University of Alberta

Productivity Analysis of Closed Circuit Television (CCTV) Sewer Mainline Inspection

by

Reza Navab-Kashani

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Abstract

Municipal underground infrastructure such as sewer mainline has an important role in public health and environmental sustainability. In the event of a system failure the consequences can be catastrophic to both municipalities and customers. For an effective sewer pipe asset management program and a comprehensive understanding of the sewer mainline physical condition, municipalities are required to have regular mainline inspection programs and monitor the deterioration trend of their drains and sewers. The most common inspection approach is closed circuit television (CCTV). Annually, large cities in Canada spend millions of dollars on CCTV inspections, and contractors should also hire trained personnel and expensive equipment to provide the CCTV service.

Planning CCTV inspections for the network requires production rate information for resource planning and project management. Also, a realistic knowledge of the production rate helps avoid delays in project completion, cost overruns, claims and disputes. However, Productivity analysis for the CCTV process has not been conducted and the influence of CCTV productivity factors which affect the production rate is not fully understood to date. Therefore this thesis focuses on conducting productivity analysis for the CCTV operations through two phases: 1) developing the production rate for CCTV inspection and analyzing the effect of the weather condition and ambient temperature on its productivity, and 2) reviewing the CCTV process through a time study, with the aim of minimizing the CCTV cycle time and productivity improvement.

Since traveling and locating manholes in the CCTV inspection process were defined as the most time consuming tasks, the traveling salesman problem (TSP) optimization method was used to optimize the CCTV trucks driving patterns. The influence of route optimization application in the CCTV process was analyzed in both daily activity and project planning stages.

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Glossary

AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion
ATSP	Asymmetric Traveling Salesman Problem
BIP	Binary Integer Programing
CB	Catch Basin
CCD	Changed-Coupled Device
CCTV	Closed Circuit Television
CDF	Cumulative Distribution Function
COE	City of Edmonton
CVRP	Capacitated Vehicle Routing Problem
df	the degrees of freedom
EM	electromagnetic
FOG	fat, oil, and grease
ILP	Integer linear Programing
LP	Linear Programming
MIM	Municipal Infrastructure Management
MS	means squares
MTV	Mainline Televising
NASSCO	National Association of Sewer Service Companies
NP-hard	Non-deterministic Polynomial-time hard
OCA	Office of the City Auditor
PACP	Pipeline Assessment Certification Program
PCU	Power Control Unit

PDF	Probability Density Function
QA/QC	Quality Assurance and Quality Control
RSMeans	Robert Snow Means
SOP	Sequential Ordering Problem
SQL	Structural Query Language
SRM	Sewerage Rating Manual
SS	Sum of Squares
TSP	Travelling Salesman Problem
VRP	Vehicle Routing Problem
VRPTW	Vehicle Routing Problem with Time Windows
WAS	Work Analysis Study
WRc	Water Research Centre

Chapter1: Introduction

1.1 Background

Municipalities are responsible for installing and maintaining their underground infrastructure including sewer lines at an adequate level of service to maintain the public's health and protect the environment from pollution. However, large Canadian cities' infrastructures are aging (Federation of Canadian Municipalities, 2012) and the municipal governments need to have a sufficient plan for maintenance and replacement of the current deteriorated waste water system (Allouche & Freure, 2002). However, limited funds and budgets in municipalities brought challenges in sewer mainline management and finance restoration of the aging infrastructure. Some municipalities delay their maintenance, replacement, and construction costs for future years, which has resulted in boosting the cost of repairing the system from an estimated amount of $3 billion in 1985 to $31 billion in 2007 (Mirza, 2007). If municipalities do not establish an effective asset management plan, they will confront significant challenges in water and waste water management. In this case, they will be expenses required to replace their existing sewer network in the future (Federation of Canadian Municipalities, 2012).

Deterioration, climate, geological conditions, and changes in application affect the condition of municipal infrastructure. Due to this, the National Research Council Canada through Municipal Infrastructure Management (MIM) Framework suggests that Canadian municipalities regularly review and survey the condition of their assets and provide a decision-assistance tool in order to void the consequences of service failing (Vanier, et al., 2009). Providing a decision-assistance tool requires collecting the physical attribute of assets, predicting the service life cycle cost by condition assessment methods, compiling maintenance strategies, and having appropriate economic evaluation tools.

Many approaches are available for sewer mainline inspection, such as electromagnetic inspection, laser inspection, and ultra/infra spectrum inspection; however, CCTV is one of the most preferred approaches among municipalities in comparison with other approaches in collecting pipe inspection data and surveying pipe physical conditions (Allouche & Freure, 2002). The reason of CCTV popularity is the recorded CCTV videos can be reviewed by experts at any time it is needed. Also, existing pipe assessment protocols support data collection through CCTV inspection. Therefore, the application of CCTV assessment is widespread.

The City of Edmonton manages a large sewer infrastructure network valued at more than $14.9 billion (The city of Edmonton, 2012). In order to preserve the service capacity and avoid the consequences of mainline failures, The City plans and executes underground pipe CCTV inspection on a regular basis from numerous sewer mainlines (including storm, sanitary, and combined) from thirty-three different industrial, commercial, and residential neighborhoods periodically. Annually, The City of Edmonton spends large amounts of capital and time in order to collect the sewer CCTV data. In addition, significance is given to the proper training of the operators based on inspection standard upgrades to provide better CCTV services. Therefore, the CCTV inspection is sensitive to new alternatives in productivity enhancement.

Televising gravity sewer mainline network, a crawler which carries a remote directional and zoom camera lens is driven inside pipes through the access of manholes. During CCTV inspection, the mainline must have low flow and be free of large objects. Therefore, for urban sewers and drains, a flusher truck is used to flush out the dirt inside sewer mainline and open the path for the crawler. The crawler is driven inside the host pipe by a control console in a CCTV truck and records the operational and structural defects inside the pipe (see appendix A). Possible defects include a wide range of deficiencies that are defined by sewer mainline assessment protocols and are recognized by direct visual inspection.

Higher productivity in CCTV process can help contractors execute CCTV projects effectively and save time and resources of the municipalities. As a result, IVIS Inc., one of the largest CCTV service providers in Edmonton, in collaboration with the University of Alberta defined a study to have a better understanding of the CCTV inspection process and improve its productivity. Support for this study included funds from the MITACS-Accelerate program, and in-kind contributions from IVIS, Inc.

1.2 Problem Statement

Although the principle of using a camera-crawler for pipeline inspection appears to be straightforward, actually conducting the CCTV process in network scale results in dealing with numerous challenges and constraints that cause complexities in CCTV project management. Selection of appropriate CCTV equipment, equipment breakdown, locating the manholes, traveling, obstacles inside pipes, redo requests, and weather condition are some of the challenges that inspection contractors face on a daily basis.

Every year, thousands of human-hours and large amount of capital are spent on CCTV sewer inspection; however, there are no official productivity standards. Currently, operators televise mainlines based on their own experience, and frequently the procedure is conducted inefficiently. Productivity data is fundamental information for project management actions which consists of estimating, scheduling, statistical analysis, and project control. Lack of understanding of the CCTV inspection operations can result in delays in completion, cost overruns, claims, and disputes. As the procedure is not executed in a controlled environment, a certain level of CCTV productivity (performance quality) cannot be guaranteed for different locations or weather conditions. Understanding the CCTV inspection process and the effects of the productivity factors on the production rate can help the CCTV service providers plan their resources efficiently and run their projects more economically.

To understand the sensitivity of the process to different productivity factors, it is essential to develop a productivity study for current CCTV inspection process. Further, there is a need to develop alternative solutions for the CCTV inspection process to improve its productivity. Such productivity study would need a comparative solution database, where alternative solutions can be evaluated for a more efficient sewer mainline inspection.

The activities causing delays in the process' production have not been investigated to date, and therefore effective alternatives to reduce the inspection cycle time have not been established.

Such a study can help understand the involved CCTV variables, identify the encountered problems during the CCTV inspection, and lead to alternative solutions to improve the productivity. The result of this study would enable savings in municipalities as the biggest owners of underground infrastructure and public payers of the CCTV cost in long-term.

1.3 Research Objectives

IVIS Inc. and the University of Alberta partnered to initiate a research project to establish the current CCTV inspection process's productivity and also to develop methods to improve the current process's productivity. The project also involves The City of Edmonton, Drainage Services, who provided a portion of the required data for the study i.e. manholes' coordinates and several daily reports. For avoiding bias in productivity study, the initial data which used for this study was planned to be collected by different CCTV operators and from different neighborhoods.

Based on the reviewed data, the main objectives of this project can be described as 1) Calculating the existing production rate for CCTV inspection in Edmonton and improving the current CCTV production rate, 2) Analyzing the effect of weather conditions and ambient temperature on the CCTV process, 3) Identifying activities in the CCTV process causing delays in production rate by analyzing the procedure, and 4) Enhancing the CCTV performance by implementation of the existing production rate and optimization methods.

This thesis is aimed to provide some basic concept about productivity, work study, CCTV procedure, and mathematical optimization in the Chapter 2. Also, The main objectives of this study are reviewed in two parts: 1) Experimental and numerical studies on production rate in sewer mainline CCTV inspection, discussed in Chapters 3 respectively and 2) Suggestions for efficiency improvements through time study and route optimization in sewer mainline physical condition assessment, provided in Chapter 4. This thesis finishes with chapter 5 which provides a conclusion of this thesis and recommendations for future study.

1.4 Research Overview and Methodology

This thesis includes two major sections that focus on: (1) analyzing the production rate for the current CCTV inspection practice, which includes an analysis of the influence of weather conditions and ambient temperature on the production rate; and (2) optimization of the CCTV inspection performance and improvement of the CCTV productivity.

Calculating the production rate, many approaches are available such as interviewing experts, data sampling, and simulation modeling. However, the most adequate method for our objectives is to monitor the process in different work conditions and analyze the productivity data, although collecting continuous experimental data might be expensive (Woldesenbet, et al., 2012).

This Study analyzed approximately 2,000 mainlines with a total length of more than 120 km from various locations in Edmonton to define the existing CCTV production rate. The operations were conducted from November 7th, 2011 to January 11th, 2013. The monthly, seasonal, and overall CCTV production rates were calculated using Structural Query Language (SQL) in a relational database. Furthermore, internal connections between the CCTV performance database and daily weather information database were used to develop a regression between the CCTV production rate and the ambient temperature, weather condition factor as well as snowfalls.

Optimizing the CCTV inspection process contains three steps: a work study as an initial, identifying the areas that inhibit the production, and finally developing and implementing alternatives for productivity enhancement. Work study identifies the existing procedure by recognizing the CCTV work units (work components) and the work flow (predecessors and successors) in the CCTV process. By calculating the time information of CCTV work components via work sampling method and mapping the existing sequence of work units, the CCTV work model is understood and the areas delaying the productions are identified. Then, alternative solutions which would be confirmed by experts and technical engineers are developed. After verification of the result, the new production rate is compared to the existing production data to calculate the level of improvement. If the level of improvement satisfies the economic and operational concerns, the new work system is established.

Developing a database to store the collected time data and performance information helps to have a sufficient data organization and effective analysis of the existing work system. Therefore, In this study a relational database recording mainline properties such as pipe material, depth, size, and service type; operators' names; type of equipment; operation date; and the work components' duration for CCTV inspection of mainlines has been developed. The database tables were connected to each other to retrieve the needed information for analyzing the CCTV performance as presented in Figure 1.1.

Enhancement are implemented which aim to increase productivity and efficiency, reduce cycle time, reduce product cost, and raise employee satisfaction. The enhancement solution focuses on elimination or reduction of extra work or non-value-adding elements in the process, combining multiple elements in one, and rearranging the work elements in order to have a more rational sequence operation (Groover, 2007). Since travelling and locating manholes have been identified (which will be elaborated on later) as work-delays in CCTV operations, this study investigates the application of the Travelling Salesman Problem (TSP) as a travelling optimization technique. As part of the methodology of this study, a brief introduction on TSP is presented in the followings.

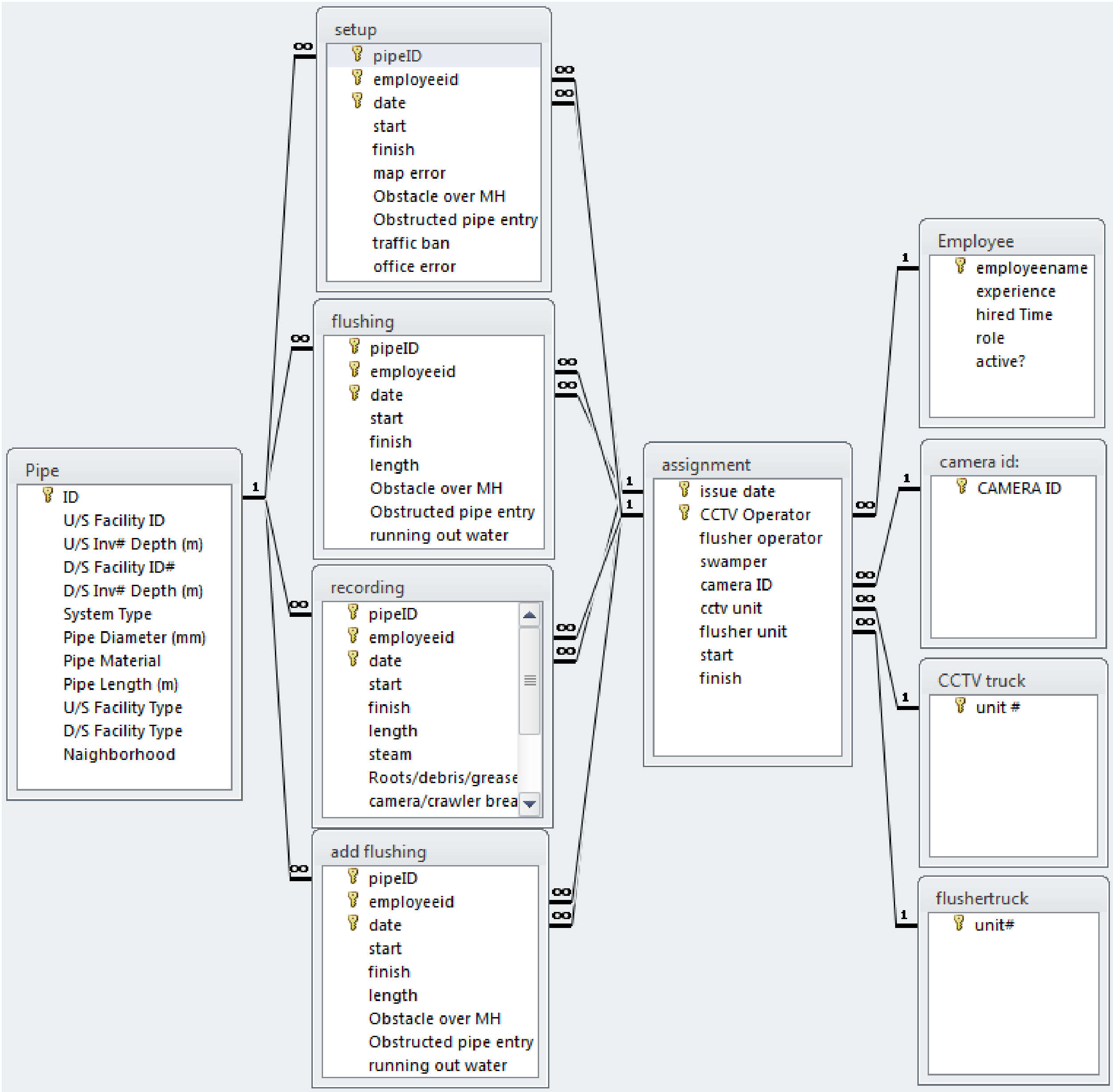


Figure 1.1: The Relationship between Select Designed Tables in the Developed Database

The possible number of path between “n” locations (manholes) is n*(n-1)/2. TSP modeling can help to find the best way to travel between the locations. TSP is a well-known mathematical problem in combinational optimization studied in Operation Research. Given a list of upstream manholes that need to be located and their pair wise distances, TSP calculates the optimal path or the shortest possible route that visits each manhole exactly once and at the end returns to the origin point (Applegate, et al., 2011).

Since the effect of TSP optimal solution, which uses linear distance for its optimization, on road condition is unknown, this study applied TSP method to CCTV truck movements in consideration of both road distances and linear distances between destinations. Road distance is defined as the road driving distance considering all the road constraints such as traffic flow, intersections, and barriers, and the linear distance would be the air distance between two points regardless any road constraints. By comparison of the resulting distances, it is possible to analyze the effects of road constraints on the optimal path retrieved by a TSP solver. To find the linear distance between locations, latitude and longitude information for each manhole is used. To calculate the traveling distance and assess the traveling time in the CCTV process, The City of Edmonton provided the manhole's coordinates to this study.

The formula that can be used to calculate the linear distance between two far points on the earth surface (regardless of any barriers) is known as the Haversine formula that is as the following. However, it is not necessary to use the formula to calculate the distances between two points in a small area or a neighborhood.

Equation 1

$$d = R * 2 * \operatorname{atan}\left(\frac{\sqrt{1-a}}{\sqrt{(a)}}\right)$$

Where:

$$a = \sin^2\left(\frac{\Delta lat}{2}\right) + \cos(lat1) * \cos(lat2) * \sin^2\left(\frac{\Delta long}{2}\right)$$

d = the distance between the two points of interest with known latitudes and longitudes,

lat1 = the latitude of the first point,

lat2 = the latitude of the second point,

Δlat = the difference between the two latitudes,

Δlong = the difference between the two longitudes.

“R” is defined as the earth’s radius, which is between 6356.752 and 6378.135 km. If the distance in kilometers is wanted, it is common to use the acceptable value of 6371 km as R. In order to calculate distances in miles, R is defined as 3,958.756 M and for nautical miles, R is defined as 3,440.065 NM.

This study uses the TSP to generate the optimal path with its optimal distance and compares them with the actual pattern of movements. The model evaluates how much the optimal solution saves in traveling time and increases the productivity at the daily activity and project scales.

To find the distance between locations, latitude and longitude information for each manhole is used.

1.5 Description of Chapters

This thesis which includes two journal manuscripts (Chapters 3 and 4) is organized in six chapters as follows:

- Chapter 1: Introduction – provides a background on CCTV sewer inspection, problem statement, research objectives, research overview and methodology, and thesis organization.
- Chapter 2: Literature Review – describes The CCTV inspection requirements (human resource and equipment), the principles in productivity and work system framework, and reviews route optimization methods.
- Chapter 3: CCTV Production Rate Analyses – studies the existing CCTV work performance includes an introduction; research background; the study overview and data collection; description of CCTV process: work preparation, pipe inspection, and work completion; the existing production rate; influence of weather factors on CCTV pipe inspection; ANOVA analysis; and conclusion.
- Chapter 4: CCTV Productivity Improvement- provides an improvement solution and calculates the impact of the improvement solution on the CCTV inspection process and includes the folliwng sections: an introduction, the study methodology, the work and time analysis, the CCTV process improvement by application of TSP, and conclusion.
- Chapter 5: Concluding Remarks and Recommendations – summarizes the findings of the research and provides recommendations for future research relative to this topic.

Chapter 2: Literature Review

2.1 Introduction

This chapter provides a literature review on CCTV inspection, productivity, work system, and TSP travel optimization methods. The CCTV Inspection reviews the CCTV process and describes the CCTV inspection employees and needed equipment. The Productivity section comprises terminological definition, calculation methods, parameters, and a framework for the productivity study. Work System Framework section provides the definition and explanation of work system, work flow, and patch processing. The Route Optimization part provides a literature review about truck movement optimization and TSP method and reviews the methods and existing algorithms to solve TSP models. At the end, this capture is summarized in Conclusion.

2.2 CCTV Inspection

Today, an efficient CCTV data collection system is beneficial in urban sewer asset management. However, The CCTV inspection requires special equipment and well-trained personnel based on the applied sewer mainline assessment protocols. Sewer mainline assessment protocols are systematic methods, developed in order to have a consistent classification of the existing sewer mainline condition data and effective prioritization of mainlines for rehabilitation or replacement activities (KhazraeiAlizadeh, 2012). A sewer mainline condition assessment protocol establishes the existing asset condition and provides a standard to compare the asset conditions and predict the deterioration rates for estimating replacement or maintenance costs, remaining life cycle, and budgeting for the future (Vanier & Danylo, 1998). Some of these protocols are accepted internationally, such as the Water Research Centre (WRc)'s Sewerage Rating Manual (SRM) (WRc, 2001) and the National Association of Sewer Service Companies (NASSCO)'s Pipeline

Assessment Certification Program (PACP) (NASSCO, 2001). Some of other protocols are developed based on local needs such as The City of Edmonton (COE)'s protocol (The City of Edmonton , 1996).

The CCTV personnel include the CCTV crew and the Quality Assurance and Quality Control (QA/QC) personnel, who generate the CCTV inspection files and review them before storing them in the corresponding database.

Often, the CCTV inspection requires one crew with four people, including one flusher operator, one CCTV operator, and two general swampers to support the operators.

The flusher operator runs the flusher unit and flushes the mainline, vacuums the excess water in the manholes, disposes contaminated flow after the operations, and fills up the flusher tank with clean water (IVIS Inc., 2013).

CCTV operators locate the manholes, setup the crawler, drive the crawler, make daily reports, and record videos (The City of Edmonton, 2009). Swampers help with traffic control, preparing the manholes for operation, locating the crawler and flusher nozzle inside the mainline for the CCTV operation and flushing. Since a CCTV operator needs to inspect clean mainlines, with low flow stream, cooperation between the crew members in the field is critical because it affects the CCTV production rate.

Major equipment in the CCTV process includes a CCTV crawler, a CCTV mobile unit, and one hydrovac combination unit (flusher unit). The description of the CCTV equipment is as the followings.

The first application of CCTV technology was introduced in 1958 in Germany. The first camera used for this purpose was built by cathode-ray technology that limited the performance of CCTV especially in aggressive environments. Years later, it was advanced by application of Changed-

Coupled Device (CCD) technology, the major expertise for digital imaging, in the 1980s (New Zealand Water and Wastes Association Inc, 2006). Today the cameras are smaller and more efficient. A variety of CCTV equipment is used for CCTV inspection, which is waterproof or brushless and are compatible with different pipe sizes. In this study, two types of camera-crawlers which are commonly used in practice are introduced: Pan and Tilt cameras for main sewer inspection and Lateral and Mainline Probe.

The Pan and Tilt camera lens is installed on a crawler and can be rotated inside the pipelines. Crawlers likewise have an adequate lighting around the lens's module to light approximately 48-inch or larger pipe diameter. Crawlers also are able to focus automatically and zoom in specific areas in case that crawler is not able to move forward. In order to have high quality images and appreciate the details in CCTV inspection, the camera lens have to be set in the middle of mainline. The transporter of crawlers could be either wheels or track chain, depending on the inspection requirements. Figure 2.1 shows an example of a crawler using different sets of wheels for various pipe conditions and sizes. The equipment shown is a WTR III crawler from Cues Inc.

A TV cable connects the crawler's connector and the modified TV system or an electrical wiring module in a mobile CCTV truck together. The images are recorded and overlaid with technical text during the televising operation, and the standardized reports are generated automatically by a computer application.

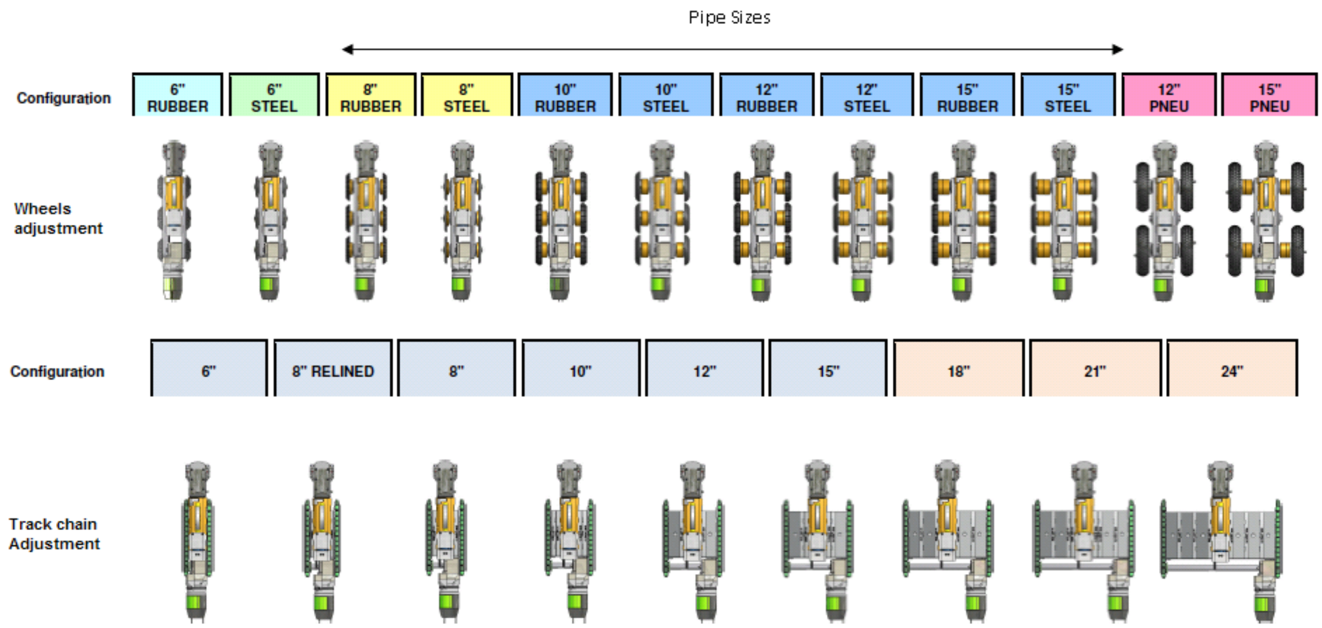


Figure 2.1: WTR III Crawler Adjustment (CUES Inc., n.d.)

The application of this type of camera is to televise pipelines with diameter size of 4 inches and larger. In case that the lines are too steep but accessible from two points, the crawler can be attached to a connect component and pulled by a winch while it is inside the mainline.

Another type of CCTV camera-crawler is the Lateral and Mainline Probe. Figure 2.2 presents a picture of the Lateral and Mainline Probe that is produced by CUES Inc. This equipment is a combination of mainline inspection equipment and lateral televising tools. The crawler carries two separate cameras, one is fixed and placed on the front head with the ability of rotation, and another camera is mounted to a semi rigid cable with the capability of 60 meter traveling inside the laterals. The crawler can fit in a six-inch to 30 inch pipe line and record three to eight-inch lateral services. In order to fit in different pipe sizes, the wheels are changeable. The front and lateral camera images are switched by CCTV operator via the control console, so the operator is able to choose the input of recording devices.

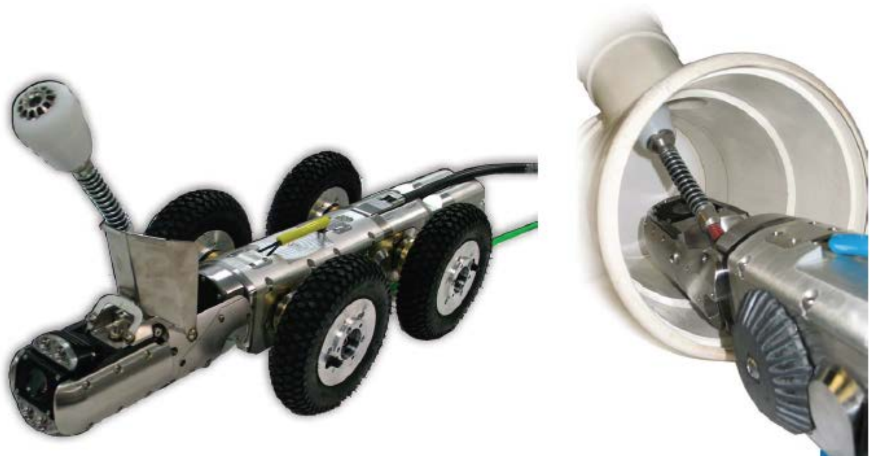


Figure 2.2: Lateral and Mainline Probe II (CUES Inc, 2011)

CCTV unit/truck is a modified vehicle that is designed specifically for the CCTV operation. A schematic view of the CCTV truck is shown in Figure 2.3. The truck is facilitated to control the camera crawler within the pipelines, save the televising images, and produce the standardized reports that are required by pipeline investigation protocols. In the truck, a heavy duty TV cable reel is installed to feed the required cable for the crawler. There is also a small movable pedestal crane, and it is used for the purpose of transferring heavy equipment inside manholes, if required. In addition, a workbench and some storage cabinets are placed inside the truck for quick maintenance, crawler adjustment, and storage of tools and other supplies. Table 2.1 shows a list of CCTV equipment that a CCTV truck may carry.

Almost one third of the truck space is adapted as a small working office for monitoring and governing the CCTV process (Figure 2.4). The working area inside the truck typically contains a computer, two monitors, recording equipment, data system, steerable Power Control Unit (PCU), generator panel, breaker box, controller console, and power transporters.

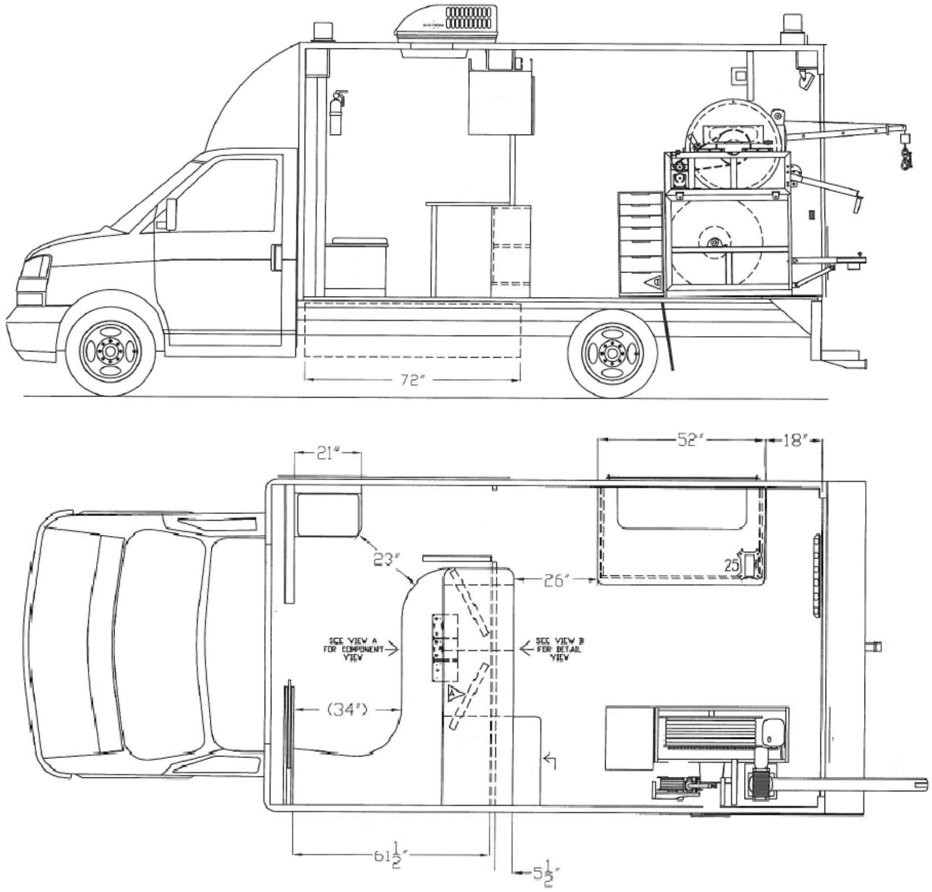


Figure 2.3: Schematic View of a CCTV Truck (Cue Inc., 2011)

Figure 2.4: Working Area inside a CCTV Truck

Table 2.1: List of CCTV Equipment inside a CCTV Truck

NO.	Tools / Equipment Description	Quantity
1	Canvas Tarp	1
2	Traffic Cones	8
3	Safety Signs (Men working)	2
4	Snap Ring Pliers	1
5	Yellow Poly Rope	1
6	25 pc Hex Key set	1
7	5 piece Pliers set	1
8	7” Strait Jaw Vise Grip	1
9	Cutter Wire Striper	1
10	Utility Knife & Blades	1
11	6”, 10” and 12” Adjustable Wrench	1
12	12 piece Screwdriver Set	1
13	Nut Driver 5/16”	1
14	Tape Measure	1
15	Pick	1
16	Sledgehammer	1
17	2 Way Mallet	1
18	Multimeter	1
19	Heat Gun	1
20	Walkie-Talkie radios	2
21	Gas Detector	1
22	Measuring heel	1

The CCTV operator is required to follow the safety protocols such as filling out the paper work for hazard assessment and place traffic control devices at the upstream manhole location in accordance with prevailing regulation. Once the flushing operation is complete, the CCTV operator sets up the CCTV software that makes the report from the CCTV images. First, the reporting software is fed with general information about the mainline. Next, the manhole to the pipeline invert is inspected to check if the CCTV operation is possible and the access path to the mainline is not blocked. Finally, the CCTV crawler is placed inside the mainline. It should be noted that the distance counter is set up to begin at 1.5 m instead of zero to account for the manhole diameter, since the distance is measured from the center points of the two end manholes. In case the crawler path is blocked by an obstacle, debris, or rocks, a short distance after the obstacle can be televised by the zoom feature and the rest of the pipeline will be televised from the downstream manhole. If the operation is not possible from either downstream or upstream directions due to encrustation/protruding, the CCTV mission is cancelled or postponed for after milling services have been completed.

For CCTV mainline preparation, a Hydro-Vac (flusher) unit is required Flusher unit is a large truck that is produced in different tank capacities such as 3.8, 6.9, 8.4, 9.2, and 12.2 cubic meters for sewer cleaning (VAC-CON, 2010). The main propose of using this equipment in the CCTV procedure is flushing and cleaning mainlines and vacuuming the excess flow from inside the manholes.

Figure 2.5 illustrates a flusher truck from Vac-Con Inc. The truck’s features are numbered and defined underneath the picture. The flushing operation can be controlled from the console that is placed in front of the truck. The truck has a high capacity water pump to vacuum extra fluid and dirt through an expandable hydraulic boom which can rotate up to 170 degrees. The trucks carry 5,700 to 7,500 liters of water and are able to pump up to 250 liters per minute at approximately 13.8 MPa for cleaning the pipelines (Town of Amherst, 2008).

1-	Hydraulically Operated, Front-Mounted Hose Reel
2-	Operating Controls In Front
3-	Hose Rewind Guide
4-	Connection for High-Pressure Handgun
5-	Polyethylene Water Tanks, Low Center of Gravity
6-	High Capacity Water Pump
7-	Lubrication Chart
8-	Debris Body Dump Control on Side of Truck
9-	Centrifugal Compressor, With Welded Corten® Steel Fans
10-	Centrifugal Separator & Clean-Out
11-	Hinged Door, Fully Opening With Hydraulic Door Locks
12-	Butterfly Drain Valve & Hose
13-	Corten® Steel Debris Tank
14-	External Load Indicator
15-	Exclusive Automatic Vacuum Breaker Shut Off System
16-	Auxiliary Engine for Independent Water System Operation
17-	Hydraulic Boom Rotates Up To 270º
18-	Weather-Tight Tool Boxes with Locks
19-	Transport Cradle for Boom

Figure 2.5: Hydro-Vac Truck (Vac-Con ®, n.d.)

A flusher nozzle is connected to the flusher Truck's hose to flush the dirt and debris out of the mainline. Flusher nozzles are built in different shapes and sizes for different purposes. Figure 2.6 presents different types of flusher nozzles available in the market.

The nozzle head or the pattern of the water thrust in flushing operation is chosen based on different physical conditions of the pipe. For example, if a pipe is in poor conditions, the water pressure or the sharp water injection can damage the interior surface of the pipe or break the pipe. In such situations, the selection of the nozzle requires extra care, and thereby low pressure flushing is applied. The nozzle is connected to the flusher jetting hose and placed into the downstream manhole. The nozzle injects the water at high pressure and high flow rate and quickly cleans the obstructions inside the pipelines. Some nozzles come with rotating chains to cut off accumulated debris such as sand, silt, grease, and rocks or roots in the situation that pressured water cannot clean the mainline.

Figure 2.6: different types of flusher nozzle (Keg TechnologiesInc., 2013)

Storm, sewer, and combined pipeline cleaning operations usually require water pressures between 8.3 to 27.6 MPa. The service type of mainlines determines the pattern of water spray and the required angle of the thruster (see Figure 2.7). For example, a thruster with a 25-degree angle is used in a plugged line situation for operations more than 45 meters; or, the thruster with a 35-degree angle is designed for runs between 30 and 45 meters long (Ultimate Washer Inc., 2012). Some nozzle types are for general cleaning purposes; they are designed with a combination of different patterning angles (see the Figure 2.8).

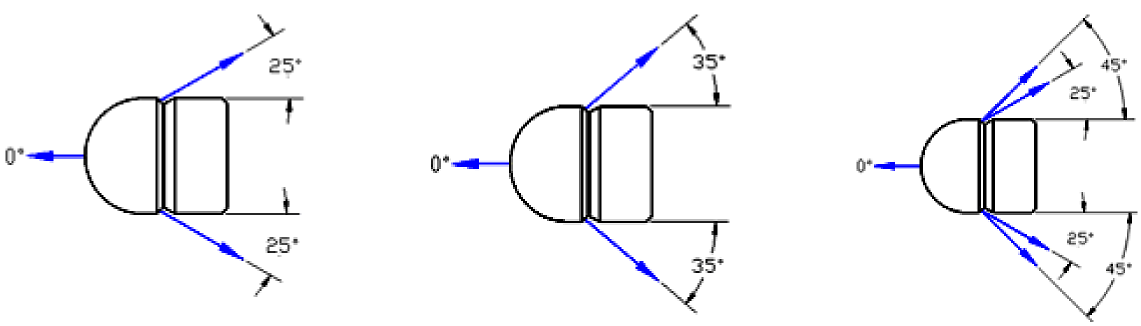


Figure 2.7: Different Patterning Angles in Flushing Nozzle (Ultimate Washer Inc., 2012)

Figure 2.8: The Placement of Nozzle inside a Pipe (Town of Amherst, 2008)

The flusher operator locates the operational manhole and places the hose reel above the manhole. Then, the manhole cover is removed and the direction and the volume of the flow are confirmed. The nozzle or the hose is lowered into the line that needs flushing. If a significant amount of debris is inside the pipe, vacuum tubes must be set up to suck out the excess flow. Flushing is started from one manhole to another through the pipeline to flush out all the dirt. If the excessive debris is noted after the first flushing operation, the pipeline must be flushed again. Thereafter, the flusher operator is required to stand by during the televising process and do extra flushing in accordance with the command of the CCTV operator.

2.3 Productivity

In a process, productivity is defined as the ratio of work output to work input. In order to monitor the productivity, it is needed to control the inputs and outputs of the work system. Inputs of the work system include material, human resources, management system, and equipment. Money (cost/unit) can also be used as an input, since it represents the human resource and equipment costs altogether. The output of the system is the rate of production or service that the work system is designed for, which in this study is televising sewer mainlines in meter and generating its related reports and video. Therefore, the productivity can be defined in descriptive ways such as performance factor, production rate, and man-hour rate.

In a work system, productivity is an important metric as it explains the ways to increase the work quantity or quality without increasing cost, time, and resources (Kien, 2012). Traditionally, productivity is measured in two ways including measuring a labour or crew performance to finish a job unit or measuring the amount of the job that is done by a labour or a crew in a given time and place (Dozzi & AbouRizk, 1993). For the CCTV process, productivity can be measured in two units: man-hour to televise one meter of mainline (man-hour/meter) or the length (meter) of mainline that can be televised by spending one man-hour (meter/man-hour). For productivity measurements, the type of equipment or how the experienced crew is to achieve a certain production rate needs to be known. Therefore, the work parameters such as workers' experience, weather condition, and equipment used in a productivity study must be defined well.

Nevertheless, these parameters are not the only factors determining the production rates. Working methodology and work sequence followed to achieve a product or service are also critical considerations. Typically, each task performance contains two types of works including the basic productive work and excess non-productive work. The basic productive work refers to the minimum amount of work that adds value to the product or service that is requested by the client; however, excess non-productive work or non-value-adding task is defined as the physical or mental activities that could be necessary, but do not add any value to the end product or service (Carreira, 2005). Some examples for non-value-adding task include logistic operations, paperwork activities, maintenance, traveling, and repairing. The excess non-productive work mostly exists because of poor design of the procedure, utilizing inefficient methods, or human errors due to insufficient training (Drewin, 1982). In order to enhance the productivity and reduce the performance cycle time, it is needed to eliminate or minimize the excess non-productive activities from the entire work sequence. This background must be considered in any work improvement action such as re-engineering the functions or components of work, operation analysis, and work measurement (Groover, 2007).

For the CCTV inspection process, a wide range of non-value-adding examples can be identified, such as the activities to fill up the flusher unit's tank, traveling, and removing obstacles (snow, vehicles and so forth) to locate or reach the manholes or pipe inverts. However, beside eliminating or reducing the non-value added activities in a work system, the work flow and work methods can be monitored to find the deficiency in the practice and to enhance the productivity.

2.4 Work System Framework

Work System Framework can be described as a systematic method to understand and analyze of a current works operation at any level of details that is required and overcome the work issues. A work system is defined by studying two fields of (1) work methods and (2) work measurement, and improved by implementation of work management methods.

Work method explains the work components and the activities which need to be completed in order to produce the products or services that the work system is designed for. Defining the work methods, it is concerned how a job is accomplished and what resources are required (Lawrence, 2000). To do so, a work measurement or work study is used for determining the work elements, the required equipment and materials, the information that flow through the work, the work performance rate, and the needed man-hours to finish a workload, and relatively the standard time of the operation is calculated (Groover, 2007).

Improving a work system, the performance and work situations are analyzed and the most efficient way of resource application and shortest possible time to do a job is suggested. Some examples of work improvement methods include implementation of traditional management methods such as motivation and application of advance methods such as using simulation modeling, optimization, and automation methods. The improvement of work system results in designing a new plan, changing the product design, developing a new process, or modifying the existing process (Groover, 2007). The Figure 2.9 shows the work system framework methodology.

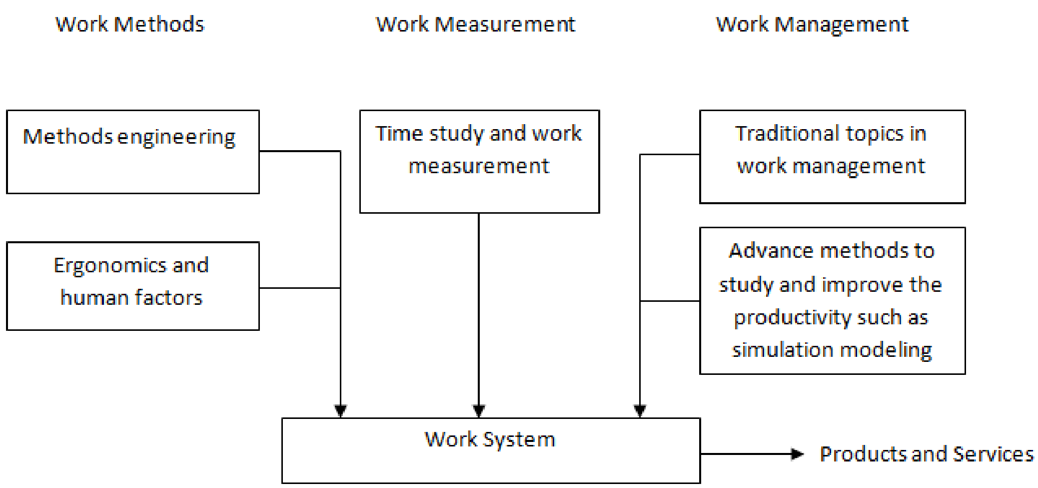


Figure 2.9: Work System Framework Methodology (Groover, 2007)

In order to define the CCTV work system, the concept of CCTV work flow and its production type is reviewed as the followings:

In the CCTV multiple operation work, there are different work units or stations that could be completed by different operators. Practically, if the work units are finished, relatively the whole job is accomplished. Work study in CCTV a mainline, it is needed to define the sequential operations and workflow through the CCTV process (Irwin, 2001).

In CCTV inspection procedure, there are different work units: Locating manholes, traveling, setup upstream manhole, setup downstream manhole, flushing, televising, and closure activities. The sequence of the work units and the CCTV workflow are shown in the Figure 3.3 for each mainline, and the description of each work unit is as the followings.

Locating manhole is the first step in CCTV process. Technically, the map of the location is provided by owner and the CCTV operators must reach the place of the desired manhole for inspection operation. Although the map of working area is provided by the project owner, locating manhole is a challenge and unpredictable task sometimes because of dealing with non-updated maps, plenty of snow or ice on manholes in winters, obstacle on manholes, and hard location to access. Occasionally, it needs extra work in office to clarify the location for the operators before taking any action.

CCTV and Flusher units travel between manholes in city's neighborhoods and reach mainlines for inspection. Moving huge trucks likewise flusher unit through urban streets deals with many challenges such as turning in narrow streets, hitting trees and branches, and confronting blocked or limited access roads. To tackle such problems, it is needed to develop an approach to minimize traveling time and avoid unnecessary traveling during project life cycle.

Before pipe televising, pipe preparation is required. The interior surface of pipes must be clean for CCTV operator to recognize the defects and to drive crawler through the pipeline easily. Technically, storm lines require more cleaning than sanitary lines as they convey the street surface water containing dirt such as leaves, limbs, and stones. Sometimes, pipelines need milling to cut off debris or roots that limit the crawler movement. The flusher truck operator inserts the nozzle of high pressure water inside the mainline and controls the speed of nozzle movement through the mainline by changing the water pressure.

After cleaning the pipe, televising phase starts. CCTV Truck which contains a control console board with a monitor and recording devices is usually placed on top the upstream manholes and the operator setups the equipment and makes the televising software ready before the start of the operation. A swamper locates the crawler inside the pipe and supports the crawler operator. If CCTV procedure is not possible from upstream manhole, the direction of the televising is changed from downstream to upstream although the movement of the crawler is slower and against the flow direction.

The CCTV operator drives the crawler through the mainline. When the crawler reaches defected areas or laterals, it is stopped for a close-snapshot. The process continues until the crawler arrives at the end of the mainline at downstream manhole. The recorded video is saved and the CCTV reports are created. At the end, the crawler is derived backward and the swamper takes the camera out. The crawler is cleaned and prepared for the next action. Finally, in closure phase, manhole lid is placed back and the warning signs or traffic cones that are used for traffic redirection or advance warning of hazards during road work are removed. At this stage, the next manhole is aimed and CCTV and flusher units are prepared to move.

CCTV production type is batch processing. In batch production, a combination of work units, material, products, information, and crew works to produce one unit of desired product or service constantly. Each product does not necessarily follow the practice’s previous character, and the production time may be changed case by case depending on the work situation. In batch processing, there is a gap between two operations. The gap may be due to the new physical setup, tools changing, equipment adjustment, or workers adoption for each stage. This changeover task is known as a non-value-adding task and must be reduced or eliminated to enhance the productivity (Daneshgari, 2010).

CCTV procedure's products are the mainline assessment reports and inspection video. For each sewer mainline, the work units of setup upstream manhole, setup downstream manhole, flushing, televising, and closure activities are undertaken, and between each CCTV work there are a time gap for traveling, locating manholes as lost production time. The CCTV lost production time during each production cycle may be changed based on the work situation. For example, traveling to different pipe location takes different time based on its location. The Figure 2.10 illustrates the sequence of traveling time followed by production run in CCTV process.

Calculating production rate, the entire production experiences must be taken into account and the average of all production rates must be understood to calculate the existing production rate. In the Chapter 3, the CCTV productivity is reviewed in details.

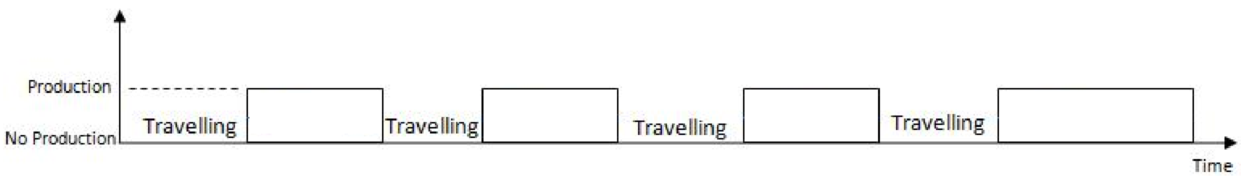


Figure 2.10: The Alternative Cycles of CCTV Work System Engaging in Batch Production (Groover, 2007)

2.5 Route Optimization

The application of operational research techniques and mathematical programing in procedure optimization has increased in real-world market during the last 50 years. The development of computer systems and mathematical modeling tools has also brought an opportunity to calculate new alternatives and solutions to improve performances within a short time. A large number of businesses have decreased the transportation costs by 10 to 20 percent and have benefited from 5 to 20 percent in cost saving by using optimization programing techniques in North America and Europe (Toth & Vigo, 2002).

The Vehicle Routing Problem (VRP) is a well-known problem in optimization. The problem is about obtaining the optimal path of vehicles traveling between a given set of customers and depots in such a way that the vehicles move in their minimum traveling length or traveling cost. The typical application of this VRP's solution is not only limited to delivery systems but in solid waste collection, street cleaning, school bus routing, dial-a-ride systems, and of maintenance or inspection units (Toth & Vigo, 2002).

VRP is defined in different variants based on the constraints and details that could be considered in the model. The constraints such as the attribute of the road network, number of available fleets or vehicles, number of depots, and number of customers or destinations (nodes) affect the characteristic of the optimal path and change the optimal sequence of movement. Moreover, considering practical problems such as each vehicle's load capacity or a specific operational pattern (e.g. having both load and unload services or having a certain operational time) on each node defines different classes and complicated VRPs which require different approaches to solve (Toth & Vigo, 2002).

In a study on gasoline delivery to gas station, first, the VRP was defined over a practical application in 1959 (Toth & Vigo, 2002). Then many linear (exact) methods and heuristic (approximate) methods were developed to solve the VRPs. In 1987, Laporte and Nobert classified the exact algorithm for VRP in three categories of direct tree search method, dynamic programing, and integer linear programing; the different formulations that result the exact optimum answer for VRP (Laporte & Nobert, 1987). In some cases that the calculation of exact optimal solution is hard and time-consuming, hence heuristic algorithms are applied. Heuristic algorithms are defined in tree classes of Nearest Neighborhood Algorithm, Insertion Algorithm, and Tour Improvement Procedures (Laporte, 1992). In 1992, Gilbert Laporte explained four different heuristic algorithms that are specified for VRP. The four algorithms include the Clarke and wright algorithm, the sweep algorithm, the Christofides-Mingozzi-Toth two-phase algorithm, and a tabu search algorithm (Laporte, 1992).

TSP is a simple model of VRP that does not consider many embellishments such as having depots, multiple fleets, traffic pattern, and precedence constraints. TSP involves retrieving the optimal sequence of movement through a set of nodes in consideration of the minimum traveling cost or traveling length in a way that each node only is passed once likewise (Rasmussen, 2011).

Theoretically, there are two ways to solve TSPs: Linear programming that gives the exact optimal solution and heuristic algorithm that calculates a reasonable solution (close to the optimal) in a short calculation time (Johnson & McGeoch, 1995). Linear Programming (LP) is a mathematical technique that contains an objective function and some constraint equations with variables. Linear programing is a way to find the minimum or maximum answer for objective function with changing variables through the constraint's equations. In other worlds, constraints define a feasible area, from which the linear method finds a solution to minimize or maximize the objective function (Sierksma, 2002).

If all the variables must be chosen from the integer set, the linear programing is called Integer Linear Programing (ILP). Variables in ILP can also be limited to a value of 0 or 1, and in this case, the model is named Binary Integer Programing (BIP). The BIP formulation of TSP is described as the follows (Punnen, 2002).

Equation 2

$$Minimize \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x_{ij}$$

Subject to

$\sum_{i=1}^{n} x_{ij} = 1,$ j=1,…, n,

$\sum_{j=1}^{n} x_{ij} = 1,$ i=1,…, n,

$x_{ij} = 0 \ or \ 1$

Where:

n = the number of nodes

c_{ij} = the distance between i and j

x_{ij} = either the path between i and j is chosen or not

Therefore, the set of $s = \{(ij): x_{ij} = 1\}$ represents the tour of traveling or the sequence of movement.

For solving integer linear programs, some advanced methods have been developed, including cutting-plane, branch and bound, branch and cut, and branch and price. These methods provide opportunities to solve large ILPs in a few minutes (Johnson & McGeoch, 1995).

Cutting-plane method was first invented by Ralph Gomory in 1958, and since then, many papers and application have been developed based on Gomory’s method (Dantzig, 1960). Cutting-plane has the capability to solve large linear problems and non-linear problems. For integer linear problems, cutting-plane first solves the problem without considering any integer condition. Then, another constraint is taken into account that refines the algorithm by sweeping and eliminating (cutting) “non-admissible extreme points” and points out the admissible answers. In case of BIP, the algorithm sieves the solutions and finds the variables with the value of 0 or 1 (Dantzig, 1960).

For optimization of CCTV trucks movement, the cutting-plane algorithm was used. the methodology of the optimization is explained in details in the Chapter 4.

2.6 Conclusions

This chapter explained the CCTV operation and its equipment and introduced the relevant basic concepts about productivity, work system framework, and route optimization methods.

The process of televising process requires a CCTV crew with four People: one CCTV operator, one flusher operator, and two swampers. Also the CCTV process is operated by three major equipment of a crawler with a Pan and Tilt Camera, a CCTV mobile unit, and a flusher truck. The operating procedures of CCTV crew members and specification of the equipment was reviewed in detailed in section 2.2.

Productivity terminologically is the ratio of output and input of a work system. Work system frame work is a systematic method to define existing work system, time study, and work management implementation to enhance the quantity and quality of a work system's products. Work study is an engineering concept that analyzes the existing work system by focusing on the work components, work flow, and the work system's products and identifies the areas delaying the production for improvement. Since the characteristic of production is sensitive to many factors, the productivity factors must be identified and the effects of environmental factors must be considered for work system analysis.

CCTV process has a batch processing production type. Each CCTV production cycle includes a combination of work components such as locating manholes, traveling, setup equipment, flushing, televising, and closure activities to produce pipe reports and video. In CCTV work system; there are time gaps between the basic productive works for traveling and locating manholes which can be improved by application of route optimization methods.

Vehicle route optimization is a mathematical method to calculate the optimal path between two points in a network. TSP is a type of vehicle routing problem that calculates the optimal solution to travel between a set of nodes in the way that each node is visited only once. Having different application of TSP and constraints in reality, many type of TSP models such as ATSP, SOP, and CVRP have been developed. To solve the problems, there are two approaches of leaner method and heuristic methods. Leaner method calculates the exact answer for the model; however, it may take a long time; heuristic method provides an answer close to exact answer in shorter time.

Improvement of computer industry and software programing, many computer applications such as Concord TSP Solver has been developed to solve TSP models. Concord is able to solve TSPs by getting the coordinates of the nodes as input and generate the optimal sequence of movement in a short time by using cutting-plane algorithm.

Considering the literatures in the Introduction and the Literature Review of this thesis, the CCTV productivity in Edmonton and CCTV improvement by application of TSP are studied in two next chapters.

Chapter 3: CCTV Production Rate

3.1 Introduction

In the sewer industry, CCTV inspection is the most common and practical approach for drainage network physical condition assessment. CCTV inspection documents are used by municipalities and land developers to ensure compliance with standards, evaluate mainlines, and determine rehabilitation or replacement needs. Moreover, the physical condition report provides an opportunity to forecast the deterioration rate of mainlines within their lifecycle and life cost, to estimate the remaining service life, and to prioritize the facilities for maintenance or replacement programs as part of an asset management program (The City of Edmonton, 2010). Therefore, the CCTV process is scheduled continuously, and the inspection data must be collected consistently to obtain adequate mainline deterioration curves and develop an appropriate asset management system and achieve improved maintenance, repair, and renewal programs.

Every year, municipalities spend millions of dollars and thousands of man-hours on sewer CCTV inspection (Cairns, 2013). Also, CCTV contractors face very significant upfront costs in equipment and training to offer competitive services. Therefore, productivity information is crucial to both clients and contractors as it is a key feature in budgeting and time management. In addition, productivity information enables a more cost effective operation. In the current CCTV process, there is no official productivity standard, and the industry cost and production rate varies from place to place. Moreover, the effects on productivity factors of weather condition and daily temperature, which are critical issues in cold countries like Canada, have not been studied. To have efficient CCTV inspections, there is a need to analyze the CCTV productivity and the impact of different productivity factors on the process. Through a CCTV productivity study, both CCTV operators and municipalities benefit in the short- and long-terms.

The acceptable productivity is the average observed production rate of goods and services that is produced or provided by average skilled personnel in normal working circumstances, including working-time (normal time) and non-working time (Zandin & Maynard, 2001). Universally, the production rate may be calculated by consulting expert knowledge, conducting site visits and time studies, or reviewing daily project reports. Usually, verifying the existing production rate that has been calculated from expert knowledge is difficult as their judgment is based on unique experiences, and thus the effects of production factors cannot easily be analyzed quantitatively. However, estimating production rate from job visits, recorded data, and daily reports provides better estimation and analysis results. Field information contains from project tasks to jobsite condition and circumstantial data; and includes project location, weather conditions and climate, crew size and working hours, performance and production, and so forth.

This study calculated the CCTV production rate in the City of Edmonton and identified and analyzed the most influential variables on the production rate. To do so, a database was developed to store the CCTV project information, such as project location, environmental and weather conditions, time records, and the daily production of different CCTV operators who have been involved in the City of Edmonton (COE)'s CCTV sewer mainline inspection. The production information was collected from IVIS Inc., a pioneer Alberta-based company that provides CCTV inspection service in large scale; and historical weather records were also collected from Environment Canada's National Climate Data and Information Archive and used to analyze the influence of weather change on CCTV productivity. This information was then used to estimate a reasonably accurate production rate for a year of CCTV activities in Edmonton.

3.2 Background

The productivity of a field construction process is influenced by many variables such as weather, site conditions, project delivery system, workforce, engineering work, available material and equipment, and utilities distribution (Russel, 1993). CCTV operation, like other construction procedures, includes various activities that are easily affected by many operational and environmental variables. Since both the video recording and documentation of sewer inspections are completely controlled by the CCTV operators, the production rate is largely dependent on the operator's level of experience. Other factors such as utilized technology, equipment, and the management system must also be considered in the productivity analysis. The physical attributes of the mainline, such as location, size, service type, and pipe material impact their inspection productivity rate. For example, the speed of the video recording in commercial or industrial areas is generally lower than in residential areas due to fat, oil, and grease (FOG) inside the sewer, and CCTV performance in storm mainline is different from sanitary mainline due to the possibility of foreign objects and debris inside of the storm mainline. Moreover, because CCTV inspection is an outdoor operation, the most influential factor on the production rate is weather conditions.

In 1983, Robert Snow Means (RSMeans) published Means Man-Hour Standards, a manual in labour productivity factors for building construction. In the manual, productivity factors are classified into the three categories of job condition, supervision, and other. Job condition factors included scope of project, site condition, material storage and movement, height of work performance, accessibility to work area, and space allowed to work. Supervision factors are measured by experience, rate of pay, and labour pool structure. Other factors comprise weather, season, construction management, local labour restrictions, building code requirements, natural disasters, availability of skilled labour, availability of material, general building condition, methods change, and replacement of material (Robert Snow Means Company, 1983). Since 1983, the RSMeans database has been updated continuously; however, it doesn't include any productivity information regarding the CCTV process. In 1993, Dozzi and AbouRizk categorized labour productivity components into two major categories: human factors and management factors. They state that the human resource is highly sensitive to its environment, and its performance is easily affected by variables such as physical limitation, training, crew and teamwork, and environmental factors. Apart from human factors, management factors can delay productivity through lack of quality in supervision and change management (Dozzi & AbouRizk, 1993). In an assessment of weather condition factors in productivity, Woldesenbet, Jeong, and Oberlender analyzed the production rate of highway construction and the influence of weather conditions on the major activates of highway projects. Their study showed that common methods in estimating production rate such as rules of thumb, experts' opinion, and engineering common sense might result in incorrect estimation in activity duration and project life cycle in comparison with analyzing data collected from the field (Woldesenbet, et al., 2012).

Specifically in drainage services, there have been some studies in productivity improvement; however, there is no study on the production factors and their effect on the production rate. The City of Edmonton, Drainage Operations, conducted an audit to review its performance efficiency and measure the productivity standard for field jobs in 1999 (Agbulos & AbouRizk, 2003). Agbulos and AbouRizk analyzed the City of Edmonton drainage maintenance crews with Work Analysis Study (WAS) and calculated the productivity standard for certain work crews. The study included developing the productivity standards in six activities of cleaning mainlines by low pressure flushing, cleaning mainlines by high pressure flushing, scheduled mechanical cleaning of catch basins, commercial establishment investigation, service line rodding, and Pull-in Place pipe televising. Through implementation of the developed productivity rate and utilizing lean theory concept and simulation modeling, they examined the work methods and improved the productivity accordingly. The study concluded that by integration of lean principles in inspection mainline televising (MTV), it is possible to improve productivity by 4.29-percent (Agbulos & AbouRizk, 2003). However, the method of MTV analyzed was Pull-in Place sewer mainline televising, which is seldom used in today’s market. Currently, CCTV with a crawler (Pan and Tilt Camera) is a more common approach in mainline physical condition assessment, and it has yet to be studied. Since mainline inspection procedures, methodologies, and equipment have changed, an updated productivity study in current mainline inspection method is required. Also, for cold regions like Alberta, it is necessary to analyze the influence of weather as the most determinant factor in outdoor construction productivity such as CCTV of sewer mainlines.

3.3 The Study Overview and Data Collection

Considering the significant impact of external factors in the CCTV process, it is almost impossible to accurately predict in advance the duration of televising a network of sewer mainlines in a large area. However, we can statistically study the practices and identify the behavior of the CCTV work system output to better understand the process and strategize its performance.

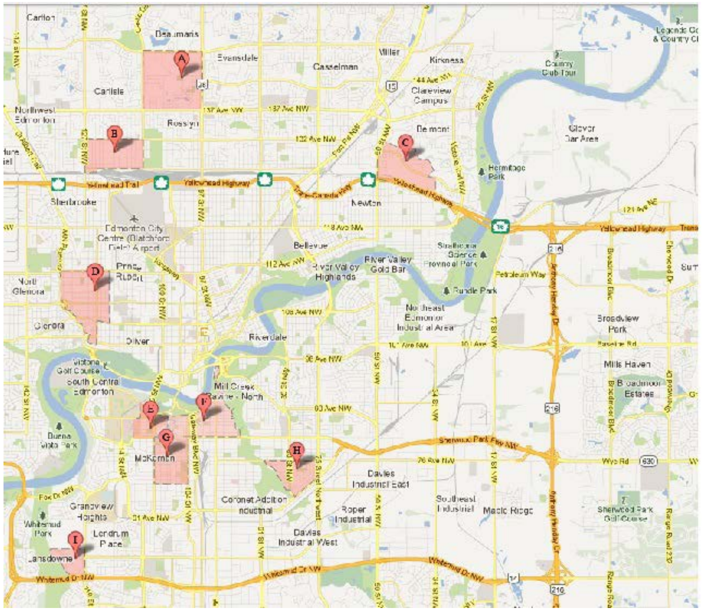
This study aims to calculate the production rate of the CCTV process for pipeline condition assessment in the City of Edmonton. The data used for this study was collected from actual

CCTV operations done by IVIS Inc. in eight different neighborhoods in Edmonton, including Avonmore, Calder, Griesbach, Homesteader, Lansdowne, Queen Alexandra, Westmount, and 83 Avenue between 96 Street and 112 Street (passing through the two neighborhoods of Garneau and Strathcona). The data was collected during a 199-day interval that spanned November 11th, 2011 to January 11th, 2013, in which 121,943 meters of mainline were televised, including 26,955 m of sanitary system, 47,146 m of storm system, and 47,842 m of combined system. The studied pipeline network included a combination of different pipe sizes, ranging from 150 mm to 675 mm in diameter. However, 79.69-percent of the mainline was between 200 mm to 375 mm in diameter; a common size in urban sewer service.

Table 3.1: Project Information and the Working Month

No	Project name	Start date	Finish date	Number of Mainlines	Total Length (m)	2011		2012												2013
						Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1	Westmount	7-Nov-11	8-Jun-12	464	27,866															
2	Avonmore	9-Dec-11	9-Dec-11	5	429															
3	Greisbach	4-Feb-12	6-Mar-12	257	17,742															
4	Homesteader	25-Apr-12	27-Sep-12	255	14,592															
5	Lansdowne	25-Apr-12	23-May-12	192	11,647															
6	Calder	12-Jun-12	9-Sep-12	364	24,041															
7	Queen Alexandra	24-Jul-12	26-Nov-12	270	19,624															
8	83 Ave	29-Oct-12	11-Jan-13	145	6,002															
Total				1,952	121,943															

Project Information and their monthly schedules are shown in Table 3.1. The location of each neighborhood is shown in Figure 3.1. As each project was not necessarily operating consistently during each recorded month, Table 3.1 notes months in which any level of production occurred. For example, if pipelines for a project were televised in one working day in March, the month of March is recorded for that particular project. Working days are defined as 8 work-hours, and dates with less than 8 work-hours were excluded from this study.



A: Griesbach Neighbourhood

B: Calder Neighbourhood

C: Homesteader Neighbourhood

D: Westmount Neighbourhood

E: Strathcona Neighbourhood

F: Garneau Neighbourhood

G: Queen Alexandra Neighbourhood

H: Avonmore Neighbourhood

I: Lansdowne Neighbourhood

Figure 3.1: The Map of the Studied Neighborhoods in Edmonton (Google Inc., n.d.)

In order to collect and save required data, a database was developed to store the scope of each project, the physical properties of each mainline, the project time records, the weather conditions and daily temperature records, and the production of different CCTV operators in the participating Edmonton neighborhoods. In total, 249 CCTV performances were collected in 199 days. During that time, seven CCTV operators with varying experience levels cooperated in data collection, and the regression of their performances was considered for the production rate of each working day. For the analysis, average monthly and seasonal production rates were calculated and compared. Also, the effects of the weather conditions and the temperature were studied based on historical daily weather reports.

3.4 Description of the CCTV Process

In the CCTV method, a Pan & Tilt Camera is installed on a crawler. The crawler is then sent inside a pipeline through a manhole and is moved through the pipeline via wheels or a track chain, depending on the pipe situation. The camera has the ability to rotate inside of the pipeline, and the crawler has adequate lighting around the lens' module to light a 48 inch or larger pipe diameter. The camera is also able to focus automatically and zoom-in in cases where the crawler is unable to move forward. In order to produce high quality images and have clear details in CCTV inspection, the camera lens must be placed in the middle of mainline.

The crawler is controlled and driven through the sewer mainline by a control panel on the surface with recording and editing capability. For the crawler to capture clean images and move smoothly, the mainline must have low stream flow and be free of large objects. A flusher truck prepares the mainline for CCTV televising. CCTV operators also require training in sewer assessment to recognize the defect types that may exist inside the pipe. Whenever the camera reaches a defect, the operators must capture the defect in detail and document the structural, operational, and constructional observations. The crawler should also be driven at a certain speed based on standard specifications; for example, the City of Edmonton has specified that the travel speed of the crawler must not exceed 9 meters per minute.

The CCTV process is a multiple operation task; it is a combination of different work units or stations completed by a three- to four-person crew with relevant equipment. As a consequence, sequential operations and workflow must be defined to show the movement through the work units and batch processing to the desired product(s) or service(s) (Groover, 2007). The daily CCTV process can be defined in three phases: work preparation, pipe inspection, and work completion.

3.4.1 Work Preparation

During this phase, the CCTV crew prepares for the field operation. Before leaving shop, the crew is required to obtain their work order, wear their personal safety equipment, ensure that the camera van and flusher units are equipped, and inspect the van, flusher unit, and camera/crawler equipment to ensure that they are working properly. Then, the crew is ready to drive to the jobsite.

3.4.2 Pipe Inspection

Locating the targeted manhole is the first step in the CCTV process. A map of the location is given to the CCTV operators by the owner (the City of Edmonton), and the operators must find the desired manhole for the operation. Although a map of the working area is given to the operators, locating the manhole can be a challenging and unpredictable task. This can be attributed to dealing with outdated maps, snow or ice cover, obstacles on manholes, and locations with hard access. Occasionally, locations require clarification in the contractors' office before the crew may take any action.

After reading the map and locating the mainline, the flusher truck and CCTV van travel to the downstream and upstream manholes. Frequently this is the most time-consuming task in the work system. Moving large trucks such as the CCTV trucks and flusher units can be challenging. In any city, there are different neighborhoods of different shapes and ages, and roads may be blocked permanently or temporarily, structured narrow, or have limited access.

Once the CCTV and flusher operators reach the manholes, they investigate the area (trees, parked cars, pedestrians, schools, playgrounds, and kids), control the traffic, open the manhole lid, determine the manhole depth, and setup/position the equipment over each manhole. This step may include issues such as dealing with objects in the manhole, obstacles over the manhole, and obstructed pipe entries.

After the equipment setup, the flusher truck begins cleaning the mainline to remove dirt from inside the pipe. The interior surface of the pipes must be clean so that defects are visible and the crawler can move through the pipelines with ease. Technically, storm lines require more cleaning than sanitary lines as they convey the street surface runoff which contains dirt, leaves, tree limbs, stones, and other materials. Occasionally pipelines need milling to remove debris or tree roots that affect the crawler movement. Therefore, mainline flushing is needed before any CCTV investigation.

Following the flushing operations, the CCTV operator begins video inspection from the upstream manhole. During inspection, if any additional flushing is needed, the flusher operator is informed by a two-way handheld radio, and the crawler stops until the water recedes and the path opens. Coordination during this task is very important as the flusher nozzle attached to a high pressure jetting hose may hit the crawler inside the pipe. The schematic view of the process is illustrated in Figure 3.2.

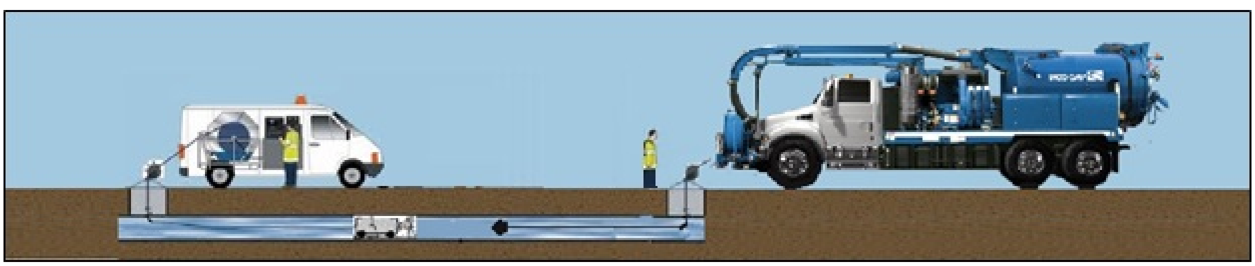


Figure 3.2: Schematic View of the CCTV Process (VAC-CON, 2010) (WRc plc, 2014)

During the pipeline televising, the CCTV operator must stop the crawler at the observed defects, capture the defects, and complete the inspection report in a timely manner. Here the crew may encounter issues such as steam (especially in the morning and during winter), roots/debris/grease in the pipe, camera/crawler breakdown, hardware module issues, lens cleaning, and an empty flusher tank. When the crawler reaches the end of the line, the televising is stopped and the crawler is driven backward to the entry point. The crawler is then cleaned and prepared for its next use. Concurrently, the recorded video is saved, and the required reports are created.

Finally, in the closure, the lid is placed back on the manhole and the warning signs or traffic cones that were used for traffic redirection or hazard warning are removed. At this stage, the next manhole to be televised is identified, and the CCTV and flusher units are prepared to move. A network diagram of CCTV workflow is shown in Figure 3.3.

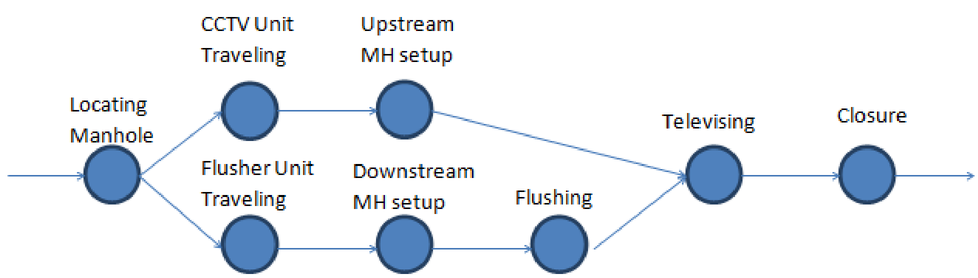


Figure 3.3: Network Diagram Representing CCTV Work Flow

3.4.3 Work Completion

At the end of the workday, the CCTV van and flusher unit return to the shop with the collected data and relevant reports, including the video files (.ptv) and the data files (.ptd). If the quality of the videos does not satisfy the quality assurance or quality control personnel (QA/QC), the work is rejected and the mainline must be re-televised at a later date.

When the trucks arrive in the shop, the operators should refuel the trucks, re-stock supplies, and assist in maintaining the equipment in good conditions by adjusting, cleaning, lubricating, storing, and performing minor repairs as required

3.5 Analysis Production Rate

Traditionally, construction productivity is determined in two ways: by measuring the labour or crew performance when completing a unit of work or by measuring the amount of work completed by the labour or a crew in a given time and a normal pace (Dozzi & AbouRizk, 1993). In the CCTV process, the productivity is also defined in those two ways: crew-hours to televise one meter of mainline (crew-hour/meter) and the length (meter) of mainline that can be televised in one crew-hour (meter/crew-hour). Productivity is easily converted to production rate (daily output) through the application of equations 3, 4, and 5. Production rate information helps to predict the duration of a project or to estimate the required man-hours needed to finish a job in a certain time. For this study, the unit of production rate is defined as pipeline meters per day.

Equation 3

$$\text{Daily Output or Production Rate (meter/day)} = \frac{\text{Crew Hours (crew}-\text{hours/day)}}{\text{Unit Crew Hours (crew}-\text{hours/meter)}}$$

Equation 4

$$\text{Duration (days)} = \frac{\text{Quantity (units)}}{\text{Daily Output (units/day)}}$$

Equation 5

Duration (labour hours) = Quantity (meter) * Unit Labour Hours (labour hours/meter)

Many productivity factors such as work method, worker's skill and motivation, work condition (e.g. visual (sight), nasal (smell), and thermal) must be considered as factors affecting work speed (Karger & Bayha, 1987). Therefore, the average of all the performances in different situation represents the existing production rate of goods or services that the work system is designed for. Collecting continuous experimental data for all of these factors provides the most accurate production rate although it is an expensive and time-consuming approach. In addition, validating the result and explaining the set of situations under which the performance data is collected is essential.

The daily time window for CCTV operation is considered 8 hours per day. The studied work management system is a matrix management framework, which assigns a resource pool to defined cross projects. Therefore, there is a possibility that two or three CCTV operators may work on the same neighborhood at the same time. As the operators' experiences are different, the average of their performance provides a better estimate of the daily production rate. Therefore, if more than one daily report is available for a given day, the average of the performances is considered for that day's output. The same approach is used to calculate the average production rate of each month and each season. For example, in the month of March, there are 19 work performances available to study, and the average of the 19 daily reports is used to calculate the daily production rate for the month. Accordingly, the daily average meters per month are calculated based on the available corresponding rates of each month.

Table 3.2 and Figures 3.4 and 3.5 show the comparison of production rates in different months and seasons and indicate that a yearly average of 489.73 meters of sewer mainline have been televised on each working day for a year and half in Edmonton. In Figures 3.4 and 3.5, the minimum and maximum horizontal dotted lines represent the average minimum and average maximum of the month's average meters per day. Also, the upper and lower bound for each month and season are illustrated. Furthermore, the most frequent range of the data in each month and season is colored to better illustrate the data changes. The black line in the middle of each bar represents the average of each month/season.

Table 3.2: CCTV Monthly and Seasonal Production Rate

No.	Month	# of effective Day	Average Meter per day	Season	Daily Average Meter per season
1	March	19	471.34	Spring	504.104
2	April	15	465.84		
3	May	31	542.70		
4	June	16	413.49	Summer	532.792
5	July	25	578.81		
6	August	38	552.75		
7	September	15	525.79	Fall	400.652
8	October	8	161.11		
9	November	19	402.72		
10	December	18	360.85	Winter	480.3
11	January	13	514.19		
12	February	32	533.72		
production Rate		**249**	**489.73**		**489.73**

As seen in Figures 3.4 and 3.5, weather conditions brought on by seasonal changes affect the CCTV process productivity significantly. October 2012 had the lowest production rate of 161.11 meters per day as the weather conditions were not stable (precipitation and climate variation). Conversely, summer was the highest productive season for CCTV with a seasonal average of 532.79 meters per day.

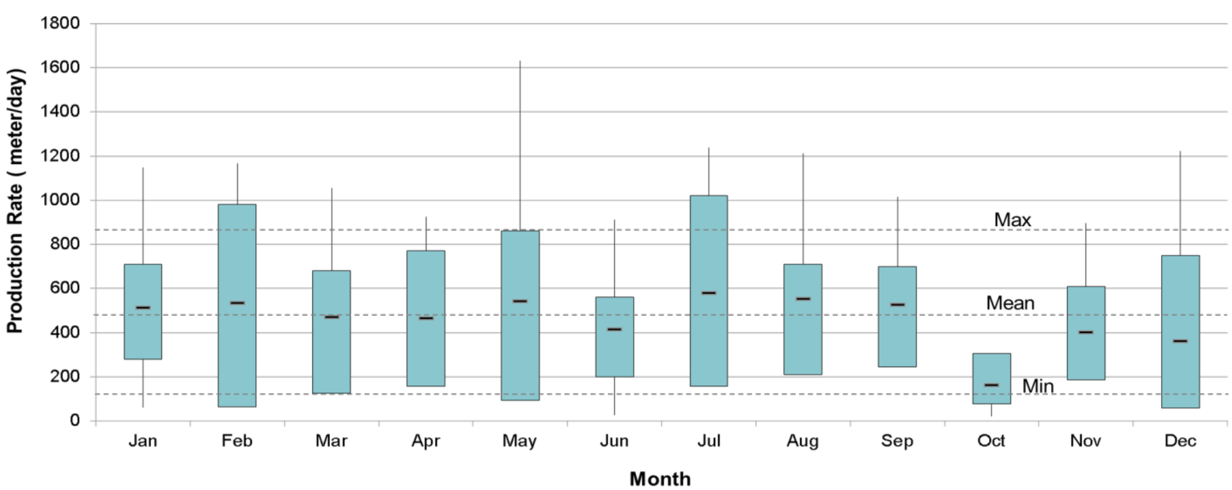


Figure 3.4: Boxplot of Production Rate in Different Months

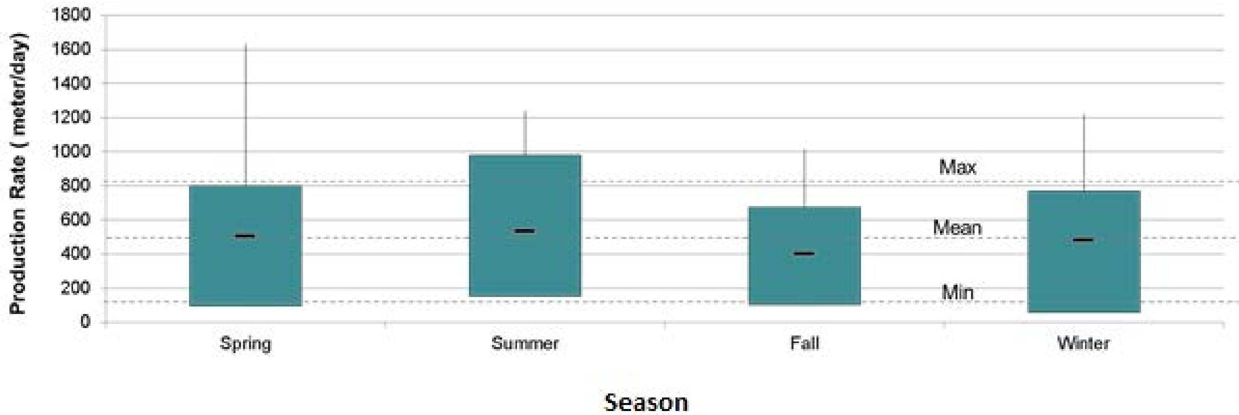


Figure 3.5: Boxplot of Production Rate in Different Seasons

In order to understand the collected data, a statistical distribution must be found that explains the behavior of the data as accurately as possible. Distributions are defined by different parameters, such as mean and variance that identify its Probability Density Function (PDF) and the Cumulative Distribution Function (CDF). For the range of available data, there is no negative numbers as data reflects the production rate. Therefore, the collected data must be compared with bounded distributions that have a minimum lower bound of zero. The data needs to be categorized in different intervals (sample points), and the frequency and the probability of the occurrence (hence, sampling) must be obtained. This would reflect the shape of the histogram that the sample follows. The methods of testing for suitability of fit to different distributions are various and include the Chi- Squared Statistic, Anderson-Darling Statistic, Kolmogorov-Smirnov Statistic, Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). However, this study used AIC method to find the best fit distribution. This testing method compare the statistical properties of the sample data and the distribution generated data, and illustrate how the histogram shapes differ or relate to each other.

Figure 3.6 shows the comparison of the collected data histogram and a Weibull distribution. It was determined that Weibull distribution with the parameters of (1.8555, 528.59, Risk Shift (3.6582)) had the best fit result with the collected data.

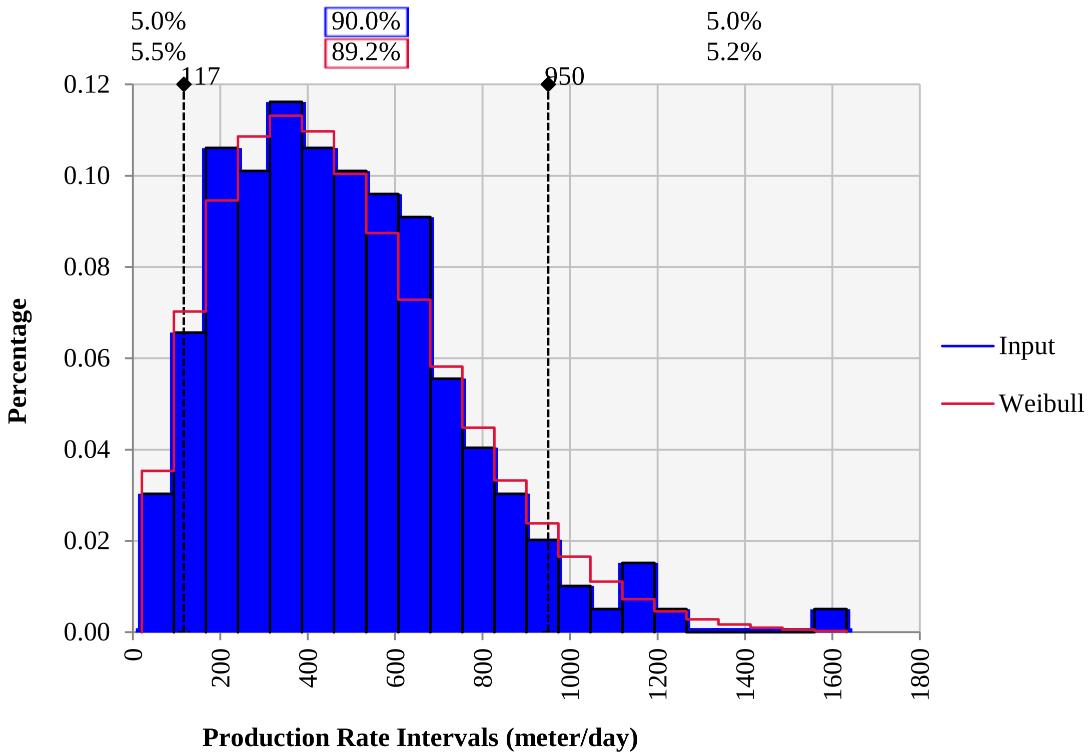


Figure 3.6: Fit Comparison with the Weibull[1] (1.8555, 528.59, Risk Shift (3.6582)) distribution - 95% Confidence Level

3.6 Study Productivity Factors on CCTV Inspection

The owners of the CCTV projects generally prefer that projects are completed in a normal speed and timely manner. However, this may not happen in some weather conditions. Based on the daily performance of mainline televising in different weather conditions we can conclude that weather conditions have a significant impact on CCTV productivity. Days with different

[1]The Weibull distribution is defined by the two parameters of λ>0 scale and K>0 shape. The PDF is $f(x;\ \lambda, K) = \begin{cases} 0 & x < 0 \\ \frac{K}{\lambda}\left(\frac{x}{\lambda}\right)^{K-1} e^{-\left(\frac{x}{\lambda}\right)^{K}} & x \geq 0 \end{cases}$ and the CDF is $1 - e^{-\left(\frac{x}{\lambda}\right)^{K}}$.

temperatures (°C) were monitored, and the average production rate at each temperature was calculated. Figure 3.7 displays the results from the data, and illustrates that the production rate has a direct relationship with daily temperature.

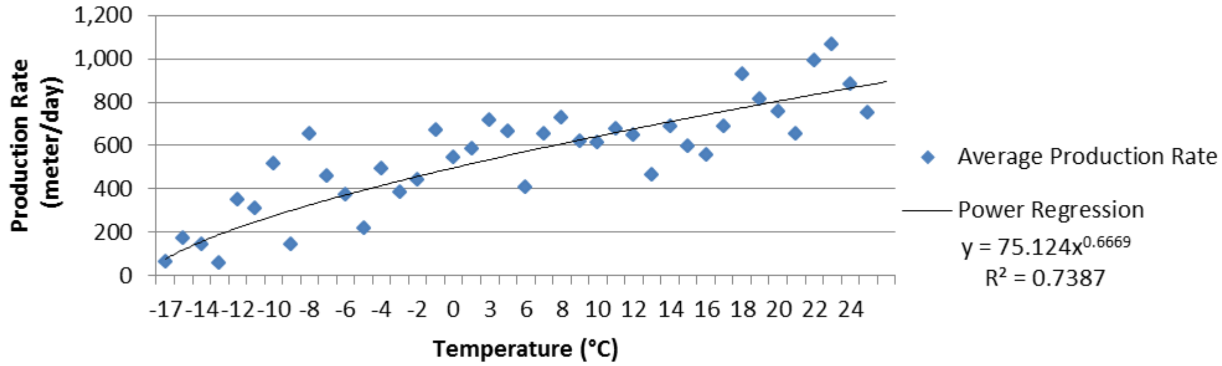


Figure 3.7: Average CCTV Production Rate vs. Ambient Temperature (°C)

Also, Figure 3.8 displays the regression for all the production data achieved in different temperature.

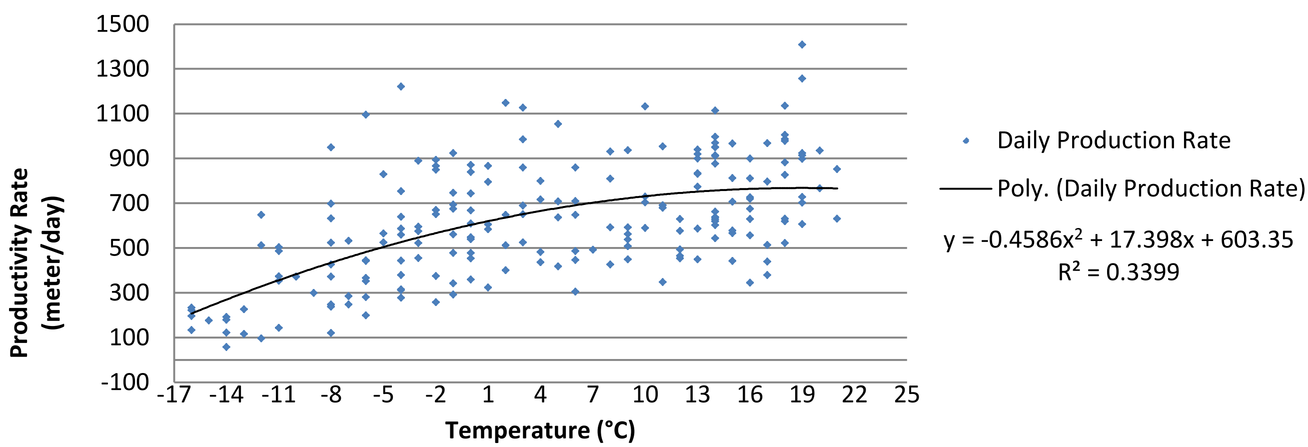


Figure 3.8: CCTV Production Rate vs. Ambient Temperature (°C)

A regression method is used to represent the trend of production rate versus temperature. Regression analysis is a statistical tool that makes it possible to estimate and analyze the relationships among different variables that affect a data set. In other words, regression analysis characterizes the conditional trend (average value) of a dependent variable against one or more independent variables based on their quintile or location parameter. In our example, the temperature factor is assumed to be an independent variable, and the other productivity factors' effects are dependent on it.

As the temperature outdoors increases from -17 to 25°C, the productivity and the trend of regression in performance increase. According to the logged explanation by operators, the associated challenges in cold weather are typically related to flushing the mainline and recording activities. Sometimes, in negative temperatures, the water in the flusher tank freezes, and the operation must be stopped. Moreover, steam in the sanitary mainline is also frequent, and the crawler must be run significantly slower to capture quality images.

As the flusher truck is unable to perform in temperatures lower than -17°C due to the potential of freezing its stored water supply, the production is stopped at this temperature, and the production rate is zero. Therefore, power regression is chosen to represent this constraint. In power regression, the equation of the trend would be $y=75.124*x^{0.67}$, Where x is temperature in degrees Celsius, and y is production rate in meters/day. Also, the R-squared value for the regression is 0.7387 for the observed data. It means that many factors impact the production rate, and the statistical fit of our developed regression is around 74-percent. The trend shows how the temperature variations in degrees Celsius affected the production rate in meter/day.

Apart from temperature, weather conditions also affect the CCTV productivity rate, with snow preciption having the most influence. Out of 249 sample days, there were 16 days with snow that have the lowest productivity. Figure 3.9 compares the production rates of snow conditions with the average production rate in one year.

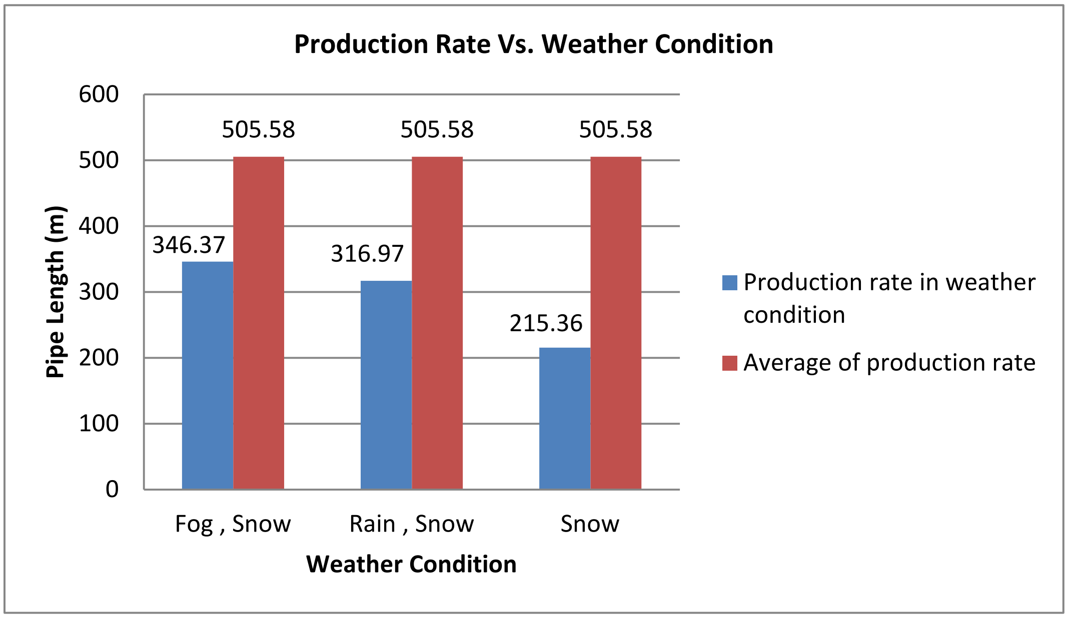


Figure 3.9: Comparison of Production Rate in Snow Conditions and the Average Production Rate

The production rate in different weather conditions was calculated separately and compared with the average of the production rate not influenced by the weather. As a result, it was possible to monitor the influence of each condition on the production rate. As the study shows, snow can decrease the productivity rate intensely.

3.7 ANOVA Analysis

Weather conditions affect the CCTV productivity rate significantly. This is visible during October 2012 production in Figure 3.4. Out of eight televising days in October 2012, six experienced snow with wind gusts of up to 48 km per hour.

In order to assess the impact of snow on the CCTV production rate, an analysis of variance (ANOVA) analysis was run between production rates on days with snow conditions and production rates on days with other weather conditions. In an ANOVA analysis, two hypotheses are defined: a Null-Hypothesis (H_0) that indicates there is no meaningful impact between two defined groups; and an Alternative Hypothesis (H_a) that indicates there is inequality between the two groups' properties. The analysis was run with a 95-percent confidence level; therefore, the P-value of the data set (the probability of rejecting the H_0) is comparable with 0.05. Through the ANOVA analysis method, F ratio (F-distribution under the H_0) was also calculated from variance analysis between the groups and within the groups' data, and it was compared to the F critical value that defines the rejection region in F-distribution. Table 3.3 shows a summary of the data set. According to the ANOVA analysis results, because the P-value is smaller than 0.05, the existing state of affairs does not apply, and the null-hypothesis is rejected. Also, the calculated F ratio is larger than the critical value of F, which means the F value falls into the rejection region. As a result, it is concluded that the effect of snow on the CCTV production rate is significant, and the CCTV productivity decreases to less than 57-percent during snow days.

.Table 3.3: Summary of Production Rate Attribute in Two Different Weather Conditions

SUMMARY				
Groups	**Count**	**Sum**	**Average**	**Variance**
Normal	130	64943.01	499.5616	77954.71
Snow	10	2153.6	215.36	38527.81

Table 3.4 is the ANOVA table that shows the sum of squares (SS), the degrees of freedom (df), the mean squares (MS), F statistics (F ratio), P-value, and F critical value for two sources of variation

According to the ANOVA analysis results, because the P-value is smaller than 0.05, the existing state of affairs does not apply, and the null-hypothesis is rejected. Also, the calculated F ratio is larger than the critical value of F, which means the F value falls into the rejection region. As a result, it is concluded that the effect of snow on the CCTV production rate is significant, and the CCTV productivity decreases during snow days.

Table 3.4: Single Factor ANOVA Table

ANOVA: (Single Factor)						
Source of Variation	**SS**	**df**	**MS**	**F ratio**	**P-value**	**F crit.**
Between Groups	750012.3	1	750012.3	9.949305	0.001975	3.909729
Within Groups	10402908	138	75383.39			
Total	11152920	139				

The following statements from CCTV operators support the observations regarding impact of snowy days on CCTV production rate:

- The manhole lid is covered by snow and locating manholes is significantly delayed.
- In snow conditions, snow-related safety procedures during the operation affect the progress of the work.
- Traffic control must be executed with caution during snow conditions, which also slows down the process.

3.8 Conclusion

The City of Edmonton is responsible for the preservation and supervision of its underground infrastructure, such as sewer mainline and manholes, and uses CCTV technology continuously to inspect its sewer mainline facilities. The CCTV process productivity is affected by many variables, such as weather conditions, operator experience, operation time, and other external interventions. However, the weather condition impact as the most influential productivity factor in open construction field in cold areas was the main objective of this research. A study on the televising of 1,952 mainlines, totaling 121,943 meters in length, shows that the average production rate for the CCTV process for eight different neighborhoods in Edmonton was 489.73 meters per day over a year and half. During this timeframe, the production rate fluctuated at different times of the year. October had the lowest production rate at 161.11 meter per day as the weather situation significantly affected process productivity. In general, because the working sites of CCTV operations are not controlled areas, the temperature and work circumstances affect the productivity rate in uncertain ways. As this study shows, the temperature has a direct effect on the production rate, which follows a regression trend of $y=75.124*x^{0.67}$ (where y is daily production in meter/day and x is the temperature in degrees Celsius) with an R-squared (Coefficient of Determination) value of 0.7387. Also, weather conditions such as snow can reduce the productivity between 30-percent and 56-percent. Further study is required to analyze each CCTV task and simulate the process to assess the effects of other productivity factors such as working experience, equipment, training, and working area on the CCTV productivity rate.

Chapter 4: CCTV Productivity Improvement

4.1 Introduction

Urban underground sewer facilities, such as sanitary sewer, storm sewer, combined mainlines, catch basin (CB), CB manholes, and manholes, are important infrastructure in wastewater management. A municipalities’ drainage services department is responsible for these underground facilities and managing their sewer drain network. In asset management, structure’s physical condition data and projected life are principal to maintenance, rehabilitation, and replacement planning (Vanier, et al., 2009).

Inspection of drains and sewer mainline, there are many approaches according to pipe diameter. Examples of sewer pipe investigation methods are: visual inspection and camera inspection (man entry, pan n’ tilt camera and digital diagnostic); electromagnetic (EM) (SmartBall®, PipeDiver®, and cable detector); laser inspection; physical inspection (smoke test, impulse hammer, and dye test); ultra/infra spectrum (ultra-sonic and infrared thermography), and leak detection (acoustic, sonic, and hydrostatic) (Allouche & Freure, 2002). However, the most practical and common inspection technique is CCTV inspection. The CCTV method is easy to use and economical in comparison to other inspection methods, and video recording pipe defects provides users with instant verification. Also, in-house developed mainline evaluation standards and universal pipe condition rating systems, such as those developed by the WRc and the NASSCO, support the CCTV inspection method.

To develop an efficient and economically responsible asset management system, data collected by CCTV plays an important role in determining mainline network deterioration rates and prioritizing maintenance/rehabilitation actions (McDonald & Zhao, 2001). As a result, municipalities regularly plan continuous CCTV inspection activities for different areas, such as industrial, commercial, and residential. CCTV inspection on a large-scale is costly, time-consuming, and challenging due to operations in not a clean environments and working on underground utilities. Millions of dollars are spent annually in buried infrastructure inspection to collect physical condition data and establish the remaining infrastructure's efficiency and service life. Municipalities across the country have been dealing with a decreased budget and reduced revenue during the past decades (Mirza, 2007). Additionally, contractors require expensive tools, modified trucks, and educated personnel to provide CCTV services. Indeed, even small improvements in the CCTV inspection process can benefit contractors, municipalities and land developers by saving a significant amount of money and time. Improving the CCTV work method and increasing productivity can help run the project efficiently and control the budget effectively.

The City of Edmonton provides sewer services to a population of more than 1.1 million people in an area of 9,428km^2 (The Minister for Statistics Canada, 2013). Yearly, 120 to 180 km of sewer mainlines are scheduled for televising in Edmonton, with operations estimated to cost the City approximately two to three million dollars (Cairns, 2013). In 1999, the Office of the City Auditor (OCA) published a report in collaboration with the University of Alberta that analyzed the efficiency and productivity of the drainage operation maintenance crew. By application of work sampling techniques, simulation techniques, and lean manufacturing practices, the City developed a work method that could increase the productivity of Pull-in Place sewer mainline televising from 366.35 m/day to 382.08 m/day; a 4.29% improvement (Agbulos, et al., 2006).

However, reengineering the procedure is not the only way to increase productivity. Earlier literature indicates that, besides work method, other components such as travelling pattern in outdoor operations can noticeably affect productivity. Many businesses in North America and Europe have lowered their transportation costs between 10% and 20% and have benefited from a 5% to 20% cost-savings by using optimization programming techniques (Toth & Vigo, 2002). In preventive maintenance (e.g. flushing, cleaning) of its wastewater collection system, The City of Edmonton can potentially improve travelling distance by nearly 8.66% (based on linear calculation) per week (Zaman, et al., 2012). Moreover, a case study in Trabzon City, Turkey has shown that route optimization in the solid waste collection process can decrease travelling distance as much as 24.6% (Apaydin & Talha Gonullu, 2008).

The Initial concept of route optimization was defined via practical application by Dantzig and Ramser in 1959 in a study that analyzed the delivery of gasoline to a gas station. Since then, the practical application of operational research techniques and mathematical programming in procedure optimization has been increasing. Route optimization has not only been applied to delivery systems but also to solid waste collection, street cleaning, school bus routing, dial-a-ride systems, transportation of handicapped or aged people, routing of salespeople, and of maintenance or inspection units (Toth & Vigo, 2002).

TSP is a well-known mathematical method in route optimization. The objective is to obtain the best route between a given set of customers and depots in order to minimize the distance and cost of travel (Toth & Vigo, 2002). TSP can have many variants. Symmetric travelling salesman problem is a closed loop TSP in which a traveler steadily progresses towards the destinations in one travel time and returns to the origin. Sequential Ordering Problem (SOP) is a type of TSP with the constraint of having a predecessor for some nodes (destinations). Capacitated Vehicle Routing Problem (CVRP) is type of Asymmetric Travelling Salesman Problem (ATSP) that considers demands for each node and a certain capacity for the server (vehicle). The goal of the

CVRP model is to find the optimal distance of travel while considering the node's demands and the server's capacity (Reinelt, 2012).

Theoretically, there are two ways to solve TSPs: linear programming provides the exact optimal solution that may take long time to solve, and heuristic algorithm calculates a reasonable solution (close to optimal) within a short time. Accordingly, many TSP optimization algorithms such as simulated annealing, Tabu search, neural network, and genetic algorithm have been used in operation research models (Johnson & McGeoch, 1995). Cutting-plane is another method for solving TSPs that has the capability to solve large linear and non-linear problems (Dantzig, 1960).

This study focuses on CCTV productivity enhancement and inspection crew performance improvement by conducting an engineering overview on the CCTV process and a time study, as well as applying a route optimization technique. This paper provides an analysis of CCTV procedures with real-time data and shows how the movement of CCTV trucks affects process productivity. CCTV crews' movements were analyzed using both road and air distances, illustrating how road constraints affect the optimal solutions provided by TSP solvers. Through the application of the TSP route optimization method, the level of improvement in CCTV production rates was calculated on both a daily and a project lifetime scale.

The subsequent sections of this paper present a brief explanation of the methodology of the study and a review the work study conducted on The City of Edmonton's CCTV process. Following that, the observations of the CCTV truck movements are analyzed, and the effect of the applied TSP optimization on the CCTV production rate is discussed. Finally, this paper concludes with a summary of the findings and suggestions for further studies.

4.2 Methodology

Current work production rate would be the base to evaluate the level of improvement after implementation of any improvement solution. Work study is a well-known engineering method used to determine the current work situation and to define and analyze the work components of a procedure. Conducting a work study includes defining the work elements and their sequence and establishing valid time and motion studies (Groover, 2007). Work study process contains three major steps: defining work scope and strategy of measurement as input, collecting data, and analyzing the work system.

This study began with defining the work measurement method, breaking down the CCTV procedure into work components, determining the sequence of the work components, and planning for time studies in different work situations. The study then established a data collection system by designing an assignment sheet form and a database for storing the collected data. Analyzing the collected data and reviewing the CCTV process performance resulted in determining the existing work system and the effect of work components (work units) on the production cycle time. In this work analysis, value added and non-value added activities and areas delaying the work system were identified, and alternatives to improve the work system were studied. The objective of this study was to analyze the CCTV operation, define potential areas for improvement, and calculate the level of improvement by applying alternative methods and solutions. To continually improve CCTV operations, new performance data must be saved in the developed database to document experiences and field data, analyze the new work system, and make decisions for further improvement. Figure 4.1 contains a flowchart illustrating the research methodology.

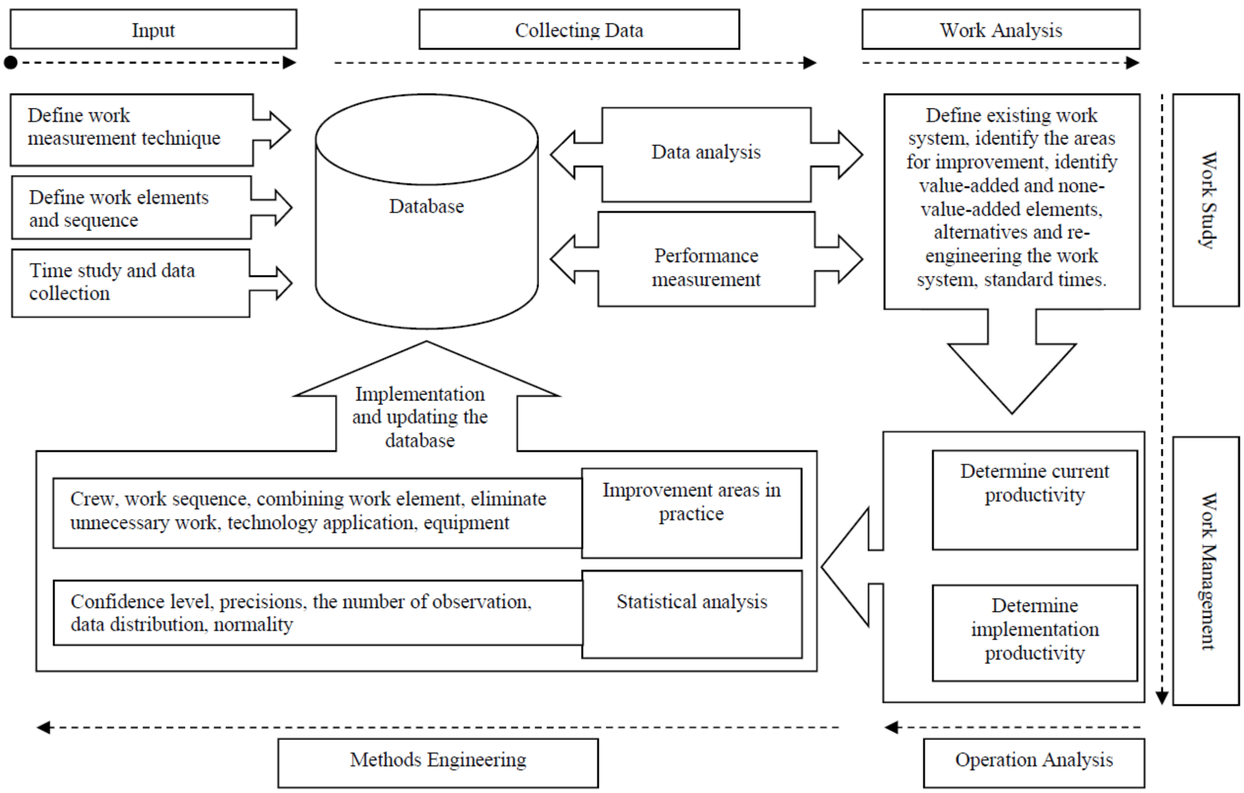


Figure 4.1: The Research Methodology

There are many approaches to improve a construction process, such as changing the management system, modifying the work sequence, using new technology, and revising the working crew size. This study analyzes CCTV performance improvement by applying TSP optimization to CCTV trucks movement planning and the CCTV crew management system. The following sections define the CCTV work system and show how the application of TSP to CCTV planning can improve the sewer mainline inspection process in practice.

4.3 Work and Time Analysis

The CCTV inspection process is a repetitive operation, and cycle time varies from mainline to mainline. The cycle time depends on the pipe condition (e.g. existing debris, grease, and holes) and construction factors such as pipe diameter, length, location, and material. The CCTV operator's experience affects the cycle time as well. Moreover, extra work, such as milling and changing the crawler, may occasionally be required. Therefore, all operational conditions in the process and the average time of the process activities were taken into account for this study.

In this analysis, the CCTV procedure is broken into seven major work units: locating manholes, travelling, upstream manhole setup, downstream manhole setup, flushing, televising, and closure. Other activities, such as travelling from the shop to the job site and operators' break time, differ case-by-case and are not considered as a part of the process cycle time. The first work unit, locating manholes, requires operators to target the next mainline from the contract work order list, locate the selected facility's upstream and downstream manholes on a map, and confirm the locations with other crew members. This stage can be confusing for operators as not all pipelines existing within a neighborhood are scheduled for televising; mainlines must be targeted as per the contract list provided by the City, and locating manholes can sometimes be challenging and time-consuming. This can be due to outdated maps or construction that has left mainlines abandoned and manholes buried under new pavement.

CCTV operations require a CCTV truck to transport televising equipment and a flusher truck to clean mainlines. Generally, the CCTV unit is placed over the upstream manhole, and the flusher truck is placed over the downstream manhole to wash dirt and debris to the downstream manholes in the gravity pipes. Travelling time to the upstream and downstream manholes may differ based on the travel path and road constraints, such as traffic flow, direction, and blocks.

Before the televising begins, the crew controls traffic, erects signs, opens the manhole lid, places the crawler and high-pressure water nozzle inside the pipe, and prepares the computer and crawler controller. During winter months, the manholes may be covered with snow, and the CCTV operators must use magnetic locators to find the manhole's lid and clear any ice or snow. Moreover, CCTV operators may be required to take field measurements (e.g. manhole depth and depth to invert) and record the facility's properties on a daily report form. Once these preliminary activities have been completed, the flusher operator washes the dirt, debris, or external objects from the mainline. After the sewer pipe is cleaned, the camera crawler is driven into the mainline. The CCTV operator stops the crawler at any observed defect, photographs the defect, and enters the defect's specified code in the computer according to the applied assessment standard (See the Appendix B for The COE protocol's coding system). During the televising operation, additional flushing may be required. When the crawler reaches the downstream manhole, the televising work is finished. The crawler is then driven backward, removed, and cleaned. Both upstream and downstream manhole lids are placed back, and the warning signs and traffic cones are removed. Figure 4.2 has been shaped in Symphony.Net environment to show the sequence of CCTV work.

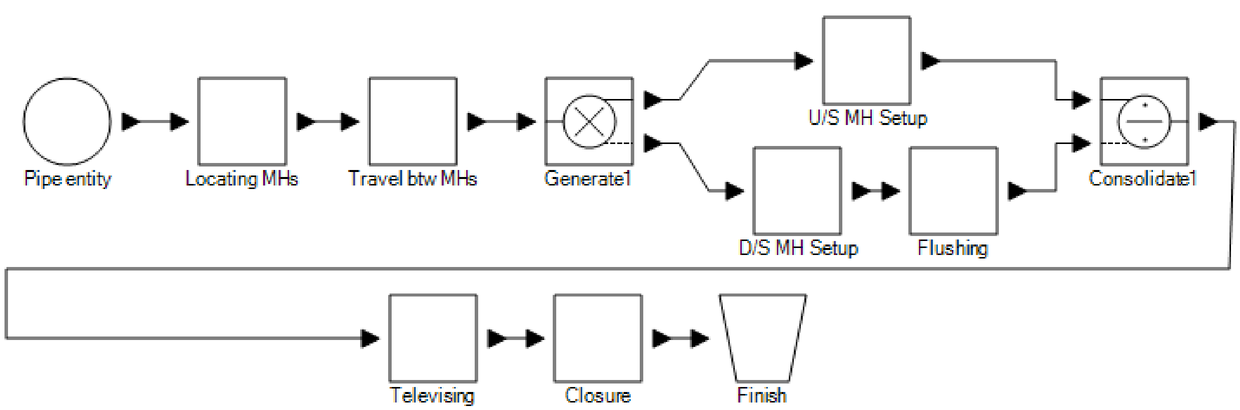


Figure 4.2: Sequence of Work Units in the CCTV Inspection Process

For this study, a CCTV assignment sheet and a database were developed to record the start and finish time of each work unit. Additional operational information, such as pipe specification, date, crew member names, equipment numbers, neighborhood, and possible cause for work delays, was also recorded. The Figure 4.3 shows the specialized form that was used for data collection. The start and finish time of each work unit was logged as a continuous reading; timing begins when the first work unit is started, and is not reset throughout the remainder of the process. When the first work unit is completed, the time is logged as two records: the first unit's finish time and the next unit's start time. This continues until the cycle time is completed (Pigage & Tucker, 1934). A work unit's duration is calculated by subtracting the finish time and start time. For example, if the flushing activity is started at 9:30 a.m. and was completed at 9:46 a.m., the duration of flushing would be logged as 16 minutes.

CCTV Assignment Sheet

CCTV Operator:________________ Unit #:________

Flusher Operator:________________ Unit #:________ Neighborhood:________________ Date:________________

Swamper:________________ Camera ID:________________ Time left the shop:__________

Pipe ID:________________ **Pipe Type:**____________ **Pipe Length:**______________

Task	Start	Finish	Length	Problems Occurred			
Locating MH and transportation				Map Error ○	Office error ○	Other ______ ○	
Upstream MH setup				Obstacle over MH ○	Obstructed pipe entry ○	Traffic ban ○	Other ______ ○
Downtream MH setup				Obstacle over MH ○	Obstructed pipe entry ○	Traffic ban ○	Other ______ ○
Flushing				Obstacle over MH ○	Obstructed pipe entry ○	Filling out water ○	Other ______ ○
Camera Installation				Obstructed pipe entry ○	Other ______ ○		
Recording				Steam ○	Roots/debris/grease in pipe ○	Camera/crawler Breakdown ○	PII box ○ Lens cleaning ○
				Do reversal ○	Cable issue ○	many sags ○	Other ______ ○
Add. Flushing				Obstacle over MH ○	Obstructed pipe entry ○	running out water ○	Other ______ ○
Camera removal				PII box ○	Other ______ ○		
Cleaning crawler				Grease ○	Other ______ ○		
Extreme weather:	Freezing	Rainy	Snowy	Explaination if not completed:			

Repairs or supplies required?________________________________

Page:__________ Meters achieved: ______________ Time returned to the shop:__________ Signature:____________________ ver:2.0-5.25.2012

Figure 4.3: CCTV Assignment Sheet for Time Study

Time data from 214 CCTV assignments was collected over a six month period (June to November 2012) from different neighborhoods in Edmonton. The data was obtained from different CCTV operators with different work experience. The time used in the data analysis included the average time of each operator's performance on different sewer systems with a variety of pipe lengths and diameters. Figure 4.4 is a pie chart of the average time spent on each work unit expressed in daily working hours. The pie chart demonstrates that solutions such as hiring advanced crawlers or enhancement of the flushing procedure have the potential to improve the share of 29.0% (recording) or 24.7 % (flushing) of the cycle time. However, the combination of locating manholes and travelling comprises 34.4% of the CCTV operation. Since travelling and locating facilities are non-value-added activities which contractors are not paid for, this study focused on minimizing the work delays, correcting travel patterns, and generating efficient daily work to improve the CCTV cycle time.

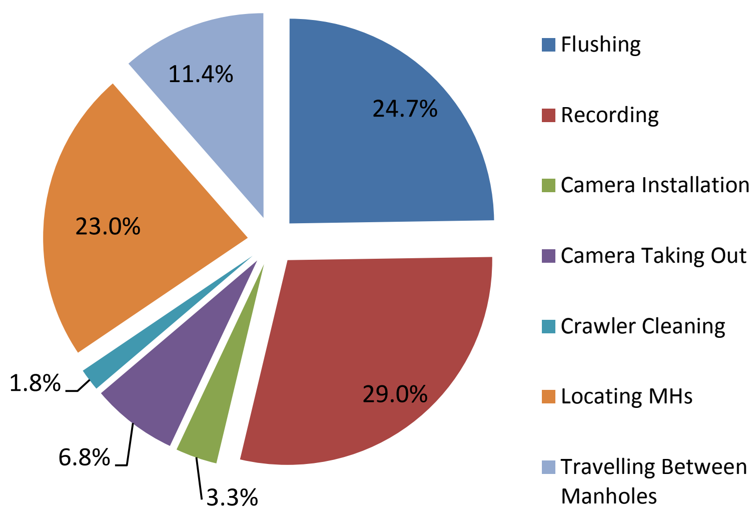


Figure 4.4: Average Share of Each Work Unit in Daily Activities

In developing a solution for increased productivity, the TSP model was used to reduce travel time and manhole searching time. The following section reviews mathematical algorithm and TSP solver application in vehicle route optimization and analyses the influence of this approach on the projected neighborhood plan and daily CCTV work.

4.4 The CCTV Process Improvement by Application of TSP

For this study, Concord TSP Solver was used to generate the optimal path between upstream manhole coordinates in a specific neighborhood. The Concord TSP Solver is a computer interface, written in the ANSI C programming language that can apply different heuristic algorithms to solve symmetric TSPs. The Concord TSP Solver calculates the optimal solution by using the cutting-plane method. It also has the capacity to hold coordinates for 24,978 nodes and solve binary integer programming (BIP) based on the requested algorithms. Concord TSP Solver is open source software for academic use supported by the Office of Naval Research, National Science Foundation, and the School of Industrial and Systematic Engineering at Georgia Tech (Cook, 2011).

Although the Concord Solver's calculation is fast, and the software is easy to use, it does not consider road constraints and intersections when determining the optimal path. To verify the Concord Solver's improvement, the gap between improvements obtained based on linear distance and road distance must be studied. To do so, this study compares the results of the travel patterns calculated by TSP and the CCTV operator's judgment (real data), reviews the potential level of improvement that the TSP optimizer suggests in both linear distance and road distance, and verifies the results with a real case sample.

Twenty daily CCTV performances from three different CCTV operators and neighborhoods in Edmonton were randomly selected to develop a regression that shows how road constraint affects the level of CCTV productivity improvement. Also, the observed sequence of movements and TSP sequence of movements in both road distance and Euclidean distance (air distance) are compared.

The Concord TSP Solver retrieved the best travel path based on manholes' geometric coordinates (X, Y) for each day's work. For example, figure 4.5 and figure 4.6 show the location of manholes and the result of a case study observed on August29th, 2012 in Calder neighborhood.

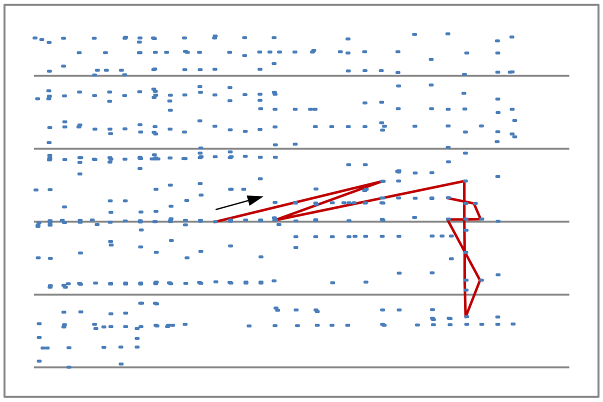
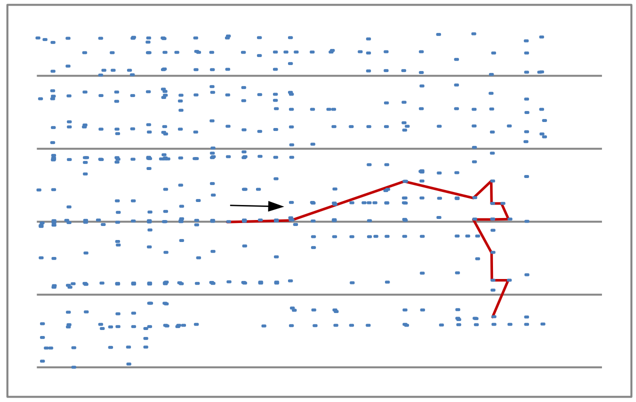
The sequence from operator's judgment	**The sequence from TSP optimizer**
	
Euclidean travelling length = 2,559.2 m	Euclidean travelling length = 1,493.1 m

Figure 4.5: The Comparison of Euclidean Path between the Observation and the Optimal Travelling Sequence Illustrated for 29/08/2012 Work Order in Calder Neighborhood, Edmonton

The sequence from operator's judgment	**The sequence from TSP optimizer**
	
Road travelling length = 4,000 m	Road travelling length = 2,200 m

Figure 4.6: The Comparison of Road Path Between The Observation And The Optimal Travelling Sequence Illustrated for 08/29/2012 Work Order in Calder Neighborhood, Edmonton (Google Inc., n.d.).

The optimal sequence was retrieved from Concord TSP Solver and illustrated in Microsoft Excel (Figure 4.5), and the same order of travel was plotted on Google Maps' web mapping service to retrieve the road distance (Figure 4.6). Based on Euclidean distance, the CCTV crew could travel 41.66% less than what they had originally traveled. Based on road distance, the optimal travel route would have resulted in 45% less travelling.

The same procedure was used to analyze other field observations, the results of which are summarized in Table 4.1.

Table 4.1: CCTV Field Observations and Comparison of The Level of Travelling Length Improvements in Euclidean Distance and Road Distance

# of Sample	Neighborhood	Date	Euclidean Distance			Road Distance		
			travel length (m)		Improvement	travel length (m)		Improvement
			Observation	TSP		Observation	TSP	
1	Lansdowne	05/18/2012	2,196.19	1,670.53	23.94%	2,700	2,100	22.22%
2	Lansdowne	05/17/2012	643.31	481.14	25.21%	740	550	25.68%
3	Lansdowne	05/07/2012	771.55	665.87	13.70%	1,000	850	15.00%
4	Lansdowne	05/12/2012	364.91	364.91	0.00%	750	750	0.00%
5	Lansdowne	04/25/2012	630.00	417.69	33.70%	869	566	34.87%
6	Lansdowne	05/09/2012	444.41	292.40	34.20%	700	500	28.57%
7	Lansdowne	05/08/2012	2,870.76	1,058.80	63.12%	4,500	1,800	60.00%
8	Calder	06/13/2012	887.68	556.70	37.29%	1,500	950	36.67%
9	Calder	06/14/2012	768.42	569.18	25.93%	1,100	800	27.27%
10	Calder	07/10/2012	1,359.40	856.85	36.97%	2,200	1,400	36.36%
11	Calder	07/12/2012	912.33	812.53	10.94%	1,000	900	10.00%
12	Calder	07/17/2012	1,197.21	842.78	29.60%	2,500	1,800	28.00%
13	Calder	07/23/2012	2,099.50	936.56	55.39%	2,400	1,100	54.17%
14	Calder	08/29/2012	2,559.20	1,493.10	41.66%	4,000	2,300	42.50%
15	Queen Alexandra	08/20/2012	1,032.10	669.18	35.16%	1,100	750	31.82%
16	Queen Alexandra	08/21/2012	1,453.60	870.03	40.15%	1,700	1,000	41.18%
17	Queen Alexandra	08/29/2012	1,232.10	872.62	29.18%	1,500	1,000	33.33%
18	Queen Alexandra	09/17/2012	4,781.90	3,161.90	33.88%	5,700	3,400	40.35%
19	Queen Alexandra	10/02/2012	2,841.50	2,467.20	13.17%	3,500	2,600	25.71%
20	Queen Alexandra	08/25/2012	1,047.50	779.95	25.54%	1,100	800	27.27%
Average					**30.44%**			**31.05%**

Reviewing the daily travel patterns revealed that, although the road and linear travelling length between two points is different, the level of improvement that the TSP optimizer calculates (based on Euclidean distance) is almost the same as that calculated for road distance. In some cases, it was even observed that the level of travel improvement for road distance was better than that which the TSP calculates based on Euclidian distance. This is because the crew does not consider traffic flow when selecting the next destination, and more distance must be covered; the crew should decide to back-track when locating the next manhole. In contrast, since the travelling salesman algorithm selects the next closest point of travel, it minimizes the need for back-tracking. Evaluating the relationship among the Euclidean and road distance improvements, the regression of scatter points shows a security level (R-Squared value) of 93.15%, as depicted in figure 4.7. This result is based on examination of both irregular-shaped neighborhoods and square-shaped neighborhoods with rectangular blocks which are common in Edmonton. According to the study, road constraints affect both the optimized and CCTV operators' paths almost equally. However, the particular coefficients in the regression may change slightly between cities depending on the relative configuration of road and sewer networks, although this change it is not expected to be significant. The coefficients in this study showed that the level of improvement achieved by TSP optimization (based on Euclidean distance) is almost equal to the level of improvement that would occur based on road distance.

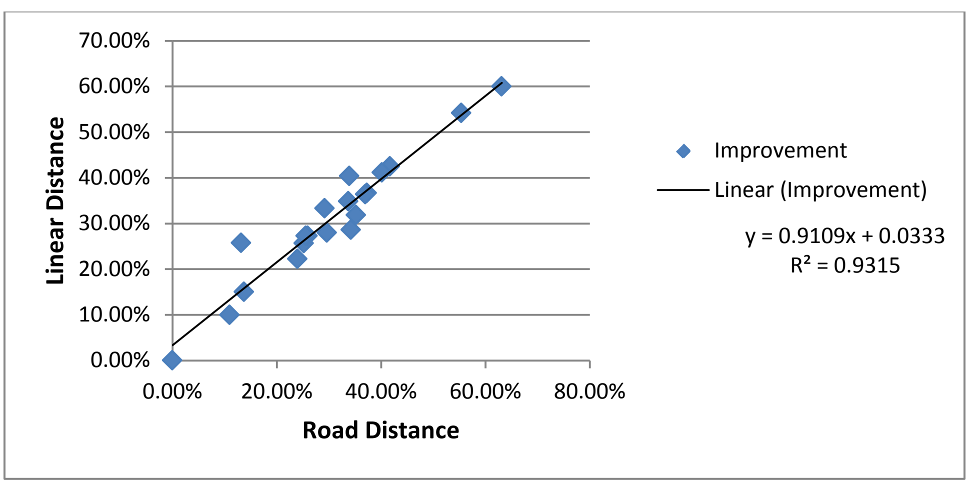


Figure 4.7: The Regression of Improvement Level Based on Linear and Road distances

Daily observations show that there is potential to improve the daily travel time by approximately 31% through the application of TSP optimization. Moreover, a preliminary study showed that by predefining the next facility for operators, the time taken to locate manholes is reduced from 40% to 50%. By mapping the pattern of movement, operators can visualize the CCTV operation, and possible crew confusion is reduced. Therefore, it is estimated that by applying TSP optimization to determine the optimum travel path for daily CCTV activities, the CCTV cycle time improves from nearly 12.7% to 15%. The estimation is calculated from equation 6; Locating Manhole's level of improvement (40%~50%) multiply by its time allotment (23%) plus the Travelling's level of improvement (31%) multiply by its time allotment (11.4%).

Equation 6

CTI $=\sum_{1}^{n}(WUI_n * WUTA_n)$

Where:

CTI = cycle time improvement

n = the number of work components in the process

$WUTA_n$ = the n^{th} work unit's time allotment

WUI_n = the level of n^{th} work unit improvement

Regardless if the map used by CCTV operators is outdated or a manhole is buried, the crew must still travel to its location and report the situation. Therefore, the process is completed faster if the route of travel is determined ahead of time via TSP, as it calculates the shortest path between travel points.

To verify these results, TSP optimization was applied to a new CCTV project in Edmonton (McKernan neighborhood, 2013), which resulted in a 13.04% improvement in the daily production rate. The average production rate on days which the travel route was un-planned was

483.1 m/day, while the average production rate on days which it was planned was 546.12 m/day. The Figure 4.8 shows the distribution of the CCTV production rate in McKernan neighborhood before and after the implementation of TSP optimization (see the Appendix B for details). This result suggests that the application of TSP has a positive impact on the performance of the daily travelling and manhole location activities in the CCTV process.

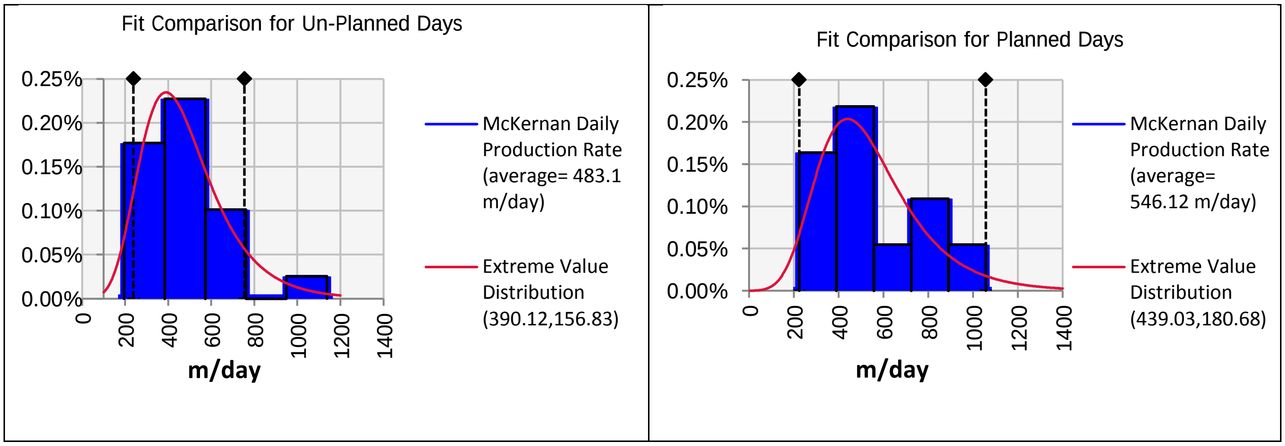


Figure 4.8: Daily Production Rate in McKernan Neighborhood and Fitting the Input Data with Extreme Value Distribution - 95% Confidence Level

To evaluate the impact of using TSP to plan CCTV truck movement through a neighborhood, all upstream manhole coordinates for the given neighborhood are considered in the optimization calculation. A large set of coordinates in a travelling network can change the optimum path significantly in comparison to a small set. As the daily performance study illustrated, the TSP application on daily movements with a set of eight to twelve facilities improves the productivity by more than 12%. However, applying TSP to a neighborhood with around 600 facilities is expected to yield higher productivity improvement.

To evaluate the expected level of improvement by pre-planning the travel route through a neighborhood, the real travel data from three different neighborhoods was compared to the solutions retrieved by TSP optimization. For this stage, the daily CCTV inspection performances in Calder, Queen Alexandra, and Lansdowne neighborhoods were studied. Calder and Queen

Alexandra are square-shaped areas with rectangular blocks, and Lansdowne is a paisley-shaped area with irregular blocks. A CCTV operator with five years of experience was assigned to both the Calder and Lansdowne projects, and a CCTV operator with six months of experience was assigned to the Queen Alexandra project. Figures 4.9, 4.10, and 4.11 compare the operators' actual movements with the optimal movement that TSP suggested.

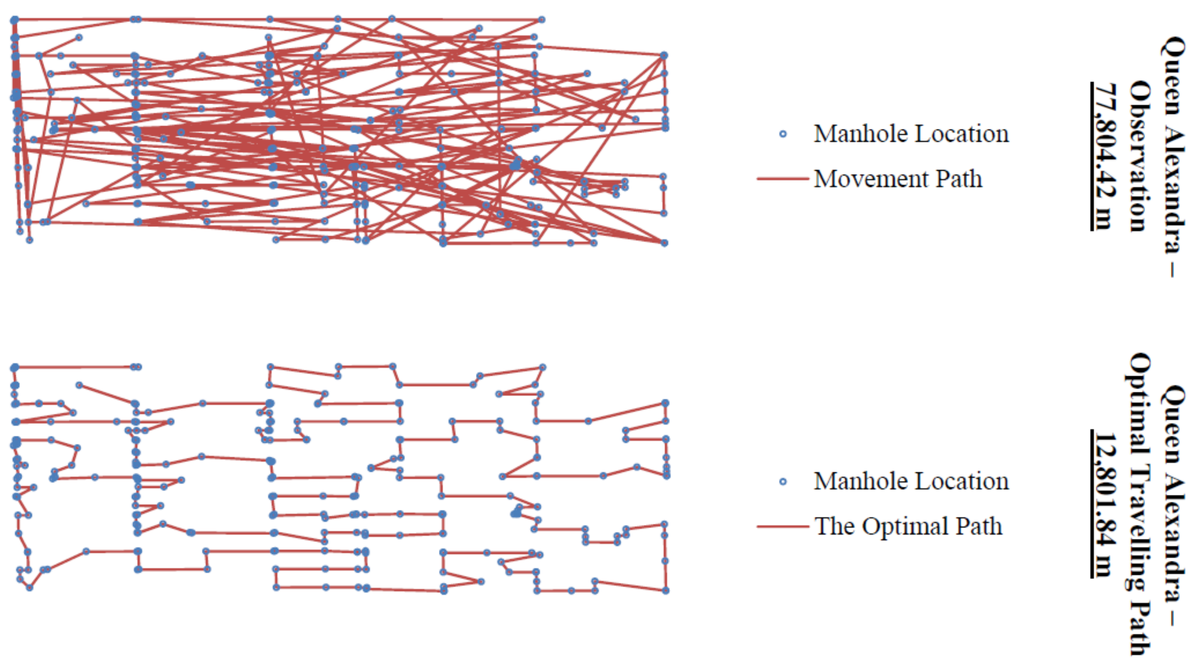


Figure 4.9: The Comparison of Road Path between the Observation and the Optimal Travelling Sequence Illustrated for Queen Alexandra Neighborhood, Edmonton.

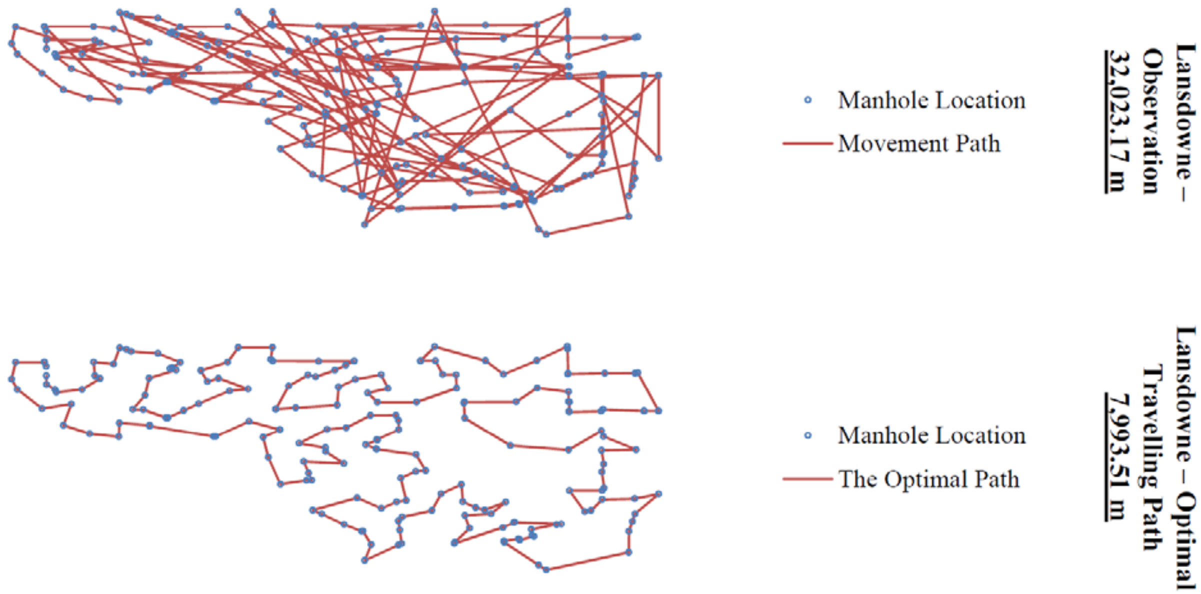


Figure 4.10: The Comparison of Road Path Between The Observation and The Optimal Travelling Sequence Illustrated for Lansdowne Neighborhoods, Edmonton.

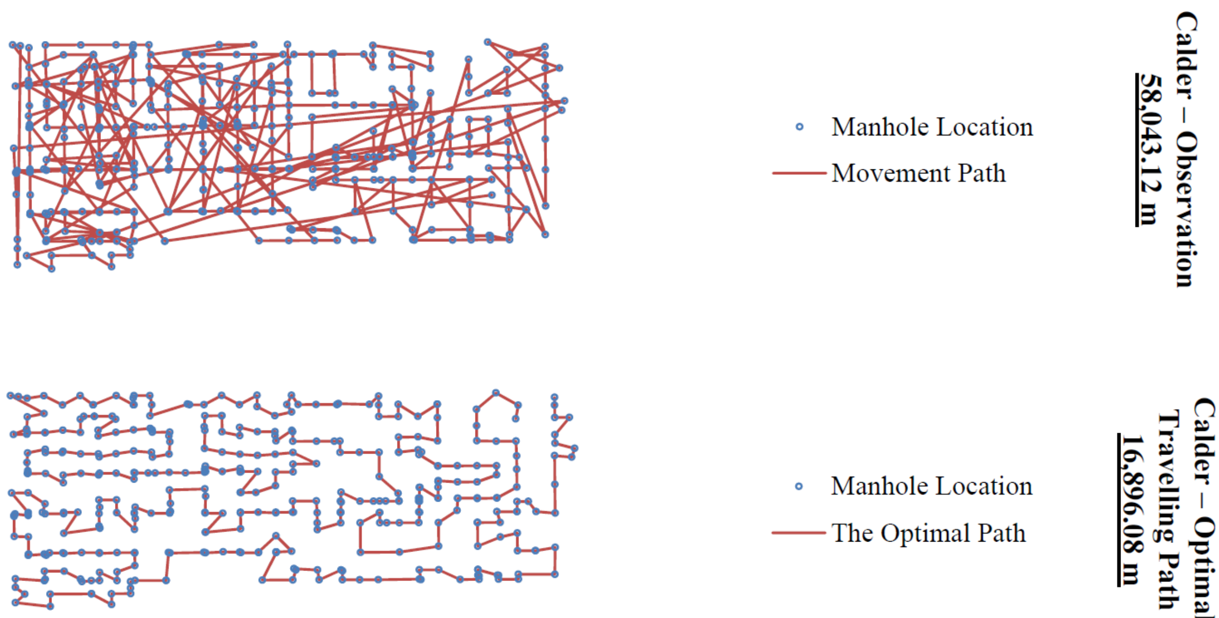


Figure 4.11: The Comparison of Road Path Between The Observation and The Optimal Travelling Sequence Illustrated for Calder Neighborhoods, Edmonton.

As Table 4.2 shows, pre-planning a neighborhood's travel sequence via TSP optimization has the potential to improve performance productivity between 18% and 21%.

Table 4.2: The Potential Improvement in Televising Sewer Mainline in Different Neighborhoods by Application of TSP Optimization

No.	Neighborhood	Observation Path Length	Optimal Path Length	The potential Improvement in Travelling		Improvement in Cycle Time (equation 6)
				Euclidean	Road	
1	Queen Alexandra	77,804.4 m	12,801.8 m	83.55%	88.06%	**20.39%**
2	Lansdowne	32,023.2 m	7,993.5 m	75.04%	78.72%	**19.32%**
3	Calder	58,043.1 m	16,896.1 m	70.89%	74.17%	**18.81%**

However, the size of the underground mainline must also be taken into account. If the next facility scheduled for televising is larger or smaller in diameter compared to the previous facility, the operator must change the crawler size, which takes time. Therefore, it is beneficial to categorize upstream manholes by sewer diameter in groups of 200mm-250mm, 300mm-450mm, and 500mm-600mm. The TSP optimizer can then calculate the optimal path for each group, which allows CCTV operators to televise the mainline group-by-group in the order determined by the optimal path.

4.5 Conclusion

CCTV is the most practical and common inspection method for the physical condition assessment of sewer mainline. As the information collected via CCTV operations is used for municipal asset management programs and provides the current deterioration rate of service lines, CCTV processes must be scheduled continuously. A significant amount of time, money, and resources is spent annually to televise sewers. Therefore, improving the CCTV process and increasing its production rate can aid in effective budget control and can also save time and resources.

One of the largest cities in Canada, Edmonton, Alberta, was targeted in this study for the analysis of its CCTV inspection performance. Over 200 CCTV assignments were analyzed in detail, and the time share of each work component in the CCTV cycle time was calculated. According to the collected data, 31.40% of the time in the CCTV process is spent on the non-value-added activities of locating manholes and travelling. Therefore, Concord TSP Solver was used to apply TSP optimization and reduce the CCTV process cycle time by determining the optimal travel path for CCTV vehicles. Since the Concord TSP Solver finds the optimal solution based on Euclidean distance, the results of TSP optimization in road situations was also studied. By plotting the travel route in Google Maps' web mapping service, it was determined that travel improvement based on Euclidean distance (approximately 30%) was similar to that of road distance. Another study on the CCTV process indicated that providing the CCTV operator with a pre-determined sequence of movement can improve time spent on manhole location by 40% to 50%. Multiplying the level of improvement in each work component by their time allotment shows that the daily CCTV production rate can improve between 12.7% and 15% via the application of TSP optimization.

To evaluate the effect of TSP optimization on neighborhood CCTV planning, an analysis was done on CCTV processes in the three neighborhoods of Calder, Queen Alexandra, and Lansdowne in Edmonton. The results show that pre-planning the travel route in a neighborhood can improve the CCTV production rate between 18-21%, depending on the project's situation.

CCTV operators are required to return to shop at the end of the workday, which is commonly 8 hours. In future studies, it may be useful to monitor the workday remaining following the completion of daily scheduled CCTV activities. To minimize the remaining time at the end of the workday and maximize time spent completing CCTV activities, careful planning in the selection of mainlines for televising is essential. As this study did not consider the workday for daily CCTV activities, this constraint should be studied further.

Chapter 5: Concluding Remarks

5.1 Concluding Remarks

In Edmonton, there are thousands of kilometers of sewer mainlines in thirty three industrial, commercial, and residential neighborhoods that require periodic inspection. The most common approach in collecting data for urban sewer mainline physical condition assessment is CCTV inspection. The collected CCTV data is used for asset management programs, budgeting, and determination of sewer network deterioration trends. To maintain updated data and support decision making, CCTV operations must be scheduled continuously. As a result, municipalities spend significant amounts of money and time annually on the collection of pipe data.

Production rate is crucial information for resource planning, progress tracking, and budget control. Moreover, identifying the impact of weather on the process can help create a better understanding of how the production rate changes in weather sensitive cities like Edmonton. Since the daily cost of the CCTV process does not change based on production volume (only the fixed costs of labour and equipment are involved), productivity enhancement in the process can also reduce production cost and help contractors provide more cost-effective operations to municipalities and land developers.

The main objectives of this study were to develop the CCTV inspection production rate in Edmonton, analyze the effects weather conditions and temperature on CCTV production, analyze the work components in the CCTV work system, and implement time study and TSP optimization techniques to enhance CCTV performance.

This thesis included five chapters to: provide an introduction to the CCTV process; review literature regarding productivity studies, work system framework, and route optimization;

summarize the results of developing the CCTV production rate in Edmonton and the effects of weather condition and temperature on CCTV productivity; and summarize the results of CCTV work improvement via the application of TSP optimization.

To develop the CCTV production rate in Edmonton, information from the televising of nearly 2000 mainlines was analyzed. The analyzed mainlines totaled approximately 122 km in length and were monitored during a 1.5 year period from November 11th, 2011 to January 11th, 2013. The impact of snow conditions and the seasonal influence on the CCTV production rate was also studied.

The productivity study, explained in detail in the Chapter 3, shows that the CCTV production rate in Edmonton followed a Weibull distribution, with parameters of $\lambda = 1.8555$, $K= 528.59$, and Risk Shift = 3.6582. On average, July was the most productive month, with a televising rate of 579 meters per day, and October had the lowest production rate of 161 meters per day. With a crew of four people, the overall CCTV production rate was 61.2 meters per hour. This study also indicates the CCTV process is sensitive to ambient temperature. An equation relating CCTV productivity and ambient temperature was obtained by regression as $y=75.124*x^{(0.6669)}$ (in which y is production rate in meters per day and x is temperature in degrees Celsius) with an R–squared value of 74 percent. Moreover, an ANOVA analysis for assessing the impact of snowfall conditions on the CCTV production rate was performed and indicated that the effect of snowfall on CCTV productivity is significant. A comparison between productivity on snow days and the average production rate of CCTV performance showed that CCTV productivity decreases during snow days to less than 57 percent.

To enhance CCTV productivity and to improve the CCTV inspection crew performance, the CCTV process was reviewed, a time study was performed, and a route optimization technique was applied as outlined in Chapter 4. The CCTV productivity improvement study was initiated by developing a relational database from detailed CCTV work component information collected from more than 200 mainline inspections. Through the analysis of the CCTV process and the collected data, the production flow was determined, and the time allotment of each CCTV work component was calculated. According to the collected data and the work study, the non-value-added activities of locating manholes and travelling were identified as the most time consuming work components in the process, taking 31.4 percent of the CCTV cycle time. Therefore, the CCTV truck movements and the locating of manholes were targeted for improvement. In developing a solution for productivity improvement, the TSP optimization technique was used to reduce the time spent travelling and locating the manhole. Concord TSP Solver was implemented to simulate manhole coordinates and retrieve the optimal travelling path between manholes. Comparison of the optimal path with the truck's actual movement shows that the implementation of TSP technique can improve the travelling pattern by more than 30 percent. Since the TSP solver considers the linear distance between mainlines (it does not consider road constraints and intersections), the travel patterns calculated by TSP and those determined by CCTV operator judgment (real data) for 20 daily CCTV performances were compared in terms of both linear and road distance. The study then reviewed the potential level of improvement that the TSP optimizer suggests in linear and road distance. The results showed that travelling improvement based on Euclidean distance (approximately 30 percent) was similar to that of road distance. In other words, the gap between improvements obtained based on linear distance and road distance is minor. Another study conducted on CCTV inspection in Edmonton's McKernan neighborhood indicated that providing the CCTV operator with a pre-determined sequence of movement can improve time spent locating manholes by 40-50 percent. It also showed that the application of TSP optimization can improve both traveling and locating manhole activities.

This study also evaluated the impact of using TSP to plan CCTV truck movement through the three neighborhoods of Queen Alexandra, Lansdowne, and Calder. This study shows that applying TSP to neighborhood movement plans has the potential to improve traveling activities by 80 percent on average. Multiplying the level of improvement in each work component by its time allotment indicated that the daily CCTV production rate can be improved between 18-21 percent via the application of TSP optimization.

5.2 Future Work

Determining CCTV inspection productivity from real data and observations collected at work sites may provide increased accuracy. However, the evaluation and quantification of all factors on-site is time and energy consuming. Instead, the application of computer tools provides an opportunity to develop more advanced methods to analyze work systems. Simulation and mathematical modeling are examples of advanced tools that are used for evaluating productivity and productivity factors. Since many factors such as equipment, labourer's experience, working motivation, training, and working area affect CCTV productivity; further study is required to analyze their effects on the CCTV process. This can be done through the application of simulation method and modeling.

Moreover, this study considered the relative geographical location of mainlines in order to optimize the CCTV truck's traveling path, but didn't review the work system during a specific daily eight-hour work period. Since CCTV operators normally return to shop after eight hours, it may be useful to consider another method for sorting mainlines in order to use the workday more effectively. For further study, it is also recommended that a model of Vehicle Routing Problem with Time Windows (VRPTW) is developed to monitor the remainder of the workday following the completion of assigned CCTV inspections. Such a model would be useful in minimizing remaining time wasted at the end of a workday and may achieve even higher productivity improvements when combined with the implementation of measures suggested in this study.

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Appendix A: Some Examples of Defects Inside a Sewer Mainline

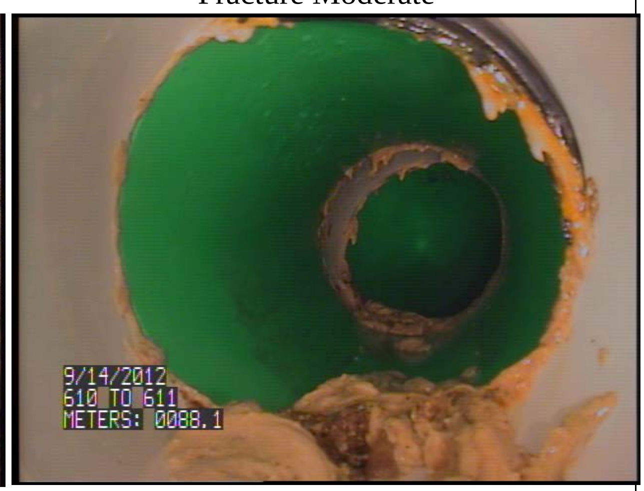
Cracked pipe, fractured pipe, deformed pipe, joint displacement, open joints, and surface damage are some examples of structural defects. The defects would be categorized based on the severity levels of the defects: light, moderate, severe, and broken or collapsed. The Table A.1 and A.2 show some examples of pipe defects.

Table A.1: Some Examples of Pipe Defects (IVIS Inc.)

Multiple Cracks from 12 to 5 o’clock

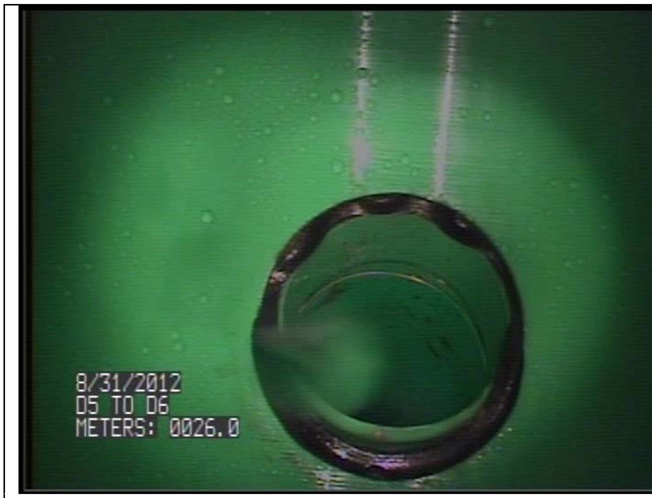
Fracture Moderate

Hole in pipe @ 6 o’clock

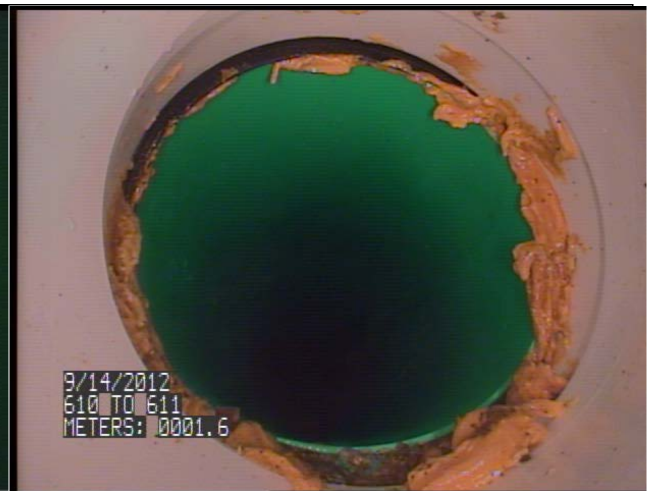


Gasket exposed @ 12 to 3 o’clock

Table A.2: Some Examples of Pipe Defects Cont.' (IVIS Inc.)



Connection Defective



Connection Defective - Gasket visible

Debris - Rocks and dirt

Roots Mass

Deformed Pipe; Multiple Fractures; Surface Damage

Broken Pipe (Pieces missing)

Appendix B: The COE Pipe Defect Codes

The COE's protocol's Sewer Physical Condition Classification Manual (SPCCM) provides a code summary of the possible defects in the sewer mainlines as the Table B.1.

Table B.1: The COE Pipe Defect Codes (The City of Edmonton , 1996)

Defect	**Code**	**Unit**	**Weight**
Crack			
Light	CL	Meter	10
Moderate	CM	Meter	37
Severe	CS	Meter	54
Fracture			
Light	FL	Meter	33
Moderate	FM	Meter	68
Severe	FS	Meter	84
Broken Pipe			
Light	FXL	Each	41
Moderate	FXM	Each	73
Light Void	FXVL	Each	86
Severe Void	FXVS	Each	100
Hole			
Light	FXVL	Each	86
Severe	FXVS	Each	100
Deformation			
Light	DL	Meter	34
Moderate	DM	Meter	70
Severe	DS	Meter	91
Collapsed Pipe			
Collapsed Pipe	DX	Meter	100

Defect	**Code**	**Unit**	**Weight**
Joint Displacement			
Light	JL	Each	28
Moderate	JM	Each	59
Severe	JS	Each	79
Open Joint			
Light	OL	Each	25
Severe	OS	Each	72
Sag			
Light	SL	Meter	25
Severe	SS	Meter	76
Surface Damage			
Light	HL	Meter	21
Moderate	HM	Meter	53
Severe	HS	Meter	76
Lining			
Abandoned Connection	LAC	Each	42
Overcut Service	LOC	Each	64
Undercut Service	LUC	Each	56
Lining – Wrinkled	LW	Meter	62
Lining – Other Defects	LZ	Meter	65

Appendix C: Details of Collected Data in McKernan Neighborhood

In order to test the hypothesis that the implementation of optimal path retrieved by TSP optimization method can improve the CCTV production rate, some working weeks for McKernan project in Edmonton were executed by work orders based on TSP planning, and some weeks were carried out based on CCTV crew's judgment (traditional approach). Table C.1 detailed the achieved daily production rates (m/day) as follows:

Table C.1: Comparison between Un-planed Days and Planed days

Planned Days		**Un-Planned Days**	
Date	**Production Rate (m/day)**	**Date**	**Production Rate (m/day)**
5/7/2013	1056.3	4/22/2013	699.5
5/8/2013	389	4/23/2013	520
5/9/2013	325	4/24/2013	481.2
5/28/2013	393.3	4/25/2013	195.6
5/29/2013	539.3	4/26/2013	754.5
5/30/2013	623.7	5/1/2013	736.7
5/31/2013	523.5	5/2/2013	251.6
6/1/2013	390.6	5/11/2013	485.6
6/11/2013	768.1	5/13/2013	1137.7
6/12/2013	774.9	5/14/2013	370.2
6/13/2013	223.6	5/15/2013	403
Average	**546.12**	5/24/2013	461
		6/3/2013	374.23
		6/4/2013	468.4
		6/6/2013	482.3
		6/23/2013	591.6
		6/24/2013	251.4
		6/25/2013	239
		6/26/2013	472.6
		6/27/2013	465.5
		7/17/2013	303.5
		Average	**483.10**