A Spatiotemporal Approach to Managing Utility Work Schedules

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Abstract

As more and more utility installation and/or maintenance activities are located in highly congested urban roadways, frequent pavement utility cuts in such areas may cause more traffic disruption as well as deteriorate pavement life and quality. Utility owners normally need to obtain permits from public road authorities before commencing utility activities; however, public road authorities in Taiwan currently just issue permits without trying to coordinate and communicate with utility owners involved to schedule their utility-related activities in a more consecutive way. An information model based on the spatiotemporal objects database technique was proposed to help public road authorities identify the utility activities that might be combined together to avoid unnecessary pavement utility cuts. In the proposed model, constraints pertaining to pavement moratorium, utility clearance distance and traffic conditions were considered. The software architecture is discussed, followed by research conclusions.

Keywords: Pavement, Utility cut, Utility permit, Spatiotemporal objects database, Temporal database

1. Introduction

As more and more people dwell in urban areas, there is an increasing number of utility installation and/or maintenance activities located in such areas that make a great impact on paved roads. The steady escalation of the internet penetration rate demonstrates the need that more communication equipment such as fiber broadband lines or wireless access points will be deployed along major transportation systems in the near future. In order to provide new services or maintain deteriorating utility networks, utility owners have to cut pavements open, install new utility facilities or fix problems identified, backfill proper materials, and restore road surfaces. Reports showed that in the District of Columbia, there were over 5,000 utility cuts in 1996 and over 6000 cuts in 2000 (Wilde et al. 2003); in New York City, more than 250,000 cuts a year were made in 2000, and the number increased by 8% each year (Khogali et al. 1999). Researchers indicated that utility activities in the U.K. rank as the second major cause of traffic disruptions with estimated delay costs of $13 billion dollars. Additionally, uneven pavement surfaces due to frequent utility cuts may further result in driver annoyance and other safety issues (Jensen et al. 2005). Others pointed out pavement utility cuts as a major problem in the transportation infrastructure of the U.S., creating serious financial stress on public road authorities (Wilde et al. 2003). In the M-Taiwan project, the government in Taiwan planned to build 6,000 km of optical fiber transmission lines during 2004-2007 to provide most residents with high-speed internet services (Lin 2005). All of the above studies reveal that pavement utility cuts are inevitable and may bring about numerous challenges associated with costs, safety, pavement maintenance, etc.

Since utility owners normally need to obtain permits from public road authorities before commencing utility activities, encouraging utility owners to work together is generally recognized by public road authorities as a potential solution to reduce unnecessary pavement utility cuts. However, in Taiwan, most public road authorities currently just issue permits to utility owners without trying to coordinate and communicate with utility owners involved to schedule their utility-related activities in a more consecutive way. Hence, a managerial tool that can keep track of the schedule and geometric boundary of every planned utility activity is highly desired. Any potential cooperation between utility owners that might reduce unnecessary pavement utility cuts would be detected by such tool, and public road authorities can use the suggestions generated to persuade the utility owners into working jointly.

To this end, this research aims at investigating an information model that can help public road authorities manage utility activities to reduce unnecessary pavement utility cuts. Literature review regarding problems associated with utility activities and their overall impact is described first. The proposed information model that is designed to best describe spatial and temporal properties of planned utility activities is presented next, followed by model exploitation and evaluation of the prototype's software architecture. The tasks required to validate the model are described, and research conclusions are made finally.

2. Literature Review

Several approaches to reducing unnecessary pavement utility cuts have been proposed and investigated. All were designed to cause minimum disturbance to traffic and to have a low impact on the environment. Briefly, these approaches can be categorized into two types: technology-based and policy-based approaches (Wilde et al. 2003). The technology type of approaches such as the trenchless technique focuses on construction methods, practices, tools, etc. that can be employed to perform the utility work. The policy type of approaches focuses on how to allocate construction resources, how to manage organizations and teams, and how to communicate and coordinate with project stakeholders in order to control frequent pavement utility cuts. The technology-based approaches usually accompany high initial cost and short history of proven success, whereas the policy-based approaches often involve incentives, disincentive, and changes of permit procedures that utility owners must follow to complete their works (Wilde et al. 2003). In fact, more researchers investigate the technology-based approaches. The policy-based approaches have less attention in the literature, and few researchers recognize the trend that since the number of pavement utility cuts is escalating, public road authorities might need a managerial tool that can assist project managers in condensing or rescheduling the work schedules of planned pavement utility cuts performed by different utility owners in order to minimize the impact on the traveling public. For example, assume that utility company A will install new facilities in a street during certain days, and utility company B will perform maintenance activities in the same area but one month later after completion of A's work. If both A's and B's work schedules are flexible, the public road authority might be able to persuade A or B to reschedule their work to perform consecutively. Identifying the project circumstances where two or more different utility activities can be combined together is very important to public road authorities because the influential area of pavements due to utility cuts can be carefully calculated so that both the number of utility cuts and the affected area can be minimized.

In addition to reducing unnecessary pavement utility cuts, public road authorities also face a challenge regarding the increasing number of interferences among the planned but not-yet-deployed utility facilities. Public road authorities or other public agencies may prescribe the clearance distances between certain types of utility lines. For instance, the Taipei City government regulates any gas pipeline to have at least 5-6m of horizontal separation. To calculate the influential area of a pavement utility cut requires consideration of these planned utility facilities. Research showed that utility permit procedures may take significant time because public road authorities need to consider myriad factors determining whether to issue the permit and coordinate with other organizations to address concerns such as environmental and archaeological issues (Chou et al. 2007). Assume that a utility company is in the progress of acquiring its permit for placing new pipelines, and another utility company would like to submit its permit application to install new facilities. Without proper coordination and communication within the two utility owners, the public road authority might not be able to detect any possible clearance violation of the new utility facilities and still issue the permits. Hence, additional pavement utility cuts may be needed when one of the utility owners performs adjustments to fix the problem. The clearance violation might be resolved if the road segment involving the two utility owners will be rehabilitated jointly because there will be a coordination meeting hosted by the public road authority to address each party's concerns. This is due to the fact that sometimes utility owners are willing to discuss with each other if the public road authority is involved. Intermediate utility facilities to keep up the service during utility work are another possible source of utility interferences. For instance, if water main lines are underneath temporal power distribution poles, serious problems such as voltage shortage or overloading may happen. Therefore, managing the interferences of planned utility activities is becoming a total nightmare from public road authorities' perspective. To reduce unnecessary pavement utility cuts, public road authorities require a systematical approach to effectively and efficiently manage any future utility installation and/or maintenance activities.

Overall, if public road authorities would like to better manage the utility activities, they might need to deal more with the utility work schedules and use a computerized tool to precisely depict the spatial information of each planned utility activity. The following section elaborates more temporal and spatial requirements of each utility activity so that an information model to capture such requirements can be proposed.

3. Temporal Properties of a Utility Activity

To schedule a set of activities, traditional techniques such as Program Evaluation and Review Technique (PERT) emphasize the importance of the constraints on the activities. Constraints involve time or resources-related rules that govern the execution sequences to complete the project. From public road authorities' perspective, since utility activities are performed by different utility owners, sharing resources among these companies is rare, and oftentimes utility owners do not want to overlap their work schedules. The primary constraints in this type of work thus become spatiotemporal-related requirements. For instance, if a utility company will install a new service line in the area, is there any active construction plan located in the same place? When will the plan start and when will it end? The location and the duration are the major spatiotemporal resources that cannot be easily shared in most of the utility activities. If one activity needs a particular spatiotemporal resource, the other activities cannot occupy without proper coordination.

One advanced database technique that has emerged as a main focus of many spatiotemporal information systems such as the digital battlefield in the military is to keep track of object locations over time and to support temporal queries about future locations of the objects (Wolfson et al. 1998)(Wolfson 2002). Called moving objects database (MOD) or spatiotemporal objects database (SOD), this technique aims to deal with geometries changing over time and to simplify the data update process through use of dynamic attributes (Guting and Schneider 2005), thereby having the potential for eliminating or reducing some of the associated challenges and complications. The way SOD employs to process the time dimension for each moving object may serve as a starting point for utility activity modeling.

In SOD, there are two time dimensions associated with each time-sensitive attribute: valid time and transaction time (Guting and Schneider 2005)(Tansel 1993). The valid time refers to the time in the real world when an event occurs or a fact is valid. The transaction time refers to the time when a change is recorded in the database. Formal definitions for Dv (valid time) and Dt (transaction time) are listed as follows:

Dt = {t0, t1, …, ti, …, now}

$$\forall t', t'' \in D_t \setminus \{now\} : t' < t'' < now \vee t'' < t' < now \vee t' = t'' < now$$

Dv = {t0, t1, …, ti, …, now, …}U{∞}

$$\forall t', t'' \in D_v \setminus \{\infty\} : t' < t'' < \infty \vee t'' < t' < \infty \vee t' = t'' < \infty$$

For example, the duration of a utility activity is defined by a manager as from January 1, 2009 to March 1, 2009, which is in the Dv domain. The manager enters this activity information, including the geometric boundary and the schedule, to a computer on November 1, 2008, which is in the Dt domain, but the schedule is changed on January 5, 2009. The new schedule is from February 1, 2009 to April 1, 2009. There is another utility activity scheduled to be performed from March 1, 2009 to May 1, 2009. The manager enters the second utility activity to the computer on December 1, 2008 (see Figure 1). In fact, the three database records regarding the two utility activities must be persisted individually since each data entry may be associated with a permit application and fees. A public road authority may ask the utility owner of the first activity to pay additional fees for the time period between January 1, 2009 and January 5, 2009, although no one indeed performs any work at that time. Recording the two time dimensions of each utility activity helps project stakeholders retrieve not only latest date but historical one for future auditing purposes.

Further, the duration of a utility activity may be associated with a different time scale. For example, if an accident destroys a power switch facility, the problem due to switching over voltages needs to be fixed within several hours. However, leaks of a water main lines may take months to fix the problem. The need of a multi-scale time hierarchy associated with each utility activity is evident; however, current relational database techniques cannot provide an appropriate solution to satisfy this need.

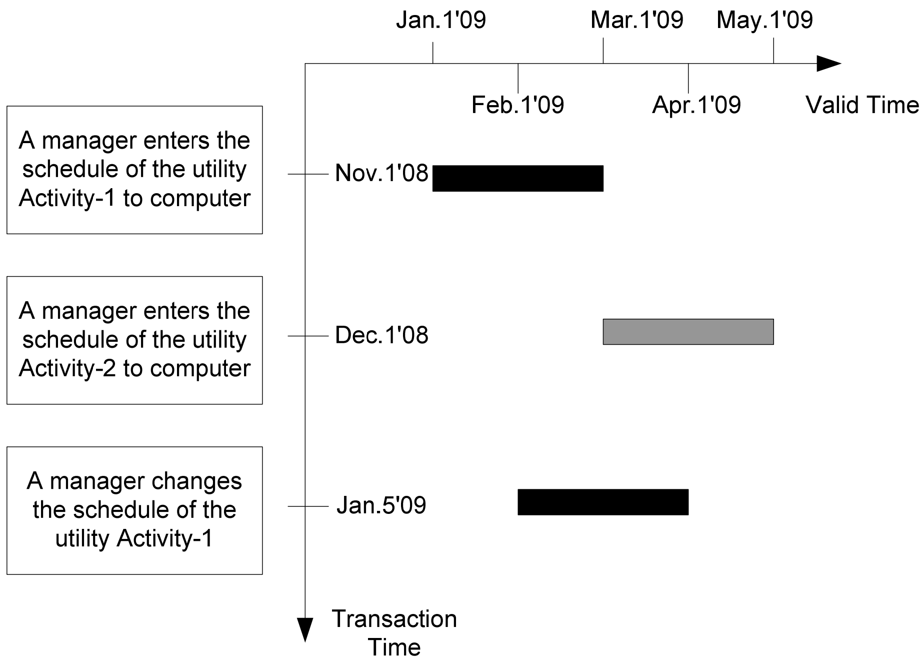

Figure 1. Valid time and transaction time for two utility activities

4. Software Architecture Analysis

In addition to the temporal requirements of a utility activity usually not implemented in current GIS commercial tools, traditional GIS techniques do not fit the internet architecture due to lack of support of the multi-user environment. Since utility permits are often created by respective utility owners at their offices, the modern three-tiered architecture aiming at dividing information presentation, processing and database operations into three layers of software components might be more adequate for our research problem. Based on the three-tiered architecture, a spatial database that can provide both common relational database and GIS functions is needed. An open-source spatial database, i.e., PostGIS, is employed for this research so that the research team can customize some default functions. Briefly, PostGIS is an add-on component designed to conform to the Open Geospatial Consortium (OGC) specification. Its relational database functions are provided by PostgreSQL, a prestigious open-source relational database. Using PostgreSQL with PostGIS, one can easily reuse the robust relational and spatial database engines. As noted before, traditional GIS techniques concentrate on providing an integrated solution to users, include map data presentation, processing and persistence; however, prevalent internet applications change this traditional approach of GIS. Indeed, the new OGC specification covers almost all GIS functions pertaining to data processing. Commercial database products such as Oracle also apply the same architecture as PostgreSQL and PostGIS.

5. Proposed Model

The proposed information model is shown in Figure 2. Elaboration of each class in the model is described in this section. Basically, the model consists of three main parts: (1) roadway classes, including RdNetwork, Road, RdSegment, MaintenancePlan, and Resurface; (2) utility classes, including UtilPart, UtilLine, UtilFacility, Abandonment, UtilSection, UtilNetwork, UtilEnterprise, and UtilDivision; and (3) permit classes, including Permit and UtilActivity. The roadway classes contain information regarding a road network itself and its maintenance plans. The utility classes are designed to capture existing utility lines and facilities, including abandoned ones that are still buried in the field. The permit classes are the reflection of the future utility plan that may have conflicts with other permits, existing utilities, and road maintenance plans. The elements of the model are described as follows:

RdNetwork: This class represents the concept of a road network. A road network object is designed to group road objects. For instance, in a city, the public road authority has four divisions. Each division is responsible for managing one quarter of the city's roads. Hence, four road network objects exist in the model.

Road: This class represents the concept of a road, e.g., Riverside Drive. A road object contains a set of road segment objects. The road class has six attributes. The "Type" attribute is designed to record the road's type, e.g., way, line, drive, road, street, avenue, and boulevard. The "Line" attribute is a "linestring" type in PostGIS, which describes a road as a set of lines. The last three attributes are used to record the traffic flow information of a road.

RdSegment: This class represents the concept of a road segment. A road segment object is the building block to construct a road object. The road segment class has four attributes. The "Lane" attribute is designed to record how many lanes the given road segment has. The "Polygon" attribute can be used to depict the geometry of the segment. The "ROWPolygon" attribute can be used to depict the right-of-way (ROW) geometry of the segment. The "BeginDate" attribute is used to record when the road segment is open to serving the traveling public. Note that this attribute pertains to the valid time dimension so the "EndDate" attribute is set to forever.

MaintenancePlan: This class represents the concept of a road maintenance plan. Most public road authorities will not allow utility owners to cut their newly paved road segment, which forms a constraint the manager scheduling the utility activities needs to consider. A road maintenance plan object can have many resurface objects, which represent the resurface activities and will be described next. The "MoratoriumMonths" attribute is used to store how long the road segment cannot be cut. The value of this attribute should be applicable to all resurface activities of the plan.

Resurface: This class represents the concept of a resurface activity. In our proposed model, the resurface activity pertains to a certain road segment; hence the influential area of a resurface activity must reside within the boundary of the corresponding road segment. The "Polygon" attribute denotes the influential area of a resurface activity. The "Duration" attribute records the start and end dates of a resurface activity. Note that a resurface activity can be a past, present, or future event.

UtilPart: This class represents the abstract concept of a utility facility. This class is a base class, and three classes, i.e., UtilFacility, UtilLine, and Abandonment, inherit from it. Basically, a road segment may have zero to many utility facilities, and the "Polygon" attribute depicts the boundary of a utility facility. The "BeginDate" attribute records the date when this facility becomes operational.

UtilFacility: This class represents the concept of an actual utility facility. Because it is derived from the "UtilPart" class, only the "Function" attribute and the "Clearance" attribute are defined. A utility facility object can be used to depict any facility or appurtenance with a clearance distance and must be contained in a utility section object.

UtilLine: This class represents the concept of an actual utility pipeline. Because it is derived from the "UtilPart" class, only the "Clearance" attribute is defined. A utility line object can be used to depict any pipeline with a clearance distance and must be contained in a utility section object. Note that a utility facility object, like a pole, can have two or more utility line objects, like a power line and a communication line suspended in the same pole.

Abandonment: This class represents the concept of an actual abandoned utility facility. Because it is derived from the "UtilPart" class, only the "Name" and "Reason" attributes are defined. An abandonment object can be used to depict any utility facility or pipeline that still exists in the field but no longer provides any service. An abandonment object must be contained in a utility network object.

UtilSection: This class represents the concept of a utility section, which contains a set of utility part objects.

The "Line" attribute is a "linestring" type in PostGIS, which describes a utility section as a set of lines. A utility section object must be contained in a utility network object and may contain zero or more utility permits.

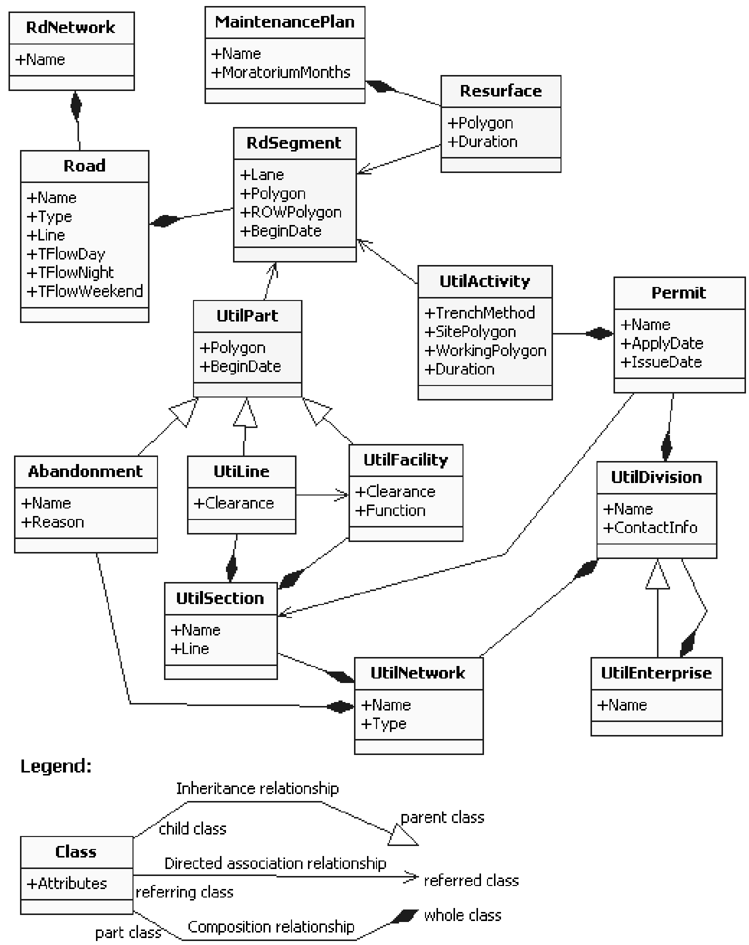

Figure 2. Model for spatiotemporal road and utility information

UtilNetwork: This class represents the concept of a utility network. A utility network object is designed to group utility section objects. For instance, in a city, the water utility network can be divided into many utility sections. Each section can be represented by a utility section object. The "Type" attribute is used to record the type of the utility network, e.g., water, wastewater, power distribution, gas, telecommunication, etc. The "Name" attribute records the name of the network.

UtilDivision: This class represents the owner of a utility network. It includes a person's contact information so that public road authorities can get in touch with him or her when any emergent event on the utility network occurs. A utility division object manages one or more utility networks. The "Name" attribute records the name of the organization.

UtilEnterprise: This class represents the concept of the utility division's business entity and inherits from the "UtilDivision" class. For example, a city government may be responsible for the water supply system, the wastewater treatment system, and the power distribution system. There must be three engineering divisions in the city government, so "UtilEnterprise" represents the city government whereas "UtilDivision" represents each engineering division. The Enterprise-Division structure can be easily extended to model any infrastructure owners' organizations.

Permit: This class represents the concept of a utility permit. A utility division may apply for several utility permits for each of their utility work. Similarly, a utility permit may pertain to one or more utility divisions who are all responsible for the utility work. A utility permit object can contain many utility activity objects. The two date attributes record when to submit the permit application and when to receive the approval.

UtilActivity: This class represents the concept of a utility activity. Each utility activity resides in one road segment. The "Duration" attribute records the duration of a given utility activity. The "TrenchMethod" attribute can be "trench," "trenchless" or "pole." The "SitePolygon" attribute contains the geometry of the trench or activity, whereas the "WorkingPolygon" attribute contains the geometry of the area needed for the work.

It should be noted that the "TranDate" attribute is added to each class in the proposed model because it represents the time when a given object is updated. The transaction time dimension is applicable to each class, whereas the valid time dimension is applicable to some of the classes in the proposed model with two formats. The first format of the valid time dimension is represented as the "BeginDate" attribute, which exists in the "RdSegment" and "UtilPart" classes. Since the road segments and the utility lines and facilities will not be demolished, the "EndDate" attribute of the valid time dimension is meaningless for the two classes. However, the "Duration" attribute of the "Resurface" and "UtilActivity" classes actually uses the start and end date fields to record the time period of a given activity.

6. Exploiting the Model

In this section, several hypothetical examples to exploit the capabilities of the model are discussed. The SQL language with system-defined or our customized spatiotemporal functions is used to explain how a spatiotemporal query can be done.

Finding Any Spatiotemporal Activity Violating the Constraints: As noted before, generally two or more utility activities performed by different utility owners cannot happen in the same place during the same period of time, unless they have been well coordinated in advance. Assume our database has accumulated enough road and utility infrastructure baseline data and recorded many utility permits data. Among these permits, it is difficult and time-consuming for a project manager to manually check all utility activities that violate the above constraint. Additionally, the pavement moratorium constraint of a road segment, the clearance distance of a utility facility or pipeline, and the traffic condition of a road all need careful examination before a utility permit can be issued. In SOD, the problem can be solved by the following steps:

1. Let Set1 = select * from UtilActivity where Duration.EndDate >= NOW

// find the utility activity data set that the work items have not been finished

2. Let Set2 = select * from Set1 as a, Set1 as b where st_intersect(a.Polygon, b.Polygon) is not null and a <> b

// list any pair of two objects that constitute a shared polygon, which means these two utility activities share the same place. Note that st_intersect is an OGC-defined function

3. Let Set3 = select * from Set2 where t_overlap(a.Duration, b.Duration) and a <> b

// because Set2 means the two activities occupy the same place, Set3 finds out whether their time durations are overlapped. Note that t_overlap is a customized function

4. Let Set4 = select * from Set1 join RdSegment join Resurface where st_intersect(Set1.Polygon, Resurface.Polygon) is not null and t_overlap(Set1.Duration, (NOW, Resurface.Duration.EndDate + Resurface.MaintenancePlan.MoratoriumMonths))

// if the space needed by Resurface and Set1 is the same, and if the work duration is overlapped, Set4 stores these records

5. Let Set5 = select * from Set1 join RdSegment join UtilPart where st_intersect(Set1.Polygon,

expand(UtilPart.Polygon, Clearance)) is not null
// if the space needed by expanding the clearance distance of a utility facility and Set1 is the same, Set5 stores these records

6. Let Set6 = select * from Set1 join RdSegment join Road where TFlow > certain_traffic_flow_valuee
// if the space needed by Set1 is the road with heavy traffic flows, Set6 stores these records

The result set is (Set3 union Set4 union Set5 union Set6), which means these planned utility activities violate one of the constraints.

Listing the Utility Activities That Can Be Performed Consecutively: In order to minimize the unnecessary pavement utility cuts, the project manager would like to list the utility activities that are planned to be performed in the approximate same place but at different times. These activities can be rescheduled to be performed consecutively to reduce unnecessary pavement utility cuts. Assume the minimum distance between the two activities that can be combined to be performed jointly is d. Assume "consecutively" means the difference between the end date of one activity and the start date of another consecutive activity is n days or less. In SOD, the problem can be solved by the following steps:

1. Let Set1 = select * from UtilActivity where Duration.EndDate >= NOW
// find the trench data set that the work items have not been finished

2. Let Set2 = select * from Set1 as a, Set1 as b where st_dwithin(a.Polygon, b.Polygon, d) and a <> b
// list any pair of two objects located nearby, which means these two utility activities will be performed in the approximate same place. Note that st_dwithin is a OGC-defined function

3. Let Set3 = select * from Set2 where (t_overlap(a.Duration, b.Duration) or a.Duration.EndDate + n >= b.Duration.StartDate) and a <> b
// Set3 finds out whether their durations are overlapped or very close

4. Let Set4 = Set2 – Set3
// the remaining data items are those activities that can be rescheduled. Set 4 is the result set

A simulation tool is currently under development. The tool will use the proposed model to simulate events of each utility activity in a small city in Taiwan. The water supply system, power distribution lines, communication lines, and natural gas pipelines are depicted in the tool. Their baseline and interdependency data are recorded in the database. With interdependency data in the database, users of the tool can find out the useful information to rescheduling.

7. Conclusions

With the ever-increasing demand for a streamlined analysis of utility activities to reduce unnecessary pavement utility cuts, public road authorities are making substantial efforts to improve the decision-making process regarding how to optimize the work plan. Because an information model is fundamental to be used to calculate and reschedule the utility activities, and because modern database technologies have provided powerful spatial query capabilities, the time dimension for the utility activities scheduling such as the one in this research can help project managers retrieve relevant information on demand. This research has designed a UML-based model that can describe spatiotemporal information with constraints. Further implementation and evaluation of the proposed model proposed is needed in order to demonstrate how such information technology can help reduce unnecessary pavement utility cuts.

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