2, \ldots, J\}$. The implementation of a mitigation activity j is represented by the variable $x_j \in \{0, 1\}$. It is noted that the duration of multiple paths could be reduced upon implementing just one corrective measure because a single activity can be located on several paths simultaneously.

For each MCS iteration, the corrective measure j is able to mitigate a certain time delay, $m_j \in \mathbb{N}_0$, which has an associated cost, $c_j \in \mathbb{R}^+$. Because the interest in this problem is the mitigation capacity of the measures with respect to the target completion time of the project, the variable time benefit, ΔD_k^j, is introduced as follows

$$\Delta D_k^j = D_k^0 - D_k^j \tag{8}$$

where D_k^0 = delay of the duration of path k with respect to the target completion time of the project, T_{tar}, when no mitigation strategy is implemented; and D_k^j = delay of the duration of path k with respect to T_{tar} when corrective measure j is implemented. Thus, the nonnegative values of D_k^0 and D_k^j are computed as follows

$$D_k^0 = \max\{d_k^0 - T_{tar}, 0\} \tag{9}$$

$$D_k^j = \max\{d_k^j - T_{tar}, 0\} \tag{10}$$

with d_k^0 being the duration of path k when no mitigation strategy is implemented; and d_k^j the duration of path k when corrective measure j is implemented. Fig. 2 depicts the rationale behind the mathematical formulation of the problem. The figure shows the effect of

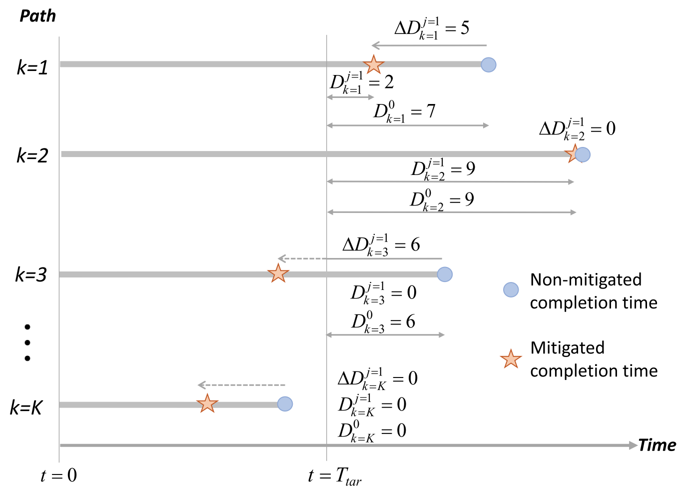

Fig. 2. Rationale behind the mathematical formulation of the problem considering one corrective measure $j = 1$.

implementing one mitigation measure $j = 1$ on the different project paths. A mitigation measure can affect one or more activities, and an activity can be located on one or more paths at the same time. Therefore, a single mitigation measure can reduce the duration of multiple paths simultaneously. There are four cases presented in the figure. The first ($k = 1$) is when both the nonmitigated and the mitigated completion times of the path are greater than the target completion time T_{tar}. The time benefit, in this case, is the difference between the two of them. The second case ($k = 2$) is when the corrective measure does not affect the duration of the path. In this case, there is no time benefit, and so $\Delta D_{k=2}^{j=1} = 0$. In the third case ($k = 3$), the mitigated completion time is less than T_{tar}. The time benefit is computed in this case as the difference between the nonmitigated completion time and T_{tar}; therefore, any benefit beyond the target duration is not considered as a benefit. The fourth case ($k = 4$) is when the path does not have any delay. Although the mitigation measure shortened its duration, it is not considered as a time benefit, and therefore, $\Delta D_{k=4}^{j=1} = 0$. The total time benefit of the mitigation measure can finally be computed as the sum of the four time benefits.

Objective Function

The multiobjective linear optimization explained previously can be expressed as a weighted objective function as follows

$$\min_{X,\Delta} \sum_{j \in \mathcal{J}} \frac{1}{\exp(\mathrm{Eff}_j)} x_j - \delta_1 \sum_{j \in \mathcal{J}} m_j x_j + \delta_2 \Delta \qquad (11)$$

where δ_1 and δ_2 = positive weighting factors; $\Delta \in \mathbb{N}_0$ = delay with respect to the target completion time of the project if the mitigation activities are not enough to guarantee the target completion time; and Eff_j = effectiveness measure of implementing corrective measure j, given by the following expression

$$\mathrm{Eff}_j = \sum_{k=1}^{K} \frac{\Delta D_k^j}{c_j} \qquad (12)$$

The effectiveness measure is used in comparative terms for all the measures analyzed in a given project; thus, if the reduction of either cost or time is more important than the other, this will be consistent for all the measures/activities and allow for a fair comparison and the corresponding optimization between measures.

The first term of the objective function returns the mitigation strategy (i.e., a combination of corrective measures) that reduces the duration of the project to guarantee the target completion time of the project (if possible) while the cost is minimum. The second term is introduced to choose between several optimal strategies, prioritizing the one with the highest duration reduction. Because this criterion is applied only to select between the equally optimal solutions, the weight given by δ_1 should be very small with respect to the first term (e.g., $10^{-8} \times \sum_{j \in \mathcal{J}}[1/\exp(\mathrm{Eff}_j)]$). The third term accounts for the extra time over the target completion time when the mitigation activities are not enough to guarantee the target completion time. This time gap should be as small as possible. Because this objective is of major importance, a large weight, δ_2, is given to this term (e.g., $10^8 \times \sum_{j \in \mathcal{J}}[1/\exp(\mathrm{Eff}_j)]$). In such a way, the search machine will first try to minimize the time gap Δ, giving a zero value in the case the corrective measures are enough to guarantee the target completion time. Secondly, if the corrective measures are not enough to guarantee the target completion time, the algorithm will deliver the most effective combination of measures that brings the project date as close as possible to the target date. In the case of a tie between the effective solutions, by means of the second term, the strategy with the highest time reduction will be picked.

It is noted that the objective function minimizes the inverse of the exponent of the effectiveness rather than the inverse of effectiveness in order to avoid the computational overflow associated with zero values of effectiveness. It is recommended to use a normalized value of the effectiveness (e.g., by normalizing with respect to the largest effectiveness) to reduce numerical problems.

Constraints

The first constraint, Eq. (13), prevents the selection of corrective measures with zero effectiveness

$$\frac{1}{\exp(\mathrm{Eff}_j)} x_j < 1 \quad \forall\ j \in \mathcal{J} \qquad (13)$$

The second constraint, Eq. (14), restricts the duration of every path to be less than or equal to the target duration. In case this cannot be satisfied because of a deficiency of corrective measures (i.e., the available corrective measures are not enough to guarantee the target duration), the constraint is relaxed by adding the time gap Δ

$$d_k^0 - \sum_{j \in \mathcal{J}} \sum_{i \in \mathcal{I}} p_{k,i} r_{i,j} m_j x_j \le T_{tar} + \Delta \quad \forall\ k \in \mathcal{K} \qquad (14)$$

Demonstrative Example

The purpose of this section is to demonstrate the applicability of the MitC in a real-life setting. The proposed MitC procedure is illustrated with an application to a real case of a recent project from the construction industry. One of the coauthors was involved as a director both during the tender and the execution phases of this project. Based on verified and validated project data, the authors adapted these for a demonstrative purpose, i.e., demonstrating the working and usefulness of the mitigation controller results. Therefore, this demonstrative example reflects reality and serves well for the objective of this paper.

The demonstrative example presented in this section can be easily replicated using the software tool previously mentioned.

Project Description

The A1/A6 project is one of the five subprojects for the Dutch highway agency Rijkswaterstaat for upgrading the road network linking Schiphol Airport, Amsterdam, and Almere (SAA) over the years 2010–2020. The total length of the SAA link is 40 km.

The contractor SAAone (with shareholders Hochtief, VolkerWessels, and Boskalis) is responsible for the section from the Diemen intersection to Almere, a distance of approximately 25 km.

The enlargement of the A1/A6 involves the reconstruction and widening of this section of the motorway, including the traffic management systems. The enlargement will also involve the construction of a permanent bypass at the Diemen intersection from the A9 to the A1. SAAone is responsible for the design and construction process of a total of 70 new engineering assets, including the cantilever bridge crossing the Amsterdam-Rhine Canal, the doubling of the Hollandse Brug bridge across the Gooimeer, and the new aqueduct near Muiden, as the most eye-catching features. The aqueduct that takes the River Vecht across 14 lanes is the widest in Europe. The new railroad bridge is the largest within The Netherlands. After the completion of the construction stage in 2017, SAAone will operate the infrastructure for 25 years as part of a so-called Design Build Finance Maintain contract.

In DBFM contracts, a delay is not permitted because the financial consequences are too high (Verweij 2015; Verweij et al. 2020). The basic principle of a DBFM contract is that risks and responsibilities are assigned to the party that can best manage and bear them. Payment to the contractor is made periodically after construction, based on the services provided. The contractor will be paid with a so-called one-off bullet payment only at the completion date. With this, the contractor can repay the loans. If the project would be delayed except for contractual delay/compensation events, an extremely high penalty will be incurred by the contractor. Therefore, the contractor sets a rigorously fixed deadline for themselves. Hence, a delay is not an option for the contractor as it is always going to fall in the nonoptimal solutions.

Finally, it is noted that the planning, costing, and risk figures used in this paper are a congruent representation of the actual figures. However, both from a confidentiality viewpoint and to serve a demonstrative purpose, the figures have been scaled and reduced into a simplified MitC case. It is noted that one of the coauthors was directly involved in this project.

Project Activities and Schedule

The analyzed project is composed of 37 activities. Table 1 lists the project activities in a logical order. The start and finish dates of every activity, as initially planned, are given in the table. Because the MitC works with durations rather than dates, the duration of every activity is calculated in Column 6 of the table as the difference between the finish and start dates, excluding weekends. It is noted that national holidays are not taken into account. The calculated

Table 1. Activities' duration and relationships

ID	Activity description	Planned activity dates		Activity duration (days)			Predecessors
		Start	Finish	Optimistic	Most-likely	Pessimistic	
0	Project	Mon 01/07/13	Wed 11/14/18	—	1,466	—	—
1	Contract date	Mon 01/07/13	Mon 01/07/13	0	0	0	—
2	Financial close	Mon 04/01/13	Mon 04/01/13	0	0	0	—
3	Design	Mon 01/07/13	Fri 07/15/16	865	920	1,040	1
4	Obtaining commencement certificate	Mon 01/07/13	Fri 07/05/13	129	130	164	1
5	Obtainment of commencement certificate	Mon 07/08/13	Mon 07/08/13	0	0	0	4, 2
6	Date of commencement	Mon 09/30/13	Mon 09/30/13	0	0	0	5
7	Maintain existing road assets A9/A1/A6	Mon 09/30/13	Thu 08/30/18	1,194	1,284	1,541	6
8	Conditioning, cables and conducts, permits	Mon 09/30/13	Fri 07/04/14	182	200	256	6
9	Preload	Mon 09/30/13	Fri 04/03/15	363	395	486	6
10	Construction of new aqueduct	Mon 12/23/13	Fri 12/19/14	234	260	325	6
11	Construction of the Amsterdam-Rijn Canal bridge	Mon 12/23/13	Fri 04/03/15	305	335	425	6
12	Road works southern A1 lane	Mon 04/06/15	Wed 09/30/15	120	128	155	9, 10, 11
13	Commissioning of the southern A1 new lane	Mon 10/05/15	Mon 10/05/15	0	0	0	12
14	Producing parts of rail bridge (part 1)	Mon 09/30/13	Mon 09/15/14	241	251	279	6
15	Producing parts of rail bridge (part 2)	Tue 09/16/14	Mon 07/20/15	209	220	279	14
16	Assembling a railway bridge on location	Tue 09/16/14	Fri 04/14/17	667	674	782	14
17	Moving railway bridge in place during train free period	Mon 04/17/17	Mon 04/17/17	0	0	0	16
18	Road works northern A1 lane	Mon 04/17/17	Fri 10/13/17	120	130	147	17
19	Commissioning of the northern A1 new lane	Mon 10/16/17	Mon 10/16/17	0	0	0	18
20	Road and construction works new part junction Diemen	Mon 10/05/15	Fri 10/13/17	519	530	620	13
21	Build new viaducts A6	Mon 12/23/13	Fri 07/03/15	396	400	460	6
22	Build second Hollandse bridge	Mon 03/17/14	Fri 07/03/15	326	340	415	6
23	Road and construction works junction Muiderberg	Mon 12/23/13	Fri 07/14/17	856	930	1,209	6
24	Road works eastern part A6	Mon 07/06/15	Fri 11/20/15	100	100	116	21, 22
25	A6 east ready	Mon 11/23/15	Mon 11/23/15	0	0	0	24
26	Reconstruction western part A6	Mon 11/23/15	Fri 06/02/17	380	400	508	25
27	Commissioning A6	Mon 10/16/17	Mon 10/16/17	0	0	0	18, 23, 26
28	Road works existing part Diemen junction	Mon 10/16/17	Fri 02/16/18	90	90	106	19, 20
29	Request availability certificate	Mon 02/19/18	Mon 02/10/18	0	0	0	28
30	Assess and obtain availability certificate	Mon 02/19/18	Fri 03/16/18	19	20	23	29
31	Demolition old A1 (part 1)	Mon 03/19/18	Mon 06/11/18	57	61	71	30
32	Demolition old A1 (part 2)	Tue 06/12/18	Mon 07/23/18	29	30	35	31
33	Greenery for old A1	Tue 06/12/18	Mon 10/15/18	82	90	107	31
34	Applications and obtaining partial completion certificates	Mon 03/19/18	Fri 08/31/18	119	120	149	30
35	Request completion certificate	Tue 10/16/18	Tue 10/16/18	0	0	0	33
36	Assess and obtain certificate of completion	Wed 10/17/18	Tue 11/13/18	18	20	24	35
37	Scheduled completion time	Wed 11/14/18	Wed 11/14/18	0	0	0	36

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duration represents the most-likely estimate of the duration of the corresponding activity. The optimistic and pessimistic estimates of the durations are also given in Columns 5 and 7, respectively. These values are usually obtained either from experience or from past data of similar projects. The optimistic, most-likely, and pessimistic values of the durations make up the three-point estimates of the activities' durations, which are used to build the PERT distributions $f(d_i; a, b, c)$. The last column introduces the predecessors of every activity using the activities' IDs. For example, Activity 5 follows Activities 2 and 4, while Activity 6 follows Activity 5. The first activity in the table, labeled 0, is not an actual activity but a summary of the project. Using the most-likely duration of each activity, the original project's duration is found to be 1,466 days.

Fig. 3 shows the project plan and its progress over time using a Gantt chart representation generated using Microsoft Project. The relations between the activities are defined with arrows. The durations used to build the Gantt chart are those corresponding to the most-likely estimate. Activities with a dark colored are the critical activities, and the path made by the critical activities is the critical path. The notions of critical activity and critical path are applicable only in deterministic project planning. In probabilistic planning, as shown subsequently, the notion of critical activity and a critical path will be reconsidered.

Description of the Mitigating Measures

In general, corrective measures are retrieved by experienced construction managers using expert knowledge databases. The corrective data used in this example (e.g., corrective measures identification and capacity uncertainty) are those that were identified and used in the project SAA A1/A6 (Table 2). These measures are possible mitigation solutions that can be executed to reduce the duration of the project. In deterministic project planning, the corrective measures become of importance when the project manager anticipates a delay in the project completion date, which could be caused by a delay in any critical activity. In probabilistic planning, corrective measures are performed to increase the probability of finishing the project at a target completion time. The three-point estimates (min, most-likely, and max) of the capacities of the corrective measures are listed in the table. Defining min, most-likely, and max is done in exactly the same way as for the activities durations (i.e., using expert knowledge databases). The three-point estimates of the corrective measures are used to build the PERT distributions $f(m_i; a, b, c)$.

Mitigating the duration of a project comes with financial consequences. Each potential corrective measure is associated with a cost. The most-likely estimate of the cost values are listed in Column 7, and they are the authors' suggestion, while the minimum (min.) and maximum (max.) estimates, listed respectively in Columns 6 and 8, are computed using Eq. (2), where the relation factor η is set to 0.5 for all corrective measures. This implies that a variation in the three estimates of the mitigation capacity has a partial influence on the variation of the three estimates of the cost. The case of partial relation between mitigation costs and mitigation capacities is considered in the example instead of extreme values (i.e., 0 and 1) for verification reasons. The last column in the table gives the relations between the corrective measures and activities. For example, a corrective measure with ID = 2 mitigates the duration of an activity with ID = 4, while a measure with ID = 3 mitigates an activity with ID = 7. The relations are introduced into the model by the relation parameter $r_{i,j}$ in Eq. (6). As discussed previously, a corrective measure can affect multiple activities at the same time. However, in this example, every corrective measure affects the duration of a single activity.

One can argue whether resource limitations would affect the feasibility of the defined measures. The measures are defined in the

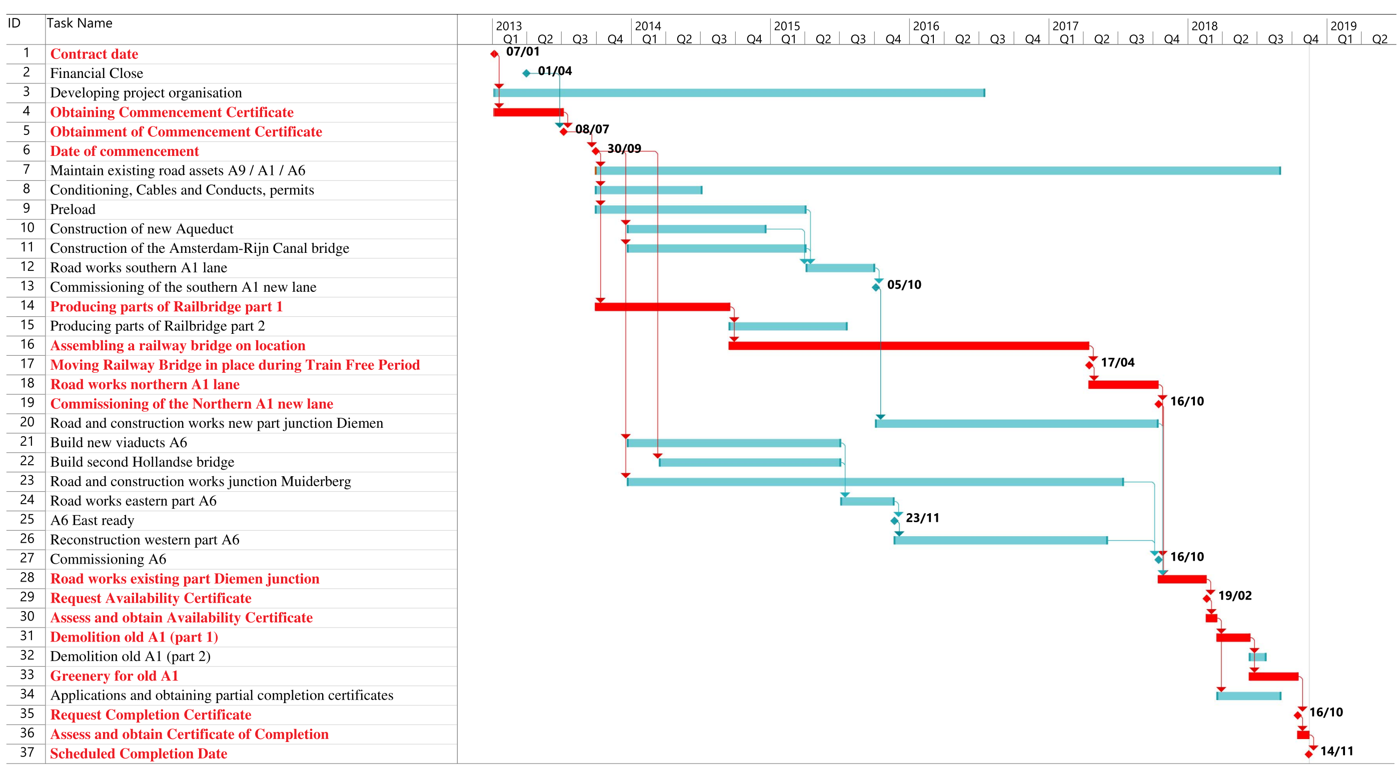

Fig. 3. Gantt chart of the project activities.

Table 2. Corrective measures' durations, relationships, and costs

ID	Mitigation description	Mitigation capacity (days)			Cost (euros) ($\eta = 0.5$)			Relations with activities
		Minimum	Most-likely	Maximum	Minimum	Most-likely	Maximum	
1	Extra engineering design office personnel	51	52	52	118,846	120,000	120,000	3
2	Extra software design capacity	7	7	7	30,000	30,000	30,000	4
3	Extra maintenance engineers	53	65	65	136,154	150,000	150,000	7
4	Extra administrators for permitting	22	26	29	44,308	48,000	50,769	8
5	Applying extra preloading material	21	26	26	677,885	750,000	750,000	9
6	Adding extra onsite construction flow	47	52	55	190,385	200,000	205,769	10
7	Extra prefab construction capacity	60	65	66	144,231	150,000	151,154	11
8	Extra M&E engineers	26	26	26	60,000	60,000	60,000	12
9	Extra welding equipment and personnel	27	33	33	90,909	100,000	100,000	14
10	Extra temporary soil measures	23	26	27	235,577	250,000	254,808	15
11	Ancillary on standby	103	104	114	199,038	200,000	209,615	16
12	Extra M&E engineers	7	7	7	30,000	30,000	30,000	18
13	Extra excavation capacity	49	52	52	121,394	125,000	125,000	20
14	Extra concrete workers/carpenters	42	52	55	67,788	75,000	77,163	21
15	Temporary ancillary construction and rework	36	39	43	1,442,308	1,500,000	1,576,923	22
16	Extra excavation capacity	31	39	42	134,615	150,000	155,769	23
17	Extra asphalt equipment and personnel	52	52	55	200,000	200,000	205,769	26
18	Extra removal works	22	26	27	69,231	75,000	76,442	28
19	Extra equipment and personnel	5	7	8	214,286	250,000	267,857	30

first place by the project manager, who is knowledgeable about the maximum available resources. Project managers are very well capable and aware of the physical and human limitations of construction activities. Therefore, (human) resource limitations are implicitly taken into account in the phase of corrective measures identification. If in the during construction it appears that the feasibility or availability of resources does change, then these specific measures can be taken out of the set of available corrective measures.

Risk Events

Risk events can occur before or during the execution of activities. In the former, the affected activities' start date is delayed, while in the latter, the affected activities are suspended for a duration of time. The amount of delay or activity suspension is a characteristic of the risk event, and in this study, it is referred to as *risk duration*. Risk events are usually hard to predict and hard to control, especially in deterministic project planning in which the variables are estimated using a single value. In probabilistic planning, on the contrary, risk events can be included by considering their occurrence probability.

A list of potential risk events has been identified for the analyzed case (Table 3) with their corresponding three-point duration estimates, which have been reasonably assumed by the authors. For every risk event, an occurrence probability p_e is defined. The probability density function $f(d_e; p_e, a, b, c)$ can be built using the three-point estimate and the occurrence probability of every event,

Table 3. Durations, relationships, and probabilities of the potential risk events

ID	Risk event description	Risk duration (days)			Affected activities	p_e
		Minimum	Most-likely	Maximum		
1	Preliminary design rejection, including extra scope of works	96	105	119	3	0.2
2	EDP audit failure	13	14	15	4	0.05
3	Existing condition Hollandse Brug deviates from maintenance plan made during tender phase	63	70	78	7	0.15
4	Unexpected gas conducts	35	35	41	8	0.2
5	Lower consolidation rate than calculated for	34	35	40	9	0.1
6	Piling machines break down	14	14	15	10	0.1
7	Late delivery of prefab elements	19	21	25	11	0.2
8	Dynamic traffic management equipment/software not functioning	20	21	22	12	0.25
9	Production equipment failure	20	21	23	14	0.05
10	Construction site subsides	13	14	15	15	0.05
11	Ancillary equipment failure	33	35	41	16	0.1
12	Dynamic traffic management equipment/software not functioning	20	21	21	18	0.25
13	Discovery of polluted soil	13	14	14	20	0.05
14	Concrete casting failure	13	14	14	21	0.05
15	Main pillar subsides	65	70	71	22	0.02
16	Discovery of polluted soil	25	28	32	23	0.05
17	Insufficient quality of base layer	39	42	47	26	0.02
18	Discovery of asphalt with too high PAK percentage	13	14	17	28	0.05
19	Additional scope of work (miscellaneous)	130	140	160	30	0.01

using Eqs. (3)–(5). The IDs of the affected activities are listed in Column 6, which are introduced into the model by the relation parameter $r_{i,e}$ in Eq. (7).

Results

Having all input data, the MitC procedure, described in the section "Implementation of the Mitigation Controller," is applied. The linear optimization problem was solved using the optimization package of MATLAB version R2019b on a desktop computer with the following specifications: Windows 10, Intel Core i5-6500 CPU @3.20GHz, and installed memory (RAM) of 8 GB, and the total simulation time was 3 min for a total number of Monte Carlo iterations of $n = 5{,}000$.

Probability of Timely Completion (S-Curves)

The frequency distribution of the 5,000 calculations provides the probability distribution for the duration of the entire project. Fig. 4 presents the cumulative probability curves of the project's completion time for three scenarios. The first scenario (*No Mit*) considers the stochastic durations of the activities without applying any corrective measure. The second scenario (*Permanent*) implies that all mitigation measures are applied within each iteration of the Monte Carlo simulation, regardless of whether they are required. This scenario is too conservative, as it will be shown. Note that the results of this scenario can be obtained by using the common Risk Management Module in Primavera. For verification purposes, we ensured that the MitC output corresponds to the Primavera output. In the third scenario (*Tentative*), corrective measures are only applied when required for meeting the completion time. This is done within every Monte Carlo iteration, and it represents the human goal-oriented scheduling behavior. The results of the *Tentative* scenario can be obtained by applying the optimization problem of MitC in the section "Implementation of the Mitigation Controller." In all three scenarios, the risk events in Table 3 are included. The original completion time of the project T_{org} (i.e., the planned completion date), which is determined using the deterministic duration of the activities, is 1,466 days. The deterministic duration of activities corresponds to the most-likely durations (Table 1).

From the figure, the probability of timely completion of the project without considering any corrective measure is estimated at 0%. The low probability is caused by considering the potential risk events and by including the uncertainty of the activities' durations. To enhance the probability of timely completion, corrective measures are introduced (Table 2). The probability of timely completion rises to around 82% when implementing all available corrective measures in the simulation (*Permanent*). This probability corresponds to the maximum probability of timely completion of the project given the available resources (i.e., the corrective measures).

The S-curves corresponding to *Permanent* and *Tentative* mitigation strategies intersect at the design point with an x-coordinate equivalent to the target completion time T_{tar}; thus, if T_{tar} changes, the design point changes. This design point always coincides with the target completion time. The reason is that in the *Permanent* case, all available mitigation measures are used in the simulation. Therefore, this case maximizes the completion probability of the project at the target duration (and at any other given duration) because all available measures are utilized. On the other hand, the MitC (*Tentative* case) maximizes the completion probability of the project *only* at the target duration by selecting the most effective measures. Therefore, both cases maximize the completion probability of the project at the target duration, and hence, the curves intersect at this point. The difference is that the MitC uses only the most effective measures that achieve this objective and not all available measures.

In this example, T_{tar} is set equal to T_{org}. The MitC implements *enough* corrective measures that maximize the probability of project completion at the target completion time. It always succeeds in bringing up the project completion probability to that as when implementing a *Permanent* mitigation strategy while using only the most effective corrective measures in every MCS iteration.

Cost Analysis

We argued in the "Introduction" section that the classical approach in which all corrective measures are considered simultaneously is overly conservative and is likely to lead to overspending significant amounts of money. This claim can now be supported by looking at the simulation results.

Significant savings could be realized by employing the MitC compared to the scenario in which all corrective measures are performed simultaneously. This is shown in Fig. 5, where the probability of the mitigation cost expressed in terms of probability density function (pdf) (the upper figure) and cumulative distribution function (cdf) (the lower figure) is given for both the *Tentative* and *Permanent* strategies. It is noted that the values on the y-axis of

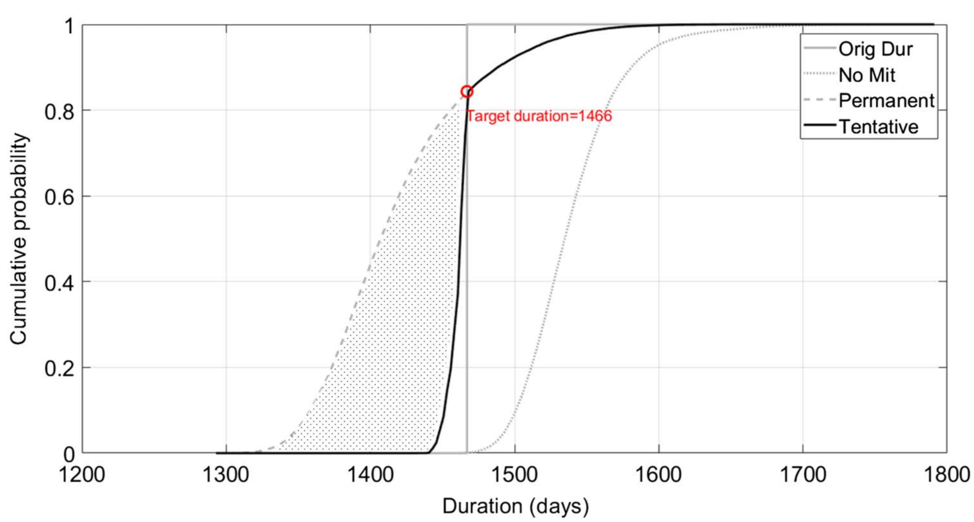

Fig. 4. S-curves produced by the Monte Carlo simulation.

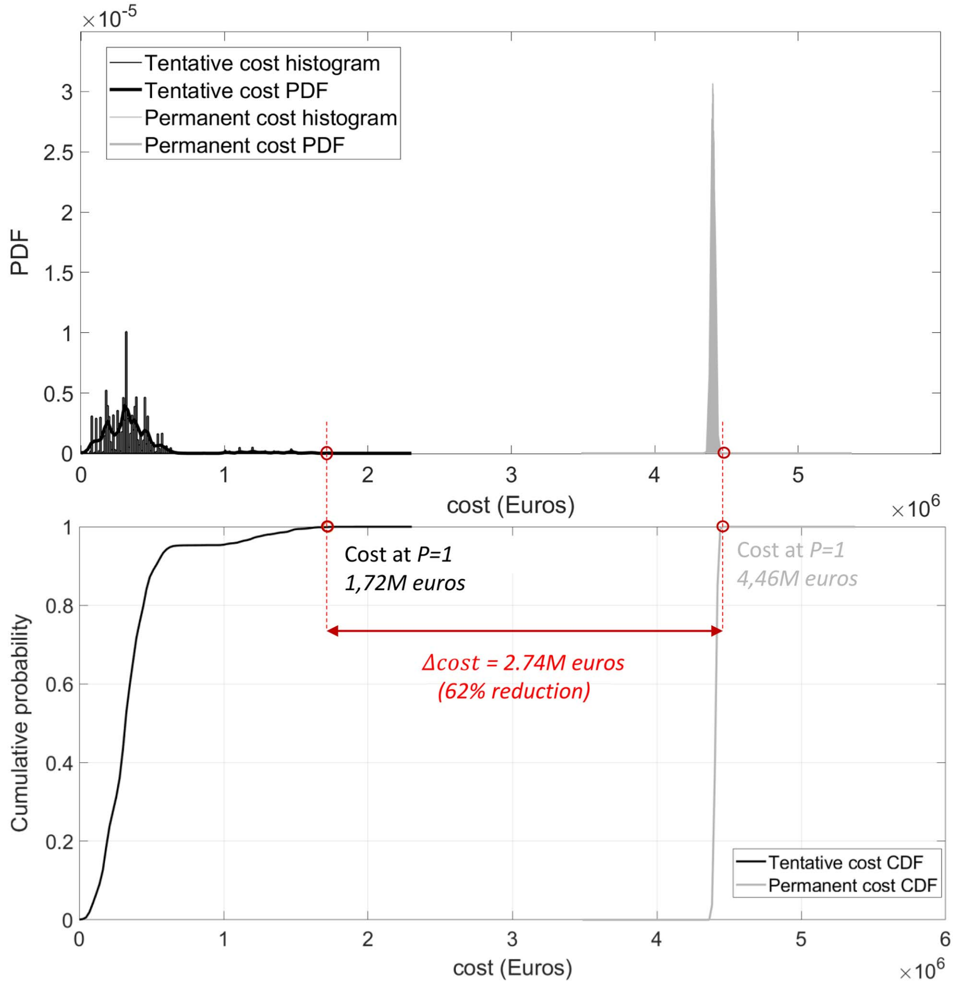

Fig. 5. Cost cumulative distribution produced by the Monte Carlo simulation for the tentative and permanent mitigation strategies.

the cdf figure are not the probability of project completion but instead the probability of incurring a given cost when applying the required optimal strategy identified by the MCS iterations. The variation in the generated mitigation costs is first due to the stochastic variation in the cost of the corrective measures (Table 2) and, most importantly, due to the variation in the chosen (i.e., optimal) mitigation strategy in the *Tentative* scenario.

Fig. 5 compares the highest costs incurred when considering measures as being tentative (approximately EUR 1.72 million) with the highest costs when considering measures as being permanent (approximately EUR 4.46 million). It is noted that this represents a snapshot of the project at its beginning, and adjustments will be made during construction, but this already signifies that the traditional probabilistic approach (*Permanent*) overestimates costs by about EUR 2.74 million (62%). This cost overestimation is the result of the ineffective use of the corrective measures.

In real projects, the manager would not execute all measures at once, but instead, s/he would try different combinations of measures in an iterative, trial-and-error manner to obtain a mitigation strategy that increases the probability of timely completion of the project and, at the same time, falls within the budget. As will be demonstrated subsequently in this example, identifying the most effective corrective measures that lead to the optimal mitigation strategy is not an intuitive process and, thus, difficult to be done manually. Therefore, one can miss out on the opportunity of substantial saving and increased probability of project completion.

Criticality Analysis for Project Activities and Paths

In project management and control, the critical activities are the activities that are typically focused on when it comes to control and mitigation. This is because noncritical activities have a float and, therefore, mitigating them would not have an impact upon the completion time. While it is generally true, it brings us again to the definition of critical activities. In deterministic project management, critical activities are those that are located on the critical path, and their duration is estimated using the most-likely duration. This results in a fixed set of critical activities. In probabilistic project management, on the contrary, the activities are modeled using stochastic durations. As a result, the activity duration can take different values, which are captured by the MCS iterations. The change in activity duration causes a change in the path durations, and hence, the critical path can change. This implies that an activity can be a critical activity in one MCS iteration but not in another. This is clearly shown in Fig. 6 in which the criticality index (CI) of every activity is calculated for the two strategies, *No Mitigation* and *Tentative*. The CI is calculated as the percentage of MCS iterations of every activity is on the critical path. While few activities remain critical in every simulation iteration (e.g., Activity IDs 1, 4, 5, and 6), the majority of activities have a fluctuating critical-noncritical state throughout the MCS. This figure suggests that the focus should not be given only to the critical activities that are identified with a deterministic analysis as this could result in potentially inaccurate decisions. It also suggests that activities with $CI = 0$

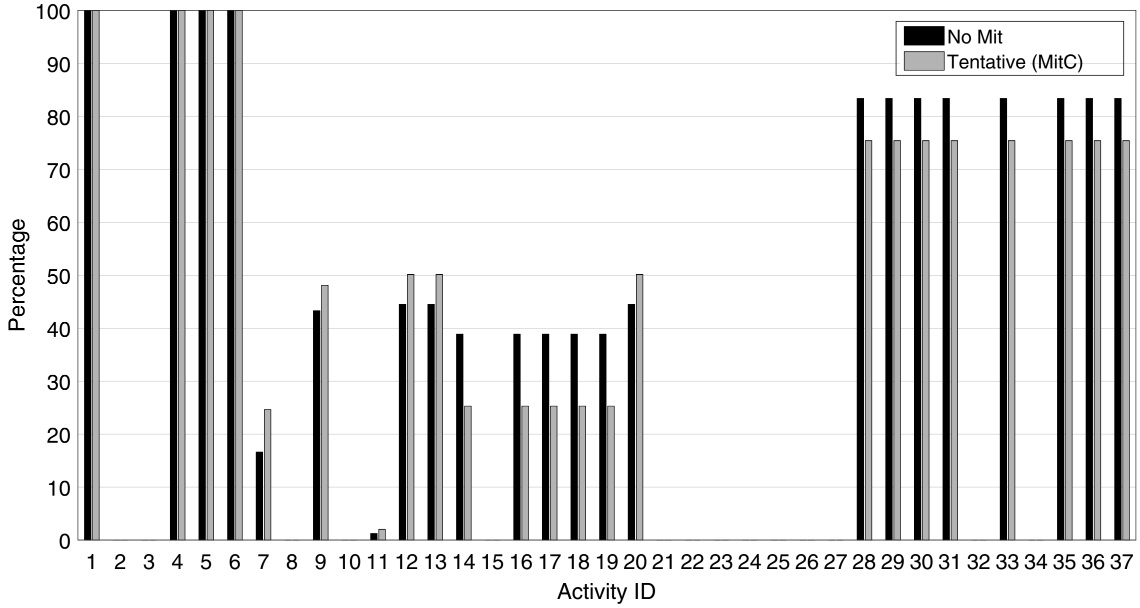

Fig. 6. Critically index of the activities: percentage of MCS iterations in which every activity is on the critical path.

should not be included in any control strategy because investing in those activities will *most-likely* bring no positive consequences to the project delivery date. In summary, the activities should be given importance according to their criticality indexes that are calculated using a probabilistic analysis. Following a deterministic analysis to evaluate the critical indexes of the activities is misleading in most cases.

To elaborate more on this, Fig. 7 classifies the activities into three ranges of importance: not critical ($CI = 0\% - 40\%$), critical ($CI = 40\% - 70\%$), and very critical ($CI = 70\% - 100\%$), using the output results of *Tentative* and *No Mit* cases in Fig. 6. In the list of activity descriptions, activities with dark colored are those that have been identified as critical following a deterministic analysis. From the figure, it can be seen that the critical activities that are identified in a deterministic analysis are not necessarily the most critical following the probabilistic analysis. For example, activities with IDs 14 and 16–19 are among the least critical activities according to the probabilistic analysis, while they are originally identified as critical activities following a deterministic analysis. This highlights the modeling error when adopting a deterministic analysis in project management.

One can argue that the criticality of activity is also a function of the activity's impact on the schedule. For example, an activity could be identified as very critical (i.e., with a high percentage of being on a critical path), but its effect, if delayed, would be very insignificant on the project completion time. Another factor that could influence the criticality of an activity is the activity's closeness to the end of the project. Activities that are close to the end of the project provide little opportunities for mitigation because there is a short time to act if these activities are delayed. Given the preceding, a composite criticality index for every activity could be built considering the additional two factors discussed.

Similarly, Fig. 8 shows the criticality index of every path in the network. Results show that Paths 2, 5, 11, and 15 are the only four paths with $CI > 0$. Interestingly, the path that was originally thought to be the critical path is Path 15. Following the probabilistic analysis performed, Path 15 is not the path with the highest CI. Thus, focusing on Path 15 would lead to ignoring a more critical path (i.e., Path 5).

Criticality Analysis for the Corrective Measures

It is important to note that the effective corrective measures are not always the same in all the MCS iterations. In every MCS iteration, a combination of corrective measures is derived. The combination of corrective measures can change from one iteration to another. To identify the most critical corrective measures, they are classified according to their criticality index (Fig. 9). The CI of a corrective measure is the percentage of MCS iterations in which measure is included in the optimal mitigation strategy. For this, the number of times every corrective is used in a mitigation strategy is tracked. As can be seen in the figure, none of the corrective measures is used in every MCS iteration. There are also several measures that have not been used at all in the MCS (e.g., IDs 1, 4, 6, 10, 14, 15, 16, and 17) and some that were used in an insignificant amount of iterations (e.g., 7 and 12). Interestingly, the corrective measure with ID = 12 is used very little, although it affects the activity with ID = 18, which is deemed as critical in the deterministic analysis (Fig. 3). On the other hand, there are some corrective measures that are used in a large number of MCS iterations, although they affect the deterministically defined noncritical activities (e.g., corrective measures 3, 8, and 13 that affect the noncritical activities 7, 12, and 20, respectively).

The results presented in Fig. 9 emphasizes the modeling error involved when performing a deterministic analysis. In a deterministic analysis, the critical activities are first identified, then corrective measures to crash these activities are implemented. If the critical activities are identified through a simplification of the real activities' performance (neglecting the associated uncertainty), it is likely that the achievement of the completion time will be attained through a nonoptimal iterative process of mitigating the deterministic critical paths identified throughout the project execution. This is obviously not the case when considering the uncertainty in the activities' durations, mitigation capacities, and risk occurrence. The results also suggest that some corrective measures can be excluded from the list of potential corrective measures (i.e., those that are not used or used very little), and some corrective measures should be seriously considered even if they do not affect the critical activities identified under a deterministic approach. It should be noted that one cannot just choose the most critical corrective measure from the

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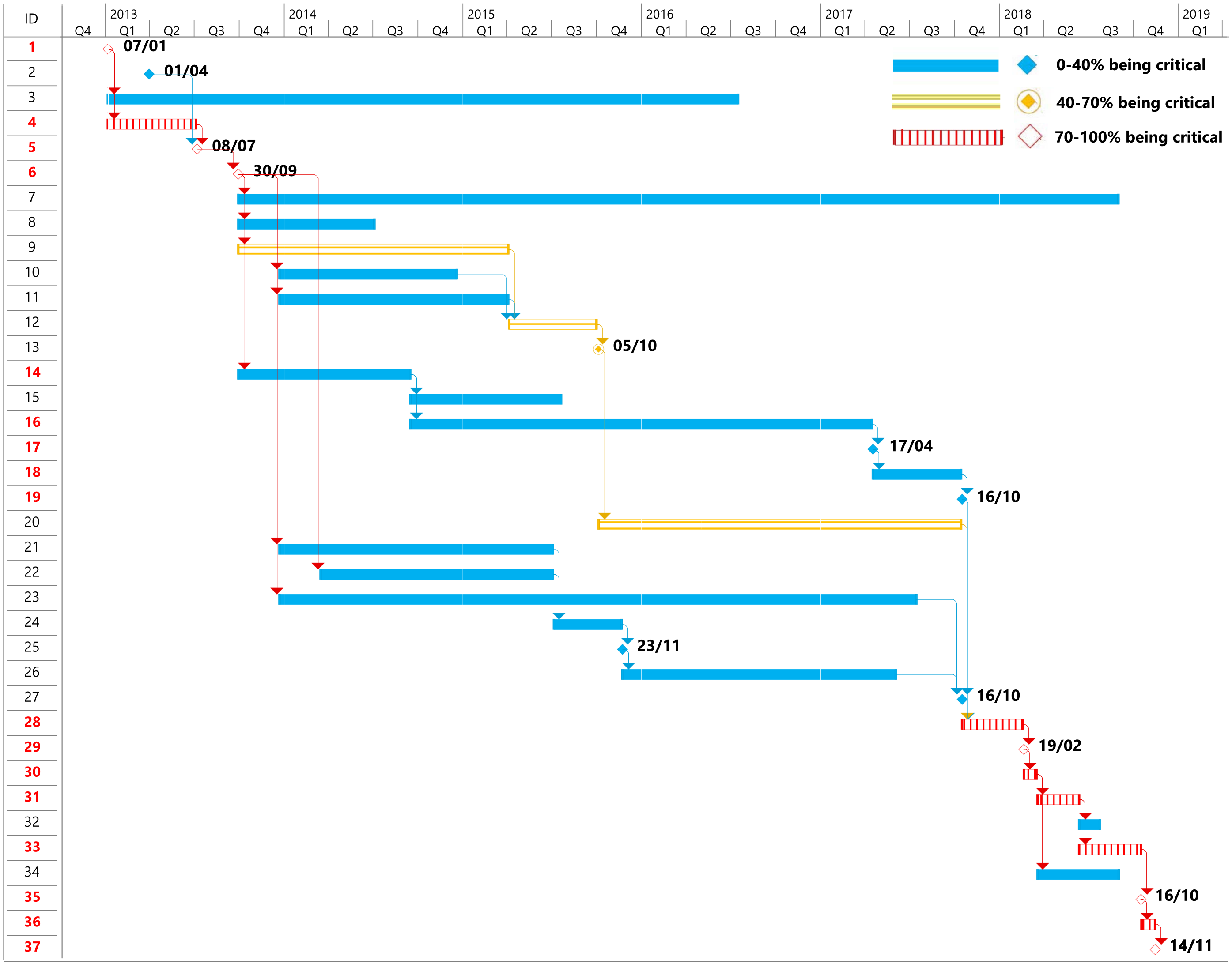

Fig. 7. Gantt chart of the project activities with activities divided according to their criticality index.

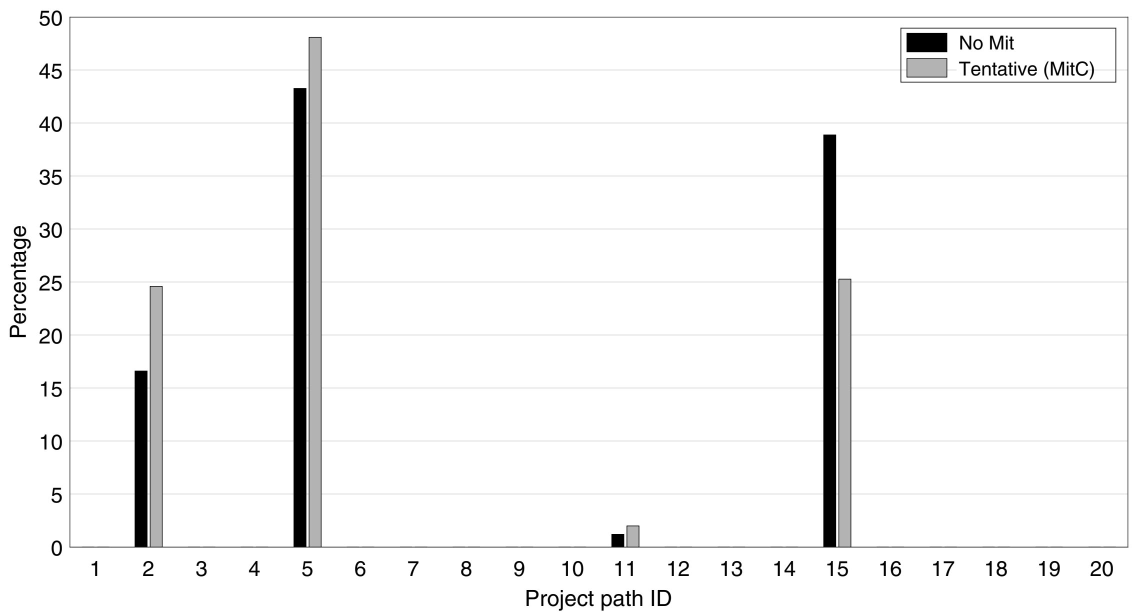

Fig. 8. Criticality index of the project paths: percentage of MCS iterations in which every path was a critical path.

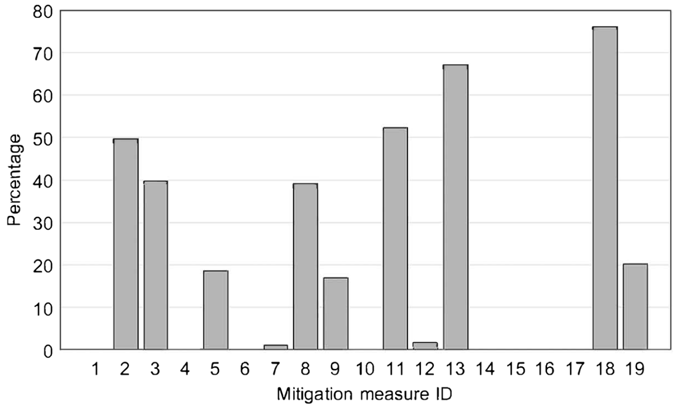

Fig. 9. Criticality index of the corrective measures: percentage of MCS iterations in which every measure is included in the tentative (optimal) mitigation strategy.

bar chart and apply it as a single permanent solution for the project. Although it is the most critical, its effect is only activated when combined with other corrective measures, forming a mitigation strategy. The project manager can choose a set of corrective measures sorted according to their criticality index, in descending order, and implement them as a permanent mitigation strategy. For example, the project manager can decide to implement the first four most critical corrective measures as a permanent strategy. The probability of timely completion of the project should then be verified by performing a simulation in which the first four correctives measures are considered permanent. The manager can then decide to add the next corrective measure on the list if s/he is not satisfied with the probability of timely completion. This aspect should be an object of further investigation.

Further Enhancement of the MitC

In this section, the limitations and the future improvements of the MitC are summarized as follows:

- Risks and uncertainties related to mitigation measures are currently defined using a PERT distribution, which is the simplest distribution for explanatory purposes. Further MitC developments will enable the use of different distributions so that a user will be able to model risks and uncertainties based on real historical data.
- The activities of the project and the corrective measures are assumed independent from one another. This assumption may impact the simulation results; therefore, correlations will be introduced among the future steps.
- In projects other than DBFM, it is very common to penalize the late completion of construction projects; yet, some sponsors are willing to reward early completion. Considering penalty and reward could result in an optimal mitigation strategy that does not necessarily allow achieving the target completion time because the design variable would be the cost rather than the completion time.
- The MitC will also be of use for construction projects with other types of time constraints or fixed intermediate moment and/or slots. For example, possession-based construction projects such as railway works are driven by a number of fixed time slots in which the activities have to be executed. The process of applying for permits is an example in which the network for a particular part (procedure) can proceed along alternative paths. The permit procedure could, for instance, take less time if there is little opposition or take longer if the opposite holds. Modeling these types of procedures is also a step forward toward refining the MitC.
- Resource limitation can affect the feasibility of implementing corrective measures. The MitC will formally include resource constraints in the optimization problem.

Finally, we are looking into the application of control concepts to budgeting problems as the application of the probability theory for maintaining a set budget can also benefit from adding human control behavior to these simulation models.

Conclusions of the MitC

This paper introduced the mitigation controller, a methodology, and a simulation tool for finding the optimal set of mitigation measures that takes the target completion time as a constraint and a set of mitigation measures as decision variables. The MitC maximizes the timely completion probability of a project while keeping the cost overrun to a minimum. The MitC incorporates both risk events and uncertainties in planned activities.

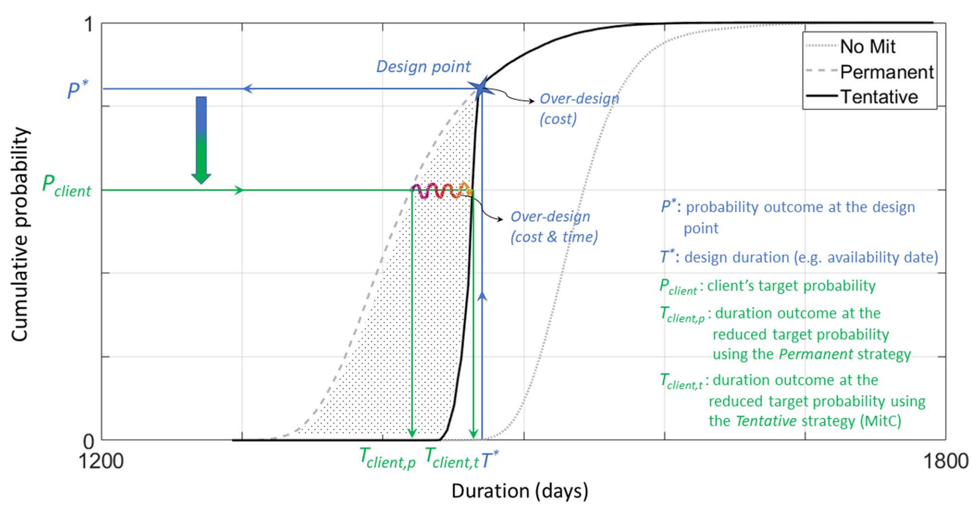

Fig. 10. S-curves produced by the Monte Carlo simulation showing the cost and time overdesign produced by the classical modeling approach (permanent) with respect to the MitC (tentative).

The resulting S-curves showing the probability of project target completion time generated by the tool are crucial for making effective managerial decisions. The MitC can act as an early-warning system for the manager allowing him/her to take prompt and effective corrective actions. In addition, the MitC provides a criticality index for every mitigation measure. This is a crucial output that cannot be obtained without the MitC. It provides information to project managers on which measures are the most important so that they can first implement them.

The MitC also allows for another important type of managerial decision-making on the run. Fig. 10 shows that the probability P^* of meeting the availability date T^* is higher than that required by the client, P_{client}. From this, it is concluded that there is overdesign as there is a gap between P^* and P_{client}. In this case, the overdesign indicates the overspending of money. Considering only the probability required by the client P_{client}, the figure shows that there are actually two types of overdesign associated with the permanent curve (following the classical MC approach) compared to the tentative curve, and this means overdesign in cost and time. The time overdesign is equivalent to the difference between $T_{\text{client},p}$ and $T_{\text{client},t}$, which correspond to the permanent and tentative strategies, respectively. Two options are then available from a managerial perspective; the first option is to implement the permanent strategy, while the second is to implement the tentative strategy. While both options guarantee the required P_{client}, the first still results in an increased cost as well as an unnecessary early completion time, $T_{\text{client},p}$.

This paper also highlighted another fundamental error related to the classical definition of the critical path and critical activities. Results showed that the critical path that is calculated using a deterministic approach was critical in less than 40% of the total MC scheduling iterations. This means that when using deterministic planning, we are then focusing our attention and resources only on activities on the classical critical path and ignoring paths that are of near-equal importance.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available in a repository online in accordance with funder data retention policies. The repository is located here: https://github.com/mitigation-controller/mitc.

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