FORECASTING CONSTRUCTION DURATION OF WATERMAIN UPGRADE PROJECT BY USING DISCRETE EVENT SIMULATION

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ABSTRACT

Practitioners in the construction industry often rely on their experience or historical data of their organizations to estimate construction duration. However, variations in site conditions are not usually taken into consideration. This paper presents a Discrete Event Simulation (DES) model that can help decision-makers accurately estimate durations of underground water-main construction projects and review key schedule milestones in detail. A case study is conducted on an actual project of a municipality in Canada. Different site conditions and the municipality's design criteria are taken into consideration to accurately reflect real world conditions. Chainage, a distance measuring system commonly used to design and locate linear infrastructure, is used as a key attribute to control the overall model and provide status of model. In addition, compaction test results that may affect the schedule at certain probability are modeled as well to measure the possible delays caused by such failures.

Keywords: discrete event simulation, construction scheduling, project management, construction management

1. INTRODUCTION

Installing, or upgrading underground watermain is one of the most common design and construction works of municipalities, civil engineers, and civil contractors. Typically, a section of watermain is a linear network of multiple pipes which requires various resources such as crews and equipment to work together. Practitioners in the construction industry often use their own experiences or historical data collected by their organizations to estimate construction schedule. However, different site conditions are often ignored in this conventional way.

With a rapid urban expansion, water distribution network becomes an important issue for urban planning and infrastructure construction. In the City of Toronto, many pipes are beyond their theoretical service life of about 80 years (City of Toronto 2009). It is also predicted by the United States Environmental Protection Agency (U.S. EPA) that in the United States alone, $138 billion will be required to replace and maintain the existing drinking water systems during the next 20 years (Selvakumar, Clark and Sivaganesan 2002). Rehan, Knight, Unger and Haas (2013) developed causal loop diagrams and a system dynamics model for financially sustainable management of urban water distribution networks and discussed on how the developed system dynamics water model can be used by water utilities to achieve a variety of utility short and long-term objectives. As a result, Asnaashari, McBean, Gharabaghi and Tutt (2013) concluded that the water industries in cities need an intelligent system that can combine all recorded data to analyze the complex relationships in the data and to assist the processes of decision-making for asset management.

With the utilization of Discrete Event Simulation (DES), this paper presents an effective tool that can help decision-makers to more accurately estimate construction schedule of underground watermain construction and enable them to review detailed schedule of activities of a project.

2. LITERATURE REVIEW

Simulation technology has been implemented in construction industry for many years. In 1976, Halpin (1997) introduced the cyclic operation network (CYCLONE) to construction industry and since then, many scholars did further study based on Halpin's work, including but not limited to INSIGHT (Paulson 1978), RESQUE (Chang and Carr 1987), UM-CYCLONE (Ioannou and Ioannou 1990), and DISCO (Huang, Grigoriadis and Halpin 1994).

Simphony is a useful simulation tool which was developed by University of Alberta (Hajjar and AbouRizk 1999), and it provides a framework for developing General Purpose Simulation (GPS) and Special Purpose Simulation (SPS) templates to help users create models based on their knowledge of simulation as well as the construction domain (Moghani, Sander, AbouRizk and AbouRizk 2011). Simphony.NET supports general purpose modeling constructs (e.g. CYCLONE) which can be used to model different construction processes, and allows users to build models utilizing abstract elements such as activities, queues, and resources. Hajjar and AbouRizk (1997) introduced special purpose simulation (SPS) and implemented it with Simphony. Special purpose simulation was designed to facilitate adoption of simulation by industry and uses a visual object-oriented modeling environment to provide a simple way for nonexpert simulators to control simulation. AbouRizk and Mohamed (2000) discussed Simphony as an integrated environment for developing Special Purpose Simulation Tools. Samples of the templates were developed using Simphony were presented to highlight some of the powerful features that can be easily included in templates by a developer. In 2002, with the chosen three construction methods in earthmoving, aggregate production and site dewatering, Hajjar and AbouRizk updated Simphony as Simphony.NET, which allows for quick, flexible analysis of various construction plans; for instance, it is a simple matter to change the soil type, the number of backhoes, or the number of crews and observe the outcome. Simphony uses a hierarchical, modular approach which considerably simplifies the development and use of complex and large simulation models (Hajjar and AbouRizk 2002). In this research, simulation model was developed by Simphony. NET 4.0 which is the latest version of Simphony.

Discrete event simulation (DES) is a particular type of dynamic simulation which could be processed by advancing time in discrete activities based on critical events. An event in the context of DES could be defined as an instant of time when an important state change occurs in the system (Pidd 1988; Labban, AbouRizk, Haddad and Elsersy, 2013). The simulation model generally starts with a given event, which triggers other events, until a termination point is met. The methodology and algorithms behind DES, which concerns “the modeling of a system as it evolves over time by a representation where state variables change only at a countable number of points in time” (Law and Kelton 1982) provides an alternative approach to project control. By predicting the future condition of a real construction system following a computer model which is based on real life statistics and operations (Lu 2003), DES is reliable and could be advisable for decision-makers. Nowadays, DES has become prevalent in various fields, such as manufacturing, telecommunication, supply chain, and finance systems.

A simulation model can be used as a flexible tool to estimate the significance of different site conditions (Agbulos Mohamed, Al-Hussein, AbouRizk and Roesch 2006). In general, construction process of watermain installation is linear and could be repeated when site is changed. Each task in this process has distinct duration and the project duration is accumulated as the task moves from one to another. Therefore, the proposed methodology in this paper is generating DES analysis with the implementation tool as Simphony.Net 4.0 (General Purpose Simulation), in order to simulate project duration and track the construction process. A simulation model of Simphony can have multiple runs, which allows a user to run scenarios and compare the results generated by statistical inputs and output.

3. CASE STUDY: WATERMAIN UPGRADE PROJECT

3.1. Project Description

A municipality in British Columbia, Canada, finished a upgrade project for approximately two kilometers of existing water distribution lines, located in its one of Northern neighborhoods. The project was to install new watermain lines and abandon existing ones that exceed their service life. The actual construction started in winter of 2012 and finished in spring of 2013, and a rough construction schedule had been estimated by using their historical data prior to the construction. However, actual construction schedule was not tracked and recorded properly due to the frequent interruptions from the city’s other construction projects where the same crew was utilized, and also due to the long holiday break in the middle of project. This study focuses on simulating project schedule and various activities based on observations of the construction inspector of the project, and developing a more accurate tool that can be used to forecast the construction schedule of similar projects.

The project included eight different sites within an area of approximately 400 metre radius. Typical plan view of a site is shown in Figure 1. Each site has its own conditions which have to be considered during construction schedule planning. Those conditions include frequency of traffic, steepness of slope, and seismic area. Each site has different length of pipes, and different number fire hydrants and service connections to install. Activity durations vary based on these factors because different construction methods, that are specified in the Design Criteria further discussed in the next subsection, have to be applied.

Pipe size varies between 4 inches to 8 inches (100mm

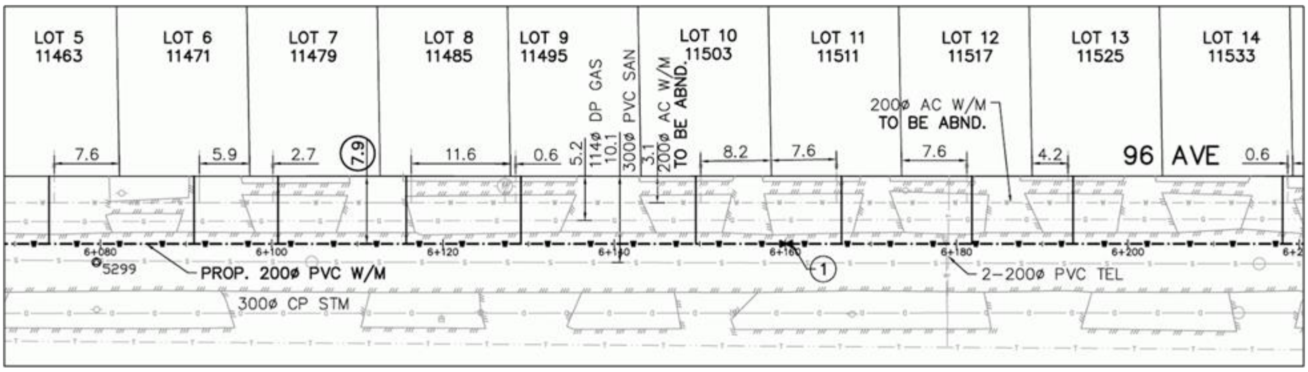

Figure 1: Typical Plan View of Watermain Construction Drawing (City of Surrey 2012)

to 200mm diameter). Ductile iron (DI), high-density polyethylene (HDPE), or polyvinyl chloride (PVC) pipes are used. Typical pipe length is 20 feet, which is 6.1 meters.

The city utilized its own workforce (hereafter referred to as the city crew) for the watermain pipe installation part, and hired third party contractors for pavement saw-cutting, traffic control and surface restoration. The city crew included three labourers, and one backhoe with its operator. Survey layout was done by the survey department of the city, and a geo-technical engineering firm was responsible for compaction tests.

3.2. Design Criteria Review

Design Criteria Manual released by the city's engineering department (City of Surrey 2004) was reviewed to reflect more detailed installation of water pipe installation. Key findings are as follows:

- Grade: When the slope of a water main equals or exceeds 10%, pipe anchor has to be used. Also, ductile iron pipe has to be used.
- Fire hydrant: Hydrants shall not be spaced more than 200 meters apart. Quantity and locations of hydrants are normally determined during the design phase.
- Seismic Area: If the project site is located within the seismic area, all pipeline shall be restrained so that they will not pull out when subjected to extension forces. Also, to minimize soil-pipe interaction, pipe shall be wrapped with polyethylene (baggy) such as is commonly used for corrosion protection. The intent of the wrapping is not to provide corrosion protection.

The conditions of sites are summarized in Table 1.

3.3. Construction Process and Activities

Typical construction process of the underground watermain installation can be summarized as shown in Figure 2. Prior to initializing actual construction, the city sends its survey crew to conduct the survey layout based on construction drawings prepared by a design firm. Once the survey layout of the first site is complete, a saw-cutting contractor is brought in to saw-cut paved area according to the survey layout marked on site. These two activities can proceed to the next sites without any dependency on the city crew's pipe installation.

Once the saw-cutting of the first site is done, the city crew can initiate their activities. First, the crew mobilizes in a location among the eight sites that they can access to the trailer from any of sites throughout the whole project. Therefore, mobilization only happens once at the beginning of main cycle of the first site.

Before starting a main cycle of a site, the crew has to determine whether traffic control is necessary for safety by checking the traffic frequency during the day time and the alignment of pipes on the road. If needed, traffic control crew is hired. Once the traffic control crew is in place, the backhoe can start removing pavement, or topsoil, and excavating trench. Whether the area is paved or not, the difference of activity duration is assumed to be negligible because the pavement is already saw-cut. A haul truck is also required to load the excavated earth, but it is ignored in this study. If trench is excavated enough as shown in Figure 3, then two laborers prepare pipe bedding and level it so a pipe can be installed as designed. Once the pipe bedding is ready, a pipe is laid down by backhoe using chainlink, and one laborer is required to assist with this activity. If the site is located in the seismic area, then joint restraints and pipe wrapping have to be applied to the pipe before connecting it to proceeding pipe. If the pipe is ready for connection, then two laborers connect the pipe to the proceeding pipe and seal it. If the slope of pipe equals or exceeds 10%, then pipe anchoring has to

Table 1: Conditions of eight sites

	Site (total of 8 sites in the project)							
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Conditions								
Total project length(m)	99	247	325	170	452	156	137	269
Start of chainage (m)	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000
End of chainage (m)	1,099	2,247	3,325	4,170	5,452	6,156	7,137	8,269
Traffic Control req'd?	No	No	No	No	Yes	No	No	No
Length (m) of trench where slope > 10%	63.8	59.2	200.0	0.0	0.0	100.0	0.0	0.0
Start of chainage (m) w/slope > 10%	1,020.0	2,123.0	3,070.0	0.0	0.0	6,055.8	0.0	0.0
End of chainage (m) w/slope > 10%	1,083.8	2,182.2	3,270.0	0.0	0.0	6,155.8	0.0	0.0
Seismic area?	Yes	Yes	Yes	Yes	No	Yes	Yes	No
No. of service connection?	4	13	26	13	22	15	14	14
No. of fire hydrant?	1	1	1	0	2	1	1	1
Length (m) of paved area	99	172	325	15	452	156	137	79
Length (m) of landscaped area	0	75	0	155	0	0	0	190

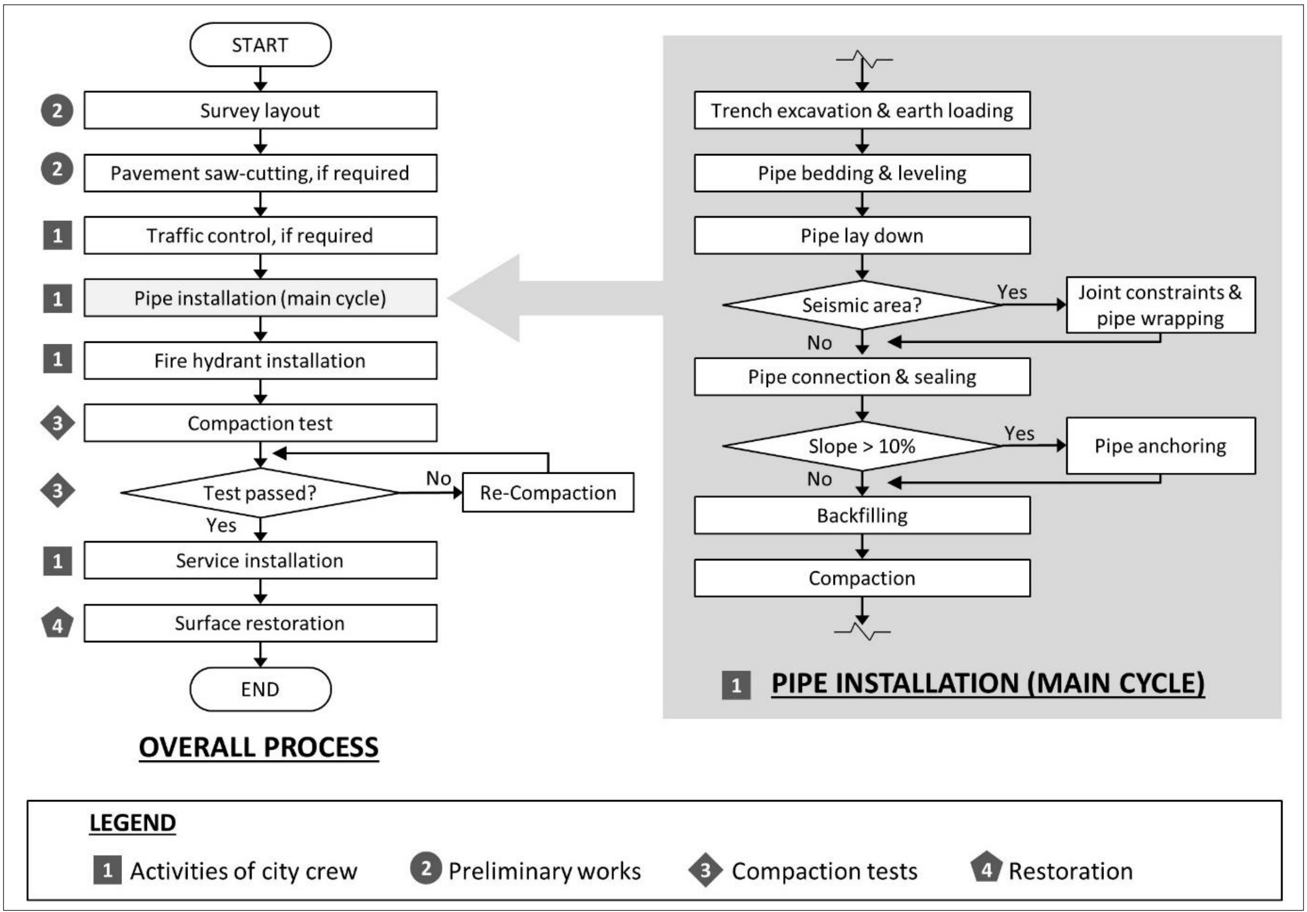

Figure 2: Construction Processes

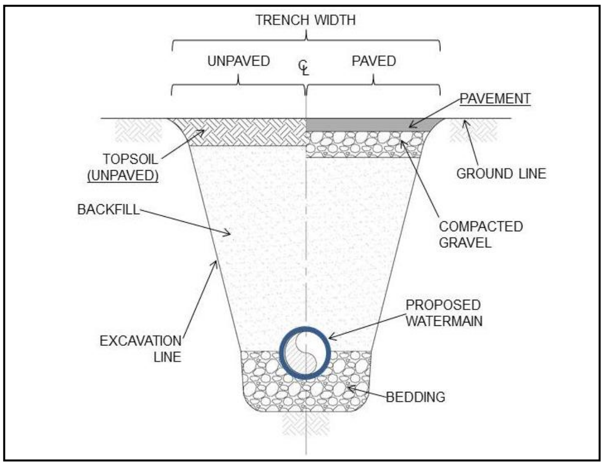

Figure 3: Typical Watermain Trench Detail

be applied by using concrete and tie-rods. When pipe installation is complete, the backhoe can backfill the trench with assistance of one laborer. The backhoe is also responsible for compacting the backfilled area with its vibratory plate installed on the opposite side of its body. This series of main cycle happens repetitively at every one pipe length (20ft, or 6.1m) until the city crew reaches the end of a site. Once the city crew completes this series of main cycles for a site, then the crew can move on to the next site. As previously mentioned, sites are saw-cut by a third party contractor independently; therefore, no delay is expected when the crew moves to the next site.

While the city crew is working on the other sites, the project manager of the city requests a geo-technical engineering firm to conduct compaction test. The geo-tech firm sends a technician at the end of every second sites (i.e. when the main cycles of 2nd, 4th, 6th, and 8th sites are complete), and conduct compaction tests. Then the firm analyzes the test results collected by its technician, and forwards the result to the project manager of the city. If the trenches are found to be compacted to the level satisfying the city’s standard, no further action is required. If the test is found to be unsatisfactory, then the project manager asks the city crew for re-compaction. Then, the backhoe is sent back to the site of which compaction was not done properly, and redo the compaction. It happens only when the crew moves between different sites. For this project, the compaction is assumed to be failed in the possibility of 10% (one fail out of ten tests), and the impact from the test failures will be measured in the simulation.

Once the city crew finishes the main cycles of all eight sites, then it moves back to each site to complete fire hydrant installation and service connections from the newly-installed watermain to each property. Installation of service connection can start only when all compaction test results are satisfactory. The city crew demobilizes when all the above activities are complete.

Surface restoration, either pavement or landscaping depending on existing site conditions, starts when all the service connections are done, and it is done by third party contractors that are hired by the city. The whole project ends when surface restoration is complete.
Durations of activities are summarized in Table 2. When sample observations are not available, a simulator can use subjective judgment of an expert knowledgeable about the work being modeled. A simulator often uses a triangular (low, high and mode estimates) or uniform (low and high estimates) distribution in such case (AbouRizk and Halpin 1992). In this paper, opinion from the project inspector was used to determine activity durations, and they are assumed to be triangular distributions for simplicity of the simulation model. However, note that mode values only are shown in the table for clarity. For instance, the mode value of Mobilization activity is assumed to be 4 hours and presented in the table, although low (minimum) estimate of 3.5 hours and high (maximum) value of 4.5 hours are also used in the actual simulation model.

4. MODEL DEVELOPMENT

The algorithm for the simulation follows the flowchart, Figure 2, previously presented in the project description. As the first step of model development, all the parties involved were identified, namely city crew,

Table 2: Description of Construction Activities

Name of activity	Duration	Done by	Remarks
Before main cycle			
Survey layout	2 hrs/100m	City's survey crew	Independent activity
Pavement saw-cutting	1 hrs/30m	Saw-cutting contractor	Independent activity
Mobilization	4 hrs	Whole city crew	One time item
Main cycle (mainly by city crew)			
Traffic control	0.5 hours	Traffic controller contractor	One time item, at the beginning of a site, only when applicable
Excavation & earth loading	6.5 min/3.05m	Backhoe	
Pipe bedding & leveling	6.5 min/6.1m	Laborer(s)	
Pipe laydown	7.0 min/6.1m	Backhoe & Laborer(s)	
Joint Restraint & Pipe wrapping	Add 50% time to 'Pipe connection & seal'	Laborer(s)	Applicable only to seismic area
Pipe connection & sealing	15.0 min/6.1m	Laborer(s)	
Pipe anchoring	25 mins / each pipe layout	Laborer(s)	For where slope is greater than 10% only, Each at end of every pipe (6.1m)
Backfill	7.5 min/6.1m	Backhoe	
Compaction	5.0 min/6.1m	Backhoe	
Moving to Next Site	30 min	Whole city crew	
**Once the city crew completes the series of main cycles of a site, the crew moves to the next site.*			
City crew's work outside of Main Cycle			
Installing fire hydrant	4 hr/ea	Backhoe & laborer(s)	Happens at the end of a site when all main cycles are complete
Installing service Connection	1 hr/ea	Backhoe & laborer(s)	Can start after fire hydrant are all installed and passing compaction test
De-Mobilization	4 hrs	Whole city crew	One time. Happens after all the service connections are complete
Other's work after each Main Cycle			
Compaction test	4 hours/each time	Geo-tech technician	Happens at end of site 2, 4, 6, and 8. If failed, backhoe is captured to redo the compaction
Contacting geo-tech firm, & Receiving test result	16 hr/ea	City crew & Geo-tech	Can overlap with other activities
Re-Compaction	45 min/site	Backhoe	
Service connection	1 hr/ea	Backhoe & laborer(s)	Can start only after passing all the compaction tests
Surface restoration, Pavement	4 min/m	Paving contractor	Can start only when the city crew is ready for demobilization
Surface restoration, landscaping	1.5 min/m	Landscaping contractor	Can start only when the city crew is ready for demobilization

survey crew, traffic control crew, pavement saw-cutting crew, geo-technical engineering firm, pavement and landscaping crew.
Instead of developing a model for each crew or firm's activity, they are grouped into four groups to simply the simulation model. For instance, pavement saw-cutting always follows survey layout, in other words, they have finish-to-start relationship. Their activities take place independently prior to city crew's work, and do not interrupt other activities. Therefore, they can be grouped. Through analysis of the whole construction process from the perspective of model design, four different sub-models were created in the main model, as shown in Figure 2 and Table 3, to simulate the watermain upgrade project using General Purpose Simulation template in Simphony.Net 4.0.

Table 3: Four sub-models

Model Description	Role in the main model
Activities of city crew	To simulate the activities of the city crew
Preliminary works	To simulate the preliminary works (survey layout & Pavement saw cutting) conducted independently by third party contractors
Compaction Test	To simulate compaction tests and their results. It captures backhoe resource when the test is failed.
Restoration	To simulate restoration works (either pavement or landscaping) that can start at the end of all activities of the city crew

Coding plays important role in this model. Global and local attributes, GX and LX respectively, are designed to carry information of different entities and current simulation time to avoid redundant elements and make the model more effective. The different conditions of each site, that are previously summarized in Table 1, are coded as shown below in the model so each site can be processed differently in the simulation. The activities of the city crew is mainly controlled by the LX(1), which is the start of chainage and is also used as the current chainage of an entity during the process. LX(1) increases by 6.1 (length of one pipe) at the end of each cycle for this purpose.

```
//Initiate each site{
Redim LX(20) //'Expand number of local
attributes
LX(0)=1 //'Site number
LX(1)=1000 //'Start of chainage (m)
LX(2)=1099 //'End of chainage (m)
LX(3)=0 //'Traffic control required?
(1:T, 0:F)
LX(4)=1 //'Seismic area? (1:T, 0:F)
LX(5)=99 //'Length(m) of paved area
LX(6)=0 //'Length(m) of landscaped area
LX(7)=4 //'Number of service connections
LX(8)=1 //'Number of fire hydrant
Return True};
```

Durations of optional activities, such as traffic control, Joint Restraint, Pipe wrapping and Pipe anchoring, are processed also based on these attributes of an entity. Example of optional activity and its coding is shown in Figure 4 and the following coding.

```
//Control Pipe anchoring {
//'LX(1) is current chainage
If LX(1)+6 > 1020 and LX(1) < 1083.8
    Return True
Else If LX(1)+6 > 2123 and LX(1) < 2182.2
    Return True
Else if LX(1)+6 > 3070 and LX(1) < 3270
    Return True
Else if LX(1)+6 > 6055.8 and LX(1) <
6155.8
    Return True
Else
    Return False
End if };
```

Key activities, including start/end of main cycle, corresponding with geo-tech, compaction tests and their results, optional activities, etc, are monitored by using 'trace' element, which provides comments whenever an entity passes the elements. Examples of comments generated by trace elements are shown below, followed by corresponding codings. Note that the time unit in this model is minute.

Preliminary work (Survey layout & pavement sawcut) for Site No.1 is complete at time 316.8
Crew starts main cycles of site no.1 at time 316.8
Crew completed mobilization and is starting main cycle at time 552.4
Chainage 1000 to 1006.1 is complete at time 614.1
Pipe anchor has been applied at chainage 1018.3 (slope > 10%)
Crew finished FH installations of site1 at time 2089.7
Crew starts main cycles of site no.2 at time 2123.8
Geo-tech arrived for compaction tests of site 3 and site4 at time 12215.9

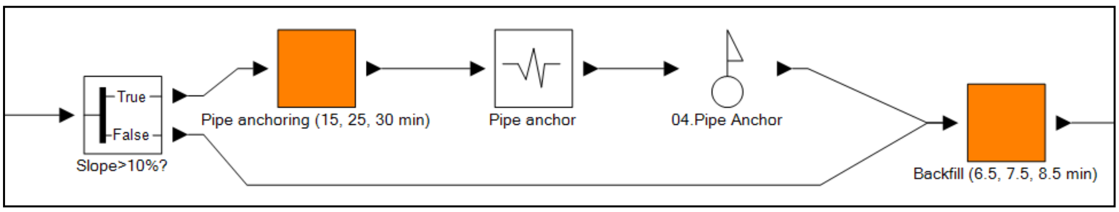

Figure 4: Conditional Decision Element for Installation of Pipe Anchoring

Table 4: Schedule of Key Activities

Key activity	Mean of Event End time*			Standard deviation
	minutes	hours	days	minutes
Mobilization	556	9.3	1.2	12
End of main cycles for all 8 sites	22,570	376.2	47.0	60
Installation of service connections for all 8 sites	30,929	515.5	64.4	485
Demobilization	31,228	520.5	65.1	537
End of restoration works	38,953	649.2	81.2	679

* Measured from the beginning of survey layout work

Compaction test FAILED for site3 and site4. Result received at time 13197.4
Backhoe is captured for recompaction of site3 and site4 at time 15910.7
Crew is starting service connections of site 1 at time 22610.6
Crew finished service connections of site 1 at time 22853.2
Crew demobilized at time 31035.7
Landscape restoration is finished at time 33778.9
Pavement restoration is finished at time 39016.2
Project is complete at time 39016.2 (Total of 81.2 working days)

```
//Coding of trace element for event of
compaction test fail{
Return "Compaction test FAILED for site"
& LX(1) & " and site" & LX(1) + 1 &".
Result received at time " &Timenow};
//Coding of trace element for project
completion{
Return "Project is complete at time " &
CSTR(Timenow) & " (Total of " &
Timenow/60/8 & " working days)"};
```

A resource is used in the model to control the activities of backhoe rather than to actually model the utilization of resources. For example, when a compaction test is failed, the backhoe is sent to the site for re-compaction. However, this activity only happens when the city crew moves between different sites, and therefore the backhoe is captured at the beginning of each site and released only at the end of each site. Higher priority is used for re-compaction activity to contact geo-tech engineering firm as early as possible and therefore to minimize delay in the project schedule. Another resource is modeled for three laborers of the city crew to check utilization of them.

5. SIMULATION RESULT ANALYSIS

Each simulation model was executed for 100 runs to provide users with statistical output such as project duration and cycle times. Also, impact of the 10% failure probability of compaction test on the total project duration was analyzed.

5.1. Project Duration

Based on 100 runs of simulation, the total project duration is found to be the mean of 38,953 minutes (649.2 hours, or 81.2 working days assuming 8 hours per day) and standard deviation of 679 minutes (See Figure 5). Schedules for other key activities are modeled as shown in Table 4. 95% confidence interval for the mean of total project duration was calculated to be between 38,824 minutes and 39,082 minutes. Although the total project duration and event end times of key activities can be used as effective information for schedule estimate, the user cannot know when the failures of compaction test happen and where they impact on the overall project schedule.

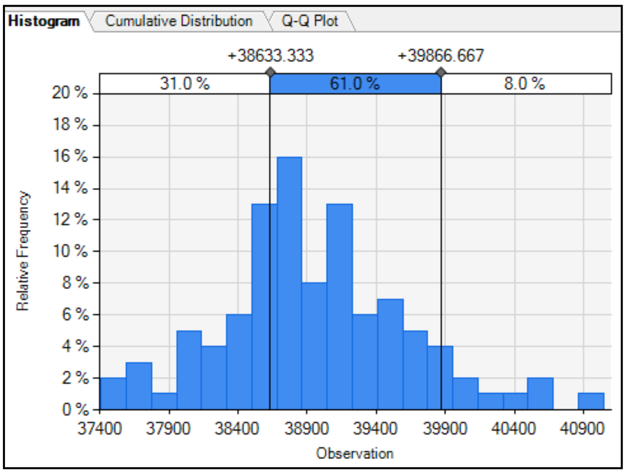

Figure 5: Total Project Duration (minute)

5.2. Cycle Time per One Pipe Length

Cycle time per each pipe length can be more desirable for more accurate schedule estimate, because it is not impacted by the 10% of probability of compaction test failure. Cycle times of this model are measured at the end of each main cycle. Although each site has different conditions and therefore the cycle time can vary, DES analysis can be used as an effective tool for schedule estimate with all the different conditions taken into the consideration. The result of cycle time is shown in the histogram, Figure 6. The mean of cycle time was measured to be 64.3 minutes per each pipe length (6.1m, 20 feet) with standard deviation of 0.14 minutes. 95% confidence interval for the mean of cycle time was calculated to be between 64.27 minutes and 64.33 minutes.

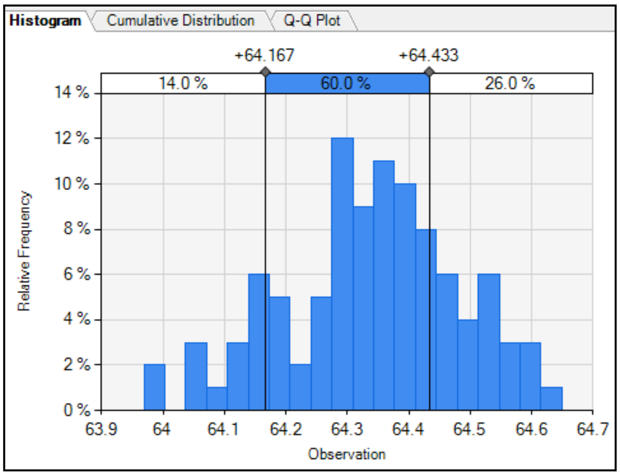

Figure 6: Cycle Time per One Pipe Length (minute)

5.3. Impact from the 10% Failure of Compaction Test on Project Schedule

As previously discussed, impact on the total project duration that can be caused by 10% failure probability of compaction test can be analyzed in this model by checking the result from 100 runs. For this purpose, two different scenarios were tested, Case 1) with 10% probability and Case 2) with 0% probability of test failure. The impact on project schedule was measured by subtracting the total project duration of Case 2 from that of Case 1. The result of this analysis is shown in Table 5.

Table 5: Calculating Impact of 10% Probability of Compaction Test Failure

	Case 1		Case 2		Impact
Minutes	38,953	-	38,827	=	126

Because the duration and number of compaction tests were modeled based on number of sites, not length of sites, the impact can be understood as a percentage factor of project duration. In this case, the overall impact on the total project duration caused by 10% failure probability of compaction test can be calculated as 0.42%. (126 minutes / 30,373 minutes * 100 = 0.42%) Note that the only duration between the end of mobilization and the end of service connection installations for all 8 sites are used in this calculation, because the other activities outside the duration happen independently and therefore do not need to be considered.

5.4. Utilization of Resources

Utilization of resources is not discussed in this study because the City usually hires, or utilizes, enough number of laborers and equipment and therefore resources do not play important role in the model.

5.5. Summary of Results

Based on the historical data and his own experience, the foreman of the city uses '40 meters per day' as his own 'rule-of-thumb', which is a typical pipe installation distance per day (m/day). This rule can be used as an expert's opinion for the purpose of validating the model developed in this study. Because his rule-of-thumb is used to estimate construction schedule of main cycles only, the duration only between the end of mobilization and the end of main cycles of all 8 sites was considered for the validation. Total length of the project is 1,855 meters and the duration was modeled, based on 100 runs, to be 22,005 minutes, which is 45.8 days. Thus, the average distance of pipe installation based on the model is calculated to be 40.5 meters per day, and it is found to be significantly close to the foreman's rule-of-thumb, 40 meters per day.

The result demonstrates that the model developed in this study can be considered satisfactorily accurate in forecasting duration of main cycles of watermain construction. Other parts of model can be validated in the further study.

6. LIMITATIONS

One limitation of this study is that the simulation model cannot consider every potential scenario such as bad weather condition, employees' vacation and unexpected delays. For instance, the actual crew of the construction experienced a unexpected delay that was caused by heavy rain during winter season. The crew had to keep dewatering trenches throughout the pipe installation, which significantly affected the construction schedule. Also, the crew sometimes encountered old underground utility lines which had not been recorded in the municipality's as-built drawings.

The simulation model presented in this study assumes a continuous work flow. Numbers of days are calculated by converting the simulation time, i.e. minute, to days using 8 hours per day. In reality, however, additional minor activities can happen at the beginning and end of a day or before and after a lunch break, which include equipment inspection, site cleaning, and moving between site and site office.

Finally, before actually implementing this type of simulation for schedule estimation, each simulation model needs to be validated and gain support from the municipality, which a simulation model would be implemented for, and its in-house experts including construction crew supervisor.

7. CONCLUSION

Underground watermain construction is one of the most common design and construction works of municipalities, civil engineers, and civil contractors. However, practitioners usually use their own experiences or historical data collected by their organizations to estimate construction schedule. This paper presents a Discrete Simulation Model developed in Simphony.Net 4.0 that can help decision-makers to more accurately estimate construction schedule and to review the milestones of schedule in detail. DES analysis was also presented to provide users with statistical output such as project duration and cycle times. The result of this study demonstrates that the simulation model can be considered satisfactorily accurate in forecasting duration of main cycles of watermain construction.

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