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# Multi-objective optimization model for urban road maintenance planning using BIM, GIS, and DCE

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**Abstract:** Urban road maintenance creates potential risks for both road users and workers in addition to traffic congestion and delays. The adverse effects of maintenance work could be minimized through mitigation measures of work zone layout and construction arrangement, such as reducing the dimension of work zone segments and scheduling construction during low-traffic periods. However, these measures inevitably escalate construction costs. Consequently, decision-making in urban road maintenance necessitates a balance among multiple strategic objectives to facilitate optimal development via a comprehensive road maintenance management system. This study aims to propose an integrated framework to accomplish the multiple and conflicting objectives for maximizing safety and mobility while minimizing construction costs by optimizing the work zone layout and construction sequence dynamically. The framework enables the seamless information exchange among building information modeling (BIM), geographic information system (GIS), and domain-specific computational engines (DCE), which perform interdisciplinary assessments and visualization. Subsequently, a genetic algorithm is employed to determine the optimal plan considering multiple objectives due to its versatility in resolving highly complex conflict problems.
**Key words:** Urban road maintenance, building information modeling (BIM), geographic information system (GIS), micro traffic flow simulation, domain-specific computational engines (DCE), multi-objective optimization

## 1. INTRODUCTION

As many road networks have been operated for a long time, road rehabilitation activities are gradually recognized as a vital part of infrastructure management. Without adequately maintaining and rehabilitating the deteriorated road networks, the design life and road service quality become generally infected [1]. It is significant to develop a road rehabilitation plan that preserves the value of road infrastructure after the rehabilitation while minimizing rehabilitation costs, traffic disturbance, and adverse safety impacts during the rehabilitation. On an urban road, the traffic stream behavior is mainly regulated by traffic signals, in addition to vehicle–vehicle interactions and vehicle–roadway interactions, which differ from place to place. Customized microscopic traffic models of each segment are often used to measure the possible impacts on the interrupted traffic flow considering vehicular traffic dynamics [2] of each work segment and corresponding strategy.

The essence of planning and assessing road rehabilitation projects includes safety, mobility, and efficiency. The safety of rehabilitation projects can be defined as maximizing the drive and construction security simultaneously. Mobility aims to ensure the accessibility and bearing capability of affected carriageways under maintenance whereas the efficiency of urban road rehabilitation projects is defined as facilitating the practicality of construction and minimizing project delays, changes, and budgets while also maximizing productivity, quality, and convenience [3]. The value of costs is usually used as an evaluation metric of rehabilitation efficiency. However, as these objectives are interrelated, urban road rehabilitation planning is complicated. For instance, the maintenance work zone segment is conventionally determined based on the construction schedule related to efficiency. However, the results of work zone dimensions further impact the safety level and mobility simultaneously. Furthermore, objectives are decided by massive decision variables, which need to be addressed iteratively, including traffic simulation characteristics, work zone design, and temporary traffic control strategies. The adjustment of one aspect would affect the performance of the others. To ensure the mobility and safety of an urban road rehabilitation plan, developers need to segment the overall maintenance area into smaller pieces to balance the requirements of traffic and construction. Larger segment dimensions necessitate fewer mobilizations and demobilizations of equipment, thereby reducing the maintenance duration and overall costs. However, the overlarge work zone significantly impedes microscopic mobility. Meanwhile, establishing temporary traffic control (TTC) zones for each maintenance segment helps guide vehicles and creates a buffer around the construction site, ensuring the safety of both workers and users. Similar to segmenting design, the TTC zone design is closely tied to the traffic performance of urban road networks. A safer TTC zone usually means more delays and queueing of traffic flow.

To optimize work zone planning of urban road rehabilitation, including work zone segmenting, scheduling, and construction sequencing, information such as work zone planning, temporary traffic control strategy, microscopic traffic simulation, safety evaluation, and cost estimations is required. Specifically, a data model for urban road rehabilitation has been developed to represent all information required during the condition assessment and planning process. This proposed data model serves as a reference for extending IFC and CityGML, contributing to the integration of domain-specific computational engines (DCE), building information modeling (BIM), and geographic information system (GIS) by mapping the extended IFC and CityGML. An integrated and formalized urban road rehabilitation framework has been established, supporting automatic alternative generation and comprehensive performance evaluation while facilitating the decision-making process. Therefore, this study integrated BIM, GIS, and DCE to provide sufficient information for the multiple optimization objectives. Heuristic algorithms are implemented to optimize the design of the work zone dimension, schedule, construction sequence, and TTC strategy to balance requirements related to safety, mobility, and costs.

The rest of this paper is outlined as follows. Section 2 reviews related work on work zone planning optimization that has been previously conducted. A BIM–GIS–DCE-based integrated framework for optimizing work zone planning is proposed in Section 3. The details of optimization rationale and operation are illustrated in Section 4. Section 5 discusses the results and concludes the study by offering limitations and suggestions for future work.

## 2. LITERATURE REVIEW

### 2.1. Existing road maintenance work zone planning problems

The first interdependent consideration in urban road rehabilitation planning is the formation of TTC strategies, which are used to provide continuity of movement for motor vehicles as well as keep a safe distance between traffic flow and the work zone to avoid accidents [4]. As illustrated by [5] and [6], the dimensions of TTC zone and different TTC measures influence the odds of common human errors causing crashes, the severity of work zone crashes, and compliance with speed limitations. Typically, the field crews design appropriate TTC plans for respective activities relayed in field handbooks, engineering judgments, and their own experience [7]. The existing impacts evaluation of a TTC plan has mainly focused on providing traffic and worker safety in development, and it is incomprehensive in empirical cases.

The consideration of mobility aspects in urban road rehabilitation projects has increasingly attracted attention. Lane closures on carriageways generated by TTC strategies exacerbate traffic queuing and delays, and the speed associated with congestion contributes disproportionately and non-linearly to roadway emissions produced throughout the lifetime of the roadway [8]. In addition to the effect of micro-traffic from individual TTC zones, the TTC strategy impacts the macro-traffic scenario. For instance, a rehabilitation lane closure on a specific carriageway may use a TTC strategy that helps maintain and manage transportation through that maintenance work zone. Nevertheless, if that road is the designated detour route for a large construction project, terminating a lane on the detour can decrease its traffic-carrying capacity, leading to congestion and delays for traffic diverting from the mainline of the large construction project [9]. An appropriate urban road rehabilitation strategy is supposed to generate the optimal trade-offs among construction safety, traffic disturbance, and cost. Because of the intricate interdependences between various aspects in urban road rehabilitation planning, the impacts of rehabilitation activities need to be addressed from the overall system management perspective in addition to the individual activity perspective. Determining an optimal urban road rehabilitation strategy during the planning process is constrained by multiple objectives, and various decision support variables constrain each goal. Thus, the planning of urban road rehabilitation demands the use of a tremendous amount of information for impact assessment from several aspects.

### 2.2. BIM–GIS–DCE application

The BIM and GIS approaches have shown notable benefits in road rehabilitation projects' information management and integration. BIM and GIS platforms can assimilate a parametric representation of the physical and functional properties of an individual entity or corresponding ambient environment. BIM and GIS have respective advantages, and a number of studies have focused on combining the vital points to support the management and planning of infrastructure projects [10]. For example, [11] proposed an integrated system including road construction data from the BIM database and topographic information from GIS to perform a cut-and-fill operation-balancing analysis to decrease the earthwork. For the operation and maintenance of an underground infrastructure, [12] developed a visualized system to connect the BIM model of a mechanical electrical and plumbing (MEP) system and surrounding subsurface pipeline network from GIS databases. The integrated system is also used in energy simulation for green building design [13], flooding damage assessment [14], supply chain management [15], traffic noise evaluation [16], etc. The application of BIM and GIS integration during the planning as well as operation and maintenance stages indicates the potential for road rehabilitation. Nevertheless, to the authors' knowledge, few studies fully support the integration of BIM and GIS regarding urban road rehabilitation planning, thereby revealing the importance and necessity of this study.

Neither BIM nor GIS can carry out crucial traffic analyses as the traffic simulation and analysis require specialized simulation, extensive calculations, and tedious information processing, which are incompatible with existing BIM or GIS platforms [17]. Several DCEs have been used to simulate transportation performance in road rehabilitation projects, including Vissim, TSIS, AIMSUM, Paramics, and TransModeler [18], [19]. These DCEs can provide in-depth ex-ante and ex-post analyses on transportation performance variation to benefit comparison and planning efforts. Therefore, an integrated BIM–GIS–DCE system can support the planning of urban road rehabilitation, which accommodates comprehensive information and provides solid analytical capabilities for various interdependent aspects. The BIM is a suitable tool to represent relevant parametric information on infrastructure assets, such as the representation of a temporary traffic control zone on urban road networks under maintenance. The specific DCE supports the microscopic traffic flow simulation considering the effects of TTC zones. Furthermore, GIS serves well to store and analyze the ambient environment's geospatial data. Ultimately, integrating BIM, GIS, and DCE could provide an interoperable platform for the rapid and consistent generation and assessment of multiple alternative plans.

### 2.3. Optimization among multiple objectives

A number of studies have analyzed the impacts of various work zone layout parameters on mobility, safety, and cost. For instance, the impact of work zone dimensions on construction was analyzed by [20]. Yet a comprehensive data model for urban road rehabilitation planning is needed to represent the unified information considered in performance assessment and alternative plan generation. The information required for impact assessment is discerned through a literature review in the early stages of data model development. For urban road rehabilitation planning, mobility, cost, and safety are three of the most concerning objectives in impact assessment [21]. Considering the interrupted traffic in urban areas, a mobility impact assessment is a process of tracking microscopic traffic flows under maintenance activities disruption [22]. The mainstream indicator of rehabilitation-related aspects assessment is expenditures, consisting of road user costs and agency costs [23]. Subsequently, safety performance is evaluated by considering crash modification factors (CMFs) [24], which estimate the crash risk resulting from multiple treatments, and the surrogate safety assessment model (SSAM) [25], which identifies conflicts and possible crashes based on vehicle trajectory data. Furthermore, rehabilitation decision variables that affect mobility, cost, and safety are identified through a comprehensive literature review. The workspace segment dimension[25], construction schedule [26], and temporary traffic control strategy [27] are included in this research as well. Several studies have optimized work zone planning from different aspects. For example, [28] used a genetic algorithm to determine cost and traffic delays. In addition, [22] considered the performance of safety, mobility, and project cost. However, these studies do not provide an integrated framework for the tailed performance evaluation of each work zone design or optimize multiple objectives at the same time.

## 3. DEVELOPMENT OF PROPOSED FRAMEWORK

### 3.1. Information representation

Having conducted the background investigation and literature review, the urban road rehabilitation planning framework is proposed based on the necessary information integration of BIM and GIS through the data-mapping model of IFC and CityGML. This framework supports analyses of interactions between transportation and rehabilitation with a formal modeling paradigm of BIM, GIS, and DCEs. The integrated framework mainly contains (1) a data model developed concerning the information involved and required in every respect of urban road rehabilitation planning, (2) the extension of the existing BIM and GIS mainstream standards (i.e., IFC and CityGML), and (3) an integrated BIM–GIS–DCE modeling paradigm, which facilitates the automatic comparison of various planning alternatives. As a result, the integrated planning framework can accommodate a seamless information exchange while allowing for solid analytical capabilities in urban road rehabilitation planning.

### 3.2. Integrated framework development

Regarding the proposed data model, the extension of both IFC entities and the ADE incorporates geometric and semantic information. Cooperative information facilitates the integration of BIM, GIS, and DCEs and development of a modeling paradigm. Hence, the selected platforms and computational engines in the modeling paradigm are expected to provide not only comprehensive information for urban road rehabilitation, but also planning capabilities for decision-making and management. The modeling paradigm consists of BIM, GIS, and DCE. With rich geometric and semantic information, BIM is the most suitable tool for model creation and editing and can provide details from the individual component perspective (e.g., TTC zone, rehabilitation schedule). The functional performance of the transportation system can be simulated through a specific DCE (e.g., PTV Vissim), and the DCE could offer in-depth ex-ante and ex-post analyses through iterative microscopic transportation simulation among disrupted road networks. Furthermore, GIS can store, analyze, manage, and visualize infrastructure asset geometrical and functional attributes in a global coordinate system. Therefore, the BIM, GIS, and DCE paradigms can be integrated into the unified process to accommodate diverse information and guarantee automatic information exchange and alternative comparisons. More details about the modeling paradigm development are illustrated in Figure 1.

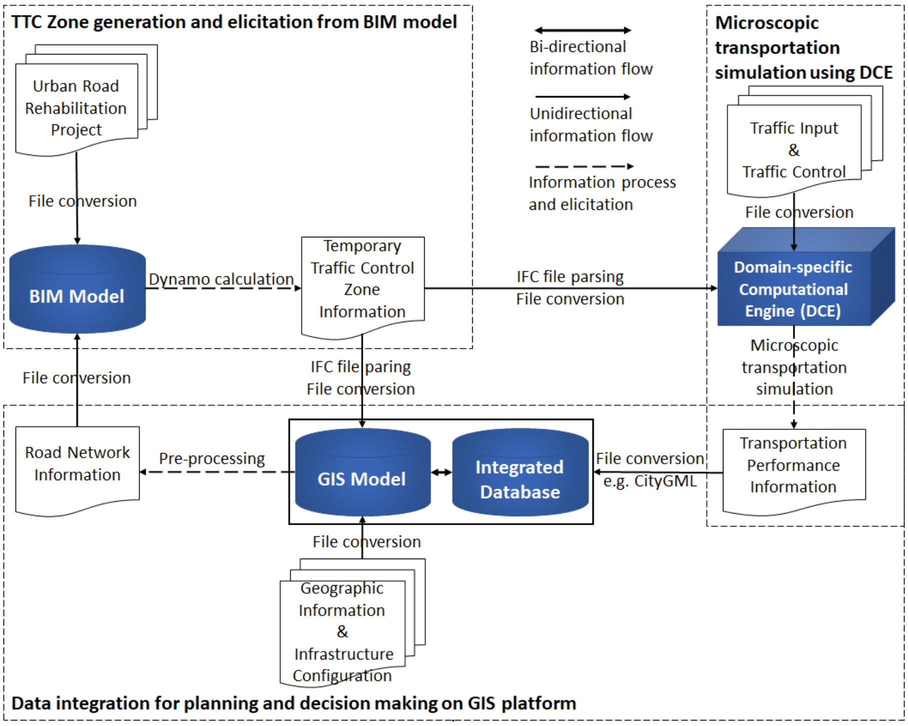

**Figure 1.** Integrated BIM–GIS–DCE modeling paradigm for urban road rehabilitation planning

## 4. WORK ZONE PLANNING OPTIMIZATION

After the development of an integrated planning and assessment framework, this stage focuses on formulating a novel model capable of optimizing all relevant work zone decision variables to identify and generate optimal trade-offs among maximizing mobility, maximizing safety, and minimizing the total cost. The formulation stage is accomplished in four sections: (1) identifying assumptions for optimization, (2) identifying all relevant work zone decision variables, (3) representing practical constraints, and (4) modeling and assessing objective functions through the proposed framework.

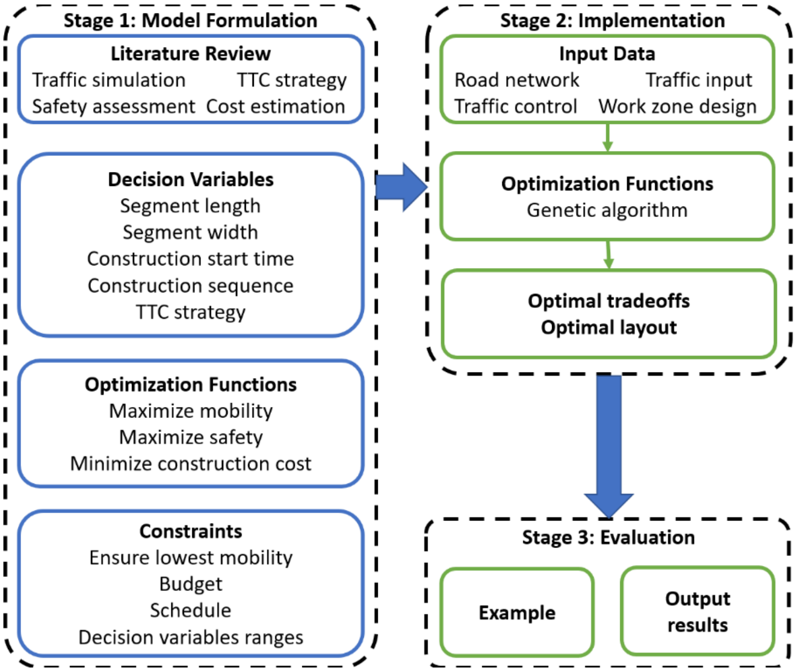

**Figure 2.** Optimization of modeling development phases

### 4.1. Assumptions

During the generation of a possible urban road maintenance work zone plan, the following assumptions must be taken into account:

1. The total cost for maintaining a zone of length is a linear function, which includes the fixed cost, independent of work zone length, and the cost of setting up the work for one zone, including traffic control setup and maintenance equipment setup.
2. The time required to complete the maintenance for a one-lane zone of length is a linear function, which includes the fixed setup time and the additional time required per work zone kilometer.
3. The construction speed remains stable.
4. Crash rate represents the safety performance, and it is calculated based on decision variables.
5. Delay represents the mobility performance and is calculated through a microscopic traffic simulation using PTV Vissim. Traffic input follows a Poisson distribution.
6. The traffic volumes in both directions are given. In practice, an equilibrium demand analysis that considers alternate routes and departure times may be needed to estimate traffic volume through work zones.
7. The temporary traffic control zone includes an advance warning section, lead-in taper, construction section, exit taper, and termination section. Vehicles slow down in the advance warning section, maintain a reduced speed during the lead-in taper, construction section, and exit taper, and speed up during the termination section.

### 4.2. Decision variables

The purpose of this section is to identify relevant decision variables affecting mobility, safety, and cost in urban road maintenance work zones. Following a comprehensive literature review, the decision variables identified in this model include: (1) work zone segment length; (2) work zone width; (3)

construction schedule and sequence; and (4) temporary traffic control zone strategy. The details of each variable are presented in Table 1.

**Table 1.** Model decision variable description

| Decision variable | Symbol | Description |
|---|---|---|
| Work zone length | WL | Length of work-zone based on segmenting method. |
| Work zone width | WW | Width of work-zone based on number of closed lanes. |
| Maintenance start time | MST | Construction start time. |
| Construction sequence | CS | Construction sequence of work-zone. |
| Advance warn section length | AWSL | The distance between the first advance warning sign and lead-in taper. |
| Lead-in taper length | LTL | The length of lead-in taper. |
| Longitudinal clearance | LOC | Distance between the work area and the lead-in taper. |
| Lateral clearance | LAC | Distance between the work area and the traffic-control barriers at the edge of the live lane. |
| Termination section length | TSL | Distance between the last warning sign and the end edge of work-zone. |

### 4.3. Constraints

After determining the decision variables, the practical constraints of these variables are summarized in Table 2 based on existing specifications and interviews.

**Table 2.** Model practical constraints description

| Decision variable | Min | Max | Step |
|---|---|---|---|
| Work zone length (WL) | User specified | (24-a1)/a2 | Length of maintenance area/50 |
| Work zone width (WW) | 2.5m | 4.5m | Original lane width – (work zone width + lateral clearance) |
| Advance warn section length (AWSL) | 40m | 600m | 10m |
| Lead-in taper length (LTL) | 30m | 182m | Based on speed limit; |
| Longitudinal clearance (LOL) | 10m | 50m | Based on speed limit; |
| Lateral clearance (LAC) | 0.5m | 1.8m | 0.1 m |
| Termination section length (TSL) | 10m | 90m | Based on speed limit; |
| Maintenance duration (CD) | 0h | 24h | Based on installation time and work zone area |

### 4.4. Formulation

The objective functions of this optimization model are formulated to provide planners with the capability to minimize costs while maximizing mobility and safety performance.

The urban road maintenance cost (CM) represents the total cost of construction activities based on the work zone area during working hours and the fixed setup cost of each work zone.

$$CM = z_1 + z_2 * L \quad (1)$$

$z_1$: average setup cost of temporary traffic control zone
$z_2$: average maintenance cost per work zone square meter
L: length of segment of work zone in kilometers

Moreover, safety performance (SP) and mobility performance (Ttd) are assessed by corresponding decision criteria evaluations (DCEs). The crash modification factor (CMF) is used to evaluate safety, calculated by SSAM based on an integrated framework. Meanwhile, Vissim is employed to evaluate traffic deterioration during construction, with a delay representing traffic performance.

$$\rho = Ca / Cb \quad (2)$$

$$\theta_1 = \rho^{\beta} \quad (3)$$

ρ: conflict modification factor between vehicles
$C_a$ = summation of the expected number of conflicts with treatment (i.e., after) at all treated sites

$C_b$ = summation of the mean number of conflicts without treatment (i.e., before) at all treated sites
β: assumed constant (e.g., 0.3)
$\theta_1$: CMF of vehicle–vehicle

$$SP=\theta_1 \tag{4}$$

SF: overall safety performance

$$T_{td} = T_d + T_m + T_a + T_q \tag{5}$$

$T_d$: Deceleration delay by vehicle deceleration before entering a work zone
$T_m$: Moving delay by vehicles passing through work zones at a lower speed
$T_a$: Acceleration delay by vehicle acceleration after exiting a work zone
$T_q$: Queuing delay caused by the ratio of vehicle arrival and discharge rates

The model facilitates planners' efforts to delineate a series of constraints for the spectrum of work zone layout parameters, ensuring adherence to the specifications outlined in the relevant design guidelines.

## 5. CONCLUSIONS

An integrated BIM–GIS–DCE framework was proposed to facilitate seamless information exchange and automatic performance evaluation. A novel multi-objective optimization model was subsequently developed to identify the optimal urban road maintenance plan, aiming to minimize agency costs while maximizing safety and mobility performance. The optimization model was designed to optimize parameters such as work zone layout, construction schedule and sequence, and temporary traffic control strategy. This study's primary contribution to the body of knowledge includes the development of an original and comprehensive information representation of urban road rehabilitation work zone planning, an integrated BIM–GIS–DCE evaluation framework, and a multi-objective optimization methodology for analyzing optimal trade-offs among three critical objectives. In the future, several practical cases will be used to validate the proposed framework and optimization model.

## ACKNOWLEGEMENTS

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