Economic Analysis and Information Modeling of Smart Multi-purpose Utility Tunnels

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ABSTRACT

Economic Analysis and Information Modeling of Smart Multi-purpose Utility Tunnels

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The traditional method of buried utilities (i.e. water, sewer and gas pipes, and electrical and telecommunication cables) has been used for many decades particularly in urban areas. Repeated excavations are needed to access these underground utilities for maintenance, repair, and renewal activities. Urban areas have been experiencing many street closures and traffic disruptions because of excavation for maintaining underground utilities. These construction works have imposed major costs on public and private utility companies as well as on citizens and local businesses (social cost). Multi-purpose Utility Tunnels (MUTs) have been built since the 19th century as a solution and alternative way that not only avoids these excavations but also facilitates inspection and protects utilities. However, MUTs are not widely used in most of the countries because of the high initial investment, safety and security issues, complicated design and construction, and complex coordination of utility companies. Despite the higher design and construction cost of MUTs, operational cost-savings can justify the investment from the project point of view. From the organization's point of view and based on cost-sharing, MUT should be more economical as well and the MUT benefits should be distributed fairly to convince utility companies to participate in the MUT project. Lifecycle Cost (LCC) analysis of the MUT and the buried utilities method is complicated because of various factors that influence the LCC. Also, there is a gap in defining the concept of fairness and applying mathematical methods for a fair cost-sharing. On the other hand, to facilitate the complicated design and construction, and complex coordination of utility companies in MUT projects, Building Information Modeling (BIM) tools are very helpful. However, BIM is mainly developed for buildings and there are efforts to extend it to civil structures (e.g. bridges, tunnels). Although using BIM for MUTs has progressed in recent years, there is still lack of a comprehensive framework covering MUT components and information requirements for all use cases, as well as its integration with Geographic Information System (GIS) and other technologies.

This research aims to: (1) improve the decision-making related to MUT selection process by developing a comprehensive and systematic approach for MUT and buried utilities LCC analysis.

In addition, this research investigates the influence of factors of utility specifications, location conditions, and construction methods. The output of this model determines the LCC of MUT and buried utilities, and the design and construction cost of MUT at the breakeven point to ensure the project decision-makers that MUT is the economic method; (2) improve the fairness of MUT cost-sharing by developing a fair model that considers fairness based on (a) balance of risk, (b) balance of benefit and cost, and (c) balance of contributed benefit and gained benefit. This model makes MUT the economical method for utility companies and distributes the benefits and costs of MUT fairly among the utility companies; and (3) improve the coordination among the MUT stakeholders by developing a framework integrating BIM and 3D GIS for Smart Multi-purpose Utility Tunnel Information Modeling (SMUTIM). The framework defines MUT information requirements, identifies SMUTIM use cases, and extends Industry Foundation Classes (IFC) to MUT.

The contributions of this research are: (1) developing a comprehensive and systematic approach for MUT and buried utilities LCC analysis by considering the factors of utility specifications, location conditions, and construction/maintenance methods. The output of this model estimates the LCC of MUT and buried utilities. The proposed model can justify whether an MUT project is an economic alternative method for buried utilities; (2) developing an MUT cost-sharing method to ensure the decision-makers of utility companies that MUT is the economic method for their company and also the benefits and costs of MUT are distributed fairly among the utility companies. The fairness is defined based on three principals: balance of risk, balanced benefit-cost ratio, and balance in contributed benefit and gained benefit; (3) categorizing and integrating smart MUT physical and functional components and their relationships in a systematic way; (4) completing, integrating, and organizing the available knowledge about SMUTIM use cases within a framework. Then, using the case study to show the capabilities and gaps of current BIM applications, GIS, databases, and facility management tools for MUT lifecycle management; and (5) partially extending IFC to MUT by proposing Model View Definition (MVD), new entities and relationships, and taking advantage of reusable IFC entities, properties, and relationships.

It is expected that the proposed model promotes using MUT by (1) facilitating economic analysis and cost-sharing for MUT projects from project and organization points of view; and (2) facilitating the design, construction, and operation of MUTs, and the coordination of utility companies.

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Dedicated to my wife and my parents for their endless love and spiritual support and encouragement.

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LIST OF ABBREVIATIONS

3D	3 Dimensional
4D	4 Dimensional
AHP	Analytical Hierarchy Process
BCR	Benefit-Cost Ratio
BIM	Building Information Modeling
CB	Design and construction cost of buried utilities
CCTV	Closed-Circuit Television
CIPP	Cured-In-Place Pipe
CIM	Civil Information Modeling
CIM	Common Information Model
CIM	Specific utility installation cost of a company in MUT
CM	Design and construction cost of MUT
COBie	Construction Operations Building Information Exchange
CR	Cost of risk management
CST	Common Services Tunnel
CT	Cost transfer
E&R	Excavation and Reinstatement
FNDM	Fiber Network Data Model
FV	Future Value
GB	Gained lifecycle benefit of a company by participating in MUT
GIS	Geographic Information System
GUID	Global Unique Identifier
HDPE	High-density polyethylene
HTML	Hypertext Markup Language
HVAC	Heating, Ventilation, and Air Conditioning
HWR	Hourly Wage Rate
IDM	Information Delivery Manual
IEC	International Electrotechnical Commission
IFC	Industry Foundation Classes
INC	Incentive for a company
IoT	Internet of Things
ISO	International Standards Organization

LCC	Life Cycle Cost
LOD	Level of Development
MUT	Multi-purpose Utility Tunnel
MVD	Model View Definition
O&M	Operation and Maintenance
OB	Operational cost of buried utilities
OCCS	OmniClass Construction Classification System
OCM	Operational cost of MUT
OCP	Open-Cut Pulverization
OV	Occupied volume of a utility company in MUT
PBC	Proportion of Buried Cost
PD	Project Duration
PODS	Pipeline Open Data Standard
PUVO	Proportion of Utility Volume Occupancy
PV	Present Value
PVC	Poly Vinyl Chloride
PPP	Public-Private Partnership
RFID	Radio-frequency identification
ROW	Right of Way
SHM	Structural health monitoring
SMUTIM	Smart Multi-purpose Utility Tunnel Information Modeling
SOCM	Specific operational cost of a company in MUT
STEP	Standard for the Exchange of Product model data
SWOT	Strengths, Weaknesses, Opportunities and Threats
TIM	Tunnel Information Modeling
TxDOT	Texas Department of Transportation
UAV	Unmanned Aerial Vehicle
UUID	Universal Unique Identifier
UV	Ultra Violet curing
VED	Vehicle Delay
VOR	Vehicle Occupancy Rate
VOT	Value of Time
VTD	Vehicle Traffic Density

CHAPTER 1. INTRODUCTION

1.1 Background

Utility networks (e.g. gas, water and sewer pipes, and electrical and telecommunication cables) are developed above and under the ground. Above ground utilities in urban areas can cause problems, such as aesthetic issues, occupation of limited urban space, limited accessibility space, safety issues related to utilities exposed to weather changes (e.g. hurricane, extreme high/low temperature, and accident). Therefore, the traditional method of buried utilities is common for the development of utility networks, especially in urban areas.

Different studies have reported that underground utilities infrastructure in developed countries has aged and almost reached their service lives (Gagnon et al., 2008; Ormsby, 2009). Therefore, to access aging buried utilities for repair, maintenance, and renewal activities, repeated excavation and street cuts are needed. Urban areas have been experiencing many street closures and traffic disruptions because of excavation for maintaining underground utilities. These construction works have imposed major costs on public and private utility companies as well as on citizens and local businesses (i.e. social cost) (Oum, 2017). As a solution, Multi-purpose Utility Tunnels (MUTs), are defined as "underground utilidors containing one or more utility systems, permitting the installation, maintenance, and removal of the system without making street cuts or excavations" (Canto-Perello and Curiel-Esparza, 2013).

Two groups can benefit from MUTs: (a) utility companies, and (b) utility users and citizens. The main benefits for utility companies include: (a) major cost-saving by reduction of repeated excavation (Cano-Hurtado & Canto-Perello, 1999; Laistner, 1997; Rogers & Hunt, 2006), utility installation (Canto-Perello & Curiel-Esparza, 2013), repair of streets and sidewalks (Hunt et al., 2014), traffic control (Gilchrist & Allouche, 2005), and repair of detour road damage bearing extra traffic load (Najafi & Kim, 2004), (b) reduced damage (Canto-Perello & Curiel-Esparza, 2013) and corrosion of utilities (Canto-Perello & Curiel-Esparza, 2003), (c) facilitated inspection and maintenance of utilities (Canto-Perello & Curiel-Esparza, 2013; Hunt et al., 2014; Clé de Sol, 2005), (d) cost savings related to facilitated future development and upgrade of utilities (Kang & Choi, 2015; Clé de Sol, 2005), (e) reduction of municipal revenue loss from parking meter machines, parking ticket (Ormsby, 2009; De Marcellis-Warin et al, 2013), and sales tax (Gilchrist & Allouche, 2005; De Marcellis-Warin et al., 2013) , (f) decrease in labor accidental injury and death (Ormsby, 2009; Clé de Sol, 2005) and (g) more organized underground space planning (Sterling et al, 2012).

The utility users and citizens mainly benefit from MUTs (social benefits) because of: (a) cost and time saving because of major reduction of traffic congestion (Gilchrist & Allouche, 2005; Clé de Sol, 2005; Ormsby, 2009), (b) increased quality of utility services and customer satisfaction (Cano-Hurtado & Canto-Perello, 1999; Laistner, 1997; Canto-Perello et al., 2009), (c) improved social health, environment, and safety by preventing problems of construction works such as accidental safety issues, noise, dust, vibration, and air, soil, and water pollution (Gilchrist & Allouche, 2005; Najafi & Kim, 2004; Ormsby, 2009; CERIU, 2010; Jung & Sinha, 2007; Ferguson, 1995), (d) reduced negative impact of construction work on local business because of fewer customers (Ormsby, 2009; Manuilova et al., 2009), and (e) decrease in damage/temporary closure of recreational facilities, e.g. parks (Ormsby, 2009).

1.2 Problem Statement and Research Gaps

Despite MUT benefits, MUTs are not extensively used in most countries, except China, due to complicated (a) lifecycle economical assessment and justification, (b) fair cost-sharing, and (c) coordination of utility companies.

- **Lifecycle economical assessment and justification of MUT:** Despite the high initial investment needed, direct operational and social cost savings can make MUT Life Cycle Cost (LCC) less than conventional buried utilities. To investigate if MUT is an economically viable alternative for the traditional method of buried utilities in a specific project, different factors should be considered related to the specifications of utilities, the location of the project, and the construction method. The LCC of each method is a function of these factors. Therefore, there is a need for a systematic approach to estimate the LCC and find a breakeven point where the costs of both methods are equal. MUT is the economic method when the estimated LCC of MUT is lower than that of buried utilities method.

- **Fair cost-sharing of MUTs:** After deciding on an MUT project, the next challenge is financing and cost-sharing of the project (Canto-Perello & Curiel-Esparza, 2013). MUT should be more economical for each utility company compared with the buried utility option (i.e. organization level economic justification), and the MUT costs and benefits should be distributed fairly to convince utility companies to participate in the MUT project. However, there is a gap in defining the concept of fairness. Mathematical methods should be applied to define fairness based on different concepts (i.e. balance of risk management costs, balance of benefits).
- **Coordination issues of utility companies:** Integrating different utilities in the confined and shared space of MUT requires a high degree of coordination among utility companies. Building Information Modeling (BIM) can be used for improving the coordination of utility companies and facilitating the design, construction, and operation of MUTs. However, BIM is mainly developed for buildings and has been extended to some civil structures (e.g. bridges, tunnels). Despite the efforts for using BIM in MUT projects, there is a gap in extending BIM to Smart MUT Information Modeling (SMUTIM). A smart MUT is equipped with sensors that monitor MUT and ancillary facilities (e.g. security, Heating, Ventilation, and Air Conditioning (HVAC), and communication systems). Also, using BIM is not enough to satisfy all the MUT information requirements because: (1) BIM cannot support the information requirements of surrounding environment (e.g. streets, buildings, underground structures); and (2) BIM is not able to process the huge amount of real-time sensory data during MUT operation. Therefore, BIM should be linked with Geographic Information Systems (GIS) to include the surrounding environment information, and external databases for supporting real-time sensory data (Lee et al., 2018). The use cases of BIM should be identified and extended to MUT. Industry Foundation Classes (IFC), as the standard of BIM, should be extended to include the MUT-specific components which are not available in buildings. Although the available resources, which use BIM for MUTs, only concentrate on one or some aspects of MUTs (Kang et al., 2014; Bao, 2017; Lee et al., 2018; Hu & Zhang, 2019; Ge & Xu, 2019; Li et al., 2019; Wu et al., 2019; Sfere, 2020; Shahrour et al., 2020, Yin et al., 2020), the full extension of BIM to MUT should benefit from the available resources to identify all the MUT components and information requirements.

1.3 Research Objectives

This research aims to achieve the following objectives:

(1) Improving the decision-making process related to MUT selection process by developing a comprehensive and systematic approach for MUT and buried utilities LCC analysis. In addition, investigating the influence of factors of utility specifications, location conditions, and construction methods. The output of this model determines the LCC of MUT and buried utilities, and the design and construction cost of MUT at the breakeven point.

(2) Improving the fairness of MUT cost-sharing by developing a fair model that considers fairness based on (a) balance of risk, (b) balance of benefit and cost, and (c) balance of contributed benefit and gained benefit. This model makes MUT the economical method for utility companies and distributes the benefits and costs of MUT fairly among the utility companies.

(3) Improving the coordination among the MUT stakeholders by developing a framework integrating BIM and 3D GIS for SMUTIM. The framework defines MUT information requirements, identifies SMUTIM use cases, and extends Industry Foundation Classes (IFC) to MUT.

1.4 Thesis Organization

The structure of this thesis is presented as follows:

Chapter 2 Literature review: This chapter reviews different aspects of MUT, such as classification, construction methods, benefits and disadvantages, lifecycle cost assessment of MUT and buried utilities, financing and cost-sharing of MUTs, and a review of MUT projects and studies around the world. Finally, BIM extension for Civil Information Modeling (CIM), the current use of BIM-based systems for MUT projects, and Industry Foundation Classes (IFC) extension for MUT are reviewed.

Chapter 3 Overview of the research approach: The overview of the proposed research approach and methodology are presented in this chapter.

Chapter 4 Lifecycle cost assessment and cost-sharing of MUT: This chapter covers cost issues including (a) economy assessment of MUT and comparison with buried utilities method, and (b) lifecycle cost-sharing of MUTs.

Chapter 5 Smart MUT information modeling for lifecycle management: This chapter goes through the details of the proposed method for BIM extension to SMUTIM. The steps include (a) proposing MUT lifecycle information modeling requirements, (b) identification of SMUTIM use cases, and (c) proposing IFC extension to SMUTIM.

Chapter 6 Summary, Contributions, and Future Works: The work done in this research is summarized in this chapter. The contributions at the end of this research are discussed and the remaining work is explained as future work.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

In this chapter, MUT classification, construction methods, benefits, and disadvantages are discussed. Lifecycle costs of MUT and buried utilities are reviewed and compared afterward. Then, the economy of MUT is compared with buried utilities within the lifecycle of MUT, to investigate the long-term economic viability of MUTs. Other obstacles for promoting MUTs, i.e. lifecycle financing and cost-sharing, are also discussed. A review of MUT projects and studies in the world and case studies of MUT are presented afterward. Then, BIM/CIM and its application and extension for MUT are discussed in this chapter.

2.1 Multi-purpose Utility Tunnel (MUT)

MUT classification, construction methods, benefits, and disadvantages are explained as follows.

2.1.1 MUT Classification

As shown in Figure 2-1, the history of MUT in the modern age started from 19th century (Laistner & Laistner, 2012). Rectangular sections and rectangular/semi-circular sections of MUTs were common in the 19th and 20th centuries. Circular sections have been used in recent years because of the uniform distribution of forces on a circular tube and less damage from the concentration of forces.

Rogers and Hunt (2006) classified MUTs based on depth, type, the position of installation, shape, and material (Rogers & Hunt, 2006). Considering the depth of cover, MUT can be categorized into three groups of flush-fitting (0.0 m), shallow (0.5–2 m), and deep (2–80 m), as shown by (Hunt et al., 2014) in Figure 2-2. Based on accessibility and internal space, MUT types of searchable, visitable, and compartmentalized are defined. MUTs can be situated under roads, pathways, and metros (Figure 2-3). They can be constructed with different shapes including trapezoid, rectangular, rectangular with lid, circular, ovoid with the gutter, and double oval. The possible materials of the tunnel are High-Density Polyethylene (HDPE), cast-in-place concrete, pre-cast concrete sections, steel, brick and mortar, and sprayed concrete.

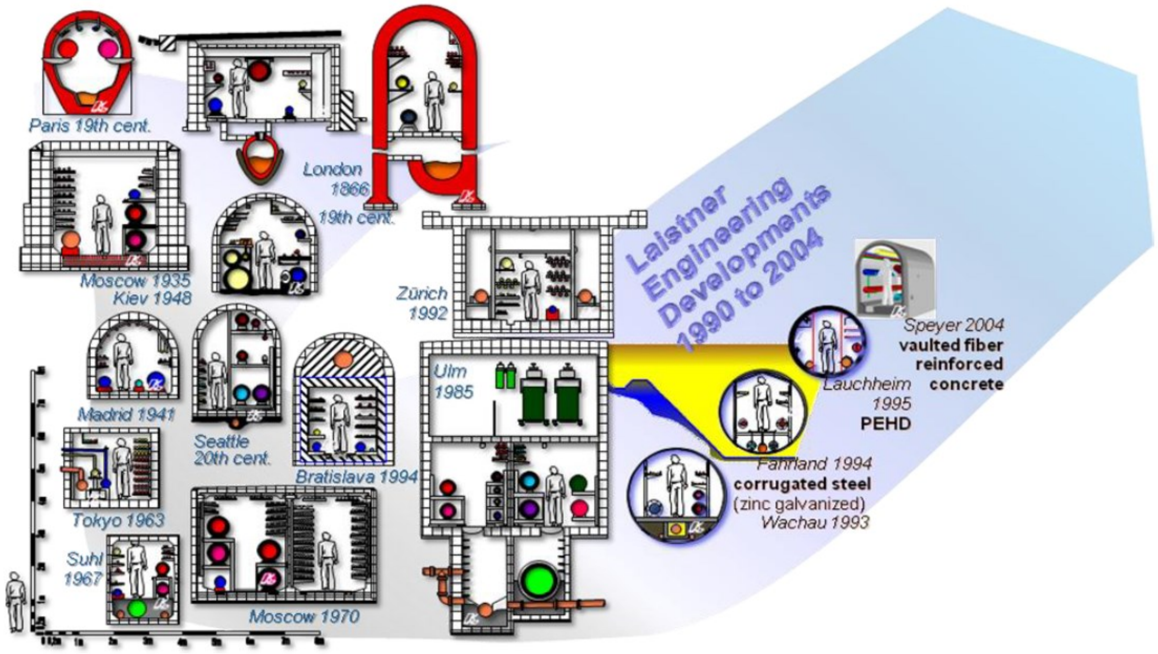


Figure 2-1 MUTs around the world from 1866 (Laistner & Laistner, 2012)

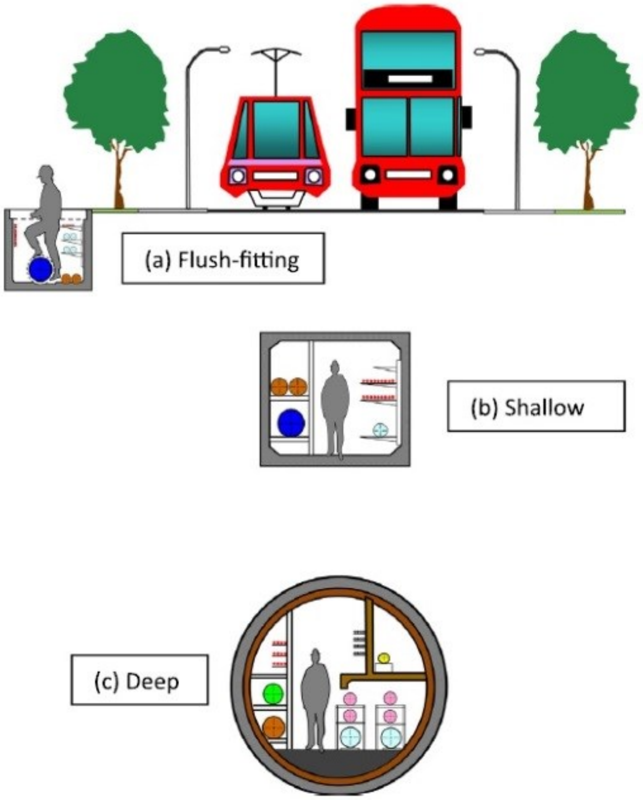
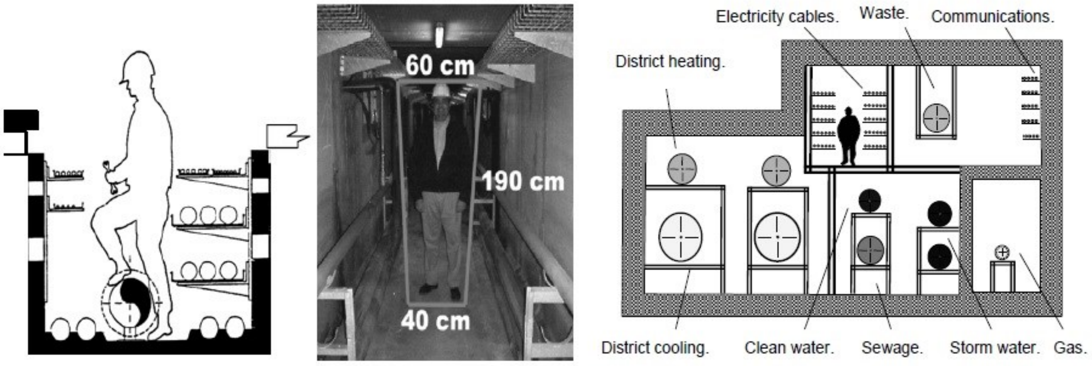
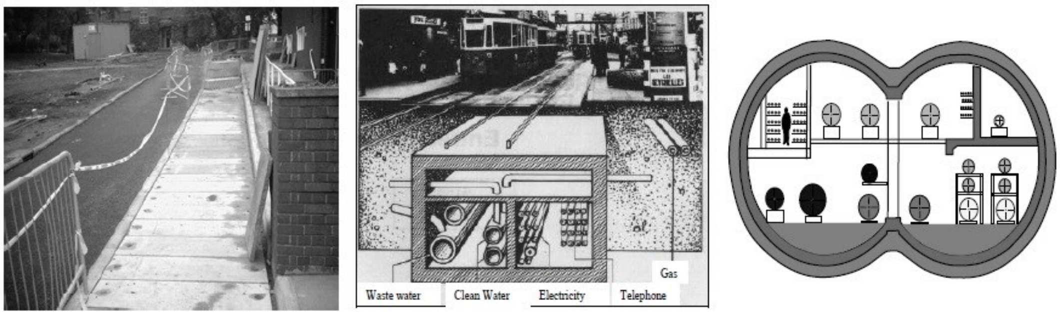


Figure 2-2 Different types of MUTs (Hunt et al., 2014)



(a) Searchable (b) Visitable (Canto-Perello and Curiel-Esparza, 2001) & (c) Compartmentalized



Position of MUTs (a) Flush fitting (b) Under metro / roadway (Pierre, 1978) (c) Deep tunnels

Figure 2-3 MUT types and position (Rogers & Hunt, 2006)

2.1.2 MUT Construction Methods

There are three methods to design and construct MUTs including (1) cast-in-place concrete, (2) prefabricated concrete/fiberglass segments (Clé de Sol, 2005; AKpipe, 2017; Ramírez Chasco et al., 2011), and (3) trenchless jack and bore (BYU, 2015; Habimana et al., 2014). Each method has advantages and disadvantages. For example, the advantage of a cast-in-place concrete method is low technical complexity with high flexibility in execution. However, the execution speed is relatively low as it needs framing, tying rebars, concrete curing, etc. The prefabricated concrete/fiberglass segment method takes less time with higher quality as it is already produced off-site with high-quality control. Transportation of segments to the site and possible weakness in joints are disadvantages of this method (Clé de Sol, 2005). The trenchless jack and bore system avoids excavation of streets and roads. However, it is more costly than the previous methods (BYU, 2015) and the underground space should be clear of utilities and other structures (Habimana et al., 2014).

The high initial investment for the design and construction of MUTs can be reduced by applying new construction technologies, such as prefabrication and modularization, which provide economy of scale. It means that the cost of production per unit is reduced with a high volume of production. Prefabrication and modular design of MUTs need to consider specific conditions of a project, such as soil characteristics, underground water elevation, on-site urban structures and facilities, the distance of transportation of modules, available space of road for transportation and installation of modules, the scale of the project, and geographic features of the region. Modularization is a new technology that can potentially reduce MUTs construction cost and time, and also improve its quality. In modularization, the modules of a system, such as a building, sewer system, tunnel, etc., are completely fabricated in a factory away from the construction site. The large modules are divided into smaller portions to be transported to the site (Haas et al., 2000). In the prefabrication process, different materials are joined, to produce a component of the building system to be installed later on the site (Tatum et al., 1987).

Modular construction is widely used for building construction (O'Connor et al., 2014). Also, the construction of sewer lines benefits from prefabricated modular segments (e.g. concrete culvert) which are buried underground. Since MUTs are underground tunnels that encompass different utilities, modularization can be used for the structure of the tunnel. It is also possible for the tunnel structure to include some utilities, such as pipes or trays, in the prefabricated segment to be joined during construction. Figure 2-4 shows an example of a modular MUT with pipes inside the tunnel (AKpipe, 2017).

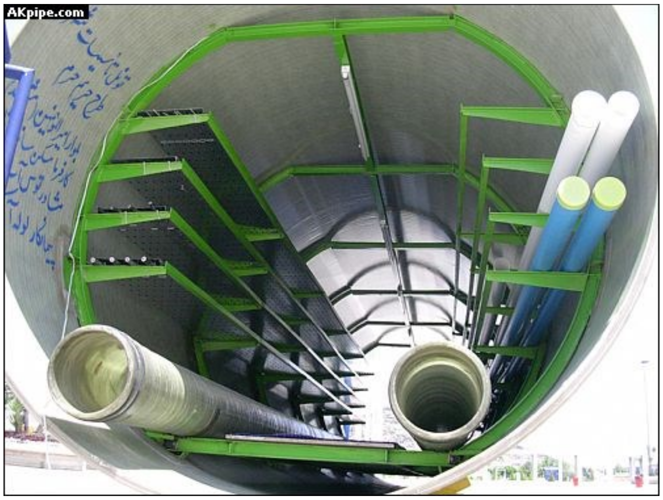


Figure 2-4 Example of modular MUT with pipes (AKpipe, 2017)

2.1.3 MUT Benefits

MUT benefits can be categorized into two groups: benefits for utility companies and municipalities, and benefits for utility users and citizens (social and environmental benefits). These benefits are explained in detail as follows.

2.1.3.1 MUT Advantages for Utility Companies and Municipalities

The municipality and utility companies (e.g. electricity and telecommunication network companies, water and sewer companies) can gain great benefits from using MUTs. These benefits are shown in Table 2-1 and explained below.

(1) Major reduction of construction costs (i.e. costs of excavation, traffics congestion, road repair, injury, and death): The costs of excavation and reinstatement related to underground utilities during their lifecycle will be greatly reduced by using MUTs. These costs pertain to the long-term sustainability costs of utilities (Cano-Hurtado & Canto-Perello, 1999; Canto-Perello & Curiel-Esparza, 2013; Laistner A., 1997; Rogers & Hunt, 2006). Maintenance work inside the space of the tunnel decreases the volume of construction work on the ground, as well as the needed equipment and machinery, workforce, and material. Blocking streets due to construction work will be reduced majorly and normal traffic continues Consequently the traffic control costs are decreased (Gilchrist & Allouche, 2005). During construction work, the vehicles use detour roads, which may not be designed for heavy traffic load. MUTs reduce the damage to detour roads by avoiding lifecycle repeated excavations and reinstatements for utility maintenance and repair (Najafi & Kim, 2004). There are fewer disturbances for local businesses and residents of that area. The impact of excavation on the roads, sidewalks, tree roots, and other structures around the project is reduced majorly, which leads to reduced repair costs (Hunt et al., 2014). Less construction work during the lifecycle of utilities results in less accidental injury and death of labor and also less collision of vehicles with traffic control and safety tools, construction structures, construction vehicles, equipment, and workers (Ormsby, 2009; CERIU, 2010).

(2) Improved inspection and maintenance of utilities: The space of MUTs provides better access for inspection and assessment of underground utilities (Hunt et al., 2014; Canto-Perello & Curiel-Esparza, 2013). This preventive inspection leads to a reduction in the failure of utilities (e.g. pipe

rupture) and an increased life span. In addition, the weather condition does not affect the inspection process, because MUTs provides an accessible underground space for utility maintenance and inspection activities (Canto-Perello & Curiel-Esparza, 2013; Clé de Sol, 2005).

(3) Minimization of damage and corrosion of utilities: In the conventional buried utilities, there is a network of utilities and their exact position sometimes may not be easy to identify. This issue can lead to damage to utilities during the excavation. By integrating all of the underground utilities inside MUTs, this problem will be solved majorly (Canto-Perello & Curiel-Esparza, 2013). Also, the MUT environment protects underground pipelines against corrosion, which usually happens in the conventional buried method (Canto-Perello & Curiel Esparza, 2003).

Table 2-1 MUTs advantages/benefits for utility companies and municipalities

	Benefit	**Sub-benefit**
MUT advantages/benefits for utility companies and municipality	Major reduction of construction costs	• Major reduction of excavation cost (1,2,3)
		• Major reduction of utility placement cost (4)
		• Major reduction of road and sidewalk repair (5)
		• Major reduction of traffic control costs (6)
		• Major reduction of detour road damage due to extra traffic load (7)
		• Major reduction of increased collision rate (8,12)
	Improved inspection and maintenance of utilities (4,5,15)	
	Minimization of damage and corrosion of utilities	• Major reduction of damage to other structures in construction work (4)
		• Major reduction of corrosion of utility (11)
	Future development and upgrade cost savings (9,10,15)	
	Major reduction of labor accidental injury and death (8,12)	
	Major reduction of municipal revenue loss	• Major reduction of lost parking meter revenue (8,13)
		• Major reduction of lost parking ticket revenue (8,13)
		• Major reduction of tax revenue reduction from business owners (6,13)
	More organized planning of underground (14)	
REFERENCES: 1) Cano-Hurtado and Canto-Perello (1999) 2) Laistner (1997) 3) Rogers and Hunt (2006) 4)Canto-Perello and Curiel-Esparza (2013)	5) Hunt et al. (2014) 6) Gilchrist and Allouche (2005) 7) Najafi and Kim (2004) 8) Ormsby (2009) 9) ITA (2010) 10) Kang and Choi (2015) 11) Canto-Perello and Curiel-Esparza (2003)	12) CERIU (2010) 13) De Marcellis-Warin et al. (2013) 14) Sterling et al. (2012) (15) Cl) de Sol (2005)

(4) Future development and upgrade cost savings: The MUTs provide a combined space not only for currently available utilities to pass through the tunnel in a protected and monitored

environment, but also make the future placement, change, decommission, and upgrading of utilities much easier and cheaper than the open-cut method (ITA, 2010; Kang & Choi, 2015; Clé de Sol, 2005).

(5) Major reduction of labor accidental injury and death: Construction work includes activities that can be harmful to the laborers and employees. It can cause illness, injury, and death. The workers are subject to the risk of trenching-related death and serious injuries (Ormsby, 2009; CERIU, 2010). Therefore, MUTs reduce labor accidental injury and death by avoiding repeated constructions.

(6) Major reduction of municipal revenue loss: By closing the streets, parking meter machines become deactivated and no more income is gained by them. The parking ticket revenue is reduced majorly too (Ormsby, 2009; De Marcellis-Warin et al., 2013). Closing streets leads to less shopping from local businesses and reduces the sale tax revenue (Gilchrist & Allouche, 2005; De Marcellis-Warin et al., 2013).

(7) More organized planning of underground space: Integrating all utilities in the closed space of MUT enables utility companies and municipalities to better organize underground space (Sterling et al., 2012).

2.1.3.2 MUT Advantages for Utility Users and Citizens (Social and Environmental Benefits)

The social and environmental benefits of MUTs are related to the users of the utilities and the roads, and generally, all citizens who are living or have a business in the area or even the city. These benefits/advantages are shown in Table 2-2, and include:

(1) Major reduction of traffic congestion or detour road: Due to traffic congestion or detour roads, the vehicles arrive destination with delay. This delay wastes the time of the vehicle passengers and imposes them delay cost (Gilchrist & Allouche, 2005; Ormsby, 2009; Oum, 2017). Also, the operation costs of vehicles increase because of the extra operation time due to traffic congestion or detour roads (Ormsby, 2009; CERIU, 2010; De Marcellis-Warin et al., 2013; Clé de Sol, 2005). In addition to the vehicle's passenger, pedestrians are also affected by delays because of construction works and losing time (Ormsby, 2009). Another cost is imposed to emergency

vehicles (e.g. ambulance, firefighter vehicle, police) because of loss of time due to the road obstruction (Ormsby, 2009; CERIU, 2010; De Marcellis-Warin et al., 2013).

Table 2-2 MUT Benefits for utility users and citizens (social and environmental benefits)

	Benefit	**Sub-benefit**
MUT Benefits for users (social and environmental benefits)	Major reduction of traffic congestion or detour	• Major reduction of vehicle delay time costs (3,5,13,14)
		• Major reduction of pedestrian delay time costs (5)
		• Major reduction of extra operation costs of vehicles (5,6,7)
		• Major reduction of emergency vehicle obstruction (5,6,7)
	Improved health	• Major reduction of the dust of construction work (6,8,9)
		• Major reduction of noise of construction work (3,4,10)
		• Major reduction of vibration of construction work (3,7,10)
	Major reduction of environmental pollution	• Major reduction of air pollution (3,9)
		• Major reduction of soil pollution (3,9)
		• Major reduction of underground water contamination (3,8,9)
	Improved safety	• Major reduction of accidental injury and death (5,6)
		• Major reduction of emergency vehicles obstruction (5,6)
	Improved quality of utility services and customer satisfaction (1,2,11)	
	Major reduction of local business loss (5,12)	
	Major reduction of damage/temporary closure of recreational facilities (5)	
REFERENCES: 1) Cano-Hurtado and Canto-Perello (1999) 2) Laistner (1997) 3) Gilchrist and Allouche (2005) 4) Najafi and Kim (2004)	5) Ormsby (2009) 6) CERIU (2010) 7) De Marcellis-Warin et al. (2013) 8) Werey et al. (2005) 9) Ferguson (1995) 10) Jung and Sinha (2007)	11) Canto-Perello et al. (2009) 12) Manuilova et al. (2009) 13) Clé de Sol (2005) 14) Oum (2017)

(2) Improved health, environment, and safety: Construction work for open-cut utility maintenance and placement activities causes safety issues (e.g. injuries or death by accident) due to falling into excavation or collapse of trenches. Also, closing roads will be an obstacle for emergency vehicles to pass fast (Ormsby, 2009; CERIU, 2010). In addition, the noise and vibration of machinery in construction works of the open-cut method (Jung & Sinha, 2007), cause health problems for citizens (e.g. high blood pressure, disturbance for sleep) and consequently reduced productivity (Gilchrist & Allouche, 2005). The dust propagation to the air from construction work and emission of toxic gases and air, soil (Ferguson, 1995), and underground water pollution (Gilchrist &

Allouche, 2005; Ferguson, 1995; Werey et al., 2005) are other issues related to the health of people and environmental problem.

(3) Improved quality of utility services and customer satisfaction: Because of better inspection and maintenance of utilities by using tunnels, the number of faults and breakdowns decreases, and the expected life span of the utilities increases (Laistner, 1997). This helps the utility companies to provide a better quality of services with fewer service disruption and cheaper services cost (Cano-Hurtado & Canto-Perello, 1999; Canto-Perello et al., 2009). Customer satisfaction increases through the higher quality of services and fewer charges.

(4) Major reduction of local business loss: The local businesses in the area of construction work can be affected negatively and lose income because of reduced customers. As an example, the businesses that provide delivery services will encounter delays as a consequence of traffic congestion and road closure (Ormsby, 2009; Manuilova et al., 2009).

(5) Major reduction of damage/temporary closure of recreational facilities: Recreational facilities (e.g. parks, playgrounds) are usually closed or damaged temporarily because of construction works. This has a negative impact on the users of these facilities (Ormsby, 2009).

2.1.4 MUT Disadvantages

The main disadvantages of MUTs are:

(1) High initial investment cost: The initial investment to construct an MUT is much more than the conventional buried utilities method and is not affordable for a single utility company (Rogers & Hunt, 2006) even by considering the possibility of renting the space to other utility companies after construction (Hunt et al., 2014). The huge investment is needed because more volume of construction work is required, from excavation to the structure of the MUT, for items such as material, labor, and equipment (McKim, 1997). Some conditions are more likely for construction of MUT (e.g. deep excavation, waterproofing, shoring) that are not needed usually for conventional open-cut methods, and add expenses to MUT projects (Najafi & Kim, 2004). In addition, the need for installing temporary bypass utilities for keeping the utilities in service and their diversion imposes an extra cost for MUT projects (McKim, 1997; Rogers & Hunt, 2006).

(2) Disruption of services: The disruption duration of utility services can be critical for decommissioning and construction of new MUTs. A high density of underground utilities needs very deep MUTs to pass under them while construction work is ongoing, to keep the services during a project (Cano-Hurtado & Canto-Perello, 1999; Hunt & Rogers, 2005).

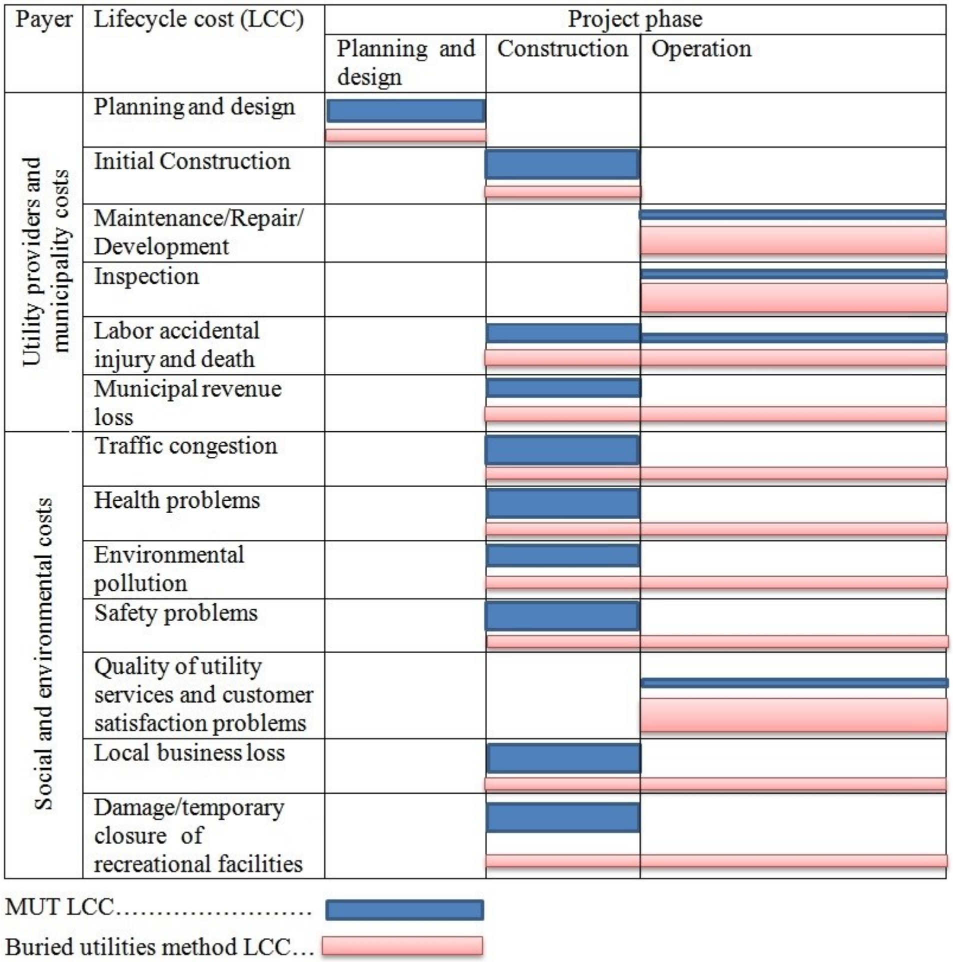
(3) Compatibility and safety issue: Placing of some utilities close to each other has a high risk, because of their incompatibility (Cano-Hurtado & Canto-Perello, 1999; Hunt & Rogers, 2005). For example, (1) housing of gas pipes and electricity cables together imposes a potential risk of fire (Canto-Perello & Curiel-Esparza, 2001; Legrand et al., 2004; Canto-Perello et al., 2009). Therefore, if a utility fails, the other utilities are in danger of damage (Hunt et al., 2014).

(4) Security risks: Providing the security of MUTs from human attacks to the integrated and accessible utilities in MUTs is another issue. To improve the security of MUTs, various solutions are suggested, such as limiting access doors, limiting access for people, sensors, and surveillance systems (Canto-Perello & Curiel-Esparza, 2013).

(5) Coordination issue: A higher degree of coordination between utility companies, municipality, and the utility users is required in MUTs for installation and maintenance activities (Canto-Perello et al., 2009). Since MUTs integrate different utilities in a tunnel, the responsible people and organizations of these utilities (e.g. technical operators and engineers) need more cooperation than the usual system (Laistner & Laistner, 2012). This coordination needs a very good level of management compared to conventional open-cut maintenance and installation works.

2.2 Lifecycle Cost of MUT versus Buried Utilities

The LCCs for two methods of buried utilities and MUTs are listed in Figure **2-5**. The costs are categorized in two groups of (a) utility companies and municipality costs, (b) social and environmental costs. Each LCC belongs to one or more than one phase of the project, namely “Planning and design”, “Construction”, and “Operation”. The LCCs need to be calculated to find the total LCC of buried utilities and MUT. Some costs are easily quantifiable, and some are difficult to quantify. In Figure **2-5**, the thickness of LCC bars are comparable and demonstrating the relative cost for two methods of MUT and buried utilities. In the other words, the thicker bars mean more cost than narrower bars.



Payer	Lifecycle cost (LCC)	Project phase		
		Planning and design	Construction	Operation
Utility providers and municipality costs	Planning and design	🟦 🟥		
	Initial Construction		🟦 🟥	
	Maintenance/Repair/ Development			🟦 🟥
	Inspection			🟦 🟥
	Labor accidental injury and death		🟦 🟥	🟦 🟥
	Municipal revenue loss		🟦 🟥	🟥
Social and environmental costs	Traffic congestion		🟦 🟥	🟥
	Health problems		🟦 🟥	🟥
	Environmental pollution		🟦 🟥	🟥
	Safety problems		🟦 🟥	🟥
	Quality of utility services and customer satisfaction problems			🟦 🟥
	Local business loss		🟦 🟥	🟥
	Damage/temporary closure of recreational facilities		🟦 🟥	🟥

MUT LCC……………………… 🟦

Buried utilities method LCC… 🟥

Figure 2-5 MUT and Buried utilities LCCs

Although quantifying the social costs is not always easy, some mathematical methods have been developed for this purpose (Oum, 2017). For example, the cost of Dirt and Dust Cleaning (DDC) for the buildings affected by construction can be calculated by Equation (2-1) (Oum, 2017):

$$DDC = LCC \times PD \times \sum_{Building\ (b)} FCB_b \times ASC_b \tag{2-1}$$

Where

LCC: local cleaning cost per m^2

PD: project duration in days

FCB_b: frequency of cleaning buildings per day

ASC_b: area of the surface to be cleaned

Another example of quantification of social costs is Vehicle Delay (*VED*) cost for both partial and complete road closures, presented by Oum (2017). A vehicle delay (*VED*) cost is defined to calculate the costs of travel delays borne by vehicle passengers because of increased travel route or time. Using Equations (2-2), (2-3) and (2-4), the needed variables to predict *VED* costs include the project duration (PD_i), the increased travel time (ΔT_{ij}), the vehicle traffic density (VTD_{ijkl}), the value of time lost in traffic (VOT_{ijkl}) and vehicle occupancy rate (VOR_k), where i is the day of the week, j is the time of the day, k is the type of vehicle and l is the type of trips (Appendix A).

$$VED_{partial\ closure, for\ vehicles\ going\ through\ the\ work\ zone} \tag{2-2}$$

$$= \sum_{i=1}^{3} PD_i \times (\sum_{j=1}^{6} \Delta T_{ij\ congestion} \times (\sum_{k=1}^{4} VOR_k \times \sum_{l=1}^{2} (VTD_{ijkl} \times VOT_{ijkl})))$$

$$VED_{complete\ closure, for\ vehicles\ that\ are\ detoured} \tag{2-3}$$

$$= \sum_{i=1}^{3} PD_i \times (\sum_{j=1}^{6} (\Delta T_{ij} + \Delta T_{ij\ congestion}) \times (\sum_{k=1}^{4} VOR_k \times \sum_{l=1}^{2} (VTD_{ijkl} \times VOT_{ijkl})))$$

$$VED_{complete\ closure, for\ vehicles\ that\ are\ normally\ in\ circulation\ on\ alternate\ roads} \tag{2-4}$$

$$= \sum_{i=1}^{3} PD_i \times (\sum_{j=1}^{6} \Delta T_{ij} \times (\sum_{k=1}^{4} VOR_k \times \sum_{l=1}^{2} (VTD_{ijkl} \times VOT_{ijkl})))$$

VED is discretized based on the day of the week (*i*= Weekday, Saturday, Sunday), the time of day (*j*= Night, Morning, Morning peak hours, Midday, Afternoon peak hour, Evening), the type of vehicle (*k*=automobile, bus, light truck, heavy truck), and the type of trips (*l*=business-trip, non-business trip). Then *VTD* can be obtained either manually or by a radar traffic counter. The assumed value of *VOT* is $17.6/per hr according to the average Hourly Wage Rate (*HWR*) of the province of Quebec. This leads to very high social costs for vehicle delays. To avoid this assumption that *VOT* of each driver is $17.6 for one hour of delay, Oum (2017) proposed to use a *VOT* based on *HWR* around $17 for business trips and a *VOT* of 1.5$ based on the price of a cup of coffee for non-business trips. For non-business trips during off-peak hours and during nighttime for all trips, *VOT* is assumed to be $0.

After a mathematical process, Oum (2017) presented Equation (2-5):

$$VED\ costs = \left(\left(a \times VTD_{auto} + b \times VTD_{light\ truck} + c \times VTD_{heavy\ truck} + d \times VTD_{bus}\right). e^{e.Road\ length}\right) \times Project\ duration^{f}) \tag{2-5}$$

where *Road length* is in meter and *Project duration* is in days. The values of coefficients are calculated using a regression method.

Finally, as shown in Figure 2-6, the result of VED costs for a complete road closure in case of reconstruction of all assets in the Plateau Mont-Royal district with water, sewer, and the road is presented. It is assumed that a water pipe is rehabilitated by Cured-In-Place-Pipe lining (CIPP) and the road treatment method is a major rehabilitation technique such as pulverization. The average duration of the project is 30 days and the maximum duration is 160 days. For example, for a segment of length 1 km for St. Denis Street, VED cost is at least CA$1 million.

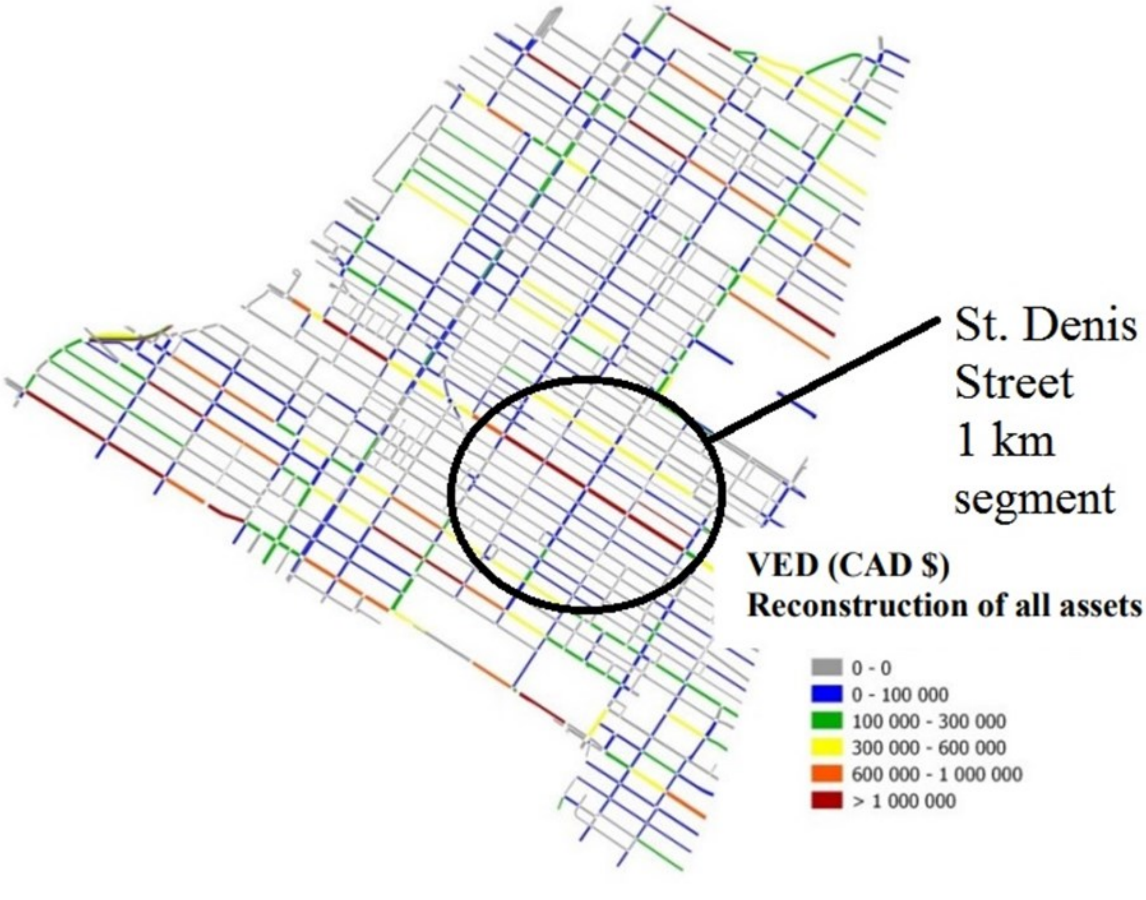


Figure 2-6 VED cost visualization (Oum, 2017)

Designing, construction, and operation of MUTs require many cost items that need to be identified and estimated. The initial investment for an MUT includes costs of planning and design plus costs of construction activities (e.g. costs of excavation, tunnel construction, utility installation, road repairs). Although the operating costs of MUTs are cheaper than the conventional buried utility method, there are still costs for inspection, repair/replacement, security, etc. As shown in Figure 2-7, the operating cost of MUT, mentioned as UT, was reported lower than the conventional method of buried utilities (mentioned as Conv.) in a study of several cases in Germany and Austria (Laistner & Laistner, 2012).

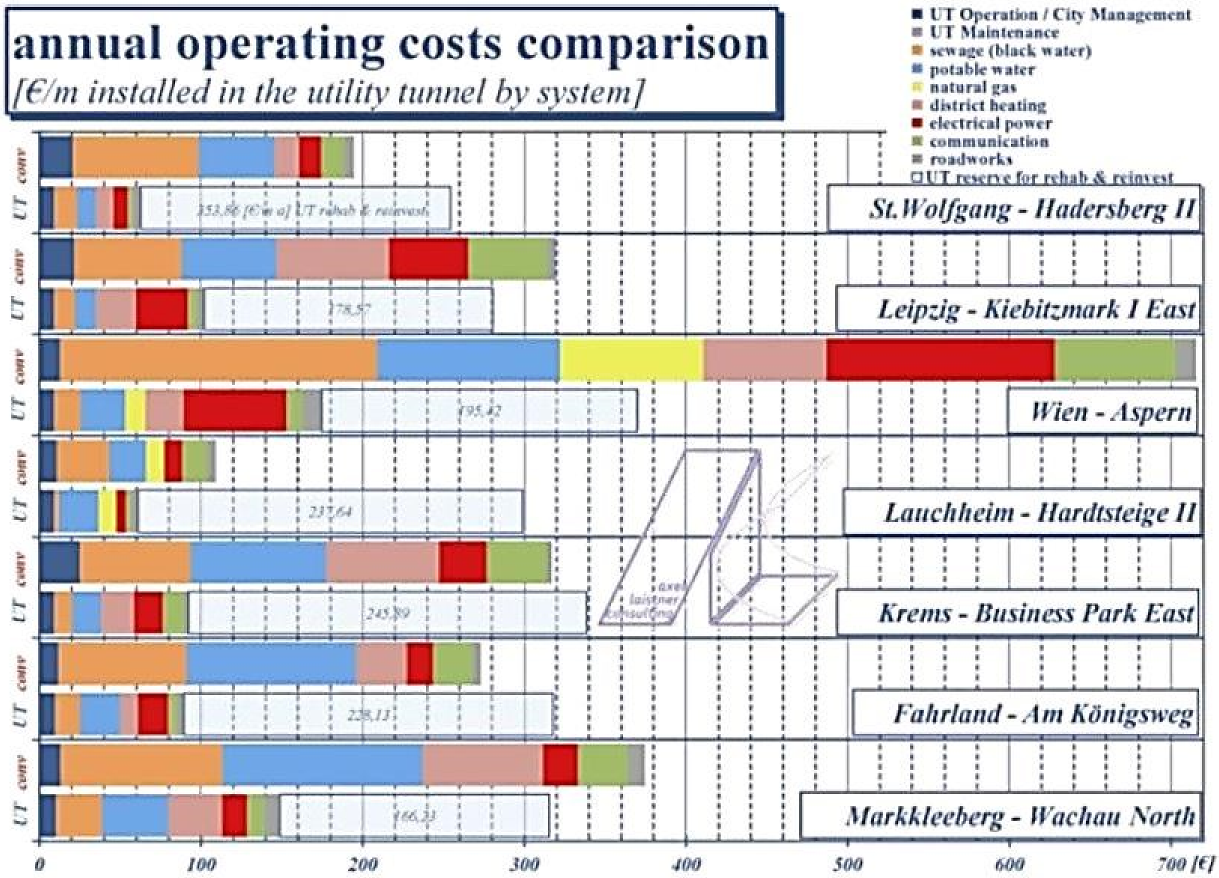


Figure 2-7 Operational cost comparison of MUT and buried utility method (Laistner and Laistner, 2012)

Designing MUTs using new technologies can save costs. Some costs will be eliminated or reduced, and some costs will be added or increased. For example, the transportation of prefabricated tunnel segments from the factory to the site is an added cost to the conventional method of construction, while the fast installation of the tunnel reduces labor costs. There is a need for identification and measurement of costs to enable project stakeholders to compare the cost savings from using new technology.

2.2.1 Economy of MUTs

The initial construction cost of MUTs is higher than the traditional buried utilities method. However, utility companies will have cost savings from MUT benefits. These benefits will be obtained during the operation phase, and make the payback period of MUT very long. From a lifecycle perspective, there is a breakeven point that the total construction and operation cost of MUTs is equal to the traditional buried utilities method (open-cut) as shown in Figure 2-8 (Yang & Peng, 2016).

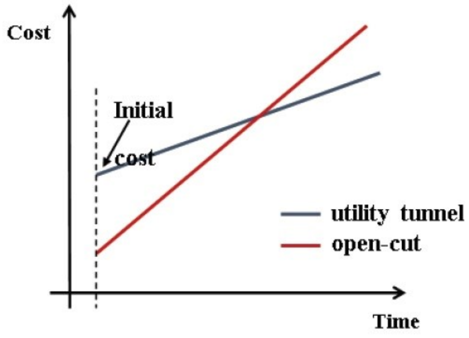


Figure 2-8 Cost curve of open-cut and MUT (Yang & Peng, 2016)

After this time, MUT cost saving makes it more economical. In addition, more cost savings are obtained by adding social benefits (Yang & Peng, 2016). There are other factors used for the economic evaluation of MUT compared to the traditional buried utilities method, such as the utility type, number of pipes (i.e. density), pipe diameter, number of excavation and reinstatement (E&R), location (i.e. undeveloped, suburban and urban areas), type of soil, and the depth of the MUT (Hunt et al., 2014). For example, point C in Figure 2-9 shows the cost breakeven point of MUT with buried utilities method when there are 14 pipes of 200 mm, 12 E&Rs for each pipe (total of 14×12=168 E&Rs in 100 years), in an undeveloped area, with deep MUT (2-80 m cover), and rock soil type (Hunt et al., 2014).

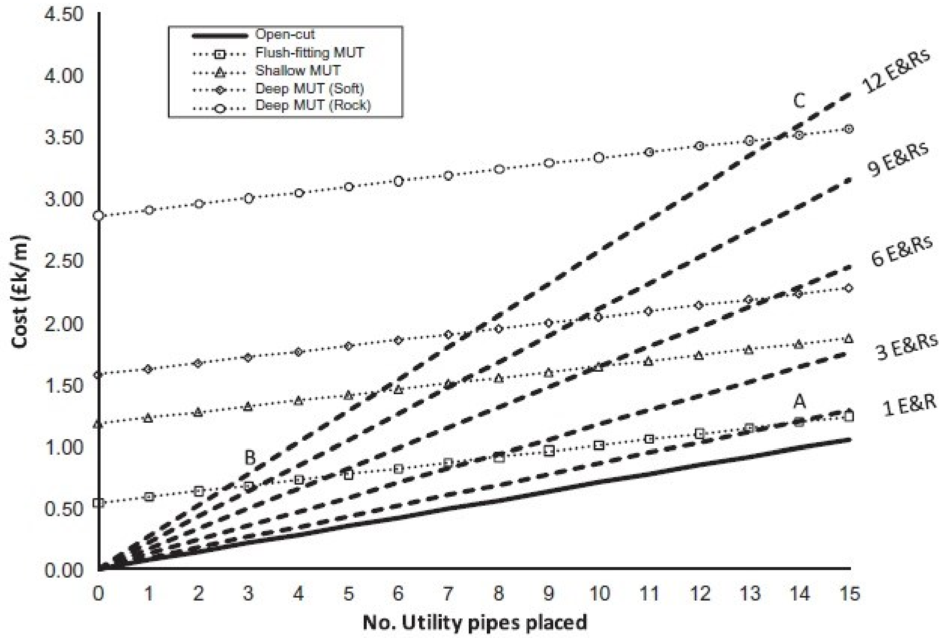


Figure 2-9 MUT costs versus open-cut with and without yearly E&R (2mm pipe, undeveloped) (Hunt et al. 2014)

The proposed model of Hunt et al. (2014) assumes several similar pipes in a linearly increasing cost graph. However, in real cases, there is a combination of utilities. Also, the linear increase of the cost is not accurate, the effect of soil, and synchronized construction and maintenance activities are not considered. Despite previous researches about the economical assessment of MUT and buried utilities, there is a gap in considering more factors influencing LCC and the breakeven point, e.g. hydrological conditions, construction methods of MUT, traffic, synchronization of excavations, etc.

2.2.2 Public-Private Partnerships

PPP is defined as a cooperation between the public and private sectors to execute projects or deliver public services, which is traditionally provided by the public sector. Both the public and private sectors gain some benefits in proportion to the degree of their involvement in specific tasks. The main purpose of PPP is to assign the risk to the sector that can better control it. The benefits of PPP are: (1) acceleration of infrastructure provision: the public sector can translate upfront capital expenditure to the income from a flow of on-going service payments and overcome capital constraints, (2) faster project implementation: the allocation of design and construction responsibility to the private sector shortens the construction time, (3) reduced whole life costs: the private sector is motivated to minimize the lifecycle cost of the project, which is sometimes hard for the public sector with constraints, (4) better risk allocation: risk transfer is optimized by transferring to the party that can better manage it, (5) better incentives to perform: through risk allocation and full payments conditions, the private sector is motivated to improve management and performance, (6) better quality of service: improved quality of services can be achieved through better integration of services with available assets, using economy of scale, innovations, incentives, and penalty mechanism , (7) gaining additional revenues: the private sector may generate more revenues from third parties by using spare capacity or disposal of surplus assets, (8) improved public management: government can better plan and monitor public services instead of managing delivery of public service. Better cost performance evaluation and transparency of public services costs are possible (European Commission, 2003).

Unlike the traditional method that the government invests in public infrastructure and provides services and accepts the risk of investment, in PPP the private sector is expected to participate in investment and providing services. Therefore, the risks are shared between the public and private entities. PPP is mainly used for, but not limited to, large scale infrastructure projects, such as roads and railways (IMF, 2004). According to Kennedy (2013) in a PPP, the government goal may be minimizing the risk of the project while the private stakeholder(s) may want to maximize its/their profit.

2.2.2.1 Incentive Mechanism in PPP

Using the incentive mechanism, mainly in form of payments to PPP project stakeholders, for different purposes have been reported in the literature. For example, Shang and Aziz (2018) investigated the incentive payment mechanisms in Canada and the USA for transportation PPP projects (e.g. roads, bridges, tunnels, airports) to encourage companies to improve their performance. The study shows that the incentive mechanism is used for safety performance, Operation and Maintenance (O&M) overall performance, fast construction, and energy-saving for improved sustainability (Shang & Aziz, 2018). Incentive regulations can be used in PPP projects by the government to encourage the private sector to increase efficiency and reduce the cost (IMF, 2004). In Finland, incentives and disincentives were used for concessionaires of PPP road projects for construction and maintenance phases. During construction, there were disincentives for closing the roadway and delays (e.g. for rock blasting) and early completion of the project was awarded. For the O&M phase, there were disincentives for violations of excessive salt usage (Mäkinen & Pakkala, 2015). According to the European Commission (2003), improved quality of services under PPP can be achieved through performance incentives and penalties.

2.2.3 Game Theory

Game theory, also called "conflict analysis" or "interactive decision theory" is "the study of mathematical models of conflict and cooperation between intelligent rational decision-makers" (Myerson, 1991). Regardless of intents and purposes, game theory is a study of decision making where the decision of each player potentially can affect the interests or welfare of the other involved players. The main goals of game theory are to predict how a game will be played and to find the optimum strategy for the players to address or solve a problem. However, based on the strategies of each player, more than one solution may be possible and different results are shown in payoff tables and/or decision trees (Kennedy, 2013). Two basic assumptions of the game theory include: the players are "rational" and reason "strategically" (Osborne & Rubinstein, 1994). Kennedy (2013) defines a player who reasons strategically as "the one who considers the other players' behavior before making his own move". Myerson defines a rational player "if he makes decisions consistently in pursuit of his own objectives" (Myerson, 1997).

2.2.3.1 Game Types

Cooperative and non-cooperative games: Based on the interactions of the players with each other, the games can be categorized into "non-cooperative" and "cooperative". The co-operative game is possible only if the players can make binding obligations, such as a contract. If no binding obligation can occur, then the game is non-cooperative. In the non-cooperative games, the order and timing of the players are essential to determine the result of the game and more details for each scenario are available. On the contrary, co-operative games timing is not important and less detail is available and the final solutions are presented (Kennedy, 2013).

Static and dynamic games: Based on the timing of decision making, two types of games are defined: static and dynamic games. In the games where the players act simultaneously without knowing the decisions of the other players, the game is static; while in the dynamic games, the players act sequentially (Ho, 2009).

2.2.3.2 Shapley Value Theorem

As explained in Section 2.2.3.1, game theory can be cooperative or non-cooperative. In non-cooperative games, there is a set of solutions based on the combination of players' choices. The Nash equilibrium is the best strategy for each player that does not will to change it. On the other hand, for a cooperative game, a solution, called Shapley value, is based on the allocation of benefits or costs considering the gain from the coalitions of players. After the calculation of the weighted average of participants' contributions, a cost or benefit is allocated proportionally to the participant's contribution to the total gain of the participant group. A cooperative game includes players, coalitional forms, and characteristic functions. Players can decide to cooperate with other players or not. Therefore, coalitional forms have resulted from players' choices. The benefit or cost given to a certain coalitional form is represented by the characteristic function. Each player is given a number from 1 to n, and the set of the players is defined as $N = \{1,2,\ldots,n\}$. N is called the grand coalition, and S is a subset of N, which includes all forms of cooperation. The maximum number of coalitional forms that players can create is 2^n. The characteristic function v, shown as $v(S)$, is a function of S and represents the gain obtained by the form of coalitions. The characteristic function satisfies $v(S \cup T) \geq v(S) + v(T)$, with $S \cap T = \emptyset$, where S and T are the subsets of N, a condition of super additivity, which means the worth of coalition is at least equal to the worth of its part acting separately (Jeong et al., 2018; Von Neumann & Morgenstern, 1944; Samsami & Tavakolan, 2016). Assuming that all the players are rational and will choose the maximum profit, based on superadditivity the players make a grand coalition and achieve $v(N)$ as the gain. After reaching the grand coalition, the challenge is how to share $v(N)$ (Jeong et al., 2018).

The marginal contribution of player i to coalition S means the value added to this coalition of the n-players cooperative game by player i's entry to the coalition and can be calculated by Equation (2-6) (Asgari et al, 2013; Shapley, 1953; Shapley, 1988).

$$M(i,S) = v(S \cup i) - v(S), \qquad \forall\, S \subseteq N \setminus \{i\} \tag{2-6}$$

According to Shapley (1953) and Asgari et al. (2013), a Shapley value of player i is a function that assigns to each game v a number $\varphi_i(v)$ for each player to distribute the total gain to the players. It satisfies three conditions: (1) the symmetry axiom: the players who are treated identically by the characteristic function be treated identically by the value, which means that the name of players does not affect in determining value; (2) the carrier axiom: the sum of $\varphi_i(v)$ over all players *i* in any carrier *N* equals $v(N)$; and (3) the additivity axiom: for any games *v* and *w*, $\varphi(v) + \varphi(w) = \varphi(v + w)$. This axiom determines how the values of different games should be related to each other.

The Shapley value (Shapley, 1988) for player i, $\varphi_i(v)$ is calculated by Equation (2-7).

$$\varphi_i = \sum_{S \subseteq N \setminus \{i\}} \frac{(s-1)!(n-s)!}{n!} M(i,S), \qquad s = |S| \;\&\; n = |N| \tag{2-7}$$

The Shapley value formula for player *i,* represented by $\varphi_i(v)$, is the result of the weighted sum of the marginal contribution of player *i,* represented by *M(i, S)*. Suppose *n* players enter a room in some order that totals to *n*! orders which are equally likely and $\varphi_i(v)$ represents the expected marginal contribution of player *i*. The probability (weight of *M(i, S)*) that player *i* enters the room to find exactly the players in $S - i$ already there is equal to $\frac{(s-1)!(n-s)!}{n!}$. Out of *n*! permutations of *N* there are $(s - 1)!$ different orders that the first $s - 1$ players can precede *i*. The remaining $n - s$ players can have $(n - s)!$ different orders after player *i* entry, which results to a total of $(s - 1)!(n - s)!$ permutations that players $S - i$ precede *i* (Shapley, 1988).

2.2.3.3 Game Theory for Infrastructure Projects

Game theory was used as a decision-making system in the water infrastructure investment of Thailand and is called "option game" (Suttinon et al., 2011). The expected payoff (profit or project value) for the public sector (Government of Thailand) and the private sector in four scenarios of this static and non-cooperative game, shown in matrix form, are calculated: (1) both public and private sectors invest, (2) the first one invests but the second waits, (3) the second one invests but the first waits, and (4) no one invests. Suttinon et al. (2011) applied various concepts of demand, probability, price, benefit, cost, and profit at starting time with a discounted rate or Net Present Value (NPV) in calculations. The waiting option is to observe these concepts for a period of time and then to decide to invest or not. Both sectors are flexible by taking the option of investing if demand is high or the option of waiting if demand is low. The proposed method of option games "addresses an existing need in water infrastructure management, which is characterized by big budgets, uncertainties, and competition between various public sector water supply schemes and private side water demand measures." (Suttinon et al., 2011). Based on the expected payoff in four scenarios, it is concluded that the best strategy for them (Nash equilibrium) is in the case that both sectors wait.

Jeong et al. (2018) proposed a cooperative and static game, shown in matrix form, a theatrical framework for allocating the cost of adaptation of water infrastructures (e.g. dam and sewer pipes) to climate change, i.e. expanding capacity or new development infrastructure of the participants. The Shapley value is applied for cost allocation according to the estimated benefits and costs of adaptation. The allocated cost is reduced "for participants who contribute more to saving the construction cost, whereas it increases for those who benefit more from flood damage prevention" (Jeong et al., 2018). Sanchez (2008) integrated game theory with Expected Utility Theory, as the theory of decision making under uncertainty to model different scenarios and to calculate the expected payoffs.

2.2.4 Financing and Cost-sharing of MUTs

The high initial construction cost of MUTs and also operational costs need to be financed and shared fairly among utility companies. Reviewing previous MUT projects in several countries shows various private and public sources of financing. In France (Clé de Sol, 2005), bank loans, MUT owner investment, and the entrance fee of MUT occupants (utility companies) are used. In China (Yang & Peng, 2016), MUT projects are financed by the government, private investors, utility companies, and bank loans. In Taiwan (CPAMI, 2011), engineering authority and utility companies invest in MUT projects. For financing MUT projects by loans at any phase of the project, extra costs, such as loan interest, the commission of arrangement, and commission of engagement, should be added (Clé de Sol, 2005).

2.2.4.1 PPP for MUT Cost-sharing

The long-term economic perspective for MUT and cooperation between several public and private MUT stakeholders make PPP a practical form of contract for these projects (Yang & Peng, 2016). PPP model was adopted for MUT projects in China and France (Yang & Peng, 2016; Clé de Sol, 2005). The Chinese government adopted the PPP approach to attract private capital to MUT construction projects. Using this approach enabled long-term cooperation (e.g. 20 years) between the public and private investors and also sharing the risks and benefits of MUT projects.

Figure 2-10 demonstrates the PPP model for MUT projects in China. In this model, the Chinese government only pays a low percentage of the construction cost of the MUT project. However, the government is responsible for providing a stable environment for the investment return of private investors. For this purpose, the main tasks of the government are providing institution environment and legislative guarantees, such as the establishment of subsidy, supervision, and payment mechanisms (Yang & Peng, 2016).

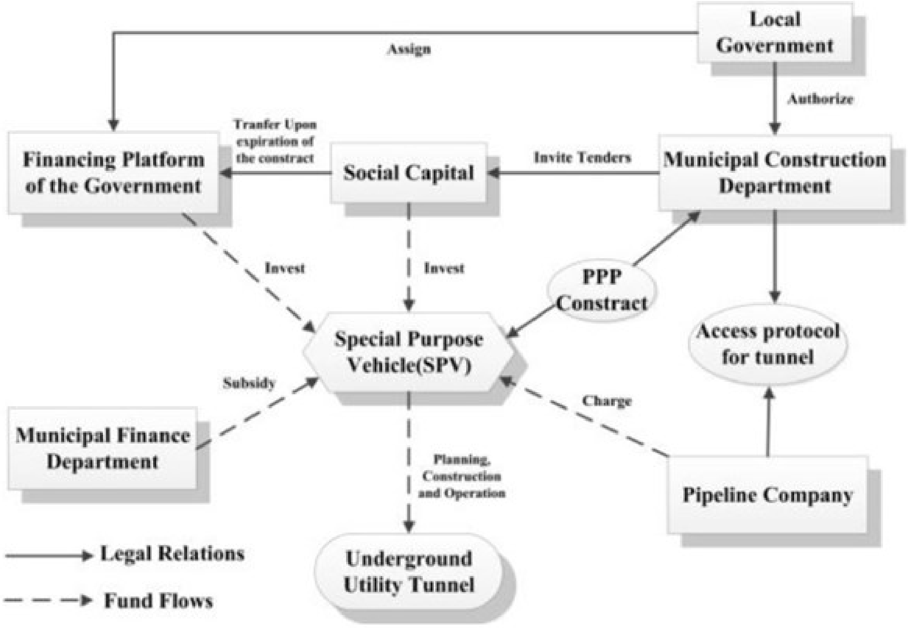


Figure 2-10 PPP model for MUT projects in China (Yang & Peng, 2016)

Zhou et al. (2017) identified 15 categories of risk in MUT projects with PPP form in China. For example, political risk can result in private-sector losses if political environmental changes lead to changes in project sovereignty, termination of the contract, government intervention, approval delays, tax adjustments, etc. Another example is a financial risk, which reflects fast domestic, and international financial market changes in foreign investment, exchange rate, and interest rate fluctuations (Zhou et al., 2017).

The PPP model of MUT for each country can be adjusted by considering the specific conditions of the context, such as the government power for interventions and guarantees in MUT projects, the anticipated profit and risks of the MUT project, etc.

Another model of MUT project organization is “municipal governance” (Clé de Sol, 2005). In this model, the municipality is the owner and manager of the MUT and the participant utility companies pay a rental fee. The MUT operation and management in the city of Prague at the Czech Republic is an example of the municipal governance model (Kolektory Praha, 2019), where operators (e.g. utility companies) have to inspect their networks once a year (i.e. visual inspection, leak inspection, hazard test) (CERIU, 2009).

Clé de Sol (2005) proposed a financing and cost-sharing model for both methods of PPP and municipal governance. Part of the model related to the PPP is explained in detail in Appendix B.

2.2.4.2 MUT Cost-sharing Methods

Utility companies, including public and private entities, are responsible for financing most or all the costs of these projects. The fairness of cost allocation for MUT projects is a challenging issue. Currently, the common two methods of MUT cost allocation are (CPAMI, 2011; Xiaoqin et al., 2011; Zhang et al., 2019): (a) The proportion of buried cost (PBC) method, in which the utility companies are charged based on the same proportion they were paying in traditional buried utilities method, and (b) The proportion of utility volume occupancy (PUVO) method, in which utility companies are charged based on the volume of space they occupy in MUT. Zhang et al. (2019) proposed to allocate occupied cross-sectional areas of utilities using the Shapely value theorem. A combination of these two methods is also proposed (Zhang et al., 2019; Xiaoqin et al.,2011). It was also proposed to use the same ratio of each company lifecycle benefit over the total lifecycle benefit from MUT for sharing the cost of MUT between utility companies (Zhang et al., 2019). The benefit of MUT is defined as the profit or construction and maintenance cost reduction of MUT (Zhang et al., 2019). Zhang et al. (2019) proposed to use bargaining power for cost-sharing in form of an index including net investment income, payback period, and cost-benefit ratio. Although bargaining power can influence the cost-sharing process, it may not always guarantee a fair cost-sharing. Therefore, there is limited research on cost-sharing models that consider fairness.

In a fair cost-sharing model, higher investment should result in a higher benefit for a utility company. In other words, the benefit-cost ratios of utility companies should not be very different. Extra costs of MUTs to manage safety and security risks can also be a challenge for cost-sharing. Fair cost-sharing of the risks should be based on this concept: the risk creator should pay the risk management cost. However, this concept is fuzzy in MUTs because risk can be distributed between two or more utility companies (e.g. risk of placing gas and electrical cables in an MUT). Therefore, there is a need to adjust cost allocation by distributing the cost of risks in the cost-sharing of MUTs. The issue regarding cost-sharing of the MUT and the resulting rules for rights and responsibilities of each stakeholder are usually agreed upon at the project initiation either in the form of a consortium or a joint venture.

2.2.4.3 Sharable Risks in MUT Cost-sharing

For the purpose of sharing the cost of risk management, only the shared risks are considered in this research. This means that the risks that are produced by a company and affect only the same company is not a sharable risk and all the costs to manage that risk should be paid by the same company. Sharable risks are defined as risks with more than one responsible company (e.g. fire because of the proximity of gas and electricity) and shared risk management actions

Table 2-3 presents a list of sharable risks, risk management actions with cost, the main responsible company, and the related MUT lifecycle phase (CERIU, 2011). The utility companies include municipality as the owner of water and sewer pipes, gas, and electricity companies. The MUT manager consists of representatives from all the utility companies and the responsibility of risk depends on the company whose representative makes the risk.

Table 2-3 Sharable MUT risk management actions (adapted from CERIU, 2011)

Risk management actions with cost	Risk	Main responsible company	MUT lifecycle phase
R1-Permanent measurement of gases concentrations (natural gas, sewer gases (e.g. Methane))	Suffocation because of gas leakage during the commissioning of the pipes	Gas company	Construction
	Fire/explosion because of gas leakage during the commissioning of the pipes	Gas company	
	Fire/explosion during the commissioning of the sewer pipes	Municipality	
R2-Ventilation by extraction or fresh air supply	Pulmonary impairment and visibility problem because of dust/silica	All	
R3-Wearing a respirator			
R2-Ventilation by extraction or fresh air supply	Suffocation because of welding of pipes when assembling	Municipality	
	Poisoning by glues and adhesives	Municipality	
	Poisoning by infiltration of gases, fluids, contaminants when connecting to external networks	All	
	Suffocation and poisoning by clogging products (e.g. resin injection, epoxy) when connecting to external networks	All	

Table 2-3 Sharable MUT risk management actions (adapted from CERIU, 2011) (continued)

Risk management actions with cost	Risk	Main responsible company	MUT phase
R4-Temperature detection	High temperature	All	Maintenance and repair
R2-Ventilation by extraction or fresh air supply			
R1- Permanent measurement of gases concentrations (natural gas, sewer gases) R2-Ventilation by extraction or fresh air supply	Suffocation by contaminants (Methane, H2S gases)	All	
	Explosion by explosive gases (Methane, H2S)	All	
R5-Control of ingress and egress (access management)	Rescue complication (unknown number of people inside)	MUT manager	
	Breakage of equipment because of the conflict of interventions		
R6-Wearing protective equipment and compliance with standards	Damage during intervention on MUT service equipment (e.g. cuts by the blade, particle projection by an electric saw, back injuries when handling)	MUT manager	
	Damage during the inspection of MUT service equipment, (e.g. fall from a height, injuries by train/trolley, electrification or electrocution)	MUT manager	
R2-Ventilation by extraction or fresh air supply	Suffocation from welding for pipe repair and pressure connection	Gas company	
	Suffocation from welding of pressure connection	Municipality	
R2-Ventilation by extraction or fresh air supply R5- Control of ingress and egress (access management) R7-Signaling	Fire during welding for pipe repair and pressure connection	Gas company	
	Fire during welding of pipe pressure connection	Municipality	
R1- Permanent measurement of gases concentrations (natural gas, sewer gases)	Suffocation because of gas leakage during operation of the pipes	Gas company	
	Fire/explosion because of gas leakage during operation of the pipes		
	Fire/explosion during operation of the pipes	Municipality	

2.2.4.4 Game Theory for MUT Cost-sharing

A method based on non-cooperative game theory for the cost-sharing strategy of MUT was proposed in China. The game is based on the decision to participate or not in an MUT project and some costs and incentives (e.g. construction and maintenance cost, subsidy) are allocated to the utility companies in each scenario (Xi & Fuling, 2013). Game theory is applied to design a government incentive mechanism for financing MUT construction. The game is based on two utility companies making four possible scenarios of sharing or not sharing the construction cost: (1) if both utility companies accept to share the construction cost, the cost is shared between them by a certain ratio. (2) If one of the two companies does not agree to share the construction cost, but the other company agrees, a percentage of the share is reduced to the paying company as a reward and added to the other company as a penalty. (3) In case both companies do not agree to share the construction cost, the MUT will be built anyways and both companies must pay a certain fee every year to place utilities inside the MUT (Xiaoqin et al., 2011).

Both of these game models for MUT cost-sharing are based on a high degree of public entities intervention, such as government or municipality. Although the role of public entities in legislative and coordination affairs is undeniable, various financing options should be given to the other private MUT stakeholders.

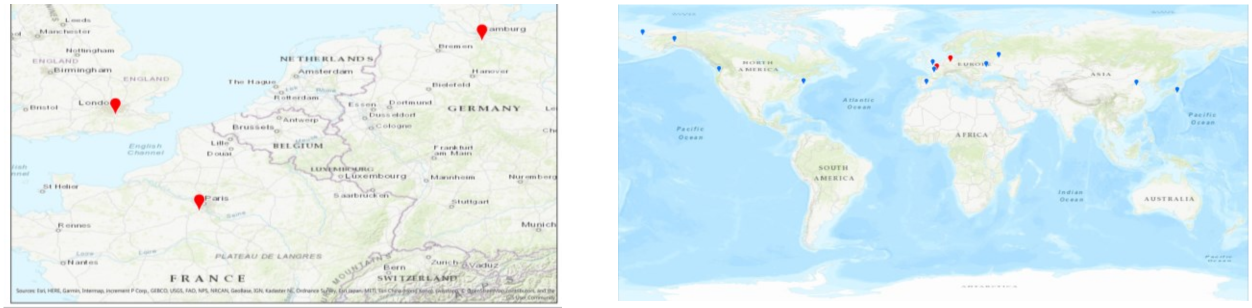
Using cooperative game theory for MUT cost-sharing is very rare. Although the Shapely value theorem was proposed to allocate occupied cross-sectional areas of utilities by Zhang et al. (2019), there is a gap to determine the contributed benefit of each utility company to the MUT project by the Shapely value theorem. The benefit that each utility company contributes to the project by participation in MUT and avoiding buried utilities is called contributed benefit of that company. A factor for a fair MUT cost-sharing is the balance of the gained benefit of a company with its contributed benefit.

2.3 Review of MUT Projects and Studies Around the World

There are many examples of MUT since the 19th century. According to Rogers and Hunt (2006), different names have been given to MUTs, such as ‘utilidors’ (USA), Common Service Tunnels in Singapore, Common Utility Tunnels in Malaysia, Common Utility Enclosures in Hong Kong, Common Utility Ducts in Taiwan and Multi-networks Gallery in France.

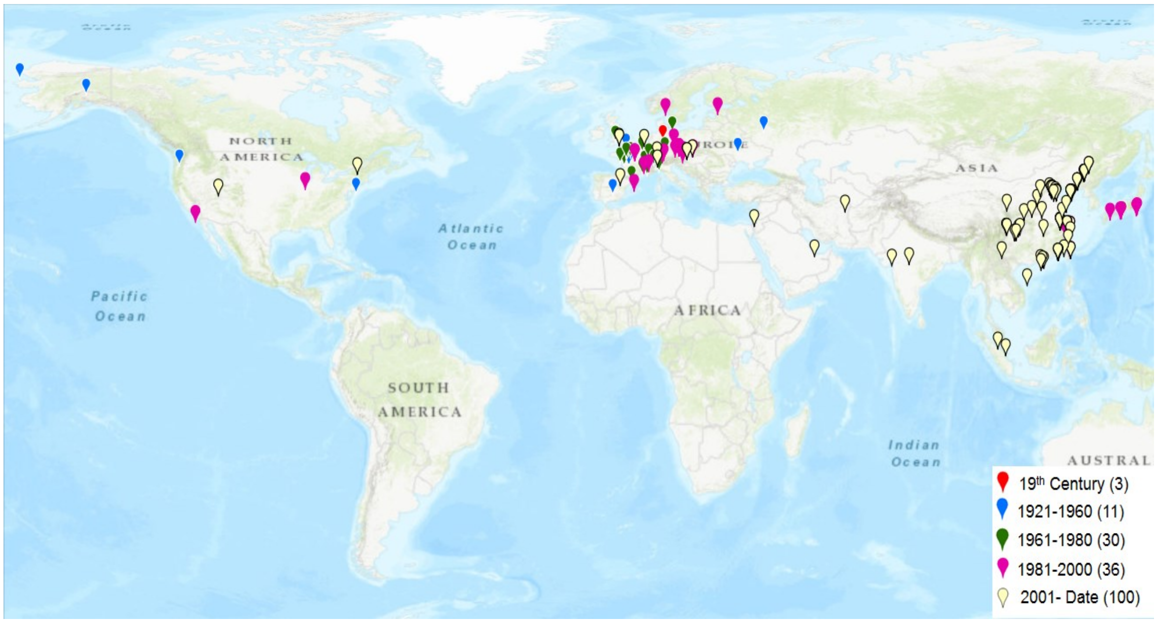
Luo et al. (2020) reviewed the history and recent development of MUTs in the world. The first MUT was built in France in 1850. It integrated the sewage system and water pipes with a large cross-sectional area (Cano-Hurtado & Canto-Perello, 1999; Canto-Perello & Curiel-Esparza, 2001; Wang et al., 2018). Subsequently, a tunnel was built in England in the 1860s to host foul and drinking water (Canto-Perello et al., 2009; Laistner & Laistner, 2012; Rogers & Hunt, 2006). This MUT allows man-access and is still in use. Germany (1893) was also among the countries that first implemented MUTs as shown in Figure 2-11(a). There was a lag from 1893 to about 1920 in the construction of MUTs. Figure 2-11(b) shows that between 1921 and 1960, several MUTs were constructed in parts of North America (Alaska), Asia (Japan), and Europe (France, Germany, Czech, etc.). Figure 2-11(c) shows that from 1961 to 1980, there was a rise in the construction of MUTs with a total of about 30 MUTs constructed. During this period, about 50% of the world's MUTs were built in France in cities like Angers, Paris, Rouen, Lyon, etc. Following the Utility Tunnel Law passed in 1963, Japan was able to build approximately 2000 km of utility tunnels in 80 Japanese cities (Wang et al., 2018). Countries like Belgium, Czech Republic, Germany, Switzerland, etc., were also involved in the construction of MUTs. Subsequently, between 1981 and 2000, the Czech Republic increased the construction of MUTs with a total of ten out of a total of about 36 MUTs constructed worldwide during this period. These MUTs were built in cities like Prague, Brno, etc. Japan increased the construction of MUTs during this period to about 30% of the world MUTs. However, countries like France and Germany continued to build MUTs. This period also saw the construction of MUTs in countries like Norway, Spain, China, and the USA as shown in Figure 2-11(d). The 21st century has seen a relative increase in the construction of MUTs in Asia. 80% of the world MUTs are currently being constructed in China as shown in Figure 2-11(e). Countries like Israel, Malaysia, India, Qatar, Singapore, and Canada have also implemented MUTs, while countries like Czech Republic, England, USA, have continued to construct MUTs with the latter two having MUTs constructed mainly on university campuses, hospitals, private establishments, and military installations.

In recent years, MUT has been developed in the world, particularly in Asia. Also, many studies have been conducted for MUT around the world. Reviewing these projects and studies provides a rich basis for the future development of MUT. Examples of MUTs around the world are presented in Table 2-4 for MUT projects in Europe, and Table 2-5 for MUTs in North America, and Table 2-6 for the Middle East and parts of Asia (Luo et al., 2020).



(a) 19th Century (3 MUTs) **(b) 1921 to 1960 (11 MUTs)**

(c) 1961 to 1980 (30 MUTs) **(d) 1981 to 2000 (36 MUTs)**



(e) 2001 to 2019 (100 MUTs)

Figure 2-11 Location of MUTs built at different time periods (Luo et al., 2020)

2.3.1 MUT Projects in Europe

Several MUTs have been constructed in Europe, examples of which can be found in Table 2-4. Most of the information contained in the table was retrieved from journal papers, websites, and reports. The grey cells in the table represent information that is either unclear or unknown. Based on the table, the Czech Republic, France, and Germany have the highest number of MUTs in Europe. Different countries in Europe built MUTs as a solution to one or more challenges, for example, France and the UK both built MUTs to stop the spread of cholera. Subsequently, the UK later built MUTs to eliminate traffic congestion caused by excavations for utility repairs. The Czech Republic on the other hand built MUTs to reduce the excavation impact in historical areas.

2.3.2 MUT Projects in North America

A large number of university campuses, hospitals, military installations, and airports in North America appreciate the advantages of adopting MUTs in the long term (Laistner & Laistner, 2012). One reason for this adoption is that these bodies own and operate their utility infrastructure (Hunt et al., 2012). Furthermore, barriers such as utility coordination, security, funding, and operation of the utilities hosted in the MUTs are easily overcome in this case. However, in the public sector, very little work has been done in recent years related to MUTs in North America. Most states in the US are interested in MUTs according to a survey (Kuhn et al., 2002). However, security and operational issues are the main concerns for undertaking MUT projects. Table 2-5 contains detailed information on some of the MUTs in North America.

Table 2-4 MUT projects in Europe (Luo et al., 2020)

COUNTRY	CITY	MUT LOCATIONS	YEAR	LENGTH (km)	DEPTH (m)	WIDTH(m)	HEIGHT(m)	SHAPE	MATERIAL	HOSTED UTILITIES								REFERENCES
										GAS	WATER	REFUSE	DISTRICT COOLING	HEATING	SEWAGE	COMMUNICATION	ELECTRICITY	
Belgium	Antwerp	Antwerp	1969					C			✓				✓	✓	✓	(Rogers & Hunt, 2006)
	Brussels	Brussels	1976	4		1.3	1.9	R	PC							✓	✓	(Rogers & Hunt, 2006)
Czech Republic	Brno	Brno Phase I	2001	1.79							✓			✓	✓	✓	✓	(ITUSA, n.d.; Sochurek, 2006; Chmelar & Sila, 2006; Pokorný, 2017)
		Brno Phase II	2005	1.651							✓			✓	✓	✓	✓	
	Jihlava	Jihlava	1984	1.7							✓							
	Ostrava	Podebradova U.T.	1999	0.7		3.5	2.6	O			✓			✓	✓	✓		
	Ostrava	Centre Consumption U.T.	2005	1.658	1.0	2.5					✓			✓	✓	✓		
	Prague	Celetna Street	1985	0.686				A		✓	▨	▨	▨	▨	▨	▨	▨	
		Rudolfinum	1985	1.08				A		✓	▨	▨	▨	▨	▨	▨	▨	
		Tyl Theatre	1985	0.563				A		✓	▨	▨	▨	▨	▨	▨	▨	
		New Town Hall	1985	0.603				A		▨	▨	▨	▨	▨	▨	▨	▨	
		RNLS U.T.	1985	0.72				A		▨	▨	▨	▨	▨	▨	▨	▨	
		Zizkov Bridge U.T.	1984	1.66		3.6				▨	▨	▨	▨	▨	▨	▨	▨	
		Prikopy U.T.	2001	1.903		2.5	3.3			✓	✓					✓	✓	
		Smichov U. T.	1998	2.58						▨	▨	▨	▨	▨	▨	▨	▨	
		Hlavkuv Bridge U.T.	1969	0.54						▨	▨	▨	▨	▨	▨	▨	▨	
		Vodickova U.T.	2008	1.263						▨	▨	▨	▨	▨	▨	▨	▨	
		Wenceslas Square U.T.	2009	0.812						▨	▨	▨	▨	▨	▨	▨	▨	
		Center IA U.T.	▨	2.684						▨	▨	▨	▨	▨	▨	▨	▨	
		Na Prikope St. Tunnel	▨	1.971						▨	▨	▨	▨	▨	▨	▨	▨	
		Revolucni	▨	0.905						▨	▨	▨	▨	▨	▨	▨	▨	
		Vodičkova	2007	1 769						▨	▨	▨	▨	▨	▨	▨	▨	
		Václavské náměstí B, C	2010	0.931						▨	▨	▨	▨	▨	▨	▨	▨	
		Centrum 1	2003	4.403						▨	▨	▨	▨	▨	▨	▨	▨	
	Tabor	Zizkovo Square	1977							▨	▨	▨	▨	▨	▨	▨	▨	
Denmark	Copenhagen	Copenhagen	1980	1.6	35			C					✓	✓				(Rogers & Hunt, 2006)
Finland	Helsinki	Helsinki	1982	40	80	5	7	R	SC		✓			✓		✓	✓	

Table 2-4 MUT projects in Europe (Luo et al., 2020) (continued)

COUNTRY	CITY	MUT LOCATIONS	YEAR	LENGTH (km)	DEPTH (m)	WIDTH(m)	HEIGHT(m)	SHAPE	MATERIAL	HOSTED UTILITIES								REFERENCES
										GAS	WATER	REFUSE	DISTRICT COOLING	HEATING	SEWAGE	COMMUNICATION	ELECTRICITY	
France	Angers	Angers	1970			1.3	1.9	OG	CSC		✓			✓	✓	✓	✓	(Legrand et al., 2004; Rogers & Hunt, 2006)
	Besancon	Besancon	1966	12		1	1.8	OG	CSC		✓			✓	✓	✓	✓	
	Dijon	Dijon	1977			2.2	3.4	R	CSC		✓				✓			
	Epinay-Sous	Epinay-Sous	1976	2		2	2	OG	CSC		✓				✓	✓	✓	
	Grenoble	Grenoble	1970	1.5	1.5	7.2	4	R	CSC		✓			✓	✓	✓	✓	
	Lyon	Lyon	1984			2.1	2.9	R	PC		✓			✓	✓	✓	✓	
	Marne La Vallee	Marne La Vallee	1972		0.5	2	2.4	R			✓				✓	✓	✓	
	Metz	Metz	1972		0.5	2.5	3.2	R	PC	✓	✓			✓	✓	✓	✓	(Rogers & Hunt, 2006)
	Normandy	Villers-sur-Mer	1971	3						✓	✓			✓	✓		✓	
	Paris	Paris-Rive Gauche	1990	2.1		4.7	10.5	R	CSC	✓	✓			✓	✓	✓	✓	
		Paris	1850s					O			✓			✓		✓		(Cano-Hurtado & Canto-Perello, 1999; Canto-Perello & Curiel-Esparza, 2001; Wang et al., 2018)
		Paris La Defense	1992	12		3.6	2.5	OG	CSC		✓		✓	✓	✓	✓	✓	(Legrand et al., 2004; Rogers & Hunt, 2006)
		Saint Germain	1971	1.3		2.1	3	OG	CSC		✓			✓	✓	✓	✓	
	Rennes	Rennes	1970	1.4										✓				
	Rouen	Rouen	1967			1.9	2	R	PC		✓				✓	✓	✓	
	Saint Ettienne	Saint Ettienne	1972	0.4		1.5	1.9	R	PC	✓	✓				✓	✓	✓	
	Toulouse	Toulouse	1972	0.7		2.2	2.5	R	CSC		✓			✓	✓	✓	✓	
		Toulouse	1945	3.8		1.5	2				✓				✓	✓	✓	(Rogers & Hunt, 2006)
Germany	Hamburg	Hamburg	1893	0.45				R		✓	✓			✓		✓	✓	(Wang et al., 2018)
	Lauchhiem	Lauchhiem	1995	0.3		2	2	C	Steel		✓				✓		✓	(Rogers & Hunt, 2006)
	Potsdam	Fahrland	1994	0.3		2	2	C	PEHD		✓				✓		✓	
	Speyer	Speyer	2004					O	VFRC	✓	✓			✓			✓	(Laistner & Laistner, 2012)
	Suhl	Suhl	1967					R		✓	✓			✓		✓	✓	(Laistner & Laistner, 2012; Wang et al., 2018)
	Ulm	Ulm	1985					R			✓			✓		✓	✓	(Laistner & Laistner, 2012)
	Wachau	Wachau	1992	4		2	2	C	PEHD	✓	✓				✓		✓	(Laistner & Laistner, 2012)

Table 2-4 MUT projects in Europe (Luo et al., 2020) (continued)

COUNTRY	CITY	MUT LOCATIONS	YEAR	LENGTH (km)	DEPTH (m)	WIDTH(m)	HEIGHT(m)	SHAPE	MATERIAL	HOSTED UTILITIES								REFERENCES
										GAS	WATER	REFUSE	DISTRICT COOLING	HEATING	SEWAGE	COMMUNICATION	ELECTRICITY	
Netherland	Amsterdam	Amsterdam	2005	0.2						✓	✓	✓	✓	✓	✓	✓	✓	(Taselaar et al., 2004; Hompetaselaar.nl, n.d.)
Norway	Oslo	Oslo	1990					R	PC		✓		✓		✓	✓	✓	(Rogers & Hunt, 2006)
Russia	Moscow	Moscow	1943	100		2	3	R	CSC		✓		✓		✓	✓	✓	(Rogers & Hunt, 2006)
Spain	Barcelona	Besos MUT	1992	4.1		2	2.5	R	PC								✓	(Gimeno, 2019)
		La Ronda MUT	1992	32		2.4	2.3	R, C	PC	✓	✓					✓	✓	
		Tarragona St. MUT	1992	0.6		4.5	2.3	R	RC		✓					✓	✓	
		22@	2004					R					✓			✓		
	Madrid	Madrid	1940	100		2.1	4.5	OG	BM		✓				✓	✓	✓	(Rogers & Hunt, 2006)
	Pamplona	Pamplona	2008	7.8	6.5						✓				✓	✓	✓	(Ramírez Chasco et al., 2011)
Switzerland	Basel	Basel	1980					R	CSC		✓				✓	✓	✓	(Rogers & Hunt, 2006)
	Geneva	Geneva	1984	0.8	0.5			R	PC		✓				✓	✓	✓	(Rogers & Hunt, 2006)
	Lugano	Lugano	1963	10				C	PC							✓	✓	(Rogers & Hunt, 2006)
	Zurich	Zurich	2002					R		✓	✓				✓	✓	✓	(Stein & Stein, 2004)
Ukraine	Kyiv	Kyiv	1950					R	PC		✓		✓		✓	✓	✓	(Rogers & Hunt, 2006)
Turkey	Istanbul	Eurasia Tunnel	2016						PC									(Ziv et al., 2019)
United Kingdom	Birmingham	Birmingham Univ.	2005	0.1	0	1.6	0.8	R	PC					✓		✓		(Rogers & Hunt, 2006)
	Liverpool	Mersey Tunnel	1972					C	PC	✓						✓	✓	(Rogers & Hunt, 2006)
	London	London Holbum Viaduct	1860s					OG	BM	✓	✓				✓	✓	✓	(Canto-Perello et al., 2009; Rogers & Hunt, 2006)
		London Barbican	1957	4.5				R	CSC			✓				✓	✓	(Rogers & Hunt, 2006)
		M6 Toll Road	2003					R	PC									(Rogers & Hunt, 2006)

Shape: C - Circular, OG - Ovoid with gutter, R - Rectangular, A - Arch Topped, O - Oval
Materials: CSC- Cast in-situ concrete PC- Pre-cast concrete BM- Brick and mortar SC- Sprayed concrete PEHD- High-Density Polyethylene VFRC- Vinyl fiber reinforced concrete

Table 2-5 MUTs in North America (Luo et al., 2020)

COUNTRY	CITY	MUT LOCATIONS	YEAR	LENGTH (km)	DEPTH (m)	WIDTH(m)	HEIGHT(m)	SHAPE	MATERIAL	HOSTED UTILITIES								REFERENCES
										GAS	WATER	REFUSE	DISTRICT COOLING	HEATING	SEWAGE	COMMUNICATION	ELECTRICITY	
Canada	Alberta	University of Alberta		14						✓	✓			✓		✓	✓	(Bell & Browsgrove, 2012)
	Montreal	McGill University	2015	0.2	15	3.0	3.0									✓	✓	(Habimana et al., 2014; Pomerleau, 2015)
United States	Alaska	Alaska Cape Lisburne	1951					OG	PC		✓				✓	✓	✓	(Huck et al., 1976; Rogers & Hunt, 2006)
		Eielson Air Force Base				1.4	1.5				✓			✓				(Huck et al., 1976)
		Fairbanks University	1938	1.0	1.8	0.9		OG	PC		✓				✓	✓	✓	(Huck et al., 1976; Rogers & Hunt, 2006)
		Fort Wainwright				1.5	1.5				✓			✓		✓		(Huck et al., 1976)
	Chicago	Chicago	1992					OG	PC							✓		(Huck et al., 1976; Rogers & Hunt, 2006)
	Connecticut	Central Connecticut University	2002	0.06						✓	✓				✓	✓	✓	(BVH Integrated Services 2018b)
	New York	New York	1952					C	PC		✓				✓	✓	✓	(Huck et al., 1976; Rogers & Hunt, 2006)
		University of Rochester	1920s							▨	▨	▨	▨	▨	▨	▨	▨	(Clemens, 2015)
	Massachusetts	University of Massachusetts								✓	✓			✓		✓	✓	(BVH Integrated Services, 2018a)
	Orlando	Disney	1982	1.0				R	PC		✓				✓	✓	✓	(Huck et al., 1976; Rogers & Hunt, 2006)
	Utah	Provo	2015	0.03	9.1			C	PC	▨	▨	▨	▨	▨	▨	▨	▨	(Huck et al., 1976; Rogers & Hunt, 2006)
	Washington	Seattle University	1940					R	PC		✓				✓	✓	✓	(Rogers & Hunt, 2006)
	Colorado	U.S. Air Force Academy						R			✓			✓		✓	✓	(Huck et al., 1976)
		City & County Buildings, Denver						R		✓				✓	✓			(Huck et al., 1976)
		Civic Center Area, Denver				2.7	4.3	R			✓		✓	✓			✓	(Huck et al., 1976)
	Texas	NASA, Houston				4.0	2.3	R					✓	✓		✓	✓	(Huck et al., 1976)

Shape: C - Circular, OG - Ovoid with a gutter, R – Rectangular
Materials: PC- Pre-cast concrete BM- Brick and mortar

2.3.3 MUT Projects in Asia

Many of the new MUT projects are in the Middle East oil countries (e.g. Qatar, Saudi Arabia, Kuwait), which shows the potential of the future widespread of MUTs in some developing countries. Some other Asian/middle east countries (e.g. Iran, Israel, India, Malaysia, Syria, Singapore) have constructed MUT in recent years as shown in Table 2-6. The cross-sections of primary and secondary utility ducts in Bhopal, India, are shown in Figure 2-12 and Figure 2-13 respectively (TATA, 2017).

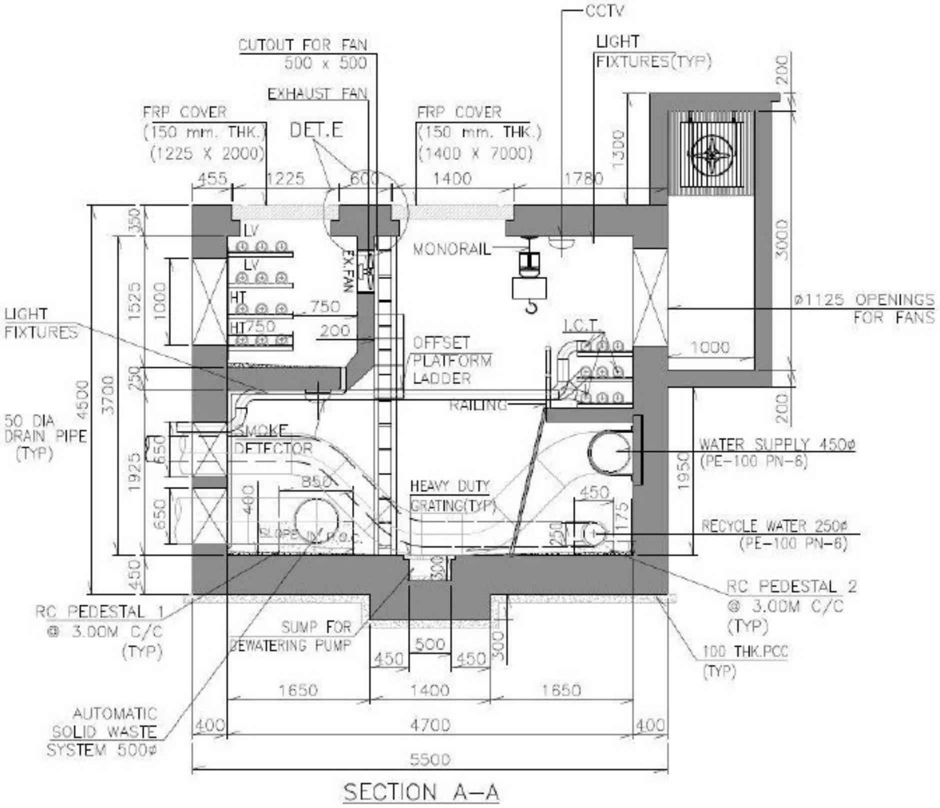


Figure 2-12 Primary utility duct in Bhopal, India (TATA, 2017)

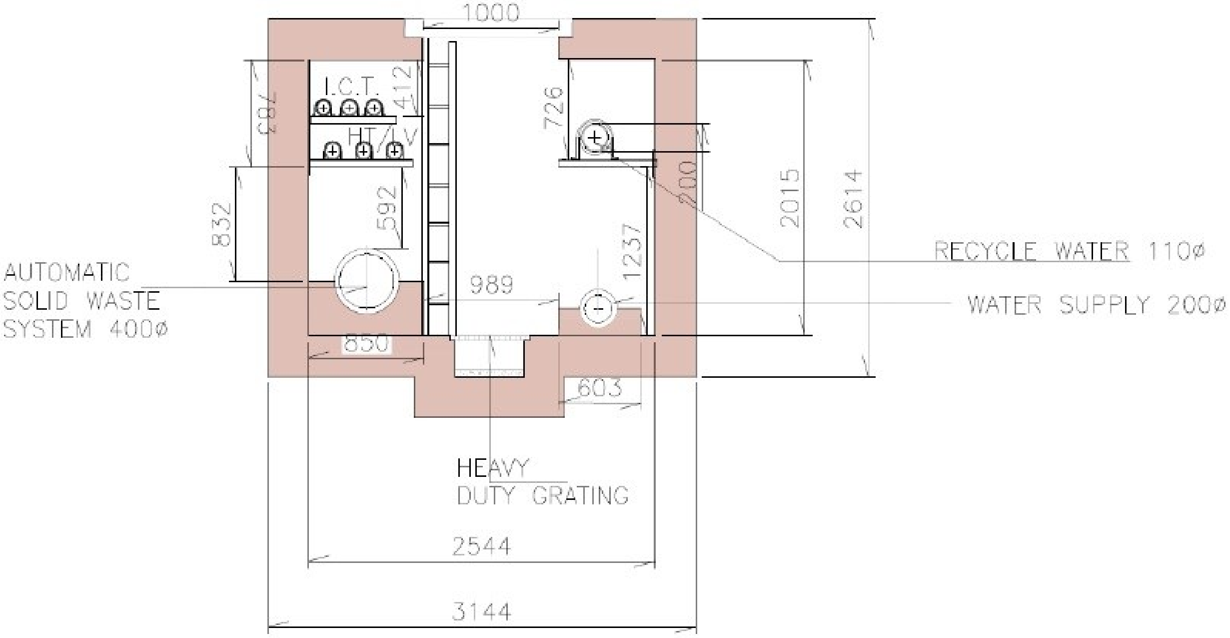


Figure 2-13 Secondary utility duct for Bhopal in India (TATA, 2017)

The map of the MUT project of Qatar mentioned is shown in Figure 2-14 and demonstrates the zone in which MUT is/will be built in Lusail city (Lusail, 2015).

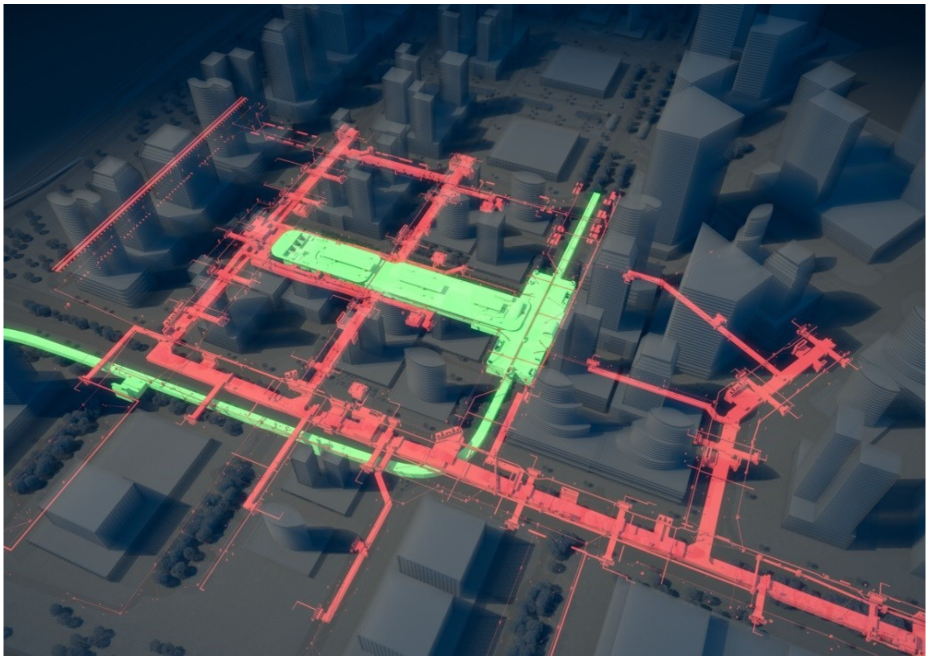


Figure 2-14 MUT development planning map in Qatar (Lusail, 2015)

Table 2-6 MUTs in the Middle East and parts of Asia (Luo et al., 2020)

COUNTRY	CITY	MUT LOCATIONS	YEAR	LENGTH (km)	DEPTH (m)	WIDTH(m)	HEIGHT(m)	SHAPE	MATERIAL	HOSTED UTILITIES: GAS	WATER	REFUSE	DISTRICT COOLING	DISTRICT HEATING	SEWAGE	COMMUNICATION	ELECTRICITY	REFERENCES
India	Bhopal	Bhopal	2001								✓	✓				✓	✓	(TATA, 2017)
	Gujarat	Gift City	2015	16	11	7.6	6.2	R			✓	✓	✓		✓	✓	✓	(Gift Gujarat, 2019; Bently, 2020)
Iran	Mashhad	Mashhad	2016	5	5			C	PC		✓					✓	✓	(Financial Tribune, 2015; AKpipe, 2017)
Israel	Haifa	Haifa	2006	1	5.5	3	3.75		PC		✓				✓	✓	✓	(Rogers & Hunt, 2006; Park &Yun, 2018)
Kuwait	Subah Al-Salem University City		2017	7.5							✓				✓	✓	✓	(Alraimedia, 2017)
Malaysia	Putrajaya		2003	15	2	8	5	R	CSC	✓	✓		✓		✓	✓	✓	(Adnan & Heng, 2003)
Qatar	Education City, Doha	South Site U.T.	2012	8.8							✓					✓	✓	(STRABAG International GmbH, 2012)
		North Site U.T.	2012	6.4														(Griffin, 2015)
	Lusail	Lusail	2009	15					CSC			✓	✓			✓	✓	(Griffin, 2015)
			2014	3			3				✓				✓	✓	✓	(Noman, 2014)
Singapore	New Downtown	Marina Bay	2016	20	2	12	4	R	CSC	✓	✓	✓	✓	✓	✓	✓	✓	(Liu & Loong, 2015)
Saudi Arabia	Jubail and Yanbu	Jubail and Yanbu	1975								✓					✓	✓	(Al-Ghamdi, 2014)
	Makkah	King Abdul Aziz Road	2019	9							✓		✓		✓	✓	✓	(COWI, n.d)
	Taif	Taif	2014								✓					✓	✓	(Al Eqtisadiah, 2014)
Syria	Damascus	Maruta City	2019	17							✓					✓	✓	(Al-iqtissadiya, 2019)

Shape: C - Circular, R – Rectangular
Materials: CSC- Cast in-situ concrete PC- Pre-cast concrete

China is one of the leading countries in building MUTs (Yang & Peng, 2016; Zhou et al., 2017) with a total length of about 500 km in major cities from 1994 to 2015, which is almost equal to the length of MUT in other cities in the world (Yang & Peng, 2016). Yang and Peng (2016) reported that about 69 cities in China have MUT construction with a total length of 1000 km. Also, 10 cities were selected in 2015 to build pilot projects of MUT with a total length of 389 km and the Chinese government invested 45% of project cost and published a series of preferential policies and guidelines for planning, financing, and solving technical issues of MUTs construction. Future MUT construction trend shows an accelerated increase rate as indicated in Figure 2-15.

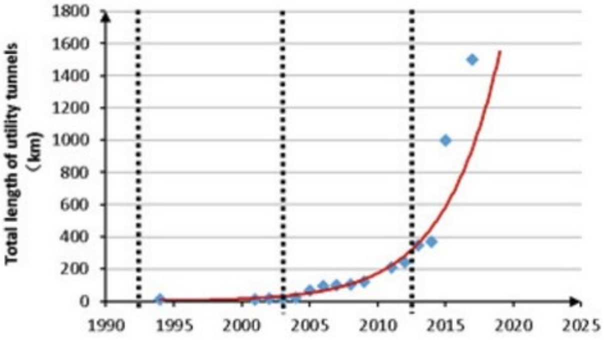


Figure 2-15 Growth curve of MUT construction in China (Yang & Peng, 2016)

According to the Common Duct Database of Construction and Planning Agency, Ministry of the Interior of Taiwan (Ministry of the Interior, 2017), MUTs have been built, or are under construction, as shown in Table 2-7.

Table 2-7 Statistics of MUT length and cost in Taiwan (Ministry of the Interior, 2017)

Project type	**Completed Length (km)**	**Under Construction (km)**	**In Design (km)**	**Total (km)**
Main MUT	67.719	7.320	0.000	75.039
Branch MUT	66.785	114.650	1.225	182.660
Cable Tunnel	58.617	6.825	4.391	69.833
Cables	358.105	167.285	184.976	710.366
Cost (C$M)	980	539	127	1646

The MUT is called Common Services Tunnel (CST) in Singapore, as the first country in Southeast Asia that constructed MUT on a comprehensive scale in Marina Bay, a downtown area in Singapore. The total length is 20 km and is executed into several phases (URA Singapore, 2006; Zhou & Zhao, 2016). The first phase of CST was completed in May 2006 with a total length of 1.4 km and a maximum depth of 20 m in some parts (NUS Institute of Real Estate Studies, 2016).

Then phase 2 with a total length of 1.6 km was built around 2010. The plan of phase 3A and 3B were scheduled to be completed in 2014 (BBR, 2010).

As shown in Figure 2-16, the installed CST networks include electricity, telecommunication, water, and Newater which transfer ultrapure reclaimed water, a distinct network of the pipeline networks in Marina Bay. The future planned networks for installation are a district cooling system and a pneumatic waste collection system (Centre for LiveableCities, 2017; Japhethlim, 2012).

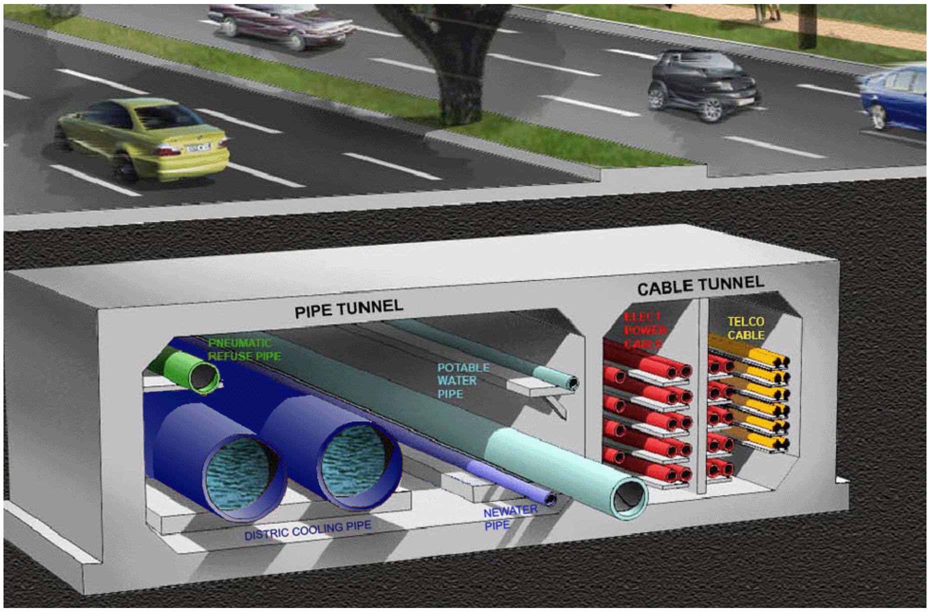


Figure 2-16 Cross-section of CST (Japhethlim, 2012)

Constructing MUT in Japan started after the Great Kantō earthquake in 1923. The second phase of building MUT started from 1960s in Tokyo, Osaka, and Nagoya. In 1963, the Japanese government issued a special law about MUT construction (Shu, 2003). Tokyo, as the capital of Japan, has a total length of 161 km MUT, in which 106 km is completed (Xu, 2005).

2.3.4 Studies about MUTs

There have been several detailed studies about MUT around the world. In the UK, Hunt et al. (2014) analyzed the cost of MUT and compared that with the cost of buried utilities. In France, Cle de sol (2005) provided a guideline about different aspects of MUT, such as cost and financing, management, security, technical issues, etc. In Germany, Laistner and Laistner (2012) compared construction and operating costs as well as the life expectancy of utilities in buried and MUT methods. In the US, Huck et al. (1976) presented a report about different aspects of MUT including (a) technical feasibility about utility characteristics and requirement systems, tunnel systems, and tunnel safety, (b) institutional factors (e.g. ownership and operation, utility companies), and (c) socio-economic impacts. The benefits and obstacles of MUT development in the US were presented in a book (National Research Council, 2013). The obstacles include inevitable abandonment of investment in existing utilities in service, concerns related to operational liabilities and risk in a shared or integrated utility environment (e.g. co-location of water or gas lines with electric lines), and administrative concerns about the access of other people to utility networks. In addition, higher initial connection costs of MUT compared with the buried utilities method is another concern. It is mentioned that "the viability, value, and benefits of utilidors may be effectively communicated with (1) development of workable scenarios for secure multi-utility facilities; (2) development of workable scenarios for effective transitioning from current configurations; (3) lifecycle cost-benefit analyses comparing separate and combined utility corridors; and (4) demonstration projects. In the United States, utilidors have been built typically as part of major old and new developments or underground transportation improvements (e.g. Disney World in Orlando, Florida, with its extensive underground service "city" and the Chicago freight tunnel network). If the United States is to improve the sustainability of its urban utility services and preserve underground space for more cost-effective sustainability opportunities for future services, then this impasse needs renewed attention" (National Research Council, 2013). The University of Washington provided a design guide for utility tunnels and trenches (UW, 2008) and the University of Oregon published the manual of "utility tunnel safety program" (UO, 2015).

The feasibility study presented by the Texas Department of Transportation (Kuhn et al., 2002) highlights an important development in utility accommodation by the use of MUT. In general, MUTs can be beneficial in situations where the current utility congestion or severe limitations on available Right of Way (ROW) compensates the increased costs of building MUT. Currently, significant barriers to use this strategy in Texas exist that need several legislative changes, including the acquisition of ROW, lease and occupancy agreements, and revenue potential. Kuhn et al. (2002) developed basic guidelines for choosing an accommodation strategy, sample specifications, and design drawings were prepared. The other contributions include sample legislation and change to the Utility Accommodation Policy, focusing on giving TxDOT the legislative authority to follow the use of MUTs and ROW acquisition for the same when warranted.

In Spain, a model of analysis for MUT planning in urban areas based on Strengths, Weaknesses, Opportunities, and Threats (SWOT) and Analytical Hierarchy Process (AHP) was developed (Canto-Perello et al., 2016). The risks and potential hazards of utility tunnels in urban areas were analyzed in another research (Canto-Perello & Curiel Esparza, 2003). In Korea, research in cost-benefit analysis for studying the economic feasibility of MUTs was conducted (Kang & Choi, 2015). Comprehensive books about MUT were published in Japan (Society of civil engineers, 2010) and Germany (Stein, 2002).

2.3.5 MUT Case Studies

2.3.5.1 Case study 1: Lezkairu Utilities Tunnel - Pamplona, Spain (Ramírez Chasco et al., 2011)

Motivation, location, date of project: According to Ramírez Chasco et al., (2011), for the expansion of the southern end of the city of Pamplona in Spain, as the new urban area of Soto de Lezkairu, building up to a total of 5,000 housing units for approximately 16,000 people were planned for 2008. For simplification of future expansion and/or repairing the utilities and minimizing the inconveniences to the citizens of the area, the MUT method was chosen.

Length, dimensions, and utilities of MUT: The length of the MUT network is 7785m, in which 5328m is the length of "main galleries" that house the distribution systems (Figure 2-17). The "secondary galleries" transmit the utilities to the edges of the buildings (Figure 2-18). The main gallery is a rectangular box of reinforced concrete with dimensions of 3.10 × 4.60 m (2.50 × 4.00 m useful space). The tunnel interior is divided into two spaces, one above the other, separated by a walkable steel grate.

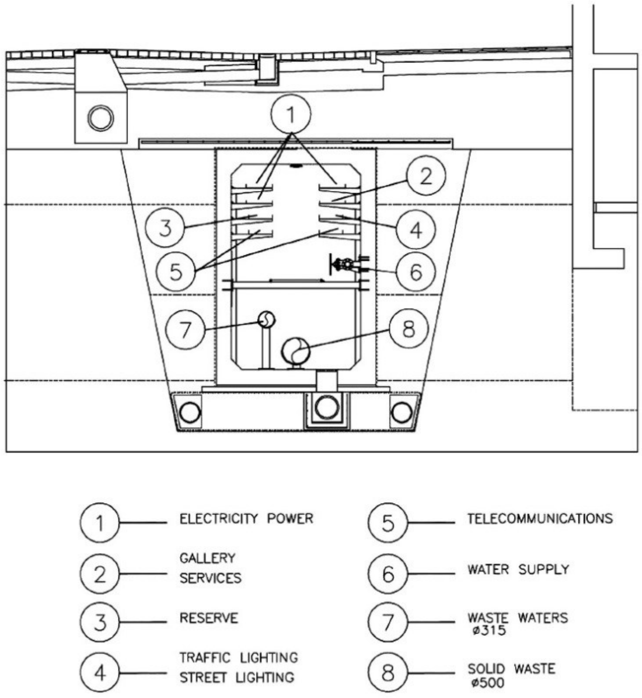


Figure 2-17 Main gallery section (Ramírez Chasco et al., 2011)

As shown in Figure 2-17, the upper subspace with trays accommodates the conduits for the street lighting system, traffic light network, electrical power, telecommunications, and the services of the tunnel itself (emergency detectors, lighting, ventilation, and detection of toxic gases); the water-supply pipes (100 mm ϕ pipe) are installed in this upper space, under the trays.

The lower sublevel is designed for the wastewater collection system (315 mm ϕ PVC pipe) and the solid waste pneumatic collection system (500 mm ϕ steel pipe). A 2% cross-sectional slope on both sides of the floor of the lower sublevel, converges on a grating and is designed to evacuate possible water leaks that may happen during the operation phase of the tunnel. This evacuation system is connected to the general drainage network of the entire gallery.

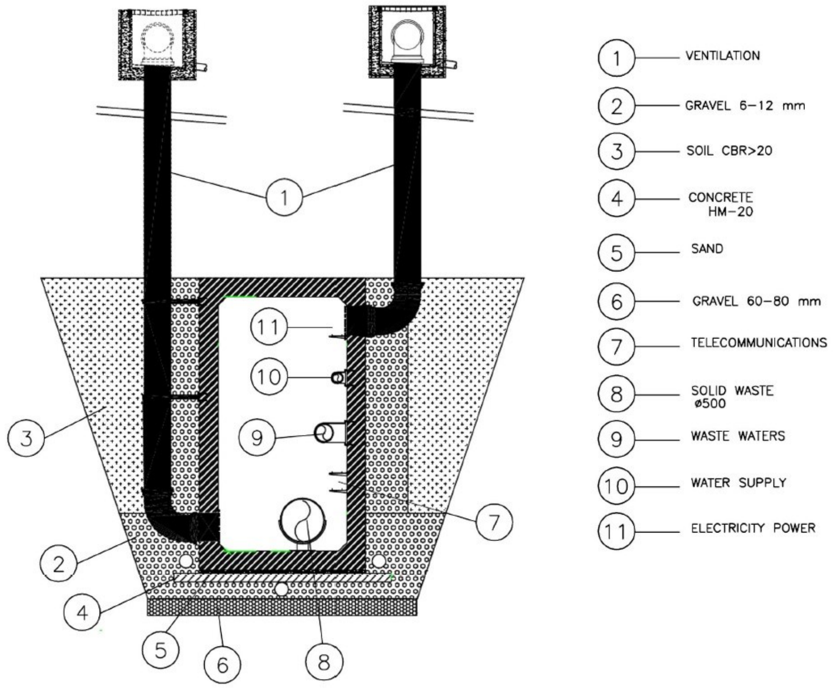


Figure 2-18 Cross-section of the secondary utility gallery that connects from the main gallery to the individual plots (Ramírez Chasco et al., 2011)

The secondary gallery tunnels are made of 2-m-long prefabricated modules of reinforced concrete with interior dimensions of 1.50 × 3.00 m. The utilities include a pneumatic solid waste collection system, in a 500 mm ϕ steel pipe; two trays to hold the fiberglass telephone network and cable TV network, respectively; a waste-water collection system passing through a 200 mm ϕ PVC pipe; 100 mm ϕ cast-iron pipe of water supply; and, finally, a tray to support all the electric power-track systems.

Construction method: Cast-in-place reinforced concrete is considered for the main gallery and prefabricated modules of reinforced concrete for the secondary gallery (Figure 2-19). The average depth is approximately 6.50 m. To solve the problem of water pressure on the sidewalls and the bottom of the concrete slab, an underground drainage system was designed for the removal of water from around the galleries. For the safety of the operation and maintenance performance, three considerations were taken into account:

- Accessibility for materials and small machinery: only one access was provided, large enough for the safety and easy entry of personnel and materials. For the personnel exit/entry, “outlets” have been designed at all the junctions or intersections between the various branches comprising the gallery, and at either end.

- Aeration and fire-fighting systems: Some of the design and equipment for fire include: (a) airtight compartments separated by fire-resistant doors (RF-90 min) and veneer firewalls of perforated brick, coated with 2 cm of cement mortar on both sides; (b) optical smoke detectors and manual alarm switches for activation in case of fire; (c) powder fire extinguishers; (d) emergency evacuation from the interior is provided by ventilation manhole shafts.

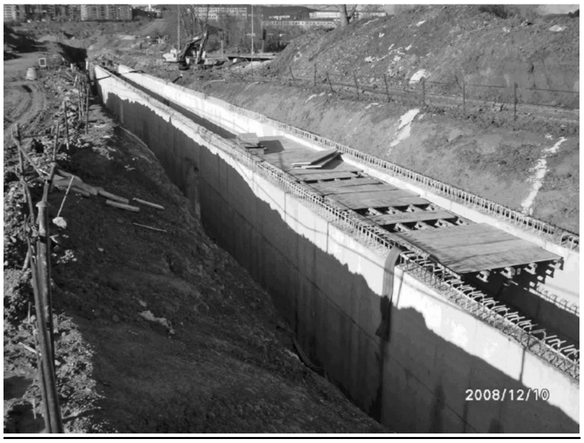


Figure 2-19 Forming of the top slab (Ramírez Chasco et al., 2011)

- Security against trespassers: Access only for personnel of all the utility companies by an electronic identity card and entering an alphanumeric code is possible. Installation of sensing devices and closed-circuit television (CCTV) surveillance system is controlled by the center of operations.

Cost: The estimated cost of MUT civil works and internal installations is 24.2 million Euro (US$34.2 million), which means an approximate unit cost of US$ 4.4 million/km.

2.3.5.2 Case study 2: MTC Utilities Tunnel - Provo, Utah, USA (BYU, 2015)

<u>Motivation, location, and date of the project:</u> According to BYU (2015), for the project of expanding Missionary Training Facilities of the Church of Jesus Christ of Latter-day Saints in Provo, Utah in 2015, the main concern was connecting utilities from the mechanical system junction box to the new buildings.

Length, dimensions, and utilities of MUT: For this purpose, a walkable underground utility tunnel of length 32.9 m including the utilities (not specified) was considered to be constructed in six weeks.

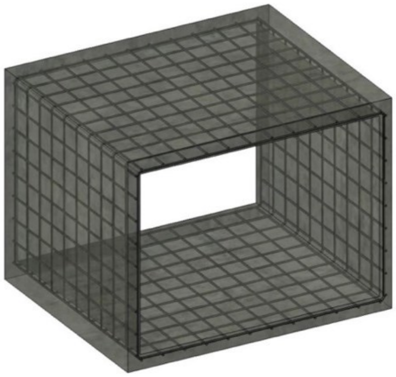


Figure 2-20 CAD drawing of rebar plan for precast reinforced sections (BYU, 2015)

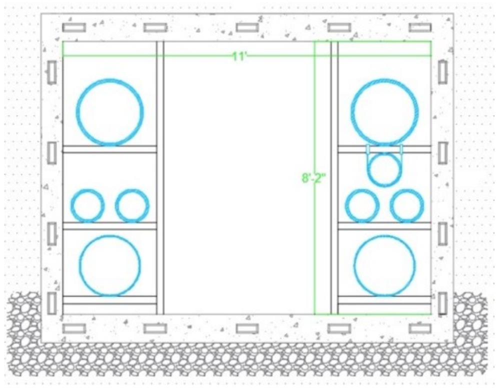


Figure 2-21 Cross-section of the precast concrete tunnel (BYU, 2015)

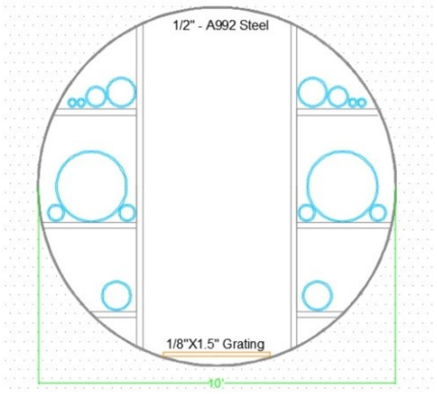


Figure 2-22 Cross-section of steel tunnel (BYU, 2015)

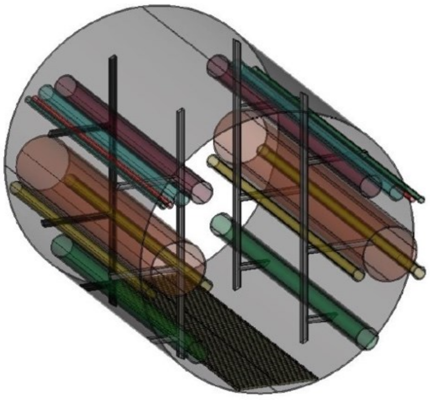


Figure 2-23 3D rendering of steel tunnel design (BYU, 2015)

The precast concrete tunnel segment has 2.49 m height and 3.35 m width (Figure 2-20 and Figure 2-21). The circular steel tunnel section is 3.048 m inner diameter (Figure 2-22 and Figure 2-23).

Construction method: In the report of the project, two design approaches were proposed: (1) a traditional open cut and cover technique, and (2) a trenchless jack and bore method. For each approach, cost estimates, drawings, and specifications were explained.

- Open cut method

This method includes excavation, shoring, tunnel placement, backfill and compaction, and road repair in two steps (i.e. one step for each half of the street to let one lane be open each way). The depth and width of excavation are 9.144 m and 4.572 m respectively. The two methods investigated for deep shoring design were sheet piles and soldier piles. Two methods of constructing a concrete tunnel are cast-in-place and precast. Although the cast-in-place method has fewer construction joints and is easier to pour around and does not need much equipment, it is a time-consuming method because of the time needed for curing and gaining strength. In the alternative method of the precast concrete tunnel, the segments are made off-site and then transported to the construction site for installation. This method is faster. However, it needs more waterproofing because of more construction joints. It also needs crane equipment for the on-site installation of the precast tunnel segments. The existing above-ground power and phone lines make working with crane dangerous for workers.

- Trenchless jack and bore design

In the jack and bore method, two shafts, one on each side of the tunnel, are excavated (Figure 2-24). The first shaft called the *jacking pit*, accommodates the jacking machine and pipe sections enter through it, and the other shaft, called the *receiving pit*, is used for removing the boring cutter head. The jacking pit is 7.62 m long by 4.572 m wide and has 9.144 m depth. A helical auger of 3.048 m in diameter with a cutting head on the front, transfers the soil back to the jacking pit while the jacks thrust the circular tunnel through the soil. Then, the jacks are back again and the next tunnel segment is lowered into the jacking pit. The two tunnel segments are welded together to be waterproof. This process will be repeated until the circular tunnel reaches the receiving pit. The receiving pit dimensions are 3.048 long by 4.572m wide.

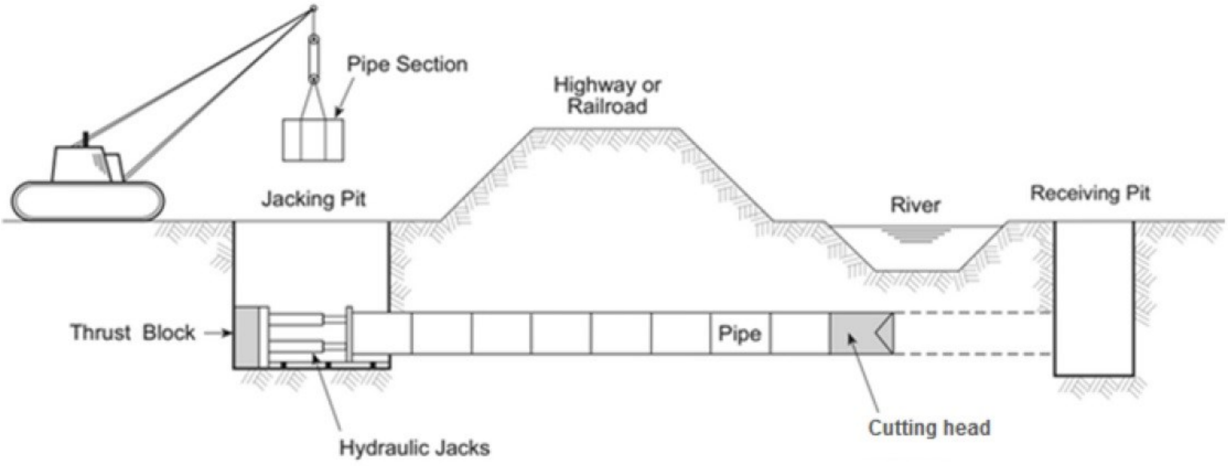
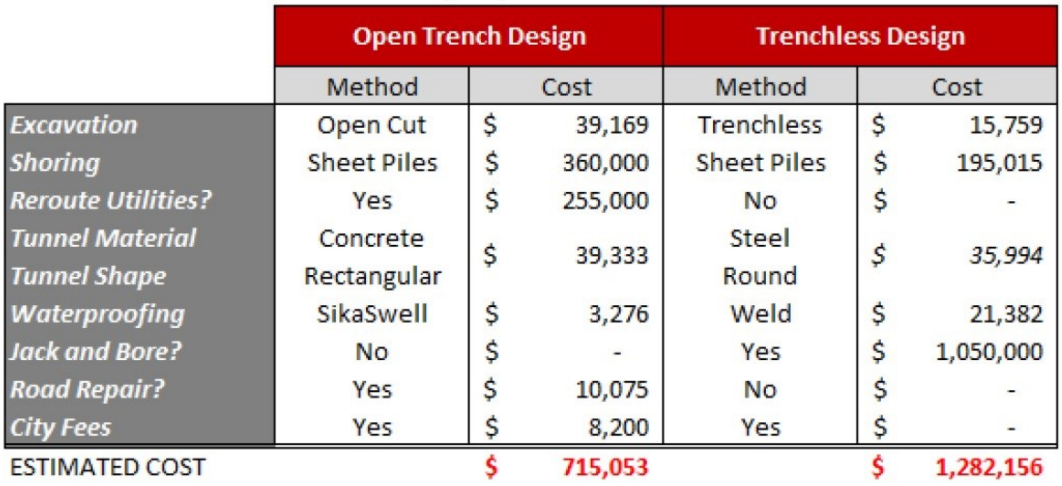


Figure 2-24 Jack and bore tunneling operation (BYU, 2015)

The trenchless method advantages are reduced the construction time, no need for rerouting of the existing utilities and road repair, and no disturbance of the traffic flow. However, there is a risk of soil settlement.

<u>Cost Estimation:</u> The cost estimation is based on the following components: excavation and backfill, shoring, rectangular concrete and circular steel tunnel, connections (concrete waterproofing and steel welding), auger boring, road repair, and city fees for road closure and permits. A summary of cost estimation is presented in Table 2-8.

Table 2-8 Cost estimate summary by alternative (BYU, 2015)



	Open Trench Design		Trenchless Design	
	Method	Cost	Method	Cost
Excavation	Open Cut	$ 39,169	Trenchless	$ 15,759
Shoring	Sheet Piles	$ 360,000	Sheet Piles	$ 195,015
Reroute Utilities?	Yes	$ 255,000	No	$ -
Tunnel Material	Concrete	$ 39,333	Steel	$ *35,994*
Tunnel Shape	Rectangular		Round	
Waterproofing	SikaSwell	$ 3,276	Weld	$ 21,382
Jack and Bore?	No	$ -	Yes	$ 1,050,000
Road Repair?	Yes	$ 10,075	No	$ -
City Fees	Yes	$ 8,200	Yes	$ -
ESTIMATED COST		**$ 715,053**		**$ 1,282,156**

The estimated unit cost of the utility tunnel in the open cut method is approximately 22,000 US$/m (US$22M/km) and in the trenchless method is 39,000 US$/m (US$39M/km).

2.4 Building/Civil Information Modeling (BIM/CIM)

Building Information Modeling (BIM) can facilitate the design, construction, and operation of MUTs and improve the coordination of utility companies. BIM is defined as "a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward" (NIBS, 2007). Another definition of BIM is "the process of creating and using digital models for design, construction and/or operations of projects" (McGraw-Hill Construction, 2009). BIM can represent geometric information of a building and the attributes of building components, such as material, cost, manufacturer, etc. (Eastman et al., 2011).

2.4.1 BIM Extension to Civil Information Modeling

BuildingSMART (2016) developed IFC mainly for buildings (Zhang et al., 2010). BIM applications are mostly developed for buildings and there are few applications for civil infrastructures (Bradley et al., 2016). BIM extension has progressed in recent years for buildings (e.g. extending IFC for Radio Frequency Identification (RFID) in buildings (Motamedi et al., 2016)). In addition, BIM has been extended for civil infrastructures (e.g. bridges, tunnels, roads), which is called Civil Information Modeling (CIM). Ghaznavi (2013) extended BIM to Tunnel Information Modeling (TIM) based on tunnel components, tunneling processes, and the capability of the IFC standard to be extended. Bridge Information Modeling (BRIM) (Marzouk & Hisham, 2012) and Road Information Modeling (RIM) for managing underground pipeline systems (Chang & Lin, 2016; Yin et al., 2020) are examples of CIM. Although researchers proposed conceptual data schemas for tunnels and have added geometric information and semantic information to them, there is a gap in data schema development for different kinds and components of tunnels. Modeling terrain and geographic information of underground tunnels should be added to data schemas of the tunnel (Cheng et al., 2016). BuildingSMART defined the scope of work on standards for BIM in infrastructure. The BIM standard for tunnels, bridges, roads, railways, and earthworks should include alignment, terrain, coordinates, linear reference system, and spatial context as shown in

Figure 2-25 (BuildingSMART, 2019). The figure also shows the potential addition of the MUT as another component of CIM, as proposed in this research.

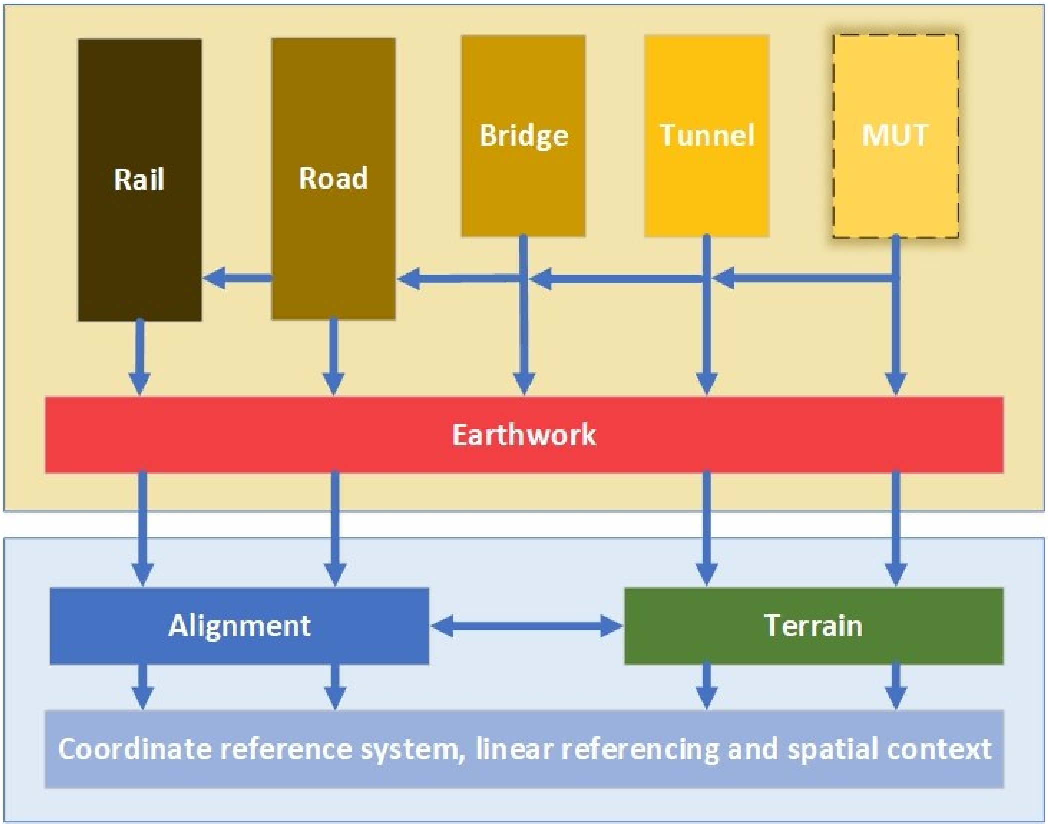


Figure 2-25 Overview of infrastructure components and dependencies (Adapted from BuildingSMART, 2019)

2.4.2 Industry Foundation Classes (IFC)

BuildingSMART Alliance (BSA) developed IFC as a standard for BIM to improve interoperability between different stakeholders of construction projects (Isikdag et al., 2008). The IFC model contains entities for (a) physical components of buildings (e.g. columns, walls, windows) and (b) non-geometric components (e.g. material, cost, schedule). Entities are linked by physical and logical relationships (Liebich, 2009). IFC was developed similar to the International Standards Organization (ISO) standard of STEP (Standard for the Exchange of Product Model Data) (Pratt, 2001). STEP is applied in different areas, such as mechanical and product design, for the general representation and exchange of product information.

2.4.2.1 IFC Architecture

The data schema architecture of the current IFC standard, called IFC4 Addendum 2, consists of four conceptual layers as shown in Figure 2-26 (IFC, 2016).

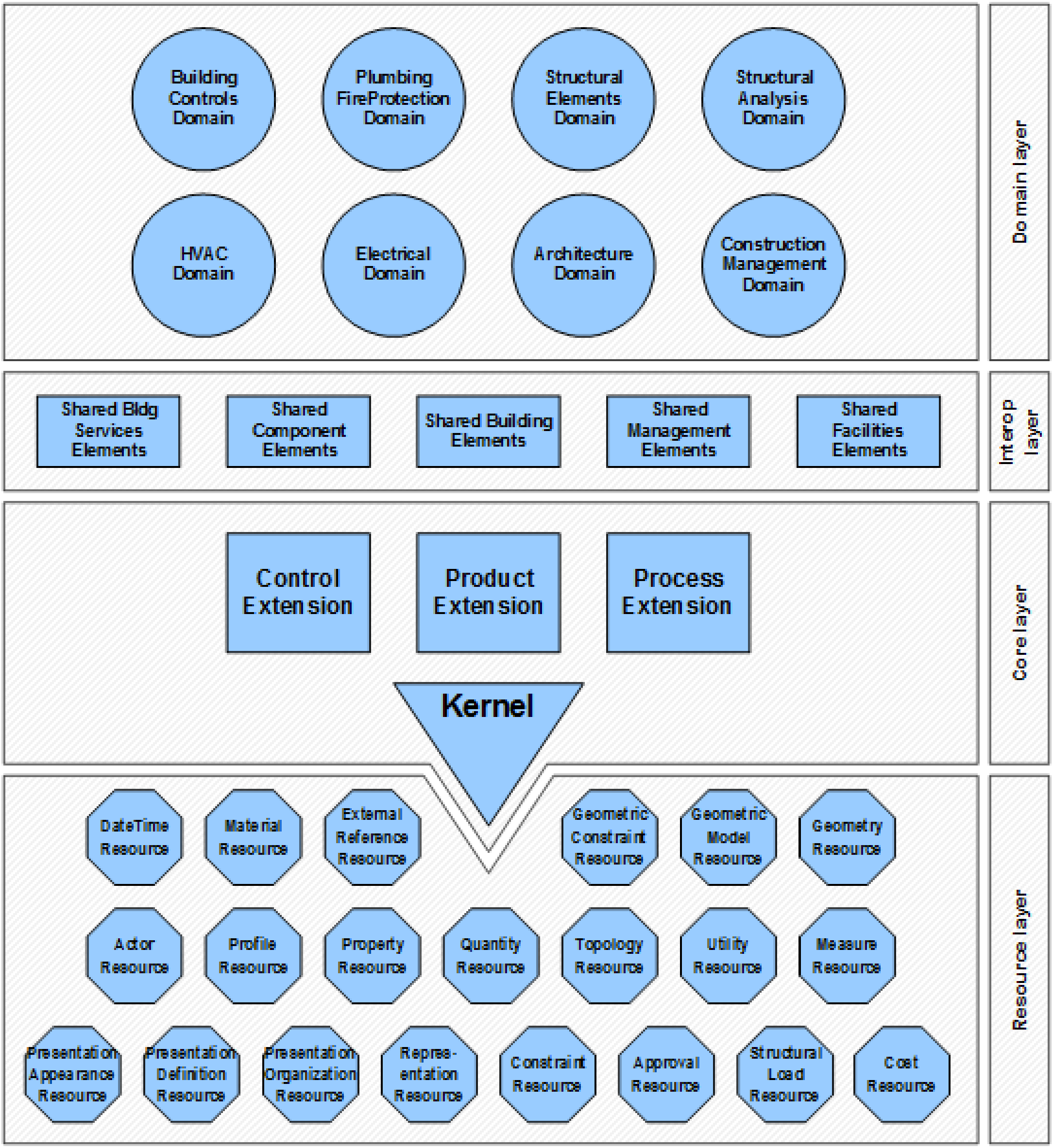


Figure 2-26 IFC Data schema architecture with conceptual layers (IFC, 2016)

Each layer includes several modules consisting of different entities, types, enumerations, property, and quantity sets (IFC, 2016):

(a) Domain layer: as the highest layer, it includes entity definitions which are specializations of products, processes or resources for a certain discipline (e.g. building controls, electrical, structural elements); (b) Interoperability layer: this layer consists of schemas including entity definitions for a general product, process or resource specialization, usage between different disciplines for inter-domain exchange and sharing of construction information. Examples include shared building services, shared building elements, shared management elements, etc.; (c) Core layer: it includes the kernel schema and the core extension schema, consisting of the most general definitions; (d) Resource layer: this layer consists of all individual schemas that include resource definitions (e.g. material resource, geometric model resource). The hierarchical and modular structure of IFC enables facilitated maintenance and expansion of the model, and lower-level entities can be used again in higher-level definitions. This facilitates model implementation in various discipline-specific software applications (Khemlani, 2004; IFC, 2016). To define new extended entities in IFC, it is important to consider: the principle of inheritance as the way of referencing the entities in the same or lower layers, object-oriented concept, and classification rules (Ghaznavi, 2013; Weise et al., 2000). Several software applications support the IFC standard and data exchange. IFC should be developed more, as it has limitations for the support of a few use cases in the AEC/FM industry (Ma et al., 2011; Weise et al., 2008).

2.4.2.2 Extending IFC

In IFC standard, entities are assigned to objects with predefined attributes. The attributes can be inherited by all relevant entities. The inheritance property of IFC from super-entity facilitates redefining the content. Therefore, it is necessary to describe entities and their inheritance relationship within the information model to clarify a holistic view of related entities (Ma et al., 2011). STEP is an international standard for the computer-interpretable representation and the exchange of product model data. The information model specification language of STEP is EXPRESS-G, the visual representation of the EXPRESS, which demonstrates the hierarchal structure of main classes and sub-classes in the IFC schema. EXPRESS consists of object-oriented, procedural and database concepts. It describes a mainly static product model completely and without ambiguity. EXPRESS defines an information domain with entities, i.e. classes of objects that share common properties and are specified by related attributes and constraints. EXPRESS-G can illustrate the static components, e.g. entities, attributes, type declarations, and hierarchies of inheritance. However, it cannot visualize functional components, local or global rules, and algorithms (Arnold & Podehl, 1999). The strength of EXPRESS is being brief and appropriate for data validation rules in the data specification. Also, an ifcXML specification is generated as an XML schema (BuildingSmart, 2016). The current IFC by BuildingSMART (2016) is developed mainly for buildings (Zhang et al., 2010). There have been previous attempts to extend BIM. For example, BIM extension was proposed for (a) defining RFID system components, their properties, and their relationships with other building elements (Motamedi, 2013), and (b) defining new entities for tunnel design and tunneling construction projects (Ghaznavi, 2013).

Consequently, it is necessary to extend the semantics of the available IFC to MUT-specific entities. For that purpose, the exchange requirements are captured using Model View Definition (MVD) (Ghaznavi, 2013). MVD is the set of information exchange requirements for the data flow between business processes at a specific stage of the project using relevant information of the model. Information Delivery Manual (IDM) can be used to extend the available IFC schema (Wix & Karlshoej, 2010). However, extending IFC needs at least two years to integrate the proposed extensions in the next IFC release by BuildingSMART and start the implementation. The other alternatives are using property sets and proxy elements as external data to link with IFC. Although these alternative methods are more practical, they need agreements about the definition of properties and proxies if they are intended to be shared with other software applications (Weise et al., 2008).

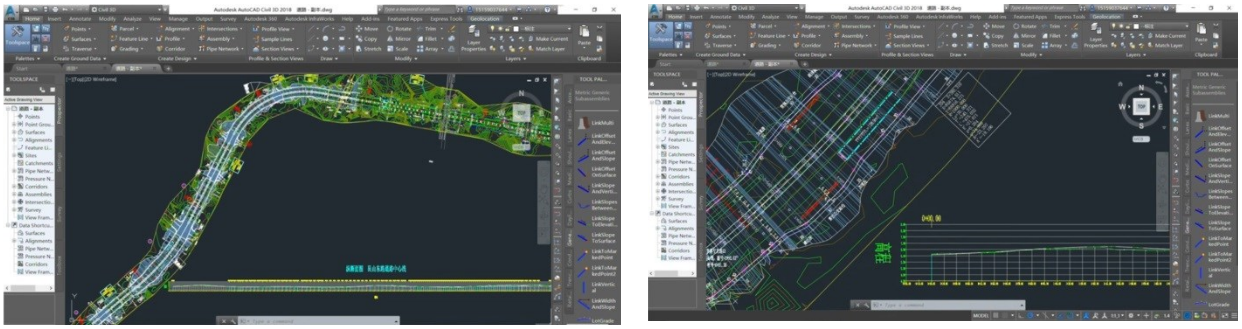
2.4.3 BIM Applications for MUT Lifecycle Management

Although BIM is not fully applicable to MUT, previous studies used BIM for different phases of the MUT lifecycle, including design, construction, and operation and maintenance.

2.4.3.1 BIM for Design and Construction Phases of MUTs

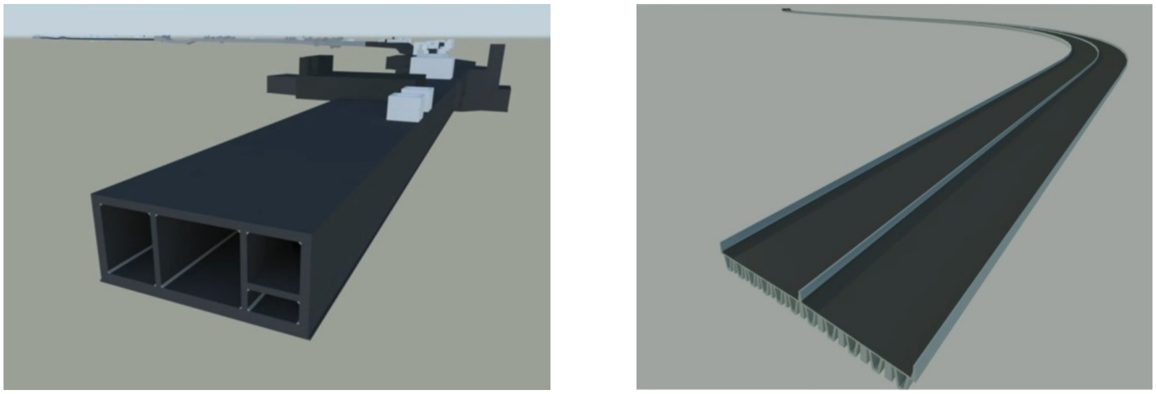
Hu and Zhang (2019) listed the information requirements for MUT design, operation, and maintenance based on BIM. They stated the benefits of collaborative MUT design enabled by BIM tools. They mentioned that the contractor’s involvement in early design stages in the development of the MUT BIM model can help construction units understand the design concept more clearly and link with the design unit better. BIM technology enables the construction management department to track the real-time progress of construction, predict the possible construction problems, and prepare earlier. Design conflicts can be solved because all the designers from several disciplines work on the same design platform with the same shared and synchronized model. Li et al. (2019) and Ge and Xu (2019) used BIM for MUT design review, clash detection and adjustment, 4D construction schedule and simulation, and quantity takeoff for cost estimation. However, they did not provide any specific MUT components. Li et al. (2019) emphasized on the importance of 4D MUT construction simulation using BIM tools. The advantages include: (a) previewing possible scenarios for installation of large pipe diameters, (b) preparing safe entry of equipment and machinery, and (c) updating construction site layout. Bao (2017) used BIM applications (i.e. Autodesk Revit, Naviswork, Civil 3D, Dynamo), combined with other technologies (e.g. virtual reality, WeChat) for a comprehensive infrastructure enhancement project in China, which includes the construction of an MUT, an elevated highway, and a road (Bao, 2017). The project length is 7.86 km, and the project cost is 1.9 billion Yuan (CA$368 million) in which, the construction cost is around 1.5 billion Yuan (around CA$290 million). The engineering challenges include numerous existing pipelines, such as sewage, water supply and drainage pipes, electricity and communication cables, passing below the roadway, intersections between the roadway and the MUT, tight schedule, and complex traffic control. The project has two stages: replacement of the existing pipeline and the main construction. BIM applications, such as Autodesk Revit, Naviswork, Civil 3D, Dynamo, etc., were used for different use cases including (a) parametric modeling, (b) construction review, (c) clash detection, (d) collaboration platform, (e) schedule management, (f) 3D clarification of construction techniques, (g) virtual construction and VR experience, (h) quality control, and (i) quantity take-off. However, these BIM use cases were not described as standard processes. The first three of these BIM applications for MUT in this project are explained as follows.

- Parametric modeling: The alignment and the profile of MUT and the elevated highway were drawn in AutoCAD Civil 3D software (Figure 2-27), then the points with location and elevation are exported to Dynamo to create the simplified 3D model of MUT (Figure 2-28).



(a) Alignment and profile **(b) Elevations**

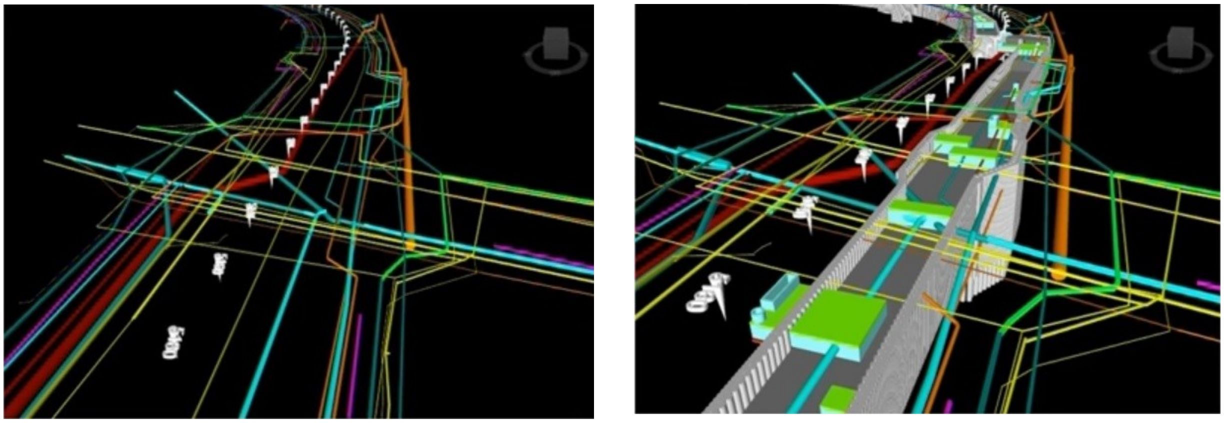
Figure 2-27 Modeling of MUT and the elevated highway in AutoCad Civil 3D (Bao, 2017)



(a) MUT **(b) Elevated highway**

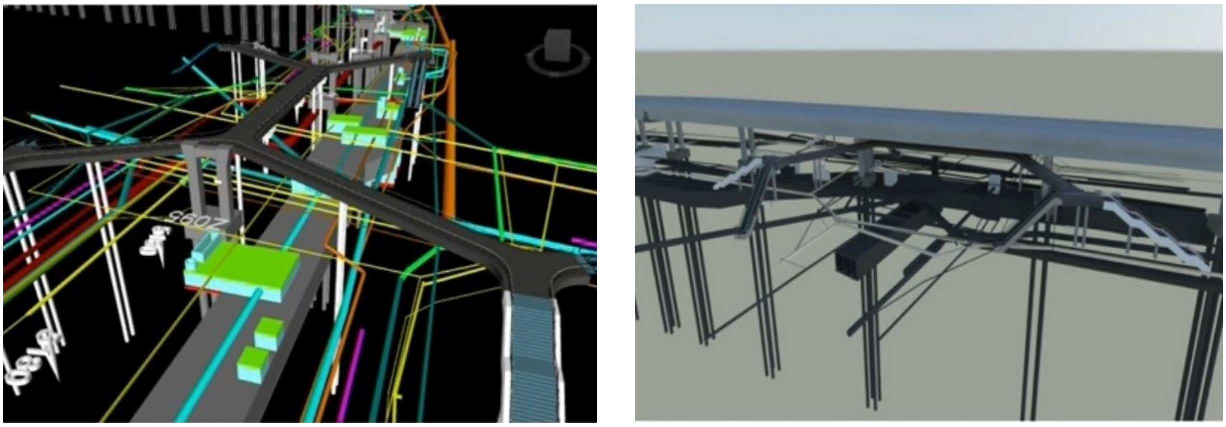
Figure 2-28 Resulting MUT and the elevated highway in Autodesk Revit using Dynamo (Bao, 2017)

- Construction review: After reviewing the plans and elevation and 3D model, at a certain location it was determined that because the sewer pipe is under the MUT, it should not be constructed after the MUT construction and must be built first. This error could be clearly seen in the 3D model. Also 27 errors or conflicts between plans and elevations were found and reported.
- Clash detection: After drawing the existing pipelines under the roadway and combining the pipelines, the barrier walls, and the piles of the elevated highway (Figure 2-29), clash detection was done, and about 250 clashes were found. For example, a clash between a support beam and auxiliary structure was identified, and consequently the beam was moved away from the auxiliary structure.



(a) Integrated pipelines

(b) Integrated pipelines and cofferdam



(c) Integrated pipelines, MUT, bridges and auxiliary structures

(d) Integrated pipelines, MUT, bridges, auxiliary structures and elevated highway

Figure 2-29 Integrated model of existing pipes with other structures (Bao, 2017)

The BIM model should contain MUT's model of the structure, pipeline and equipment, sensors, and devices. BIM cannot solve the problem of visualization of the surrounding environment because of the characteristics of MUTs, such as the long length and being under the ground. Therefore, a combination of BIM with GIS can address this problem (Lee et al., 2018; Wu et al., 2019). BIM and GIS both represent the built environment with different perspectives and terminology. BIM concentration is on the detailed building components and project information (e.g. cost and schedule) and GIS focuses on the shape of buildings and building components and geographical information (Cheng et al., 2015). The 3D GIS model should include topographic and coordinate information, and surrounding building information (Lee et al., 2018). Wu et al. (2019) presented a list of requirements for an integrated BIM and 3D GIS model of MUT. However, the requirements were not fully explained and did not include several MUT systems (e.g. communication, access control, hoisting system). An example of BIM-3D GIS model of MUT developed by Lee et al. (2018) is shown in Figure 2-30.

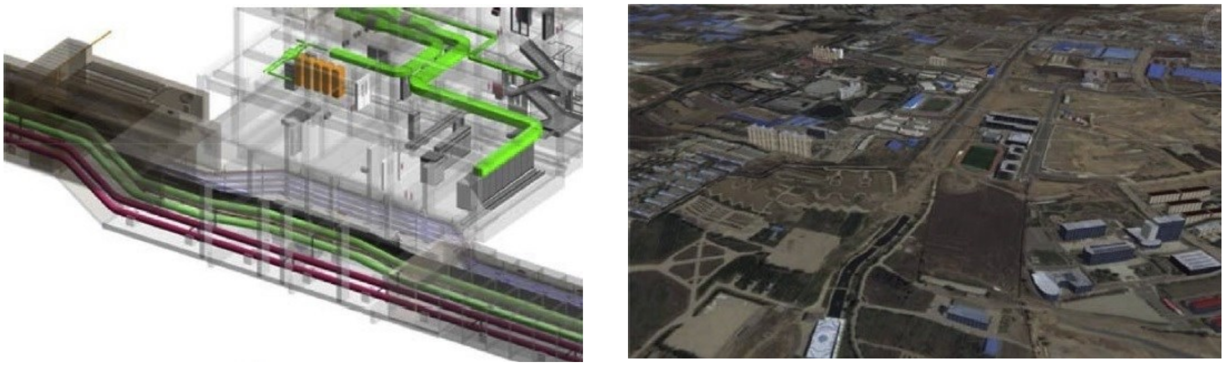

(a) BIM **(b) 3D GIS**

Figure 2-30 BIM model and 3D GIS model (Lee et al., 2018)

The review of BIM application for the design and construction phases of MUT showed that the main use cases are design, clash detection and resolution, 4D construction simulation, and cost estimation.

2.4.3.2 BIM for Operation and Maintenance Phase of MUT

The use case of BIM for facility management during the operation and maintenance phase of MUT has been emphasized in different researches. Yin et al. (2020) proposed a framework to support the operation and maintenance (O&M) of MUTs, including three modules of the BIM model, O&M database, and monitoring system. Hu and Zhang (2019) proposed a framework for a BIM-based MUT smart operation and maintenance system, which is linked with sensors and monitoring equipment. Kang et al. (2014) presented a framework for BIM facility management of MUTs. The multi-tier architecture of this framework includes database, BIM facility management system, Geo-3D map positioning system, and web publishing platform. The modeling elements are categorized into four groups: tunnel, utilities, auxiliary structures, and ancillary facilities. Sfere (2020) developed a smart O&M integrated platform of 3D GIS-BIM, cloud database, maintenance information, real-time monitoring and alarm information. Shahrour et al. (2020) proposed a framework for using smart technologies to improve MUT management. The smart system collects data about the tunnel and the accommodated utilities, operations, inspection, and maintenance data.

Lee et al. (2018) presented an integrated BIM and 3D GIS web-based maintenance management system to provide the visualized real-time monitor data (e.g. temperature, humidity, carbon dioxide concentration, smoke sensory data) and to support management decisions of MUT. Maintenance management data include complete equipment maintenance plans, equipment and sensor lists, employee information, product data, supplier information, etc. The data sources of this MUT are presented in Table 2-9.

Table 2-9 An example of MUT model data elements and data sources (Lee et al., 2018)

Model elements	Data sources
Topographical surface and information (GIS)	National open map database
Surrounding buildings	Unmanned Aerial Vehicle (UAV)-Based Oblique Photogrammetry
Utility tunnel model (BIM)	Design and construction plans
Sensors	Sensors installation plan

All the BIM and 3D GIS, maintenance management, and monitoring data are integrated into a database. The proposed prototype system of Lee et al. (2018) contains three layers of data, data linking and processing, and application as shown in Figure 2-31. For data linking and processing, different techniques have been applied, e.g. exporting 3D data files via FBX and GIS files via CityGML using Global Unique ID (GUID) and Universal Unique ID (UUID) in IFC format, using coding systems of Construction Operations Building Information Exchange (COBie) or OmniClass Construction Classification System (OmniClass or OCCS) to identify a device (component) with a unique ID, and adding the ID to the BIM element attributes to enable data linking. The GUID in the IFC format includes letters and numbers. For using in database, the GUID format can be converted to a digital ID, which includes only numbers and is called Element ID. In addition to BIM and 3D GIS programs, a web-based maintenance management system written in Hypertext Markup Language (HTML) and JavaScript is used to link the database.

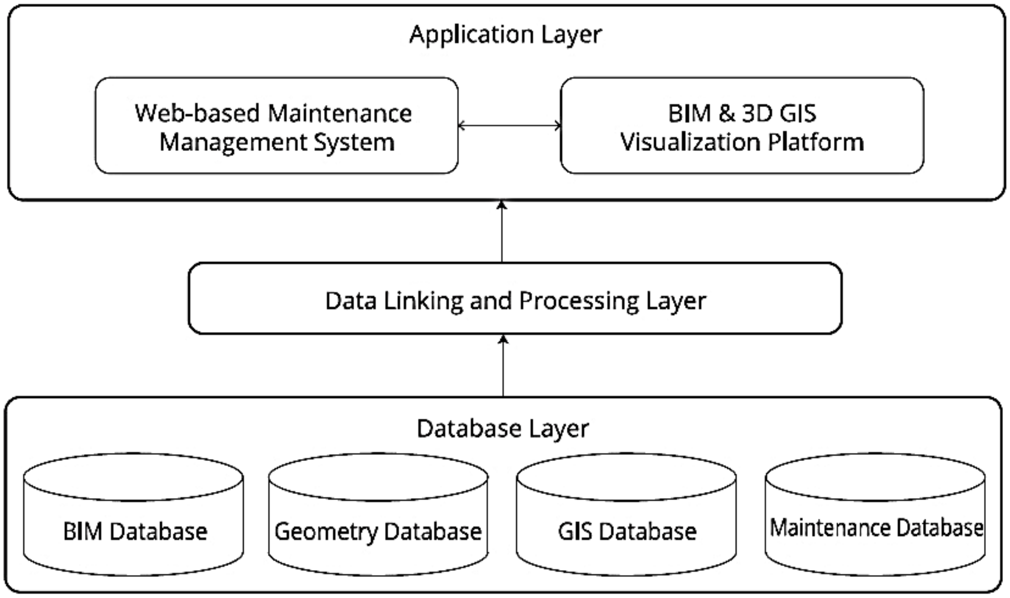


Figure 2-31 The Structure of the proposed framework of BIM-3D GIS integration (Lee et al., 2018)

The data flowchart of this BIM-3D GIS integration and maintenance management framework is shown in Figure 2-32. Data linking of BIM, GIS and geometric information are connected by Element ID and also coordinates and elevation link. The data is linked between BIM information and maintenance management information via COBie/OmniClass based unique ID.

Although the above-mentioned studies provided valuable contributions related to the application of BIM for MUTs, none of them provided a comprehensive modeling approach for MUT lifecycle management including the tunnel, utilities, ancillary facilities, and the relationships between them. The experience of using BIM-based technologies for MUT lifecycle management shed light on their benefits and clarified the information requirements of MUT components (i.e. product model) and use cases (i.e. process model) to a certain level of detail. However, there is a gap in covering the complete list of MUT physical and functional components and their relationships comprehensively. In order to standardize the use cases, there is a need to complete, integrate, and organize the available knowledge within a standard framework which includes all the requirements of the use cases (i.e. project users, required resources, mechanism, restrictions, and inter-relationship with other BIM use cases).

Table 2-10 summarizes the main research works about using BIM and GIS-based systems for MUT and the covered applications. The current research aims to develop SMUTIM which can cover all these applications in a comprehensive framework.

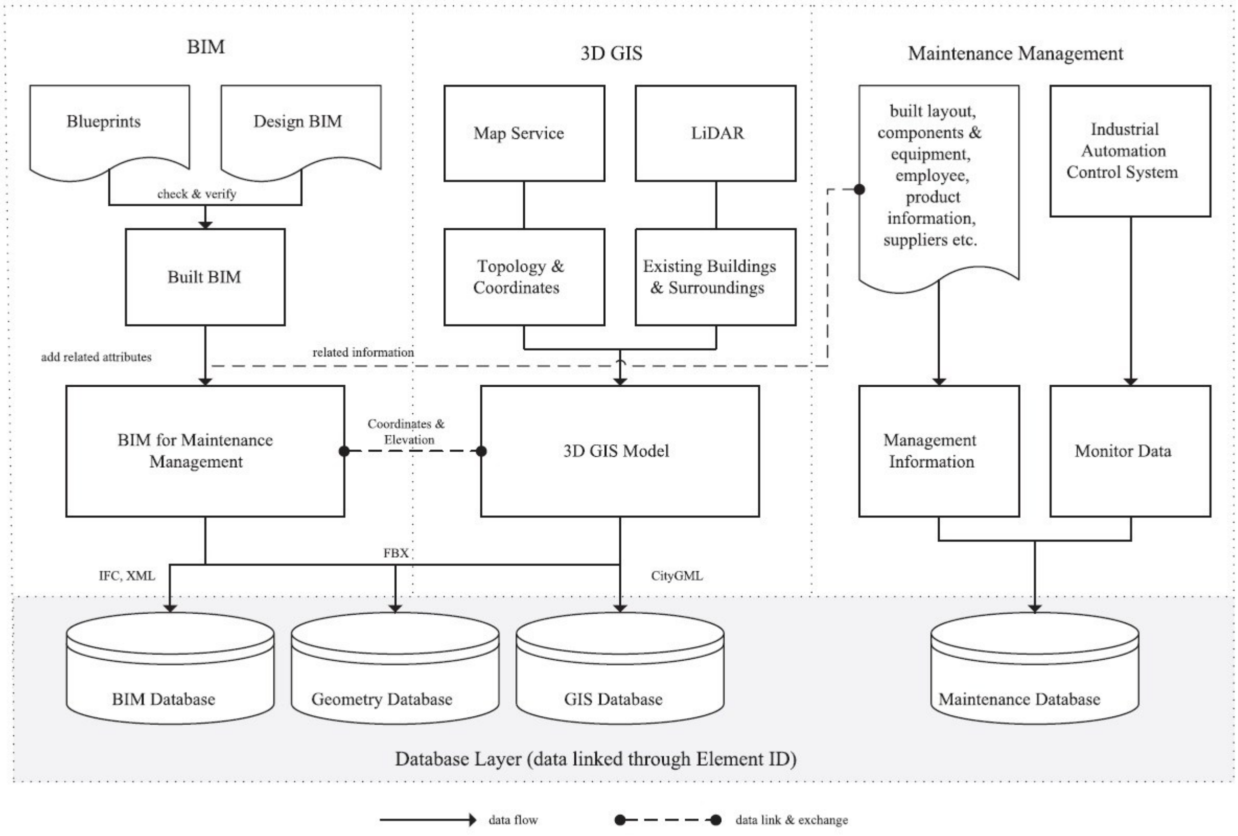


Figure 2-32 Data flow of the proposed BIM-3D GIS and maintenance management framework (Lee et al., 2018)

Table 2-10 Summary of research using BIM and GIS for MUT

Reference	BIM				GIS	IFC extension
	3D Design	4D simulation	Cost estimation	Facility management		
Kang et al. (2014)	✓	-	-	✓	-	-
Bao (2017)	✓	✓	✓	-	✓	-
Lee et al. (2018)	✓	-	-	✓	✓	-
Hu & Zhang (2019)	✓	-	-	✓	-	-
Ge and Xu (2019)	✓	✓	✓	-	-	-
Li et al. (2019)	✓	✓	✓	-	-	-
Wu et al. (2019)	✓	-	-	✓	✓	-
Sfere (2020)	-	-	-	✓	✓	-
Shahrour et al. (2020)	-	-	-	✓	-	-
Yin et al. (2020)	✓	-	-	✓	-	-
Current paper	✓	✓	✓	✓	✓	✓

2.5 Summary and Conclusions

This chapter provided a comprehensive critical review of all the domains of this research with respect to MUTs. A list of the main related research works with their covered domain(s) is presented in Table 2-11. A general review of MUTs including classification, construction methods, benefits, and disadvantages, provides an understanding of the nature, necessity and challenges of MUTs. With respect to financial feasibility and analysis, different aspects of economy, financing, and cost-sharing of MUTs were explained in detail. Despite previous researches about economical assessment of MUT and buried utilities, there is a gap in considering more factors influencing LCC and the breakeven point. Fairness of cost allocation for MUT projects is a challenging issue and should be improved based on risk and benefit factors. Afterward, MUT projects and studies around the world were discussed. Several examples and case studies were reviewed in detail to provide a general understanding of MUT and different countries. The results showed that based on the context, the benefits and barriers, physical specifications, cost and financing, and technology usage of MUTs can change significantly. Technology can be used to maximize the benefits and minimize MUT disadvantages. One of the new technologies in this field is BIM. Using BIM combined with other applications (e.g. 3D GIS, databases, sensors, web applications) to support real-time data of MUT operation, can facilitate design, construction, and operation. This chapter reviewed BIM extension to CIM. IFC, as a standard data model of buildings with hierarchal structure, has the capability to be extended to MUTs. The IFC architecture and extension methods were reviewed. The current use cases of BIM for MUT lifecycle management were investigated in design, construction, and operation and maintenance phases, and the limitations and future potential developments were discussed. Although the available BIM software applications can be used to model information of MUT, they should be extended to MUT. IFC extension is to accommodate MUT-specific requirements in BIM. There is a gap in covering the complete list of MUT physical and functional components in a standard way. In order to identify the use cases attributes, there is a need to integrate, complete, and organize the available knowledge within a comprehensive framework which includes all the requirements of the use cases (i.e. project users, required resources, mechanism, restrictions, and inter-relationship with other BIM use cases).

Table 2-11 List of the main related research works

Example references	Covered Domain(s)							
	MUT				Prefabrication & Modularization	Quantification of social costs	BIM/ CIM	Game Theory
	General/ other aspects	Life cycle cost analysis	Finance/ cost sharing	Information modeling				
Hunt et al. (2014)	✓	✓	-	-	-	-	-	-
Rogers & Hunt (2006)	✓	✓	-	-	-	-	-	-
Canto-Perello et al. (2016)	✓	-	-	-	-	-	-	-
CERIU (2011)	✓	-	-	-	-	-	-	-
UW (2008)	✓	-	-	-	-	-	-	-
Habimana et al. (2014)	✓	-	-	-	-	-	-	-
Kuhn et al. (2002)	✓	-	-	-	✓	-	-	-
Clé de sol (2005)	✓	-	✓	-	✓	-	-	-
CERIU (2010)	✓	✓	✓	-	-	-	-	-
Boileau (2013)	✓	✓	✓	-	-	-	-	-
Canto-Perello & Curiel-Esparza (2013)	✓	-	✓	-	-	-	-	-
CPAMI (2011)	✓	-	✓	-	-	-	-	-
Huck et al. (1976)	✓	✓	✓	-	-	✓	-	-
Ramírez Chasco et al., (2011)	✓	-	-	-	✓	-	-	-
BYU (2015)	✓	-	-	-	✓	-	-	-
Xiaoqin et al. (2011)	✓	-	✓	-	-	-	-	✓
Yang & Peng (2016)	✓	✓	✓	-	-	-	-	-
Zhang et al. (2019)	✓	✓	✓	-	-	-	-	✓
Laistner & Laistner (2012)	✓	✓	-	-	-	-	-	-
Laistner (1997)	✓	✓	-	-	-	-	-	-
Canto-Perello & Curiel-Esparza (2001)	✓	-	-	-	-	-	-	-
Canto-Perello & Curiel-Esparza (2003)	✓	-	-	-	-	-	-	-
Canto-Perello et al. (2009)	✓	-	-	-	-	-	-	-
Cano-Hurtado & Canto-Perello, (1999)	✓	-	-	-	-	-	-	-
Legrand et al. (2004)	✓	✓	-	-	-	-	-	-
Kang & Choi (2015)	✓	✓	-	-	-	-	-	-
Lee et al. (2018)	✓	-	-	✓	-	-	-	-
Bao (2017)	✓	-	-	✓	-	-	-	-
Kang et al. (2014)	✓	-	-	✓	-	-	-	-

Table 2-11 - List of the main related research works (Continued)

Example references	Covered Domain(s)							
		MUT			Prefabrication & Modularization	Quantification of social costs	BIM/ CIM	Game Theory
	General/ other aspects	Life cycle cost analysis	Finance/ cost sharing	Information modeling				
Hu & Zhang (2019)	✓	-	-	✓	-	-	-	-
Ge and Xu (2019)	✓	-	-	✓	-	-	-	-
Li et al. (2019)	✓	-	-	✓	-	-	-	-
Wu et al. (2019)	✓	-	-	✓	-	-	-	-
Sfere (2020)	✓	-	-	✓	-	-	-	-
Shahrour et al. (2020)	✓	-	-	✓	-	-	-	-
AKpipe (2017)	✓	-	-	-	✓	-	-	-
O'Connor et al. (2014)	-	-	-	-	✓	-	-	-
Werey et al. (2005)	-	-	-	-	-	✓	-	-
De Marcellis-Warin et al. (2013)	-	-	-	-	-	✓	-	-
Gilchrist & Allouche (2005)	-	-	-	-	-	✓	-	-
Najafi & Kim (2004)	-	-	-	-	-	✓	-	-
Ormsby (2009)	-	-	-	-	-	✓	-	-
Oum (2017)	-	-	-	-	-	✓	-	-
Ghaznavi (2013)	-	-	-	-	-	-	✓	-
NIBS (2007)	-	-	-	-	-	-	✓	-
McGraw-Hill Construction (2009)	-	-	-	-	-	-	✓	-
BuildingSMART (2019)	-	-	-	-	-	-	✓	-
Cheng et al. (2016)	-	-	-	-	-	-	✓	-
Liebich (2009)	-	-	-	-	-	-	✓	-
Isikdag et al. (2008)	-	-	-	-	-	-	✓	-
Eastman et al. (2011)	-	-	-	-	-	-	✓	-
IFC (2016)	-	-	-	-	-	-	✓	-
Ma et al. (2011)	-	-	-	-	-	-	✓	-
Motamedi et al. (2016)	-	-	-	-	-	-	✓	-
CIC (2011)	-	-	-	-	-	-	✓	-
Kennedy (2013)	-	-	-	-	-	-	-	✓
Ho (2009)	-	-	-	-	-	-	-	✓
Jeong et al., (2018)	-	-	-	-	-	-	-	✓
Asgari et al, (2013)	-	-	-	-	-	-	-	✓

Table 2-11 - List of the main related research works (Continued)

Example references	Covered Domain(s)							
		MUT			Prefabrication & Modularization	Quantification of social costs	BIM/ CIM	Game Theory
	General/ other aspects	Life cycle cost analysis	Finance/ cost sharing	Information modeling				
Shapley (1953)	-	-	-	-	-	-	-	✓
Shapley (1988)	-	-	-	-	-	-	-	✓
Von Neumann & Morgenstern, (1944)	-	-	-	-	-	-	-	✓
Suttinon et al., (2011)	-	-	-	-	-	-	-	✓
Sanchez (2008)	-	-	-	-	-	-	-	✓
Xi & Fuling, (2013)	-	-	✓	-	-	-	-	✓

CHAPTER 3. OVERVIEW OF THE RESEARCH APPROACH

3.1 Introduction

As discussed in Section 1.2 and Chapter 2, MUTs are not extensively used because of complicated (a) lifecycle economical assessment and justification, (b) fair cost-sharing, and (c) coordination of utility companies. To address these problems and achieve the research objectives mentioned in Section 1.3, the proposed research approach is developed in three phases:

Phase 1 - MUT lifecycle economy assessment: In this phase, the first objective of this research about development of a model for LCC assessment of MUT and buried utilities by considering the influencing factors is achieved. Section 4.2.1 extends this phase in depth.

Phase 2 – Lifecycle cost-sharing of MUT: The second objective of this research regarding development of a fair model of MUT cost-sharing that considers balancing risks and benefits among utility companies is achieved in this phase. This phase is elaborated in Section 4.2.2.

Phase 3 – BIM extension to MUT: The third objective of this research about development of a comprehensive framework of smart MUT information requirements, linking SMUTIM with GIS and databases, identifying use cases, and extending IFC, is achieved in this phase. Chapter 5 aims to pusure this objective.

3.2 Overview of the Proposed Approach

Figure 3-1 shows the structure of the proposed research approach in three phases. Each phase is introduced in this chapter.

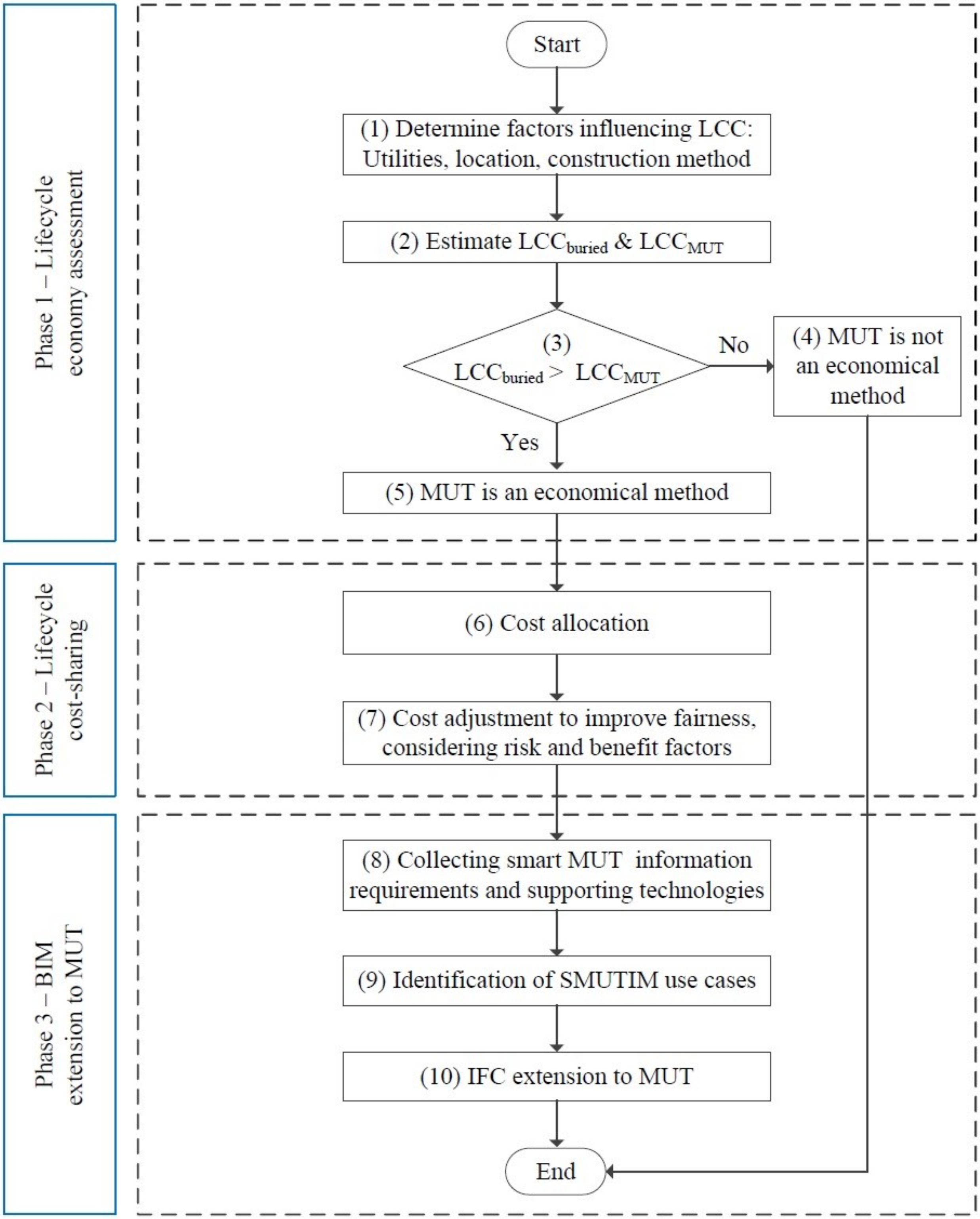


Figure 3-1 Structure of the proposed research approach

3.2.1 MUT Lifecycle Economy Assessment

The proposed approach starts with the lifecycle economy assessment of buried utilities and MUT considering the influencing factors. To investigate if MUT is an economically viable alternative for the traditional method of buried utilities in each specific case (project level), different factors should be considered. In general, the factors influencing the LCC of MUT and buried utilities can be categorized into three groups as follows (Figure 3-2).

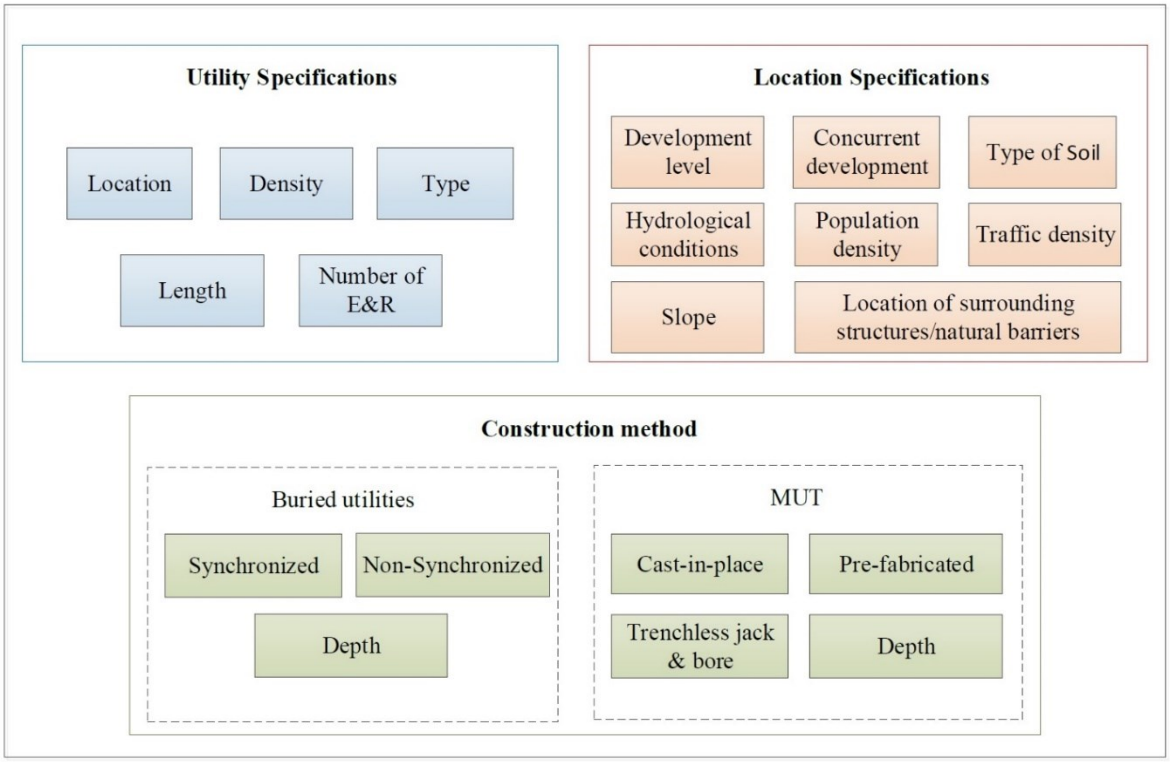


Figure 3-2 Factors influencing the lifecycle cost of MUT and buried utilities

(a) Utility Specifications: the factors that are related to the physical characteristics of utilities.

(b) Location Specifications: the factors that describe the geological and hydrological conditions, urban development, and human-related conditions of project location (e.g. population density).

(c) Construction method: the depth and method of construction for both buried utilities and MUT.

The LCC of each method is a function of these factors. Therefore, there is a need for a systematic approach to estimate the LCC and find the breakeven point, where the costs of both methods are equal.

In this phase, the LCC is estimated for both methods. The influence of each factor on LCC can be different and should be evaluated. MUT is the economic method when the estimated LCC of MUT is lower than that of the buried utilities. The details of this method are given Section 4.2.1.

3.2.2 Lifecycle Cost-sharing of MUTs

After deciding on an MUT project, the next challenge is financing and cost-sharing of the project (Canto-Perello & Curiel-Esparza, 2013). MUT should be more economical for each utility company as well (organization level) and the MUT benefits should be distributed fairly, to convince utility companies to participate in the MUT project. This research proposes a cost-sharing approach, and fairness is provided by mathematical methods. As shown in Figure 3-1 the first step in the cost-sharing of MUT projects is cost allocation. As explained in Section 2.2.4.2, two methods of MUT cost allocation have been proposed: the PBC method (CPAMI., 2011; Xiaoqin et al, 2011; Zhang et al., 2019) and the PUVO method (Xiaoqin et al, 2011; Zhang et al., 2019). This research proposes using the PBC method for the design and construction phases, based on the logic that the burden of the design and construction costs for each company participating in the MUT should have the same ratio as in the case of buried utilities. It is also proposed to use the PUVO method for the operation phase of MUT because the proportion of the occupied volume of MUT during the operation phase should determine the ratio of usage cost. It is assumed that the specific costs of each utility company will be paid directly by that company, and only the common costs of MUT should be shared. Although the proportion of costs in the PBC and PUVO methods are the main factors for allocation of MUT cost to utility companies, there are other factors to be considered for cost-sharing to satisfy (a) balance of risk, and (b) benefits: balanced benefit-cost ratio, and balance in contributed benefit and gained benefit.

(a) Risk Factor. Accommodation of certain utilities together imposes safety risks on the MUT (see Section 2.2.4.3). For example, the proximity of gas pipes and electrical wires in the MUT increases the risk of fire. In addition to the insurance cost for safety issues, an extra cost is needed for the safer design of the MUT and the installation and operation of safety devices (e.g. fire detectors and sprinklers). A fair cost-sharing method should allocate the costs of risk management to the utility companies that are responsible for the risks (i.e. proportional allocation of the cost of risk management and responsibility of risk).

(b) Benefit factors:

- Balanced Benefit-Cost Ratio (BCR): As explained in Section 2.1.3, the benefits of MUTs are obtained during the operation phase. However, utility companies may not benefit from MUT with the same BCR. Therefore, for the sake of fairness, it is important to calculate the BCR for each utility company and balance BCR among the utility companies. It means companies that benefit more should pay more for the MUT and vice versa.
- Balanced contributed and gained benefit: The benefit that each utility company contributes to the project by participation in MUT and avoiding buried utilities is called contributed benefit (ConB) and can be determined using Shapley value in cooperative game theory (see Section 2.2.3.2). However, there is no guarantee that the gained benefit (GB) of a company is close to its contributed benefit. For the sake of fairness, ConB and GB should be balanced, and their difference should be less than a threshold.

The public entities (e.g. municipality) are usually the main beneficiary of MUT projects because of their social responsibility and the significant benefits of MUTs for the society. Therefore, they may consider some incentives for the other utility companies to increase their benefits and encourage them to participate in MUT projects.

3.2.3 BIM Extension to MUT

This research proposes the development of an integrated BIM and 3D GIS framework of SMUTIM that includes three main steps: (a) MUT lifecycle information requirements definition, (b) identification of SMUTIM use cases, and (c) extending IFC to accommodate SMUTIM. The proposed framework is based on the analysis of the literature review, expert opinions, and the resources about MUT and utilities information requirements.

3.2.3.1 MUT lifecycle Information Requirements

BIM and other technologies (e.g. GIS, sensors, databases) can support different types of MUT lifecycle information (i.e. geometric and non-geometric). The information requirements are categorized into five groups: (a) managerial, (b) surrounding environment, (c) tunnel structure, (d) utilities, and (e) ancillary facilities. Each information group includes sub-categories as follows.

(a) Managerial information: The managerial information sub-categories include economic assessment, risk management, financing and cost-sharing, ownership and management issues, permission setting, and employee information.

(b) Surrounding environment information: This information group covers geotechnical information, hydrological information, the terrain model and above-ground structures, traffic density, underground structures and buried utilities, and population and buildings functionality.

(c) Tunnel structure information: This information group is about different parts of a tunnel structure including tunnel main structure and foundation, foundation pits, and auxiliary structures (i.e. access, node, lateral tunnel, and waterproofing and drainage structures).

(d) Utilities information: The utilities are categorized into two groups of pipes (i.e. drinking water, sewer, and gas) and cables (i.e. electrical and telecommunication).

(e) Ancillary facilities information: The continuous operation of the MUT is supported by the ancillary facilities. These systems include sensory (i.e. structural health monitoring (SHM), access control and geo-localization, and environmental monitoring systems), HVAC, drainage, lighting, power supply, security monitoring and alarm, fire extinguishing, hoisting, and communication systems.

The relationships between the information groups are defined and explained by four categories of relationship: (1) subsumption, (2) partonomy, and (3) supporting (i.e. monitoring, controlling, serving).

3.2.3.2 SMUTIM Use Cases

Four main use cases of SMUTIM (i.e. 3D design, 4D construction simulation, cost estimation, facility management) are identified. To describe a SMUTIM use case, the following attributes should be specified:

- Project phase: In what phase(s) of the project the use case can be applied?
- Project users: Who are the project stakeholders involved in the use case?
- Required resources: What resources are required to fulfill the use case?
- Mechanism: How the project users use the resources to perform the use case?
- Restrictions: Under which limitations is the SMUTIM use case implemented?

- Output: What are the results of the use case?
- Interrelation with other use cases: Is there any other use case output used as an input for this use case, or vice versa?

A case study is used to demonstrate the applicability of the identified use cases.

3.2.3.3 IFC Extension to MUT

Organizing MUT information requirements is a basis for extending IFC to MUT. For this purpose, it is needed to develop MVD, to identify the reusable IFC entities, properties, and relationships and define new ones. This research focuses on the extension of IFC for the physical and spatial components of MUT and a partial implementation of IFC for MUT. The proposed MVD categorizes the MUT physical components into three main groups of tunnel structures, utilities, and ancillary facilities. Each main group includes subcategories.

The new IFC entities for the physical components are presented and some of the reusable entities, properties, and relationships are explained as examples. Partial implementation of the proposed SMUTIM IFC extension is presented in a STEP-based platform.

3.3 Summary

This chapter presented the research approach which has three phases: (a) MUT lifecycle economy assessment, (b) lifecycle cost-sharing of MUT, and (c) BIM extension to MUT. Chapter 4 is allocated to the phases (a) and (b) and Chapter 5 explains the phase (c). To realize the proposed methodology, each of the abovementioned phases will be conducted as follows.

(a) MUT lifecycle economy assessment: This phase includes formulating and evaluating of LCC of buried utilities and MUT by considering the influencing factors: utility specifications, location specification, and construction method, and finding LCC and the breakeven point.

(b) Lifecycle cost-sharing of MUT: The process of lifecycle cost-sharing includes the selection of MUT cost allocation method, cost adjustment using risk and benefit factors, and game theory.

(c) BIM extension to MUT: This process includes three main steps: (a) MUT lifecycle information requirements definition, (b) identification of SMUTIM use cases, and (c) extending IFC to accommodate SMUTIM.

CHAPTER 4. LIFECYCLE COST ASSESSMENT AND COST-SHARING OF MUT

4.1 Introduction

As explained in Section 2.1.3, although MUTs have numerous benefits, they are not widely used because of the high initial construction cost, the need for high level of safety and security, and coordination between utility companies (see Section 2.1.4). As discussed in Section 2.2.1, despite the high initial investment needed, direct operational and social cost savings can make LCC of MUTs less than conventional buried utilities. As explained in Section 3.2.1, to investigate if MUT is an economically viable alternative for the traditional method of buried utilities in a specific project, different factors should be considered related to the specifications of utilities, the location of the project, and the construction method. The LCC of each method is a function of these factors. Therefore, there is a need for a systematic approach to estimate the LCC and find a breakeven point, where the cost of both methods is equal. MUT is the economic method when the estimated design and construction costs of MUT is lower than the breakeven point. After deciding on an MUT project, the next challenge is financing and cost-sharing of the project (Canto-Perello and Curiel-Esparza, 2013). MUT should be more economical for each utility company compared with the buried utility option (organization level) and the MUT benefits should be distributed fairly, to convince utility companies to participate in the MUT project (see Section 3.2.2).

This chapter aims to achieve the first two objectives of this research in Section 1.3. A comprehensive approach for MUT and buried utilities LCC analysis that considers factors of utility specifications, location conditions, and construction methods is developed at project level. The result reveals the conditions that MUT project is an economical method. At the organization level, this chapter proposes an MUT cost-sharing model to ensure that MUT is the economical method for the utility companies and that all the utility companies benefit from MUT fairly.

4.2 Proposed Method

The proposed method considers the MUT economy at the project level as well as the cost-sharing between stakeholders. Figure 4-1 shows the proposed model of economy assessment and cost-sharing of MUT.

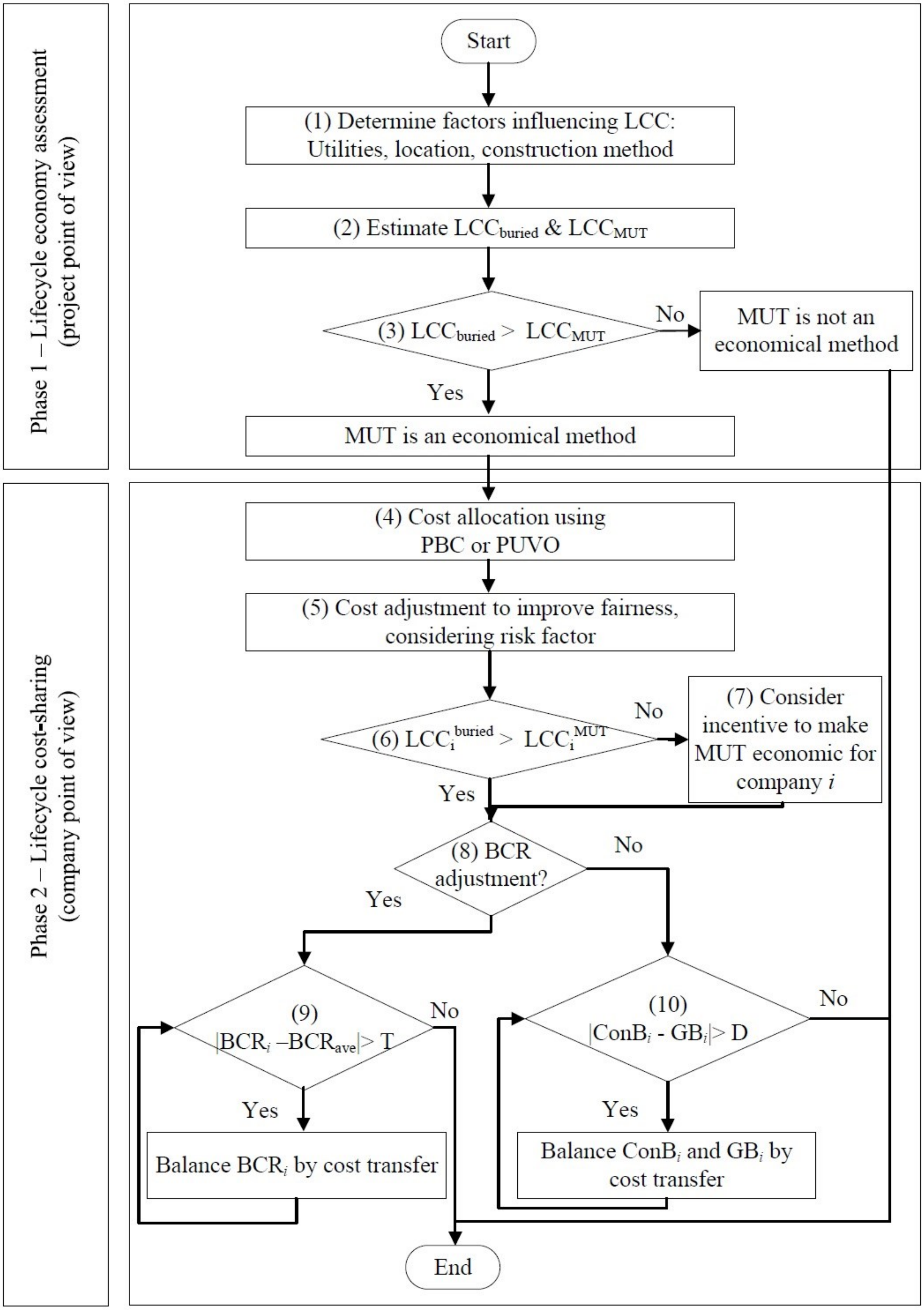


Figure 4-1 MUT lifecycle economy assessment and cost-sharing method

4.2.1 Phase 1: Lifecycle Economy Assessment of MUTs

In the first phase, lifecycle economy assessment determines if the MUT project is an economical method or not. This phase has the following steps.

Step 1. The factors that influence the LCC of MUT and buried utilities should be determined. These factors can be categorized into three groups: (a) utility specifications: the factors that are related to physical characteristics of utilities, (b) location conditions: the factors that describe the geological conditions, urban development, and human-related conditions of project location, and (c) the method of construction and maintenance and relevant attributes for both buried utilities and MUT. These factors are categorized based on relevance to these groups and linked with MUT or buried utilities as shown in Table 4-1.

Table 4-1 Factors influencing the lifecycle cost of MUT and buried utilities

Factors		Buried utilities	MUT
Utility factors	Location of utilities	✓	-
	Density of utilities	✓	✓
	Type	✓	✓
	Length	✓	✓
	Number of E&R	✓	-
Location factors	Development level	✓	✓
	Concurrent development projects	✓	✓
	Type of soil	✓	✓
	Hydrological conditions	✓	✓
	Population density	✓	✓
	Traffic density	✓	✓
	Slope	✓	✓
	Location of surrounding structures/natural barriers	✓	✓
Construction/maintenance factors	Depth	✓	✓
	Synchronization	✓	-
	Tunnel building method	-	✓

(1) Utility specifications

(a) Location of utilities: The location of existing utilities or planned future buried utilities are needed to estimate the cost of excavation, installation, and reinstatement.

(b) Density of utilities: The locations with a high number of utilities in a limited space (i.e. high density of utilities) give the chance of co-located and synchronized construction of buried utilities or their accommodation in the same MUT. Therefore, some construction and maintenance costs can be shared (e.g. the costs for construction equipment and labor, traffic control, and other social costs) resulting in a smaller unit cost. However, higher density of utilities can lead to larger dimensions of the tunnel or MUT compartments that add extra construction cost.

(c) Type: Type of utilities can be defined by specifications, such as diameter, material (Hunt et al., 2014), and lifespan. Larger diameters are more costly and need a larger volume of excavation, resulting in higher cost. The cost of utilities is also directly related to the material. Selecting the utility material depends on many factors, such as the needed protection, technical requirements, needed capacity, availability of material, etc. The age of existing utilities and life expectancy of future utilities are critical factors in economic analysis.

(d) Length: This factor represents the relation between the length of utility/MUT with the unit cost. For each project, there are two types of costs: fixed and variable costs. The fixed costs do not depend on the size of project, such as overhead costs including insurance, taxes, office rent, office supplies, accounting, etc. The variable costs depend on the size of project. By increasing the size of the project, only the variable costs will be added and the fixed costs do not change. Therefore, the unit cost decreases because of the economy of scale. Utilities/MUTs can vary significantly in length. Therefore, the size of the project affects the unit cost considerably. Large utilities/MUT projects are potentially more economical than small ones.

(e) Number of Excavation and Reinstatement (E&R): In order to access buried utilities for maintenance and repair, excavation and reinstatements (E&Rs) are needed during the lifecycle, which will increase the lifecycle cost of buried utilities.

(2) Location Conditions

(a) Development level: As explained in Section 2, the costs of buried utilities increase from undeveloped areas to suburban and urban areas because of the extra costs that urban areas impose on the projects, such as decommissioning and bypass cost of existing utilities, traffic control, buying underground space, social costs, etc.

(b) Concurrent development projects: Synchronizing the construction and maintenance of buried utilities or MUT with other planned underground development projects at the same location (e.g. metro, shopping centers, pedestrian corridors) can save the costs by sharing the resources.

(c) Type of soil: The type of soil influences directly the cost. For example, excavation of hard rocks can be more expensive than clay. Also, the stabilization of weak soils (e.g. clay) imposes extra costs.

(d) Hydrological conditions: Underground water or the existence of rivers and lakes in the route of utilities or MUT can add extra costs. Examples of extra cost can be for dewatering of construction site, waterproofing of utilities/MUT, deviation of utilities/MUT route to avoid water, utility towers/bridge over the water, etc.

(e) Population density: Population of an area can impact the LCC of MUT and buried utilities. In city areas with high-rise buildings, a single branching secondary MUT can provide utilities to more users than in suburban areas. Therefore, the cost per user will be reduced. MUT reduces the social costs by decreasing repeated excavations to access buried utilities during the lifecycle. Therefore, in high population density areas, MUT can be more beneficial from the social cost point of view.

(f) Traffic density: For the utility companies, the cost of traffic control and detour roads adds extra costs to construction and maintenance of buried utilities, especially in areas with high traffic density. Also, the added travel time because of traffic congestion and/or longer travel distance in detour roads imposes extra costs to the passengers (social costs).

(g) Slope: Land slope can impose or save the cost of buried utilities and MUTs. Lack of slope can be costly when there is a need for slope (e.g. gravity sewer). Therefore, to provide the needed slope, the excavation and installation will be deeper gradually, which adds to the cost. In cases that there is more than needed slope, special design and construction technics (e.g. soil filling and vertical/slopped MUT) may be required to address the issues.

(h) Locations of surrounding structures/natural barriers: The existing surrounding structures (e.g. metro) or natural barriers (e.g. rivers) can impose costly restrictions on the location of future buried utilities/MUT. To overcome the restrictions, deep excavation and protective structures can be considered, which imposes an extra cost. However, deep excavation may save some costs by avoiding existing utilities using trenchless methods.

(3) Construction/maintenance methods

(a) Depth: The depth of buried utilities or MUT affects the cost. Deeper excavation is more expensive usually, unless in special situations.

(b) Synchronization for buried utilities: In order to share and save the costs, construction/renewal and maintenance of buried utilities can be synchronized. Synchronization can vary in the number of utilities. However, the lost lifespan of some utilities, which are renewed before ending their lifespan because of synchronization, should be considered as an extra cost (Oum, 2017).

(c) Tunnel building method: Selecting the construction method of MUT depends on many factors. For example, pre-fabrication can be appropriate for large scale or fast track projects and inappropriate for designs with high complexity. Trenchless jack and bore system is the most expensive method but needed for deep MUTs passing under buildings, and other underground facilities/utilities.

For the lifecycle economy assessment of each specific MUT project, all of the abovementioned factors should be determined. Figure 4-2 presents the required sources of data and links them to each lifecycle economy assessment factor.

GIS maps can provide a wide range of data about utilities specifications, location conditions, and construction/maintenance method. The location, material and diameter (type), number, and historical data for the number of E&R of existing utilities, are mostly available in GIS. Geological maps in GIS can provide data about the type of soil, slope, and locations of underground surrounding structures and/or natural barriers. Population maps can determine population density. Hydrological maps can be used to understand the hydrological conditions of a certain location, e.g. underground water level, rivers and lakes. Streets and building maps can represent the development level of an area (e.g. urban, sub-urban, and undeveloped) and also influence the selection of the construction method.

Municipal development plans determine what development projects (e.g. metro, shopping centers, pedestrian corridors) are planned in the future at the same location of buried utilities/MUT. The historical data about the vehicle traffic of a certain area may be available or may need to be collected. These data will be used for estimating the social impact of MUT projects. The project information can be available in high-level documents, such as organization/municipal strategy,

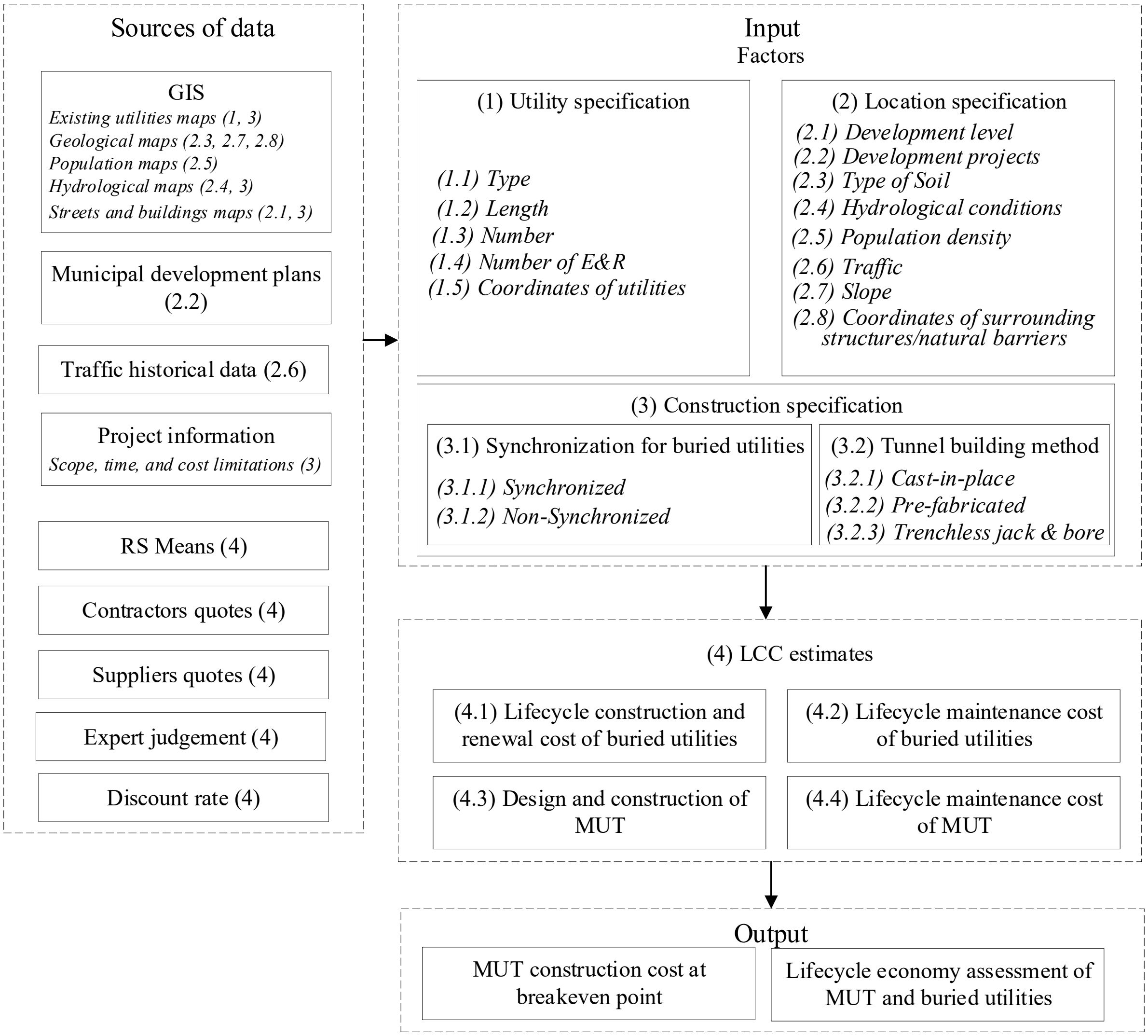


Figure 4-2 Data requirements of the proposed MUT lifecycle economy assessment model

organization budget, project charter, etc. These documents reflect any limitation for the budget, schedule, and scope of a buried utilities/MUT project and influence the construction specification.

As a reference and standard of construction cost data, RS Means is used by construction professionals for creating budgets, project cost estimation, validating with internal cost data, and planning for facilities maintenance (RSMeans, 2019). This source of data is very useful for LCC estimation of buried utilities and MUT. Price quotations can be requested from qualified contractors for the construction and maintenance services that they provide. Also, price quotations from the material, labor, and equipment suppliers can be useful for LCC estimation. For the unique and/or complicated cases that cost estimation cannot be accurate by cost databases and quotations, expert judgment can be beneficial. By providing the required data sources to the experts, they can consider the complexity of the situation and use similar past cases (if available) to judge for cost estimation. The discount rate is dependent on the economic conditions and is used to calculate the Future Value (FV) and Present Value (PV).

Step 2. The Lifecycle costs of buried utilities (LCC_{buried}) and MUT (LCC_{MUT}) should be estimated. LCC is the total cost of design, construction, and maintenance during the lifespan of MUT or the utilities. Although the social cost is not borne by the utility companies, it can be added to LCC since public entities (e.g. municipalities) are responsible for social costs. To evaluate the lifecycle economy of MUT versus buried utilities, the LCC of each method, must be estimated. The Present Value (PV) of LCC of buried utilities (LCC_{buried}) can be calculated by the total PV of design, construction, and operational (maintenance and repair) costs of all utilities as shown in Equation (4-1):

$$LCC_{buried} = design \,\&\, construction\ cost\ (CB_{Total}) + operation\ cost\ (OCB_{Total}) \tag{4-1}$$

$$= \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{k}\frac{\left(CB_{ij}^{t} + S_{cij}^{t}\right)}{(1+r)^{t}} + \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{k}\frac{\left(OCB_{ij}^{t} + S_{mij}^{t}\right)}{(1+r)^{t}}$$

The Present Value (PV) of LCC of MUT (LCC_{MUT}) can be similarly calculated by the total PV of design and construction cost (CM_{Total}), and operational (maintenance and repair) costs of MUT (OCM_{Total}) as presented in Equation (4-2):

$$LCC_{MUT} = design\ \text{and}\ construction\ cost\ (CM_{Total}) + operation\ cost\ (OCM_{Total}) \tag{4-2}$$

$$= CM_{Total} + \sum_{t=1}^{k}\frac{OCM_{MUT}^{t}}{(1+r)^{t}}$$

For LCC_{buried}, the social costs (e.g. traffic delay cost) are added because of the need for excavation and road closure and/or detours. The variables included in Equations (4-1) and (4-2) are described as follows.

i: utility type
n: total number of utility types
j: specific segment of the same utility type
m: total number of segments of the same utility type
t: year

CB_{ij}^{t}: design, construction, and renewal costs of buried utility type i, specific pipe/cable j at year t.

S_{cij}^{t}: Social Cost for construction/renewal of buried utility type i, specific pipe/cable j at year t.

r: discount rate

CM_{Total}: design and construction costs of MUT.

OCB_{ij}^{t}: operation (maintenance and repair) cost of buried utility type i, specific pipe/cable j at year t

S_{mij}^{t}: Social cost for maintenance and repair of buried utility type i, specific pipe/cable j at year t

k: MUT lifecycle in years

OCM_{MUT}^{t}: Maintenance and repair cost of MUT at year t

It should be considered that many factors related to utility, location and construction method influence the estimation of LCC in Equations (4-1) and (4-2) (Oum, 2017).

Step 3. To determine if MUT is an economical alternative for buried utilities, LCC_{MUT} must be less than LCC_{buried}. Another form of economical evaluation is calculating the payback period of MUT and comparing the CM_{Total} at breakeven point ($LCC_{buried} = LCC_{MUT}$) with the estimated CM_{Total}. Since the high initial construction cost of MUT is usually the main barrier, it is important to calculate the payback period. In this step, a comparison between LCC_{buried} and LCC_{MUT} is used to determine the economic feasibility of MUT projects. If LCC_{buried} is more than LCC_{MUT}, then MUT is an economical method from the project point of view. The further calculation is needed to share MUT cost (steps 4 and 5), make sure MUT is economic for all utility companies (steps 6 and 7), and finally balance benefits (steps 8 to 10). If LCC_{buried} is less than LCC_{MUT}, then the MUT project is not justified economically and may be ignored. In some cases, other considerations, such as political, legal, environmental, and limited underground space, may justify MUT projects.

4.2.2 Phase 2: Lifecycle Cost-sharing of MUTs

Step 4. As explained in Section 2.2.4.2, there are two methods for MUT cost allocation: the PBC method (CPAMI., 2011; Xiaoqin et al, 2011; Zhang et al., 2019) and the PUVO method (Xiaoqin et al, 2011; Zhang et al., 2019). This research proposes using the PBC method for the design and construction phases, based on the logic that the burden of the design and construction costs for each company participating in the MUT should be the same ratio, as in the case of buried utilities.

It is assumed that the specific costs of each utility company (e.g. costs of materials, installation of the utilities inside the MUT, maintenance of utilities, etc.) will be paid directly by each utility company. Only the common costs of MUT, including building and maintenance of the tunnel and shared services, will be shared between utility companies. The design and construction cost part of the MUT for utility company *i* (CM_i) based on the PBC method can be calculated by Equation (4-3).

$$CM_i = CIM_i + \frac{CB_i}{\sum_{i=1}^{n} CB_i} \times CM_{Total\ shared} \tag{4-3}$$

where CIM_i is the specific cost of installation of company *i* in MUT, CM_{Total} shared represents the total shared design and construction cost of MUT tunnel structure and equipment, and CB_i indicates the design and construction cost of utility company *i* in the buried method. It is also proposed to use the PUVO method for the operation phase of MUT, because the proportion of the occupied volume of MUT during the operation phase should determine the ratio of usage cost. The total operational cost part of the MUT for utility company *i* (OCM_i) based on the PUVO method can be calculated by Equation (4-4):

$$OCM_i = SOCM_i + \frac{OV_i}{\sum_{i=1}^{n} OV_i} \times OCM_{Total\ shared} \tag{4-4}$$

where $SOCM_i$ is the specific operational cost of company *i*, which excludes the MUT shared operational cost, OCM_{Total} shared indicates the total shared operational cost of MUT, and OV_i is the occupied volume of utility company *i* in the MUT. The lifecycle cost of MUT for company *i* (LCC_i^{MUT}) is the sum of costs of design and construction phase, and the operation phase, as shown in Equation (4-5).

$$LCC_i^{MUT} = CM_i + OCM_i \tag{4-5}$$

Step 5. The proximity of some utilities (e.g. gas and electricity) increases safety risks inside the MUT. It is necessary to distribute the cost of risk management among the utility companies fairly. For this purpose, the total cost for the management of risk *k* in phase *p* (CR_{kp}) should be redistributed among utility companies using the risk indicator of company i (γ_i) such that $\sum_{i=1}^{n} \gamma_i =$

1. The cost of management of risk k for utility company i in phase p of the project (CR_{ikp}) can be calculated using Equation (4-6) (see Table 2-3):

$$CR_{ikp} = \gamma_i \, CR_{kp} \tag{4-6}$$

Step 6. After risk adjustment, it is necessary to verify that MUT is an economical method for each individual utility company. MUT is economical for company i if the lifecycle cost of buried utilities for company i (LCC_i^{buried}) is greater than the lifecycle cost of MUT for company i (LCC_i^{MUT}). Otherwise, the utility company i may refuse to participate in the MUT project due to lack of economic benefit. In case MUT is not economical for a utility company, the management of project should grant incentives to make MUT beneficial (step 7).

Step 7. Incentives can make MUT beneficial for the utility company i. Incentives can be in different forms, such as tax exemption, subsidy, etc. and usually is granted from the municipality, which is the main beneficiary of MUT.

Step 8. After making sure all the MUT participants gain benefit from the MUT project, the gained benefit must be distributed fairly among utility companies. The project needs to choose one of the two logics for fairness of gained benefit distribution in this step:

(a) balanced Benefit-Cost Ratio (BCR) is selected if there is no need to encourage any utility company to participate in MUT, then the logic that higher cost (LCC_i^{MUT}) should result in higher benefit for each company is followed (steps 9).

(b) balanced contributed and gained benefit is selected to encourage a utility company, which has a high contribution, but a low benefit, to participate in MUT (steps 10).

Step 9. This step ensures that the utility companies have a balanced BCR_i. The gained lifecycle benefit of a company (GB_i) by participating in an MUT project can be calculated using the estimated difference of LCC of buried utilities and MUT plus any possible incentive for company i (INC_i) (Equation (4-7)). GB_i must be positive to make MUT economical for company i.

$$GB_i = LCC_i^{buried} - LCC_i^{MUT} + INC_i \tag{4-7}$$

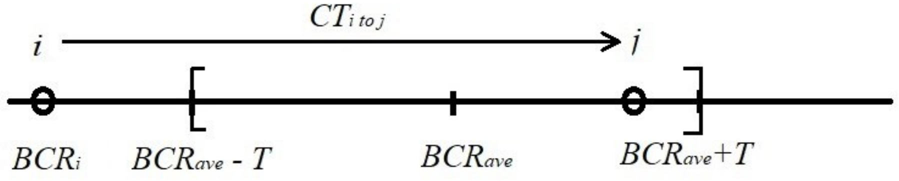
The MUT benefit-cost ratio for utility company i (BCR_i) is calculated by dividing GB_i by LCC_i^{MUT} after risk adjustments using Equation (4-8).

$$BCR_i = \frac{GB_i}{LCC_i^{MUT}} \tag{4-8}$$

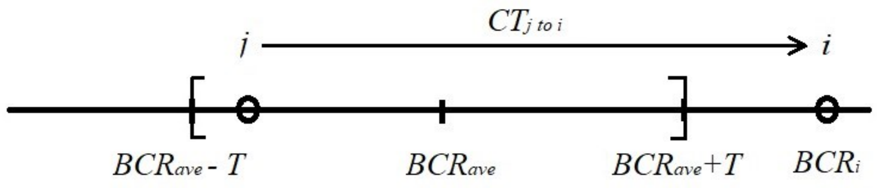
To ensure a balanced BCR_i, the variance of BCR_i from the average MUT benefit-cost ratio (BCR_{ave}) has to be less or equal to an agreed-upon threshold T (Equation (4-9)).

$$|BCR_i - BCR_{ave}| \leq T \tag{4-9}$$

In case this condition cannot be satisfied, there are two scenarios as shown in Figure 4-3:



(a) Scenario 1



(b) Scenario 2

Figure 4-3 BCR Balancing based on the threshold T and cost transfer

Scenario (1): for companies with $BCR_i < BCR_{ave} - T$, a portion of the cost ($CT_{i\ to\ j}$) of the company with the lowest BCR_i is transferred to the company with the highest BCR_j in order to satisfy Equation (4-9).

$CT_{i\ to\ j}$ can be calculated by Equation (4-10). This process can be iterative and for all other companies until Equation (4-9) is satisfied.

$$CT_{i\ to\ j} = LCC_i^{MUT} - \frac{GB_i}{BCR_{ave} - T} \tag{4-10}$$

The scenario (2) applies to companies that satisfy the condition $BCR_i > BCR_{ave} + T$. A portion of the cost of the company with the lowest BCR_j ($CT_{j\ to\ i}$) is transferred to the company with the highest BCR_i to satisfy Equation (4-9). The amount of $CT_{j\ to\ i}$ can be calculated using Equation (4-11). This process can be iterative and applied to all other companies until Equation (4-9) is satisfied.

$$CT_{j\ to\ i} = \frac{GB_i}{BCR_{ave} + T} - LCC_i^{MUT} \tag{4-11}$$

If both scenarios appear at the same time, the company with a larger variance of BCR_i from BCR_{ave} will transfer the cost first. If the variance is equal in both scenarios, scenario (1) will be used. $CT_{i\ to\ j}$ or $CT_{j\ to\ i}$ is deducted from LCC_{MUT}^{i} during lifecycle of MUT.

Step 10. The benefit that each utility company *i* contributes to the project by participation in MUT and avoiding buried utilities, is called contributed benefit of company *i* (*ConBi*) and can be determined using Shapley value in cooperative game theory. However, there is no guarantee that the gained benefit of a company (GB_i) is close to its contributed benefit. For the sake of fairness, the difference of the contributed and gained benefits should be less than a threshold D (Equation (4-12)).

$$|ConB_i - GB_i| \leq D \tag{4-12}$$

If the difference is more than the threshold D, defined by the project organization, the contributed and gained benefits should be balanced by transferring a part of the cost. The amount of cost transfer equals to the exceeding amount from threshold D. The amount of cost transfer $C_{i\ to\ j}^{T}$ equals to the exceeding amount of benefit difference from threshold D and can be calculated by Equation (4-13). Cost transfer is from the company with the highest ($ConB_i - GB_i$) to the lowest ($ConB_j - GB_j$). This process can be iterative and applied to all other companies until Equation (4-12) is satisfied, similar to BCR adjustment.

$$C_{i\ to\ j}^{T} = |ConB_i - GB_i| - D \tag{4-13}$$

Either an MUT project chooses BCR balancing method or benefit balancing method, the amount of cost transfer should respect the MUT being economic for each utility company.

4.3 Case Study

The case study is considering MUT lifecycle economy assessment and cost-sharing for a segment of Ottawa Street (between Peel Street and De Montagne Street) in Montreal with the length of 250 m. The proposed method is implemented as follows.

4.3.1 Phase 1: Lifecycle Economy Assessment

Step 1. LCC influencing factors: the factors are categorized in three groups of utility, location, and construction method and must be determined for the specific location of the project. Figure 4-4 shows the GIS map of Ottawa Street with the buried utilities in ArcGIS. Table 4-2 shows the gathered data about this case study. Some data were not available, such as the attributes of telecommunication cables.

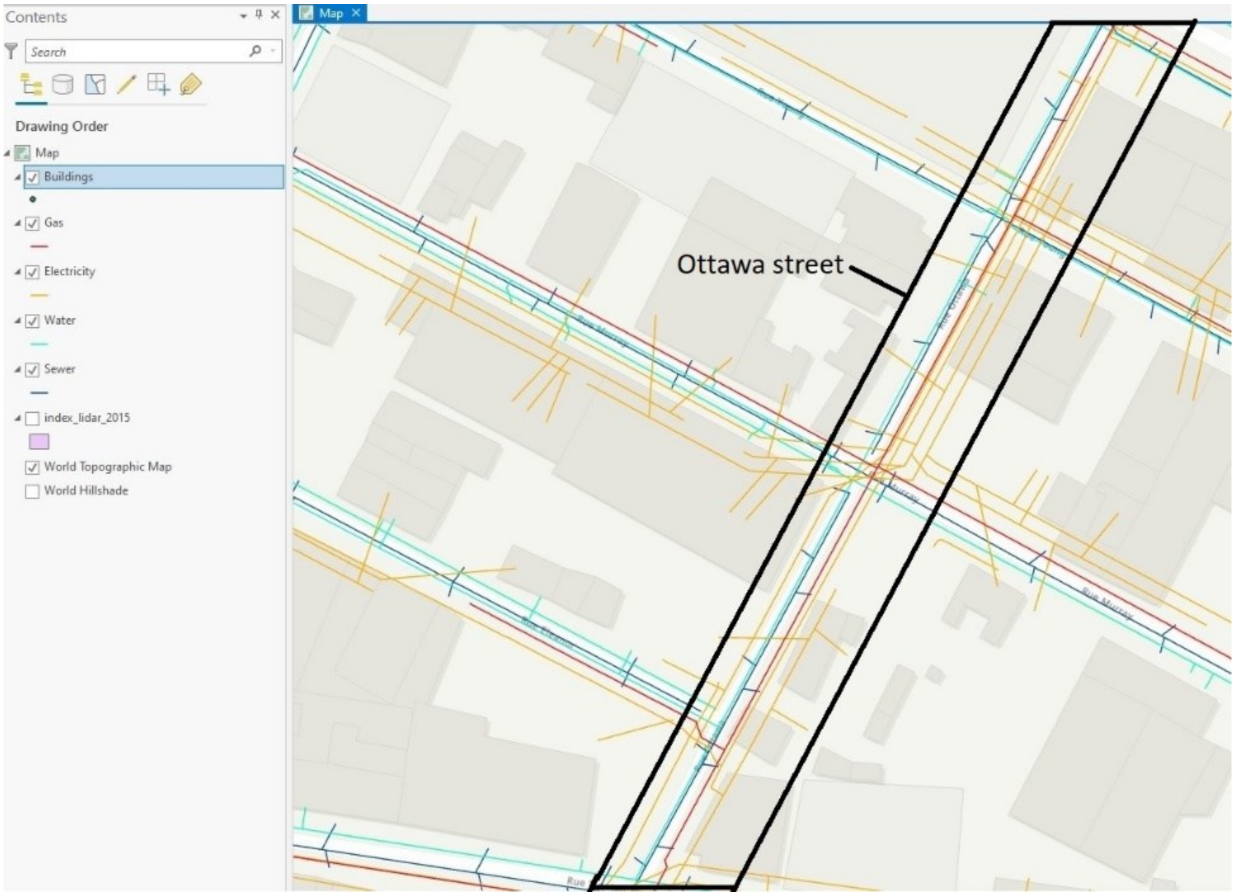


Figure 4-4 Buried utilities in Ottawa Street in ArcGIS

Table 4-2 Case study information about MUT or buried utilities factors

Factors			Type of utilities					Resource
Utility			Water	Sewer	Gas	Telecom	Electricity	GIS
	Number of utilities		1	1	1	2	2	
	Length		250	250	250	250	250	
	Type	Diameter (mm)	300	600	114	Not available	Not available	
		Material	Ductile iron	Reinforced concrete	Plastic	Not available	Not available	
		Voltage	NA	NA	NA	NA	Medium	
	Number of E&R		Not available					NA
	Location of utilities		-1.5 m deep					GIS
Location	Development level		Urban					GIS
	Concurrent development projects		No					GIS
	Type of soil		- Basal till (90 m) - Sand with some gravel (160 m)					GIS
	Hydrological conditions		Underground water level = Not available					NA
	Population density		27,078 (person/km^2)					GIS
	Traffic density		Not available					NA
	Slope		0					GIS
	Location of surrounding structures/natural barriers		No barrier					GIS
Construction/ maintenance	Depth		1.5 m					Project info
	Tunnel building method		Prefabricated					Project info
	Synchronization		Every five years					Expert judgment
NA: Not applicable								

Step 2. Construction and operation cost estimation: Considering the above-mentioned factors, cost database, and experts judgment, the cost estimates are presented in Tables 4-3 to 4-5 (Boileau, 2013). As a limitation and conservative method, the social costs are not considered for LCC. It is obvious that adding social costs will make MUT more economic.

Table 4-3 Total shared design and construction cost of MUT ($CM_{\text{Total shared}}$) (Adapted from Boileau, 2013)

	$CM_{Total\ shared}$	*Total*
Tunnel	2,081,975	2,206,975
Service equipment	125,000	

Table 4-4 Design and construction cost of buried utilities (CB_i) and specific cost of installation in MUT (CIM_i) (Adapted from Boileau, 2013)

		CB_i *($)*		CIM_i *($)*	
Municipal (m)	Water	353,625	955,250	139,500	600,000
	Sewer	601,625		460,500	
Gas (g)		42,500		156,250	
Electricity (e)		725,800		759,000	
Telecommunication (t)		769,200		111,000	
Total		2,429,750		1,626,250	

Table 4-5 Operational (maintenance) yearly cost of buried utilities (OCB_i) and MUT ($SOCM_i$). (Adapted from Boileau, 2013)

Cost ($)		OCB_i		$SOCM_i$
Municipal (m)	Water	22,500	29,250	4,000
	Sewer	6,750		6,500
Gas (g)		188		300
Electricity (e)		31,875		6,000
Telecommunication (t)		31,875		6,000
Total (for 250m)		93,188		22,800

Using Tables 4-3 to 4-5, Equation (4-1) and assuming that (a) effect of the discount rate will be cancelled by the inflation of the costs over time, (b) k=100 years, and (c) each buried utility needs one renewal within 100 years after the construction $LCC_{buried} = CB_{\text{Total}} + OCB_{Total} = 2\times(2,492,750) + 100\times93,188 = \$14,304,300$.

Similarly, assuming that the total shared operational cost of MUT ($OCM_{Total\ shared}$) is \$25,000 per year, and using Tables 4-3 to 4-5 and Equation (4-2), $LCC_{MUT} = CM_{Total} + OCM_{Total} = (2{,}206{,}975 + 1{,}626{,}250) + 100\times (25{,}000 + 22{,}800) = \$8{,}613{,}225$. Therefore, the value of CM_{Total} at the breakeven point is \$9,524,300.

In order to find the year of breakeven point (t_{br}), the LCC of buried utilities method and MUT should be equal and the calculations are shown as follows:

$$LCC_{buried} = LCC_{MUT}$$

$$CB_{Total} + (t_{br} \times OCB_{Total/year}) = CM_{Total} + (t_{br} \times OCM_{Total/year})$$

$$2{,}492{,}750 + (t_{br}\times 93{,}188) = (2{,}206{,}975 + 1{,}626{,}250) + (t_{br}\times (25{,}000 + 22{,}800))$$

$$t_{br} = 31\ years$$

It is assumed that the breakeven point happens before the renewal of buried utilities. Therefore, only one CB_{Total} is taken into account.

Step 3. LCC comparison: The results in step 2 shows that $LCC_{buried} > LCC_{MUT}$. Moreover, CM_{Total} at the breakeven point (\$9,524,300) is larger than the estimated cost (\$3,833,225). Therefore, MUT is the economical method.

4.3.2 Phase 2: Lifecycle Cost-sharing

Step 4. MUT Cost allocation: By knowing CB_i (Table 4-4) and OCB_i (Table 4-5), LCC_i^{buried} can be calculated by Equation (4-1) as presented in Table 4-6. By knowing $CM_{Total\ shared}$ (Table 4-3), CIM_i (Table 4-4), and CB_i (Table 4-4) and using Equation (4-3), the values of CM_i is calculated and presented in Table 4-8. By knowing the occupied volume of utilities in MUT (OV_i) (Table 4-7), $OCM_{Total\ shared}$, $SOCM_i$ in Table 4-5 and using Equation (4-4), the values of OCM_i is calculated and presented in Table 4-8. Finally, LCC_i^{MUT} is calculated using CM_i , OCM_i, and Equation (4-5) as shown in Table 4-8. The cross section of MUT is shown in Figure 4-5.

Table 4-9 provides a comparison between the construction and yearly operational costs of utilities for buried and MUT methods. It shows that construction cost for all utilities is higher in the MUT method; however, the operational costs of utilities are less, except for gas.

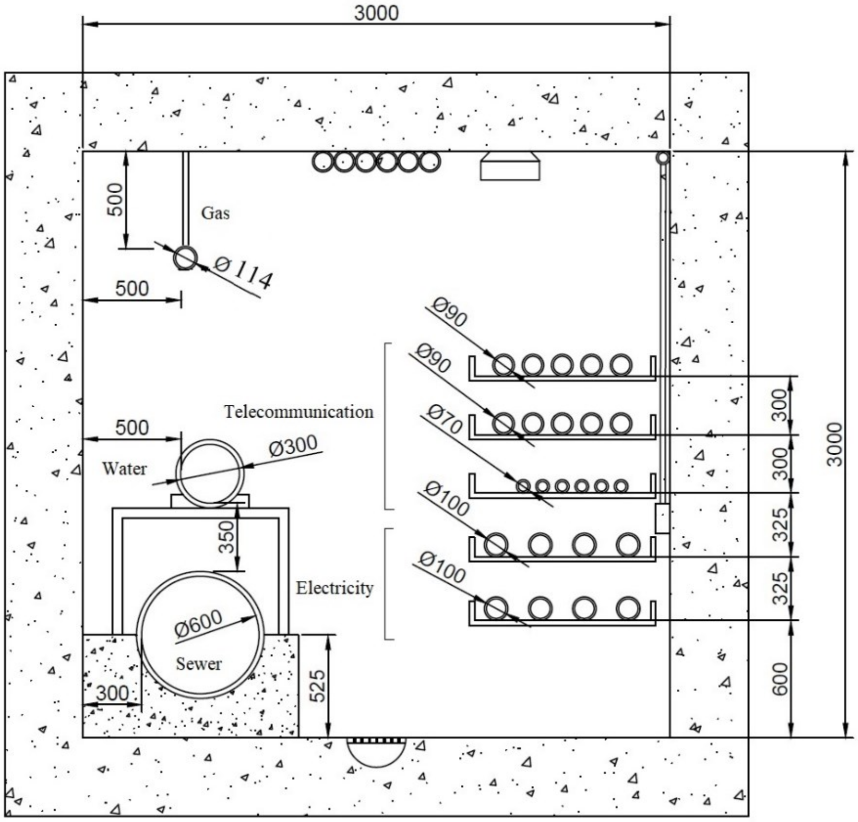


Figure 4-5 Cross-section of MUT (adapted from drawings provided by City of Montreal)

Table 4-6 Lifecycle cost of buried utilities

Cost ($)	CB_i	OCB_i	LCC_i^{buried}
Municipal	955,250	29,250	4,835,500
Gas	42,500	188	103,800
Electricity	725,800	31,875	4,639,100
Telecom	769,200	31,875	4,725,900
Total	2,429,750	93,188	14,304,300

Table 4-7 Occupied volume of utilities in MUT

Description		Width (m)	Height (m)	Section area (m^2)	Occupied volume (m^3)	Occupation (%)
Municipal	Water	0.5	0.6	0.3	75	6%
	Sewer	1.2	1.2	1.44	360	27%
Gas		0.8	0.5	0.4	100	7.5%
Electricity		1	1.83	1.83	457.5	34.5%
Telecommunication		0.9	1.5	1.35	337.5	25
Total				5.32	1330	100%

Table 4-8 Lifecycle cost of utilities in MUT and gained benefit (before risk and benefit adjustments)

Utility type	CM_i ($)	OCM_i ($/year)	LCC_i^{MUT} ($)	LCC_i^{buried} ($)	GB_i ($)
Municipal	1,445,738	18,677	3,313,407	4,835,500	1,522,093
Gas	193,878	2,180	411,848	103,800	-308,047
Electricity	1,401,592	14,600	2,861,555	4,639,100	1,777,545
Telecom	792,017	12,344	2,026,415	4,725,900	2,699,484
Total	3,833,225	47,800	8,613,225	14,304,300	5,691,075

Table 4-9 Comparison of the construction and operational costs of buried utilities and MUT

Utility type	CB_i ($)	CM_i ($)	OCB_i ($/year)	OCM_i ($/year)
Municipal	955,250	1,445,738	29,250	18,677
Gas	42,500	193,878	188	2,180
Electricity	725,800	1,401,592	31,875	14,600
Telecom	769,200	792,017	31,875	12,344
Total	2,429,750	3,833,225	93,188	47,800

Step 5. Risk cost adjustment: The shared risks considered in this case study for cost adjustments are presented in Section 2.2.4.3. The cost of risk management actions is estimated and shown in Table 4-10.

Table 4-10 Cost distribution for MUT sharable risk management actions

Design and Construction (DC) phase					
Risk management action (R)	$CR_{R/DC}$	γ_m^{DC} $CR_{R/m/DC}$	γ_g^{DC} $CR_{R/g/DC}$	γ_e^{DC} $CR_{R/e/DC}$	γ_t^{DC} $CR_{R/t/DC}$
R1-Gas detection	$8,000	0.3	0.5	0.1	0.1
		$2400	$4000	$800	$800
R2-Ventilation	$50,000	0.5	0.2	0.15	0.15
		$25,000	$10,000	$7,500	$7,500
R3-Respirator	$3,000	0.4	0.3	0.2	0.1
		$1,200	$900	$600	$300
Total	$61,000	$28,600	$14,900	$8,900	$8,600
Operation phase					
Risk management action (R)	$CR_{R/Op}$	γ_m^{Op} $CR_{R/m/Op}$	γ_g^{Op} $CR_{R/g/Op}$	γ_e^{Op} $CR_{R/e/Op}$	γ_e^{Op} $CR_{R/t/Op}$
R1-Gas detection	$3,000/year	0.3	0.5	0.1	0.1
		$900/year	$1,500/year	$300/year	$300/year
R2-Ventilation	$7,000/year	0.4	0.3	0.2	0.1
		$2,800/year	$2,100/year	$1,400/year	$700/year

Table 4-10 Cost distribution for MUT sharable risk management actions (continued)

Operation phase					
Risk management action (R)	$CR_{R/Op}$	γ_m^{Op} $CR_{R/m/Op}$	γ_g^{Op} $CR_{R/g/Op}$	γ_e^{Op} $CR_{R/e/Op}$	γ_e^{Op} $CR_{R/t/Op}$
R4- Temperature detection	$3,000/year	0.1	0.3	0.5	0.1
		$300/year	$900/year	$1,500/year	$300/year
R5-Access management	$5,000/year	0.4	0.4	0.1	0.1
		$2,000/year	$2,000/year	$500/year	$500/year
R6-Protective equipment	$4,000/year	0.2	0.3	0.4	0.1
		$800/year	$1,200/year	$1,600/year	$400/year
R7-Signaling	$1,000/year	0.5	0.5	0	0
		$500/year	$500/year	0	0
Total	$23,000/year	$7,300/year	$8,200/year	$5,300/year	$2,200/year

Step 6. Comparing LCC_i^{MUT} and LCC_i^{buried}: After risk adjustment, the LCC_i^{MUT} of each company is calculated using shown in Table 4-11. As shown in Table 4-11, for each individual utility company expect gas company, the LCC_i^{buried} is more than LCC_i^{MUT} or the gained benefit in MUT participation is positive.

Table 4-11 Lifecycle cost of utilities in MUT and gained benefit after risk adjustment

Utility type	CM_i ($)	OCM_i ($/year)	LCC_i^{MUT} ($)	LCC_i^{buried} ($)	GB_i ($)
Municipal	1,450,961	18,454.135	3,296,376	4,835,500	1,539,125
Gas	207,737	8,650.376	1,072,775	103,800	-968,975
Electricity	1,392,731	11,987.97	2,591,528	4,639,100	2,047,571
Telecom	781,793	8,707.52	1,652,546	4,725,900	3,073,354
Total	3,833,225	47,800	8,613,225	14,304,300	5,691,075

Step 7. Incentive: For making MUT project beneficial for the gas company, an incentive needs to be granted. For this project, it is assumed that the municipality will pay the amount of $1,068,975 as an incentive so that the gas company obtains an agreed-upon lifecycle benefit of $100,000. The incentive is paid only from the municipality to the gas company, as the municipality is responsible for providing social benefits, e.g. reducing vehicle (VED) delay costs; and therefore, encouraging utility companies to participate in MUT. Although the gained benefit of $100,000 is relatively low in comparison to the other utility companies, it encourages the gas company to participate in the MUT project.

Step 8. BCR adjustment: In this case study, first BCR adjustment is applied. Afterward, the method of balancing gained and contributed benefits is used to compare both methods.

Step 9. BCR variance and balancing: The BCR_i, BCR_{ave}, their variances, and cost transfers are presented in Table 4-12 (1st iteration) and Table 4-13 (2nd iteration). The value of agreed-upon threshold T is assumed as 0.5 because this value is close to the average of the variances before BCR adjustment (i.e. 0.528). Therefore, BCR_t is not acceptable and needs to be adjusted according to Equation (4-11) for scenario (2). The amount of $CT_{j\ to\ i}$ is transferred from the gas company to the telecommunication company in the first iteration and from the municipality to the gas company in the second iteration.

Finally, LCC_i^{MUT} and GB_i after risk and BCR adjustment are presented in Table 4-14.

Table 4-12 The amounts of BCR_i, BCR_{ave}, and their variances at 1st iteration

	BCR_i	$\lvert BCR_i - BCR_{ave} \rvert$ Before BCR adjustment	$CT_{j\ to\ i}$	BCR_i	$\lvert BCR_i - BCR_{ave} \rvert$ After BCR adjustment
BCR_m	0.4669	0.3355 (negative)	-	0.4669	0.6496 (negative)
BCR_g	0.0932	0.7092 (negative)	-\$707,034	2.2065	1.0899
BCR_e	0.7901	0.0123 (negative)	-	0.7901	0.3265 (negative)
BCR_t	1.8597	1.0572	+\$707,034	1.002	0.1137 (negative)
BCR_{ave}	0.8025	-	-	1.1166	-

Table 4-13 The amounts of BCR_i, BCR_{ave}, and their variances at 2nd iteration

	$CT_{j\ to\ i}$	BCR_i	$\lvert BCR_i - BCR_{ave} \rvert$ Before BCR adjustment
BCR_m	-\$133,472	0.5288	0.3889 (negative)
BCR_g	+\$133,472	1.3492	0.4314
BCR_e	-	0.7901	0.1276 (negative)
BCR_t	-	1.0028	0.0851
BCR_{ave}	-	0.9177	-

Table 4-14 LCC_i^{MUT} and GB_i after risk and BCR adjustment

Cost (\$)	LCC_i^{MUT}	GB_i
Municipal	\$3,162,903	\$1,672,597
Gas	\$499,213	\$673,562
Electricity	\$2,591,528	\$2,047,572
Telecommunication	\$2,359,580	\$2,366,320
Total	\$8,613,225	\$6,760,050

Step 10. Contributed and gained benefit variance and balancing: The contributed benefit of company *i* (CB_i) can be determined using Shapley value in cooperative game theory. The utility companies in the coalition are the ones that participate in MUT and the rest use the traditional buried method. LCC is the sum of LCC of all utility companies, whether in or out of MUT.

Table 4-15 represents the coalitions and the corresponding LCC and benefits of cooperation. Coalitions 1 to 4 are in buried utilities method with the related LCC and have no benefit. Coalitions 5 to 15 show the utility companies in MUT with corresponding LCC and lifecycle benefit from MUT.

Table 4-15 Value of LCC and lifecycle benefit for each coalition

No	Coalition	LCC	Benefit of cooperation
1	{m}	$4,835,500	0
2	{g}	$103,800	0
3	{e}	$4,693,100	0
4	{t}	$4,725,900	0
5	{m, g}	$4,988,901	-$49,601
6	{m, e}	$7,355,626	$2,118,974
7	{m, t}	$6,682,626	$2,878,774
8	{g, e}	$4,947,901	-$205,001
9	{g, t}	$3,608,506	$1,221,194
10	{e, t}	$5,475,231	$3,889,769
11	{m, g, e}	$6,664,110	$2,914,289
12	{m, g, t}	$8,029,060	$1,636,139
13	{m, e, t}	$8,007,835	$6,192,664
14	{g, e, t}	$6,869,085	$1,530,739
15	{m, g, e, t}	$7,544,250	$6,760,050

It should be noted that the incentive in step 7 is not considered in the $\mathrm{LCC}_i^{\mathrm{MUT}}$ in coalition 15. Using Shapley value (Equation (2-7)), the values of $ConB_i$ are calculated and the differences from GB_i are presented (Table 4-16).

Table 4-16 Contributed benefits and differences from gain benefit, cost transfer and LCC_i^{MUT}

	$ConB_i$	$\lvert ConB_i - GB_i \rvert$	$C^T_{i\ to\ j}$	LCC_i^{MUT}
CB_m	$2,206,101	$666,976	-$21,505	$3,274,871
CB_g	-$11,466	$111,466 (negative)	-	$1,072,775
CB_e	$2,313567	$265,995	-	$2,591,528
CB_t	$2,251,849	$821,505 (negative)	+$21,505	$1,674,051
CB_{Total}	$4,309,800	-	-	$8,613,225

According to the calculated *ConB$_i$* and considering a threshold D=$800,000 for the acceptable variance between contributed and gained benefit about 10% of the LCC$_{MUT}$ for the great coalition, a cost transfer of $C^{T}_{i\ to\ j} = \$21{,}505$ from the municipality to the telecommunication company is needed. Table 4-16 shows the cost transfer and LCC_i^{MUT}.

After all cost adjustments the values of LCC_i^{MUT} are shown in Figure 4-6. The most variation is for the gas and telecommunication companies. Since the gas company is more responsible for most of the shared risks, its LCC is more after risk adjustment. However, because of the negative gained benefit, an incentive is considered for the gas company. Because of a relatively low BCR, a part of the LCC of the gas company is transferred to the other companies in the BCR adjustment. However, in the contributed and gained benefit adjustment, the cost of the gas company does not change. Instead, the telecommunication company pays a part of the municipality LCC to satisfy a balanced contributed and gained benefit. The telecommunication company LCC is reduced after risk adjustment, but it is increased later to balance BCR, and contributed and gained benefits.

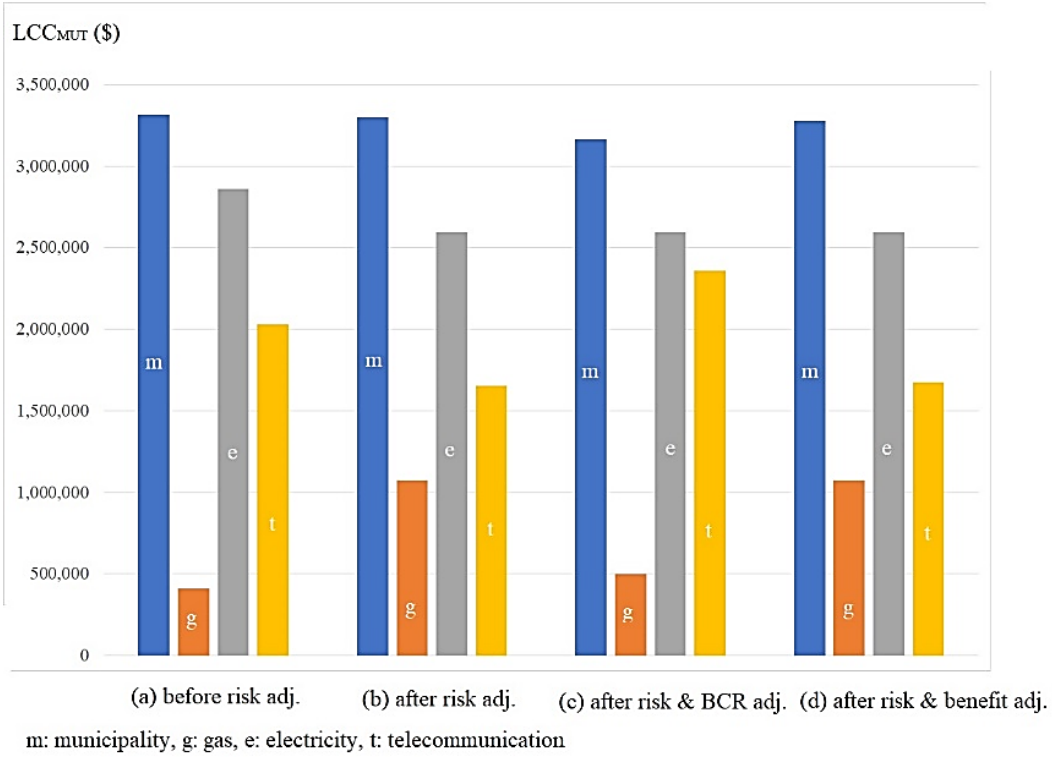


Figure 4-6 LCC_i^{MUT} before and after cost adjustments

4.4 Summary and Conclusions

This chapter proposed a comprehensive and systematic model for MUT and buried utilities LCC analysis by considering the factors of utility specifications, location conditions, and construction/maintenance methods. The output of this model estimates the lifecycle cost of MUT and buried utilities. The proposed model can justify whether an MUT project is an economic alternative method for buried utilities. In addition, an MUT cost-sharing method is proposed to ensure the decisionmakers of utility companies that MUT is the economic method for their company and also the benefits and costs of MUT are distributed fairly among the utility companies. The fairness is defined based on three principals: (a) balance of risk, (b) balanced benefit-cost ratio, and (c) balance in contributed benefit and gained benefit. It can be concluded that (a) the influence of factors on the LCC of MUT and buried utilities can differ significantly case by case, (b) the LCC of MUT must be less than buried utilities for the project and also for each individual utility company to justify MUT, (c) PBC and PUVO methods of cost-sharing are necessary, but not enough for a fair cost-sharing, (d) risk adjustment provides fairness by proportionally allocating the cost of risk management and responsibility of risk to the utility companies, (e) BCR adjustment aims to improve fairness by balancing BCR of utility company based on the logic that higher cost should result in higher benefit for a company, but with balanced BCR, and (f) balancing contributed and gained benefit encourages utility companies with high contributed but low gained benefit to participate in MUT. The limitations include lack of data availability for some factors (e.g. E&R, underground water level, traffic density).

CHAPTER 5. SMART MUT INFORMATION MODELING FOR LIFECYCLE MANAGEMENT

5.1 Introduction

As discussed in Section 1.2, complicated coordination of utility companies is a barrier for promoting of MUT projects. In Section 2.4, it is explained that Building Information Modeling (BIM) can facilitate the design, construction, and operation of MUTs and improve the coordination of utility companies. However, BIM is mainly developed for buildings and has been extended to some civil structures (e.g. bridges, tunnels). Using BIM for MUTs is in its infancy and should be standardized. Also, BIM cannot satisfy all the MUT information requirements because: (1) MUTs are linear underground structures interacting with the surrounding environment (e.g. streets, buildings, underground structures); and (2) BIM tools are not able to process the huge amount of real-time data for MUT operation (e.g. sensors for safety monitoring, access control detectors, security cameras). Luo et al. (2019) stated that by using sensors that support the operation and maintenance phase of a smart MUT, the MUT risks can be controlled. Therefore, BIM should be linked with other tools, including Geographic Information Systems (GIS), externally linked data, and user interfaces (Lee et al., 2018). Extending BIM and integrating it with other technologies can be done based on specific use-cases for the design, construction, and facility management of MUTs. This extension can benefit from available resources related to MUT components and the information requirements (Kang et al., 2014; Bao, 2017; Lee et al., 2018; Hu & Zhang, 2019; Ge & Xu, 2019; Li et al., 2019; Wu et al., 2019; Sfere, 2020; Shahrour et al., 2020, Yin et al., 2020). However, the available resources only concentrate on one or some aspects of MUTs.

This chapter aims to achieve the third objective of this research in Section 1.3. For this purpose, all aspects of MUTs including overall management, design, construction, and operation information of the MUT and its surrounding environment are covered. This chapter proposes an integrated framework for SMUTIM and linking with GIS and databases. The framework focuses on gathering information requirements for lifecycle management, analyzing BIM use cases of SMUTIM, and extending the Industry Foundation Classes (IFC) to SMUTIM. The smart concept in SMUTIM emphasizes applying new technologies that work together (e.g. Internet of Things

(IoT)) for the collection of huge amounts of monitoring MUT sensory data during the operation phase. In addition, these technologies can improve the functions of ancillary facilities (e.g. security, Heating, Ventilation, and Air Conditioning (HVAC), and communication systems). SMUTIM can improve the design, construction, and facility management of MUTs by facilitating the coordination and collaborative decision-making through sharing information among the MUT stakeholders. A case study is used to demonstrate the applicability of the proposed framework.

5.1 Proposed Framework for Smart MUT Information Modeling

The proposed framework of integrating BIM and 3D GIS for SMUTIM includes three main steps: (a) MUT information requirements definition, (b) identification of SMUTIM use cases, and (c) extending IFC to accommodate SMUTIM. Figure 5-1 shows the research methodology.

The proposed framework is based on the analysis of the literature review, expert opinions, and the resources about MUT information requirements. There are standards about the information requirements for tunnel modeling (HB 138 Model Basis, 2012; Ghaznavi, 2013). Some utility information standards include Pipeline Open Data Standard (PODS) as a data model of pipelines (PODS, 2017), Common Information Model (CIM)/Distribution Management (IEC61968) for electricity distribution networks (IEC, 2003; Wang et al., 2003), and Fiber Network Data Model (FNDM) for telecommunication networks (FNDM, 2015).

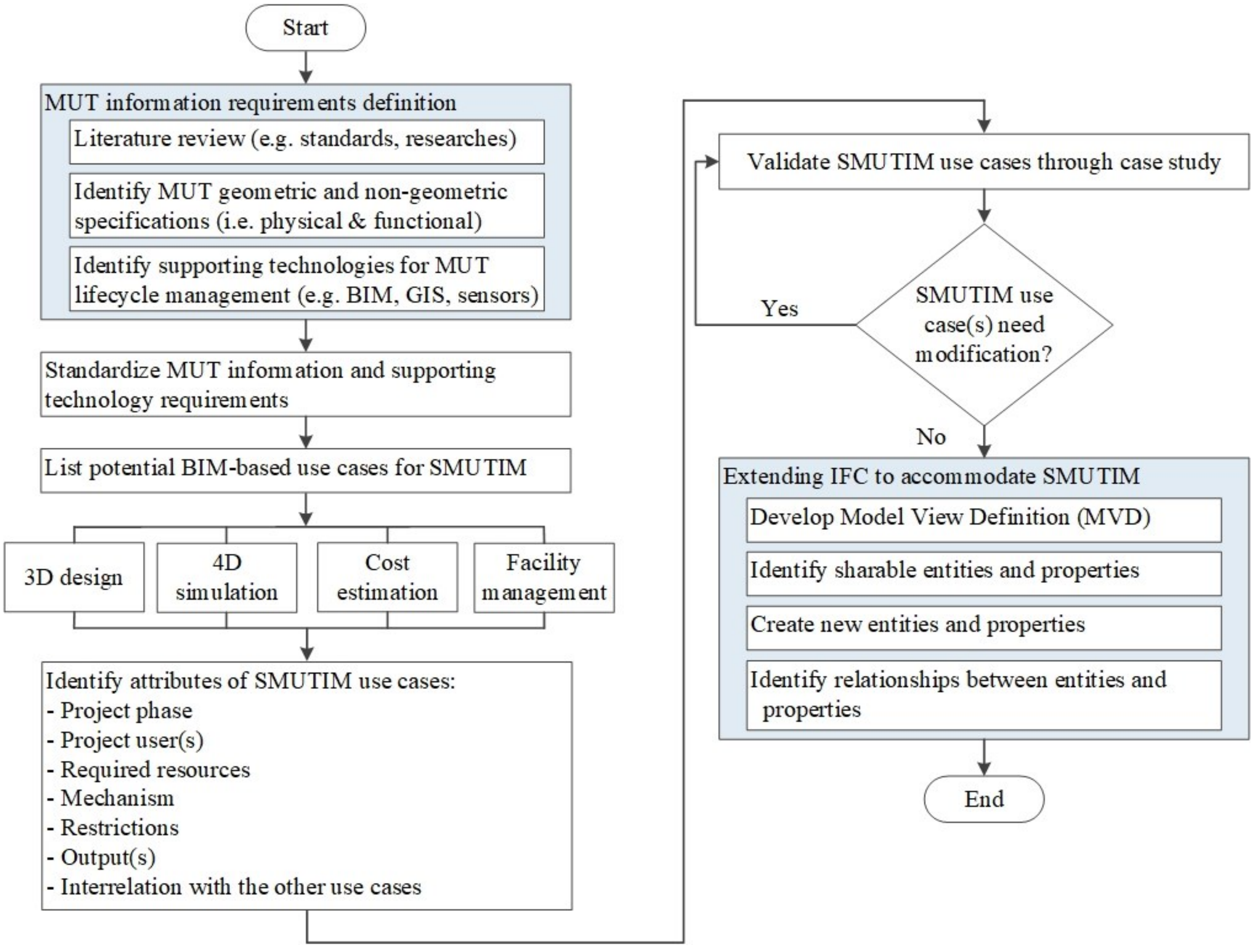


Figure 5-1 Research methodology

5.1.1 MUT lifecycle Information Requirements

Different types of MUT lifecycle information (i.e. geometric and non-geometric) can be modeled, stored, and presented using BIM and GIS applications, and databases. The information requirements are categorized into five groups as shown in Figure 5-2: (a) managerial, (b) surrounding environment, (c) tunnel structure, (d) utilities, and (e) ancillary facilities. The relationships between the groups are explained in Section 5.1.1.6.

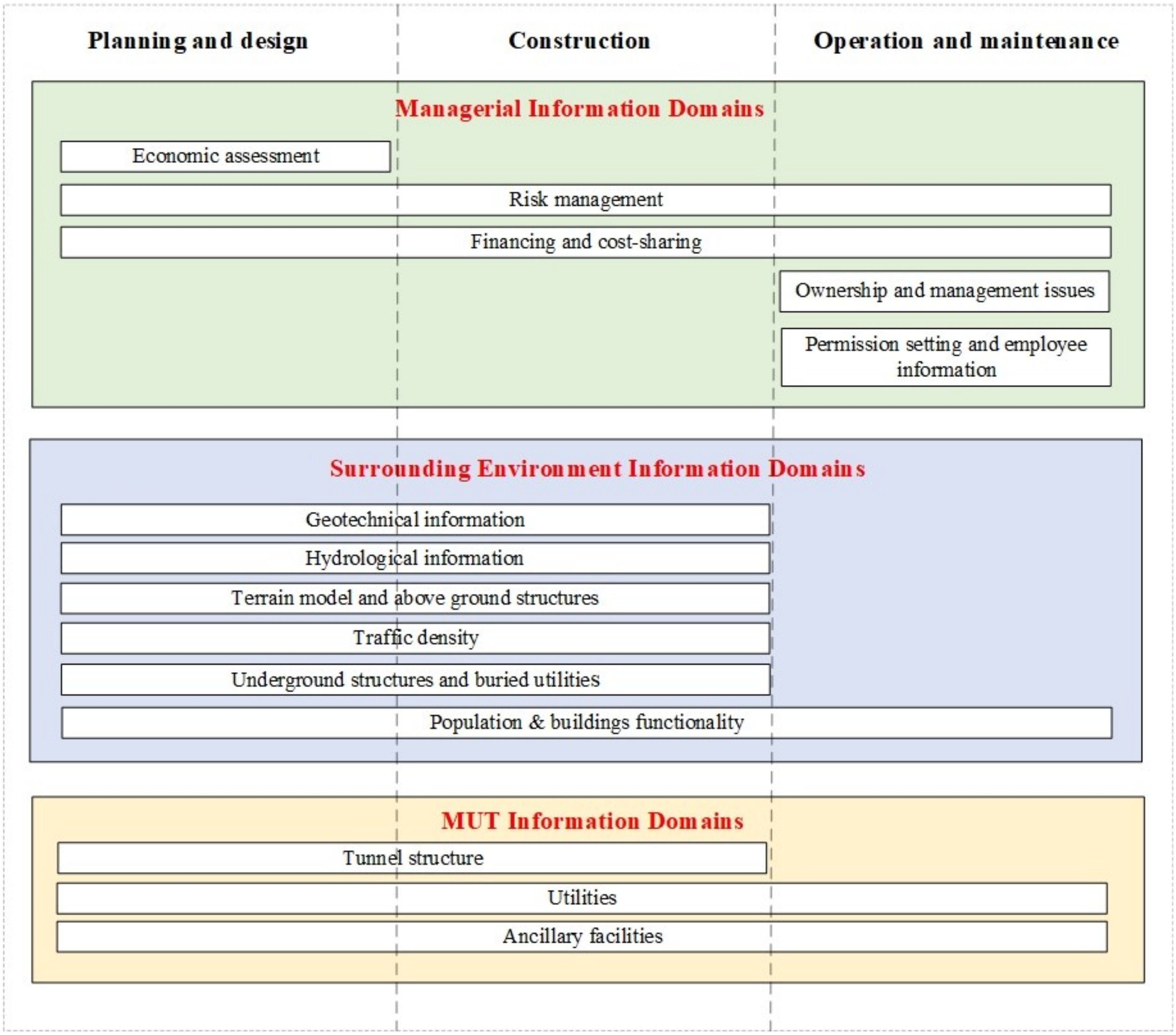


Figure 5-2 Overview of MUT lifecycle information domains

5.1.1.1 Managerial Information

The managerial information about the project include:

(a) Economic assessment: Economic assessment based on cost-benefit analysis of the MUT project as a whole and from the point of view of each organization should be done during the planning phase. Different factors related to utility specifications, location conditions, and construction and maintenance methods should be considered (Alaghbandrad & Hammad, 2020).

(b) Risk management: The proximity of some utilities imposes safety risks (e.g. fire caused by the proximity of gas and electrical networks). Therefore, risk management is needed. The risk management process includes risk management planning, risk identification, risk qualitative and quantitative analysis, risk response planning and implementation, and risk monitoring (Project Management Institute, 2017). The arrangements for distributing the cost of risk management among utility companies are another aspect of managerial information.

<u>(c) Financing and cost-sharing:</u> The lifecycle financial sources of MUT (e.g. bank loan, utility companies, government, and municipality) and cost-sharing model should be determined. Different methods for cost-sharing have been proposed including (a) The proportion of buried cost (PBC) method, in which the utility companies share the costs with the same proportions they used to pay in the traditional buried utilities method (CPAMI, 2011; Xiaoqin et al., 2011; Zhang, et al., 2019), (b) The proportion of utility volume occupancy (PUVO) method, in which utility companies are responsible for costs according to their occupied volume in the MUT. A combination of the two previous methods is also proposed (Zhang et al., 2019; Xiaoqin et al., 2011); (c) benefit ratio: sharing cost based on the ratio of each utility company lifecycle benefit (Zhang et al., 2019). Alaghbandrad and Hammad (2020) proposed an MUT cost-sharing framework that considers a combination of PBC and PUVO methods and factors of risk and benefit.

The long-term economic perspective for MUT and cooperation between several public and private MUT stakeholders make Public-Private Partnership (PPP) a practical form of contract for these projects and it was adopted in China and France (Yang & Peng, 2016; Clé de Sol, 2005). In PPP projects, the main goal is to assign the risk to the sector that can better control it (European Commission, 2003).

<u>(d) Ownership and management issues:</u> During the operation phase, the ownership of a single entity or co-ownership by utility companies and/or rental arrangements, the constitution, members, and power of the organization that manages MUT are the main issues that should be planned in advance. One model of MUT project organization is “municipal governance” (Clé de Sol, 2005). In this model, the municipality is the owner and manager of the MUT, and the participant utility companies pay a rental fee.

<u>(e) Permission setting and employee information:</u> During the operation phase of MUT, the permission setting should determine the authority of the utility companies and their employees. These permissions specify permitted access areas, allowed personnel and equipment, prohibited actions, working hours, instructions for emergencies, and instructions to using ancillary facilities

(e.g. communication, electricity, lighting, ventilation, and access control and geo-localization systems).

5.1.1.2 Surrounding Environment Information

Surrounding environment information is useful for deciding the location of MUT, design considerations, traffic control and detour, the slope of the terrain, etc. These factors also affect project costs. GIS as “a computer system for entering, storing, querying, analyzing and displaying geographic data” (Lee et al., 2018), can support the presentation of the surrounding environment of an MUT. The information about the surrounding environment includes geometric information (i.e. location, dimensions) and non-geometric information. The main information groups include: **(a) geotechnical information:** information about the types and characteristics of soils and rocks (e.g. hardness, cohesion, stabilization) in the project should be provided. Based on the geotechnical conditions, some techniques (e.g. bursting the rock, stabilization of weak soils (e.g. clay)) may be needed; **(b) hydrological information:** underground water and other water sources (i.e. river, lake) should be considered for waterproofing, draining, deviation of MUT route to avoid water, utility towers/bridge over the water, etc. In a project in China, cofferdams were constructed at the intersections of rivers and MUT to pump out water from the working areas (Bao, 2017); **(c) the terrain model and above-ground structures:** the elevation of the earth's surface, the surrounding above-ground structures, and natural barriers are presented by the terrain model and influence MUT project. For example, lack of enough terrain slope for a gravity sewer can be compensated by deeper MUT. More than enough slope needs special design and construction techniques (e.g. soil filling and vertical/slopped MUT); **(d) traffic density:** traffic control and detour roads should be considered during the project. The traffic control costs should be added to the project costs. The traffic congestion and/or longer travel distance in detour roads impose added travel time and costs to the vehicles’ passengers (social costs); **(e) underground structures and buried utilities:** the existing underground structures (e.g. metro, tunnels, underground pedestrian corridors, underground buildings) and buried utilities are available in GIS. Design and construction considerations should be taken to avoid the clash of MUT with these structures and utilities. Deep excavation can be a solution to this issue. CityGML is an open standardized data model and exchange format for 3D objects and features of cities and landscapes (CityGML, 2018) that can be integrated with SMUTIM; and **(f) population and buildings functionality (e.g. residential,**

commercial, educational): the number and needed capacity of utility users depends on the development level of MUT location (i.e. undeveloped, suburban and urban area) (Hunt et al., 2014).

5.1.1.3 Tunnel Structure

The physical/spatial components of the tunnel structure, and their general and specific information requirements are presented in Table 5-1. Figure 5-9 shows an example of the tunnel structure used in the case study. As the general requirements are well-known and common among all structures, they are only listed in Table 5-1 and more details about specific information requirements of structural elements are provided as follows.

The tunnel structure is divided into different parts:

- **Tunnel main structure and foundation:** The principal tunnel of MUT connects to nearby buildings through lateral mini-tunnels and has access for workers and materials. The high-level distribution of MUTs in a district can be shown on a map as a network. Specific considerations for designing the tunnel are needed to withstand the loads (e.g. soil, vehicles, above-ground structures). The compartments in the MUT structure divide the internal space of the tunnel and can improve safety by physically separating the utilities. The foundation takes the same specific requirements of the main structure.
- **Foundation pits:** These are temporary pits for building the foundation and structure of MUT. They need support structures (e.g. steel sheet piles) and should provide space for labor and machinery access during construction.

The auxiliary structures are integrated with the MUT structure and include:

- **Access structures:** These structures connect the main tunnel structure to the outdoor environment and include material input port, human access port, and ventilation manhole.
- **Node structure:** The intersections of the main tunnels have special design requirements. There should be enough space for human movement within the node structure of the tunnel which is usually crowded with utilities in two directions. Respecting safety buffers of utilities is more complicated in the intersections.
- **Lateral tunnel structure:** The connections of the main tunnel structure and utilities to the adjacent buildings needs the same special design requirements of node structures.

- **Waterproofing and drainage structure:** There are special design requirements to drain the water inside the tunnel to the outside (i.e. drainage) and to avoid water penetration to the tunnel (e.g. coating, joint waterproofing). The waterproofing locations, coating technical requirements, and drainage capacity need special design considerations.

All the tunnel structural components need indication signs (e.g. safety warning, instructions, indicating authorized personnel, navigation) (Wu et al., 2019).

5.1.1.4 Utilities

The utilities are categorized into two general groups of pipes and cables. The details about each group are given in Tables 5-2 and 5-3 and explained in this section. The pipes and cables are supported by hangers or shelves. They have labels and signs attached to them.

5.1.1.4.1 Pipes

There are three main types of pipes, namely drinking water, sewer, and gas pipes. The general and specific information requirements for the pipes are listed in Table 5-2. The general information requirements cover the common features of all types of pipelines (e.g. location, size, material and coating, capacity, maintenance history). The specific information requirements are:

- **Drinking water:**
    - <u>Water pipeline network:</u> The network supplies the drinking water for the surrounding buildings and the street hydrants. The hydraulic specifications of the system are an important part of the design (Duzinkiewicz & Ciminski, 2006; National Research Council, 2006).
    - <u>Water monitoring system (ancillary system):</u> The real-time information of flow rate, pressure, quality, leakage, and contamination should be measured and recorded. Waterborne contaminants (e.g. lead, arsenic, bacteria and viruses) can be harmful to the health (Water Quality Association, 2020) and should be detected continuously.
- **Sewer:**
    - <u>Sewer pipeline network:</u> There are sanitary sewers to collect municipal sewage and storm sewers to convey surface runoff. These systems can be separated, partially separated (i.e. sanitary sewers convey some drainage), or combined (City of Toronto, 2009). The sewers can be designed as gravity-based or under pressure (Water security agency, 2012).

- Sewer monitoring system (ancillary system): The sewer gases can be poisonous and corrosive (e.g. methane and hydrogen sulfide are flammable). They should be detected and the leakage history should be recorded. Other measurements (e.g. flow rate, quality) should also be recorded. The hydraulic specifications should be determined at the design stage.

- **Gas:**
  - Gas pipeline network: The network supplies the gas for the surrounding buildings. The network (e.g. pipes, valves, regulators) is designed based on the required capacity.
  - Gas monitoring system (ancillary system): Some features of the gas distribution pipeline in MUT including gas flow rate, density, pressure, and temperature should be measured and recorded. Gas leakage should be monitored (Herrán-González et al., 2009). The types of sensors should be determined for this system.

5.1.1.4.2 Cables

There are two types of cable in MUT: electrical and telecommunication cables. The general and specific information requirements for the cables are listed in

Table 5-3. The general information requirements cover the common features of all types of cables (e.g. location, size, material and coating, capacity, maintenance history).

- **Electrical cables:**
  - Electrical cable network: The specific information requirements for electrical cables include: the model of the system (i.e. line model, distribution model, voltages regulator model, distribution feeder model), the capacity of cables (i.e. voltage), and the type of monitoring data (e.g. cable temperature, frequency).
  - Electrical monitoring system (ancillary system): The monitoring data for the network includes cable temperature, tension, current, frequency, switch status, and consumption.
- **Telecommunication cables:**
  - Telecommunication cable network: For telecommunication cables, the type of cables (e.g. fiber optic, copper), the supported network (e.g. TV, phone, Internet), as well as the protocols and codes about the system components (e.g. color code, labeling protocol) should be specified.

- Telecommunication monitoring system (ancillary system)**:** The network should be monitored for potential hazards (e.g. cable temperature, water ingress,) and regular conditions (e.g. switch status, outages).

5.1.1.5 Ancillary Facilities

The ancillary facilities are required for the continuous operation of the MUT. In addition to ancillary systems used for monitoring the utilities as explained in Section 5.1.1.4, other ancillary systems monitor safety, security, environmental and structural health, and provide the required services of MUT (i.e. power, access control and geo-localization, fire extinguishing, HVAC, drainage, communication, hoisting, lighting). The group of facilities that are mainly for detection using sensors is called sensory systems. All the ancillary facilities need supports or hanger and indication signs. The ancillary facilities are presented in Table 5-4. The general information requirements are common between all facilities. The specific requirements are explained as follows.

- **Sensory systems:**
  (1) Structural health monitoring (SHM) system: Optical fiber sensors are installed to monitor structure deformation and displacement (i.e. vertical and horizontal displacement due to adjacent excavations) (Nakano et al., 2011). The hydrostatic leveling system can be used to detect the vertical settlement of the tunnel because of excavation in the surrounding environment (Yin, 2013).
  (2) Access control and geo-localization systems: The access control system and geo-localization system have different functionalities:
    (a) Access control system: The physical access doors can be equipped with the traditional key locks, magnetic/smart access card readers, code/barcode locks, fingerprint readers, or facial recognition systems. The access procedures and history, and the information of authorized maintenance staff to access the MUT should be defined and recorded in the system.
    (b) Geo-localization system: This system can be used to track the location of authorized staff or unauthorized intrusions in the MUT.
  (3) Environmental monitoring system: Different parameters should be monitored in real-time to control the environmental health of MUT. The acceptable range of temperature and

humidity should be defined and measured. Air quality monitoring includes measurement of CO, CO_2, Methane, etc. (Xtralis, 2018), and detection of smoke, fire, and any air contamination (e.g. dust, microbiologic gases). Overflow and water infiltration can be a result of pipeline leakage (i.e. water and sewer pipes) or structural water penetration from cracks, joints, or defected drainage system.

- **HVAC system**: The HVAC system can be used to circulate, filter, and adjust the air temperature inside the MUT. The system specifications include: ducting network, heating and cooling system, air pump, and air filter and register vent specifications. The airflow rate, temperature, and ventilation mode (indoor circulation/fresh air) should be monitored.
- **Drainage system**: The drainage system evacuates any water leaked from utilities or infiltrated into the structure from external sources. The drainage can be by gravity or using water pumps. The capacity of the drainage system should be specified, and the water flow rate should be monitored.
- **Lighting system**: The lighting system is supported by the power supply system to provide the required light of the tunnel interior. This system is composed of cables, switches, ducts and conduits, and sensors. The distribution model of the system and other attributes (e.g. voltage, type of lights and sensors) should be determined. The sensors can adjust the light according to the requirements.
- **Power supply system**: The purpose of the MUT power supply system is to provide electricity to ancillary facilities and the tunnel (e.g. lighting system, power outlets). Therefore, in addition to the specifications of the power system (e.g. voltage, line model), the location and specifications of the ancillary systems should be determined.
- **Security monitoring and alarm system**: The goal of the security system is to detect the intrusion of unauthorized people, who may be able to deceive the access control system, to MUT with different purposes (theft, vandalism, attack).
- **Fire extinguishing system**: In case a fire is detected, the alarm and the fire extinguishing system are activated. The water supply system supports sprinklers to extinguish the fire and the ventilation system is activated to evacuate smoke and heat. In sensitive locations where the water of a fire sprinkler is dangerous, fire suppression systems are designed to extinguish a fire. In locations that personnel work, clean agent or inert gas suppression systems should be used to avoid health risks. In locations where there are few or no personnel, CO_2 fire suppression systems are used (Koorsen, 2017).

- **Hoisting system**: The hoisting system supports carrying heavy loads inside the MUT via rails. The system specifications and functional information (i.e. load capacity and spatial coverage) should be defined.
- **Communication system**: The communication system enables staff inside and outside the MUT to talk using wired/wireless technologies. The specifications and locations of equipment (i.e. industrial telephone, access point, cables, and the wireless system) should be designed for MUT needs. The authorization levels of communication should be defined.

5.1.1.6 Relationships Between MUT Lifecycle Information Groups

Sections 5.1.1.1 to 5.1.1.5 categorized MUT lifecycle information requirements in five groups of the managerial, surrounding environment, tunnel structure, utilities, and ancillary facilities. As these information groups are related to each other, their relationships should be clarified. The relationships among the concepts can be subsumption, partonomy (El-Gohary & El-Diraby, 2010), and supporting. A subsumption relation connects the general concept and a sub-concept (i.e. is-a relationship). For example, the HVAC system is an ancillary facility. A partonomy relation represents a part-of relationship between the concept and its parts with patronymic hierarchies (is-part-of relationship). For example, the node and lateral tunnel structures are parts of the tunnel structure. There are four types of supporting relationships: (1) Monitoring (i.e. is-monitored-by): the conditions of a physical/spatial component which is monitored by an ancillary facility. For example, the tunnel main structure is monitored by the SHM system and the environmental monitoring system; (2) Controlling (i.e. is-controlled-by relationship): a controlling ancillary facility receives a signal from a monitoring system. Then the actuators convert the signal to a mechanical motion. For example, the switches of the access control system send signals to the actuators to open the door for the authorized personnel. In case of fire, the environmental monitoring system sends a signal to the HVAC system actuators to evacuate smoke and to sprinklers to release water; (3) Informative (i.e. provide-information-for relationship): The relationships between the managerial or surrounding environment information and the tunnel structures, utilities, and ancillary facilities are informative and are used to support decision-making. For example, employee information can support the access control system by providing the information of authorized staff to access MUT; (4) Serving (i.e. is-served-by relationship): A system is served by another system or utility network to accomplish its tasks. For example, the HVAC system is served by the power supply system for its electricity need.

The relationships are shown in Figure 5-3 and explained as follows. To clarify, each relationship is coded with a number (e.g. R1 means relationship number 1) and type (i.e. subsumption (S), partonomy (P), supporting monitoring (SM), supporting controlling (SC), supporting informative (SI), and supportive serving (SS)).

- The node, lateral tunnel, access, and tunnel main structure are (a) served by the lighting (R1-SS) and hoisting systems (R2-SS), (b) monitored by SHM system (R3-SM), environmental monitoring system (R4-SM), and security monitoring and alarm system (R5-SM), and (c) monitored for personnel positioning (i.e. geo-localization) and controlled for personnel access (i.e. access control) by the access control and geo-localization system (R6-SM & SC).
- The power supply system is served by the electrical cable network for the required electricity (R7-SS). Then, the power supply system supplies electricity to the other ancillary facilities (i.e. serving relationship) (R8-SS).
- The access control and geo-localization system provides information about the ingress/egress and location tracking of personnel for the security monitoring and alarm system (R9-SI).
- The access control and geo-localization system is served by the communication system at the ports of entry for the communication of personnel (R10-SS). The communication system is served by the telecommunication utility network for the required infrastructure (R11-SS).
- In case that the environmental monitoring system detects a fire, an alarm is sent to the fire extinguishing system to control the fire (R12-SC). The fire extinguishing system is served by the HVAC system to evacuate smoke and heat in case of fire, and fire extinguishing gases (e.g. CO_2) after the fire (R13-SS). The fire extinguishing system is served by the water utility network for supplying the water of sprinklers (R14-SS). Also, the drainage system serves the fire extinguishing system to evacuate the water from sprinklers (R15-SS).
- If the environmental monitoring system detects that MUT temperature, humidity, or air quality are not acceptable, an alarm is sent to the HVAC system to control the environment (R16-SC). Also, in the case of water penetration and overflow in MUT, the environmental monitoring system sends an alarm to the drainage system to evacuate the water (R17-SC).
- The utility networks should be monitored by the monitoring systems (R18-SM to R22-SM). In case that the gas monitoring system detects a gas leakage, it should be controlled by the HVAC system (R23-SC). If water leakage is detected by the water or sewer monitoring systems, the drainage system should control by water evacuation (R24-SC and R25-SC). If the sewer

monitoring system detects a sewer gas leakage, the HVAC system is alarmed to control it by air evacuation (R26-SC).

- The waterproofing and drainage structure (e.g. canals) is controlled by the drainage system to add more capacity of the water evacuation from the tunnel (e.g. in case of flooding) (R27-SC).
- Each MUT structural component (e.g. foundation, node, access, and main structures) is part of the tunnel structure (R28-P). Each utility network is a utility (R29-S). Each ancillary system (e.g. power supply and SHM systems) is an ancillary facility (R30-S).
- The managerial and surrounding environment information domains provide information to support decision-making about MUT (R31-SI and R32-SI).

Table 5-1 Information requirements for tunnel structure

Components		Information requirements	
		Specific	General
Main structure and foundation		• Network map of the tunnel • Load support threshold • Compartments	• Geometric (i.e. location, dimensions) • Design details • Construction method • Material • Cost parameters • Scheduling parameters • Maintainer and operator information • Inspection, monitoring, maintenance, repair, and operational documents, procedures, data (real-time and/or history) and reporting requirements
Foundation pits		• Supporting walls system	
Auxiliary structures	Access structures	• Types: material input port, human access port, ventilation manhole (i.e. air/gas opening)	
	Node structures (tunnel intersections)	• Space requirements • Utility safety buffer requirements • Connected utilities	
	Lateral tunnel structure (connection to buildings)		
	Waterproofing and drainage	• Capacity requirements • Needed places for waterproofing • Coating specifications	
Note: All the tunnel structural components have indication signs.			

Table 5-2 Information requirements for pipes and their monitoring systems

Components		Information requirements	
		Specific	General
Drinking water	Pipes	• Hydraulic specifications (e.g. roughness, velocity) • Hydrants distribution model	• Specifications of pipeline components (e.g. location, size, materials and coatings, capacity) • Specifications of cathodic protection facilities • Leak detection surveys requirements • Risk analysis • Energy consumption data • Indication signs contents • Inspection, monitoring, maintenance, repair and operational documents, procedures, data (real-time and/or history) and reporting requirements
	Valves		
	Pumps		
	Meters		
	Fittings and gaskets		
	Hydrants		
Water monitoring system		• Water flow rate measured by automatic meter readings (AMRs) • Water pressure recorded by pressure cells • Real-time water quality (turbidity, pH, temperature, chlorine, conductivity) • Water leakage history • Water contamination	
Sewer	Pipes	• Hydraulic specifications (e.g. slope, roughness, velocity)	
	Valves		
	Pumps		
	Meters		
	Fittings and gaskets		
	Siphons		
Sewer monitoring system		• Monitoring: water level or flow rate sensory data and history, water quality (turbidity, temperature, pH), water leakage, sewer gas leakage	
Gas	Pipes	• Types of sensors • Gas detection system instruction	
	Valves		
	Compressors		
	Meters		
	Fittings		
	Pressure cells and regulators		
	Splitters		
Gas monitoring system		• Gas monitoring system detecting data: gas leakage and measured gas pressure, density, temperature, and flow rate	
Note: All pipes have supports or hangers, and indication signs			

Table 5-3 Information requirements for cables and their monitoring systems

Components		Information requirements	
		Specific	General
Electrical	Cables	• Voltage • Line model • Distribution load model • Voltage regulator model • Distribution feeder model	• Specifications of cables physical components (e.g. location, size, materials and coatings, capacity) • Energy consumption data • Risk analysis • Indication signs contents • Inspection, monitoring, maintenance, repair and operational documents, procedures, data (real-time and/or history) and reporting requirements
	Voltage regulator		
	Transformer		
	Distribution feeder		
	Ducts and conduits		
	Switch		
Electrical monitoring system		• Monitoring data: cable temperature, tension, current, frequency, switch status, and consumption	
Telecom	Cables	• Type of cables (e.g. fiber optic, copper) • Supported networks (e.g. TV, phone, Internet) • Wiring color codes • Labeling protocols for cables and ports	
	Port connections		
	Maintenance loop		
	Ducts and conduits		
	Splice boxes		
Telecommunication monitoring system		• Monitoring data: cable temperature, water ingress, switch status, and outages.	
Note: All cables have supports or hangers, and indication signs			

Table 5-4 Information requirements for MUT ancillary facilities

Components		Information requirements	
		Specific	General
Main sensory systems	Structural health monitoring (SHM) system	• Structure deformation and displacement monitoring by optical fiber sensors	• Specifications of physical components (e.g. location, size, materials, capacity) • System technical documents (i.e. manuals, guides, photos, videos) • Energy consumption data • Indication signs contents • Inspection, monitoring, maintenance, repair, and operational documents, procedures, data (real-time and/or history) and reporting requirements
	Access control and geo-localization control system	• Tunnel access history (ingress/egress time and location, the identity of users) • Staff members information (identity, contact, hierarchy, and authorized area in the tunnel) • Human presence tracking data (real-time and history)	
	Environmental monitoring system	• Sensors types and specifications • Temperature data • Humidity data • Air quality (oxygen, smoke, fire, air contamination) data • Overflow/water infiltration detection data • Alarm specifications and locations	
HVAC system	Temperature and airspeed setting control	• Ducting network specifications • Heating and cooling system specifications • Airflow rate data • Temperature data • Air pump specifications • Ventilation mode (indoor circulation, fresh air) • Air filter and register vent specifications	
	Air pumps		
	Air ducts		
	Air filters		
	Heating system		
	Cooling system		
	Register vents		
Drainage system	Pipes	• Water pump Specifications • Pipes and/or canals specifications • Drainage capacity • Water flow rate real-time data	
	Canals		
	Drainage grates		
	Water pumps		
Lighting system	Cables	• Distribution model • Type of lights • Type of sensors • Voltage	
	Switches		
	Ducts and conduits		
	Sensors		

Table 5-4 Information requirements for MUT ancillary facilities (Continued)

Components		Information requirements	
		Specific	General
Power supply system	Cables	• Voltage • Line model • Supporting ancillary facilities • Power outlets locations and specifications	• Specifications of physical components (e.g. location, size, materials, capacity) • System technical documents (i.e. manuals, guides, photos, videos) • Energy consumption data • Indication signs contents • Inspection, monitoring, maintenance, repair, and operational documents, procedures, data (real-time and/or history) and reporting requirements
	Switches		
	Ducts and conduits		
	Power outlets		
Security monitoring and alarm system	Security cameras	• Security cameras specifications and locations • Alarm specifications and locations • Sensors specifications and locations	
	Alarm		
	Sensors		
Fire extinguishing system	Sprinkler	• CO_2 or clean agent/inert fire suppression system • Sprinkler specifications and locations • Water supply system specifications • Ventilation specifications	
	Water supply system		
	Pipes		
	Valves		
	CO_2 or clean agent/inert gas cylinder		
Hoisting system	Engine	• Load capacity • Type (e.g. hydraulic, chain, cable) • Spatial coverage • Engine and mechanical equipment specifications	
	Mechanical equipment		
	Rail		
Communication system	Industrial telephone	• Specifications and locations of industrial telephone, access points, cables, and wireless system • Authorization level	
	Access point		
	Cables		
	Wireless system		
Note: All the ancillary facilities have supports or hangers, and indication signs			

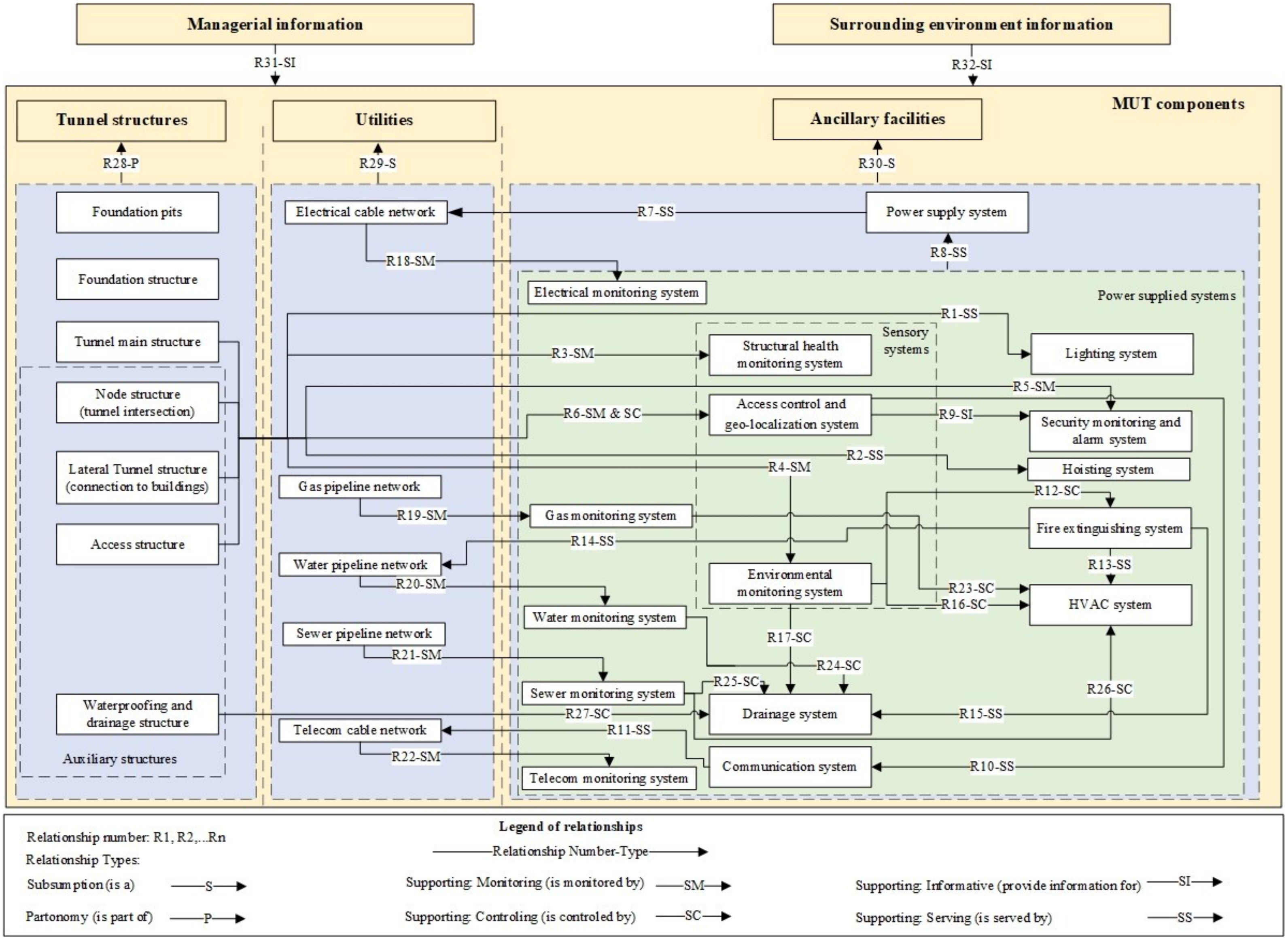


Figure 5-3 Relationships between MUT components and information domains

5.1.2 SMUTIM Use Cases

To describe a SMUTIM use case, the following attributes should be specified:

- Project phase: In what phase(s) of the project the use case can be applied?
- Project users: Who are the project stakeholders involved in the use case?
- Required resources: What resources are required to fulfill the use case?
- Mechanism: How the project users use the resources to perform the use case?
- Restrictions: Under which limitations is the SMUTIM use case implemented?
- Output: What are the results of the use case?
- Interrelation with other use cases: Is there any other use case output used as an input for this use case, or vice versa?

Four main use cases of SMUTIM are identified as shown in Figure 5-4.

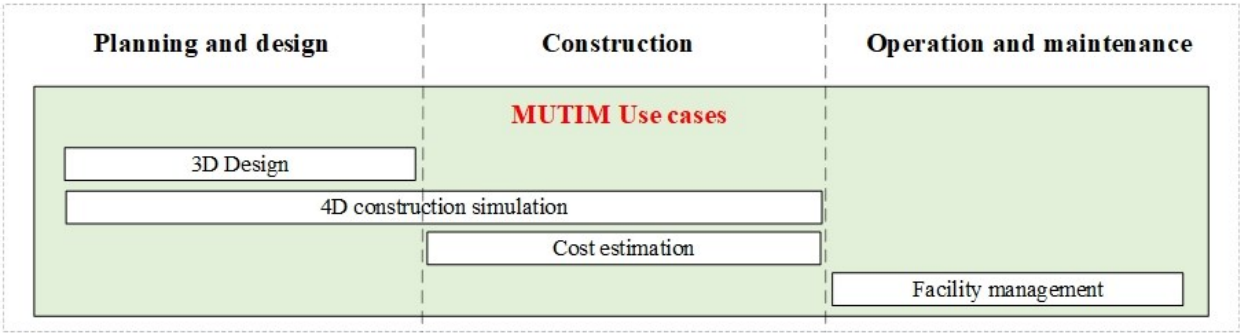


Figure 5-4 The main SMUTIM lifecycle use cases

5.1.2.1 3D Design

The attributes of the use case of 3D design are explained as follows.

Users: All the utility, engineering, and construction companies participate in the 3D design process of the MUT, either to design or to review the design. The process of using 3D software to develop the SMUTIM based on the design criteria is called design authoring. The 3D design will be used by other audit and analysis tools to review and add more information to a model (e.g. cost, schedule). The 3D design should be reviewed by the involved stakeholders to check progress, compliance, and other factors (e.g. aesthetics, ergonomics, security) (CIC, 2011). After design models from all stakeholders are integrated, any physical clash between the MUT components should be detected and resolved using clash detection software (CIC, 2011; Indiana University, 2015).

Resources: To design an MUT, engineering and utility companies need design software with clash detection functionality and skilled personnel. To review the design, and clash detection and resolution, an integrated information model of MUT combined with GIS is required. The standards, codes, and regulations regarding the MUT, ancillary systems, and utilities for design, construction, operation, and safety are needed. In addition to the software, interactive review space, and hardware with the capability of processing large model files are required (CIC, 2011).

Mechanism: The design authoring, review, and clash detection and resolution process includes the following activities:

- Design authoring: The civil engineering company designs the MUT structure and the other engineering companies design the ancillary facilities within the MUT structure. The utility companies design their own utility networks. The design process should consider a pre-defined layout of ancillary facilities and utilities inside the MUT to avoid conflicts. At the final stage, all the designed models should in combined to create a single integrated SMUTIM which can be added to the surrounding environment GIS 3D map (i.e. terrain model including streets, buildings).
- Safety review: After a primary design is completed, it should be checked for compliance with safety codes and concerns. For example, to improve safety by reducing the risk of fires and explosions, safety buffers should be provided for certain utilities (e.g. gas pipes and electrical cables). In addition, environmental monitoring, fire extinguishing, and HVAC systems should be designed according to the standards.
- Constructability review: The designed MUT, ancillary facilities, and utilities should be checked for constructability. The construction method (e.g. cast-in-place or modular concrete elements) should be decided based on the project conditions and reflected in the design. The access structures and main tunnel structure should be large enough to allow the movement of humans, equipment, and utilities during construction. The required clearance between utilities

for the installation phase should be provided. If the gravity sewer system is part of MUT, the needed slope should be designed.

- Clash detection and resolution: The integrated SMUTIM should be imported to the clash detection program (e.g. Navisworks) for detecting the clashes. The clashes can be the result of the collision of components or not respecting the safety buffers (i.e. soft clashes). The identified clashes are documented in a report and reviewed in a meeting with the committee. The solutions should consider safety and constructability.
- Operation and Maintenance (O&M) review: Access to utilities inside the MUT for maintenance activities during the operation phase should be provided with enough space for the movement of personnel and equipment (CIC, 2011). Ergonomic design considerations for the comfort of the labor movement inside the MUT are the other aspects of the review.

Restrictions: The restrictions of 3D design use case include: (1) restrictions from utility users (e.g. physical limitations for MUT lateral connections to buildings, technical limitations for connecting utilities to buildings), (2) legal restrictions (e.g. liability of users), (3) geographic restrictions, and (4) the limited space of MUTs for installation and maintenance activities as the main limitation of clash resolution.

Output: The output is the integrated SMUTIM.

Interrelation(s): The designed SMUTIM supports all other use cases (i.e. construction simulation, cost estimation, and facility management).

5.1.2.2 4D Construction Simulation

The time dimension can be added to the SMUTIM to integrate the construction schedule of MUT with the model elements. The construction process of MUT is simulated using an appropriate software application.

Users: The construction company is the main user of 4D construction simulation. The utility companies will benefit from this process if they are involved in the installation of their own utility networks in the MUT.

Resources: The team of construction coordinators should have the SMUTIM. The required human resources, equipment, and schedule of the MUT construction method are needed.

Mechanism:

- Importing SMUTIM and GIS model: The SMUTIM and GIS model of the project location should be imported and combined in the construction simulation software.
- Adding equipment and human resources: The required equipment (e.g. trucks, excavators, cranes), and human resources should be added to the simulation.
- Link schedule: The construction schedule should be linked with the construction elements (i.e. MUT components, and equipment).
- Construction simulation and coordination: Simulation software is used to check constructability and safety requirements.

Restrictions: The main restrictions to consider in the 4D construction simulation of MUT include:

- Safety requirements: Different safety requirements can be better managed by visualization in the 4D construction simulation. The safe distance between (a) labors and equipment with pits to avoid falling in pits, (b) equipment with labors and other equipment (i.e. work zones) to avoid collisions, and (c) equipment and surrounding environment to avoid collisions with surrounding structures (e.g. buildings, traffic signs), are the main safety concerns that can be better controlled by the simulation process.
- Traffic requirements: Certain traffic restrictions should be considered in construction simulation. These restrictions include (a) allowed durations and areas of partial street closures, (b) allowed detour roads, (c) maximum street capacity (i.e. dimensions, pavement bearing load), and (d) allowed working hours.

Output: The output includes the simulation of the construction process.

Interrelations: The SMUTIM and GIS model are inputs of the 4D construction simulation. This process affects the cost estimation process by affecting the usage of some project resources (e.g. human resources, machinery, and equipment).

5.1.2.3 Cost Estimation

Construction cost estimation of MUT projects can benefit from SMUTIM by automated quantity takeoff, which reflects the effects of changes, additions, and modifications on the cost. Cost data can be added to the 4D SMUTIM to track the budget during the construction phase (CIC, 2011).

Users: The MUT project stakeholders involved in the process of cost estimation include all the utility and construction companies.

Resources: The required resources include model-based cost estimating software, design model with enough level of detail, and cost data (e.g. MasterFormat, Uniformat data, RSMeans). According to CIC (2011), cost estimation is based on the ability to extract quantities from the model for the needed estimating level (e.g. rough order of magnitude).

Mechanism: The cost estimation includes the following steps.

- **Quantity take-off:** The SMUTIM can represent a certain Level of Development (LOD) depending on the stage of the project. DDC (2012) defined five LODs. Higher LOD results in more accurate cost estimation.
- **Adding cost data:** The cost of each MUT component should be added to the cost estimation software. There are cost databases (e.g. RSMeans in the construction industry) that help professionals in cost estimation and creating budgets. Other ways for estimating the costs of MUT components are price quotations from the suppliers and the contractors, and expert judgment.
- **Construction cost estimation:** By having the MUT components quantities and their costs, cost estimation can be automated using specialized software. Those processes can save the time of cost estimators and increase accuracy.

Restrictions: The restrictions of cost estimation are: (1) LOD: the accuracy of cost estimation depends on the LOD and increases as more design details are available; (2) cost data: availability of cost databases, price quotations, and accuracy of expert judgments; (3) location conditions: concurrent development projects to be synchronized, type of soil, hydrological conditions, slope, and locations of surrounding structures/natural barriers.

Output: The output is the estimated construction cost of MUT for utility companies and the society (i.e. social cost).

Interrelation(s): The design process provides the SMUTIM, which can be used for quantity take-off. The 4D construction simulation gives the schedule of activities, which influences construction costs estimation.

5.1.2.4 Facility Management

SMUTIM capability in storing lifecycle information of MUT components is valuable for facility management. However, the SMUTIM cannot store a large volume of data (e.g. real-time monitoring sensory data) and should be linked with other external databases to improve facility management. For example, Theiler and Smarsly (2018) emphasized on linking sensory data of the SHM system with external databases.

Users: The operators of MUT (i.e. utility companies) are the main users of the facility management process.

Resources: The required resources include (a) an up-to-date SMUTIM, (b) 3D GIS model of MUT surrounding environment, (c) facility management systems (e.g. sensory monitoring systems, security systems), and (d) facility managers able to work with BIM-based systems.

Mechanism: The mechanism of SMUTIM based facility management can be clarified by defining the application of SMUTIM, and how SMUTIM can be linked with facility management systems. The required information includes:

- **MUT component static information:** The static information about MUT components (e.g. location, technical specifications, materials, manuals, vendors information) can be stored in the SMUTIM.
- **Inspection, maintenance, and repair history:** The information about inspection, maintenance, and repair of MUT structure, utilities, and ancillary systems should be stored in BIM software or the linked database systems. The history is updated during the operation period and can assist in facility management.
- **Real-time monitoring data:** The monitoring data is too huge to be stored in SMUTIM software. These data can be stored in separate databases and represented in user interfaces designed for facility management.

Restrictions: The restrictions of a SMUTIM facility management system include (1) managing the huge volume of data: although database systems can host a large amount of data, designing systems for the analysis and representation of information is challenging, (2) quality control: some information can be added manually to the SMUTIM (e.g. inspection, maintenance, and repair history). However, the quality of this information should follow standardized information requirements.

Output: The output includes all information and data in the operation and maintenance phase of MUT.

Interrelation(s): The facility management system receives the updated SMUTIM from the 3D design process to link information to the MUT components.

5.1.3 IFC Extension to Accommodate SMUTIM

After organizing MUT information requirements as explained in Section 5.1.1, the following steps are needed to extend IFC to MUT: development of MVD, new IFC entities, properties, and relationships. The focus of this research is to extend IFC for the physical and spatial components of MUT. Therefore, this research presents a partial implementation of IFC for MUT and further IFC extension efforts are needed to cover non-physical components and software implementation, testing, and certification. Some IFC entities, especially for utilities and systems, are reusable for MUT (e.g. *IfcSensorTypeEnum, IfcPipeSegment, IfcCableSegment*) and some only need to add sub-classes for meeting MUT requirements.

5.1.3.1 Model View Definition

The information requirements are captured using Model View Definition (MVD) (Ghaznavi, 2013). MVD is the set of information exchange requirements for the data flow between business processes at a specific stage of the project using relevant information of the model. Information Delivery Manual (IDM) can be used to extend the available IFC schema by extending available entities or creating new entities (Wix and Karlshoej, 2010). The requirements for MUT lifecycle information modeling are organized in MVD for future IFC extension as shown in Figure 5-5. The physical components are the newly defined physical element of an MUT (i.e. tunnel structure, utilities, and ancillary facilities). These physical components are divided into more detailed elements. For example, auxiliary structures include lateral tunnel structure, node structure, waterproofing and drainage; and access structure is divided into material port, human access port, and ventilation manhole.

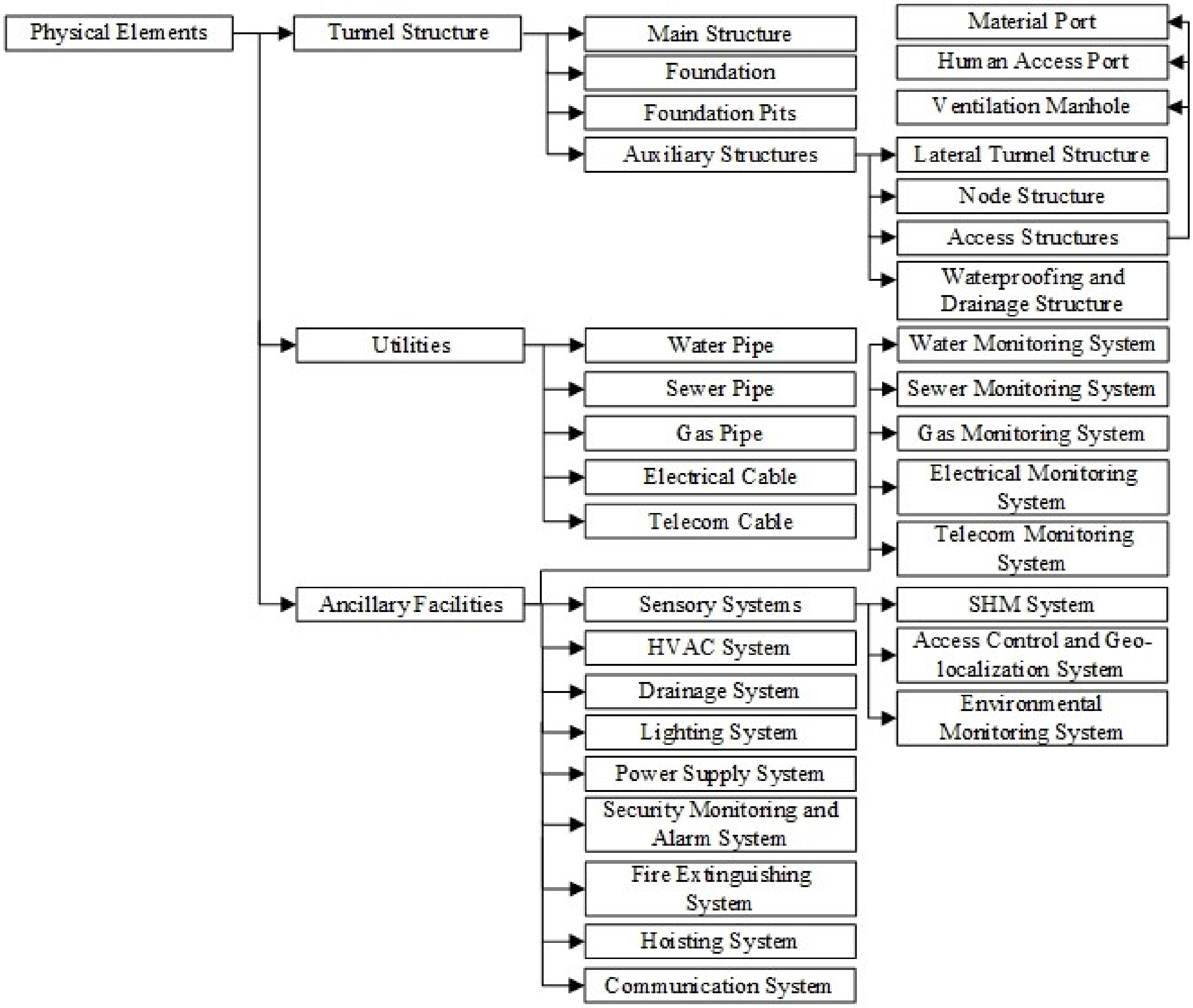


Figure 5-5 MVD for MUT components

5.1.3.2 MUT New and Available IFC Entities, Properties, and Relationships

In the IFC schema, the entities are categorized based on the representation of objects, properties, or relationships: The object entities represent any “thing” that is described semantically; the properties include all characteristics assigned to the objects; and the “objectified relationships” determine the relationships between objects (Theiler & Smarsly, 2018).

There are some available entities and property sets in IFC that can be re-used for SMUTIM. For example, actuators, alarms, and sensors are described by *IfcActuator*, *IfcAlarm*, and *IfcSensor*, respectively. Different types of IFC elements are also defined under entities inherited from the *IfcTypeObject* entity. For example, the *IfcSensorTypeEnum* defines the range of different types of sensors that can be specified (IFC, 2016). Some of the available sensors that are applicable for MUT are defined in *IfcSensorTypeEnum* are presented in Table 5-5. Pipes can be described by *IfcPipeSegment*. Some of the available property sets of *IfcPipeSegment* that are reusable for MUT are presented in Table 5-6 (IFC, 2016).

Table 5-5 Available sensors in IfcSensorTypeEnum applicable for MUT (IFC, 2016)

Name of the sensor	**Detected element**
CO SENSOR	Carbon monoxide
CO_2 SENSOR	Carbon dioxide
FIRESENSOR	Fire
GASSENSOR	Gas concentration
CONTACTSENSOR	Contact (e.g. for detecting if a door is closed)
FLOWSENSOR	Flow of a fluid
HEATSENSOR	Heat
HUMIDITYSENSOR	Humidity
MOISTURESENSOR	Moisture
MOVEMENTSENSOR	Movement
PRESSURESENSOR	Pressure
SMOKESENSOR	Smoke
TEMPERATURESENSOR	Temperature
WINDSENSOR	Airflow speed and direction

Table 5-6 Some of the available property sets applicable for MUT in IfcPipeSegment (IFC, 2016)

Name of Pset	**Description**
Pset_PipeConnectionFlanged	This property set is used to define the specifics of a flanged pipe connection used between occurrences of pipe segments and fittings.
Pset_PipeSegmentOccurrence	Pipe segment occurrence attributes attached to an instance of *IfcPipeSegment*.
Pset_PipeSegmentPHistory	Pipe segment performance history common attributes.
Pset_PipeSegmentTypeCommon	Pipe segment type common attributes.
Pset_ElectricalDeviceCommon	A collection of properties that are commonly used by electrical device types.
Pset_Condition	Determines the state or condition of an element at a particular point in time.
Pset_PackingInstructions	Packing instructions are specific instructions relating to the packing that is required for an artifact in the event of a move (or transport).
Pset_ServiceLife	Captures the period of time that an artifact will last.
Pset_Warranty	An assurance given by the seller or provider of an artifact that the artifact is without defects and will operate as described for a defined period of time without failure and that if a defect does arise during that time, that it will be corrected by the seller or provider.

The IFC gaps for SMUTIM entities are determined by comparing the MUT requirements (Table 5-1 to Table 5-4), SMUTIM use cases attributes (see Section 5.1.2), and MVD of MUT components (Figure 5-5), with the available IFC entities. Figure 5-6 shows the new MUT physical and spatial IFC entities, together with some examples of entities for MUT sensory (e.g. *IfcSensor*), pipe (e.g. *IfcPipeSegment*), and electrical systems (e.g. *IfcElectricalCircuit*).

A relationship entity describes a relationship between object entities. There are different types of relationship entities as subtypes of *IfcRelationship*, namely *IfcRelAssigns, IfcRelDecomposes*, *IfcRelAssociates*, *IfcRelDefines*, *IfcRelConnects*. Each of these relationship entities has subtype(s) and are used to realize the relationships between the MUT entities. As shown in Figure 5-6, in case of the new MUT physical and spatial IFC entities, a decomposition relationship using *IfcRelAggregates* as a subtype of *IfcRelDecomposes* can be used to show an MUT structural components. The entity of *IfcRelDefinesByType* defines the relationships between an object type and objects (e.g. between *IfcSensor* and *IfcSensorType*). The entity of *IfcSensorTypeEnum* defines the variety of different types of sensors that can be specified (e.g. CO sensor, CO_2 sensor, fire sensor, gas sensor).

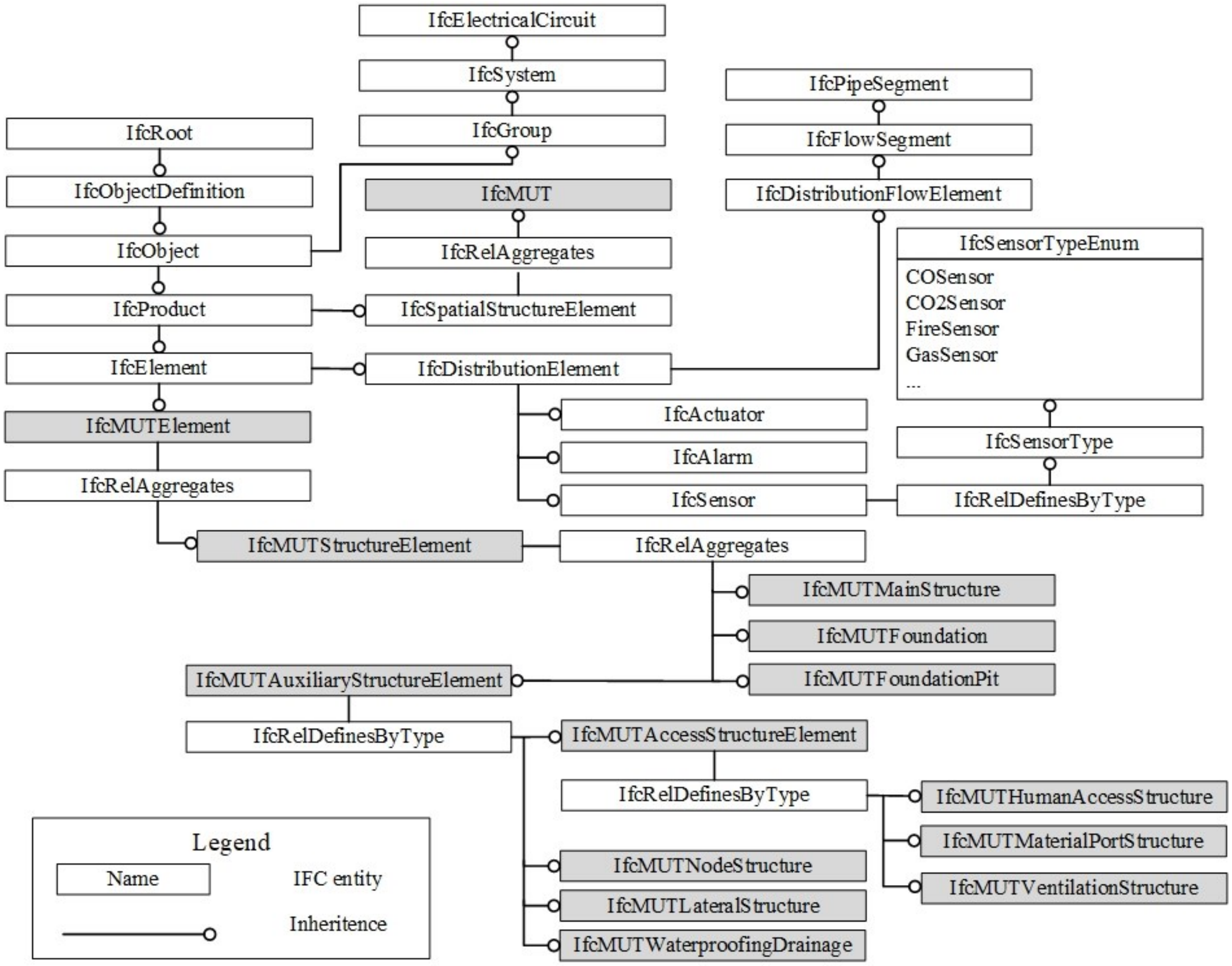
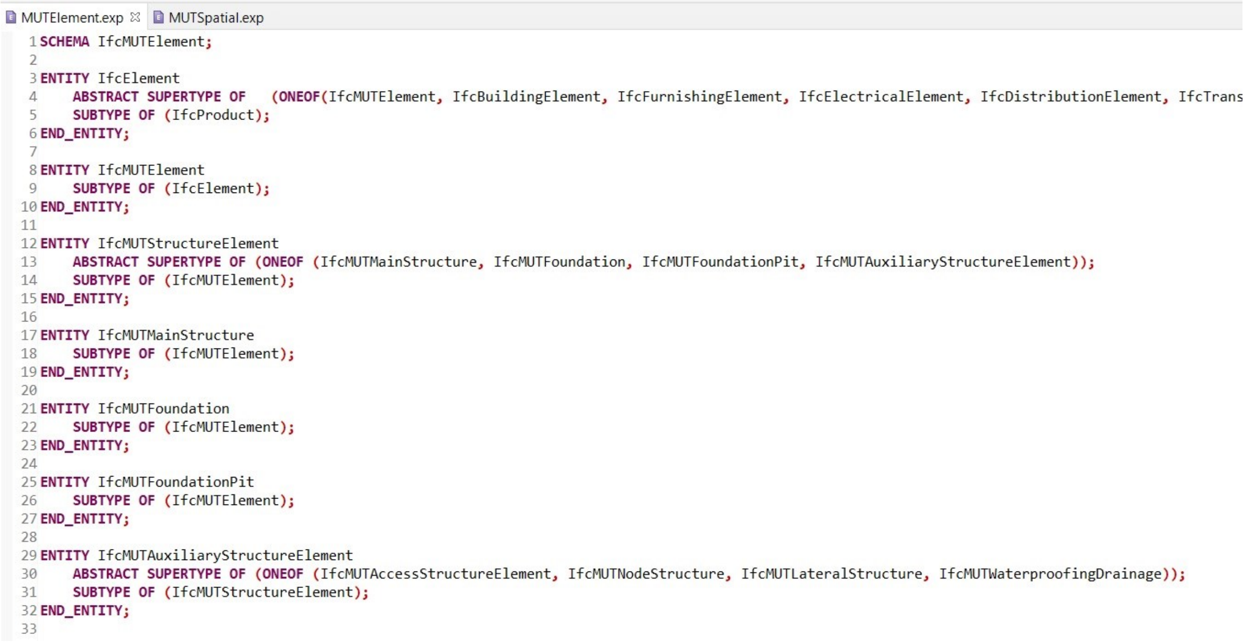


Figure 5-6 New MUT physical and spatial IFC entities (new entities in gray) and examples of entities for MUT sensory, pipe, and electrical systems

5.1.3.2.1 Partial Implementation of SMUTIM IFC Extension

To implement the SMUTIM specific entities, a STEP-based platform able to read and write EXPRESS-based object-oriented data models is needed. In this research, the JSDAI™ for the Eclipse platform as an open-source application programming interface (API) is used.

To add the information that is not available in the defined semantics of IFC structure, *IfcProxy* classes in the original IFC is an option. Therefore, SMUTIM new entities can be exported as *IfcProxy* classes and then converted as a new STEP file of SMUTIM to be used as a SMUTIM central inventory by product server systems, which exchanges information with other software applications. Figure 5-7 shows the snapshot of JSDAI™ for the Eclipse platform, where SMUTIM classes are implemented in the EXPRESS language. The figure shows a part of the *IfcMUTElement* entity in the EXPRESS file.



```
SCHEMA IfcMUTElement;

ENTITY IfcElement
    ABSTRACT SUPERTYPE OF   (ONEOF(IfcMUTElement, IfcBuildingElement, IfcFurnishingElement, IfcElectricalElement, IfcDistributionElement, IfcTrans
    SUBTYPE OF (IfcProduct);
END_ENTITY;

ENTITY IfcMUTElement
    SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcMUTStructureElement
    ABSTRACT SUPERTYPE OF (ONEOF (IfcMUTMainStructure, IfcMUTFoundation, IfcMUTFoundationPit, IfcMUTAuxiliaryStructureElement));
    SUBTYPE OF (IfcMUTElement);
END_ENTITY;

ENTITY IfcMUTMainStructure
    SUBTYPE OF (IfcMUTElement);
END_ENTITY;

ENTITY IfcMUTFoundation
    SUBTYPE OF (IfcMUTElement);
END_ENTITY;

ENTITY IfcMUTFoundationPit
    SUBTYPE OF (IfcMUTElement);
END_ENTITY;

ENTITY IfcMUTAuxiliaryStructureElement
    ABSTRACT SUPERTYPE OF (ONEOF (IfcMUTAccessStructureElement, IfcMUTNodeStructure, IfcMUTLateralStructure, IfcMUTWaterproofingDrainage));
    SUBTYPE OF (IfcMUTStructureElement);
END_ENTITY;

```

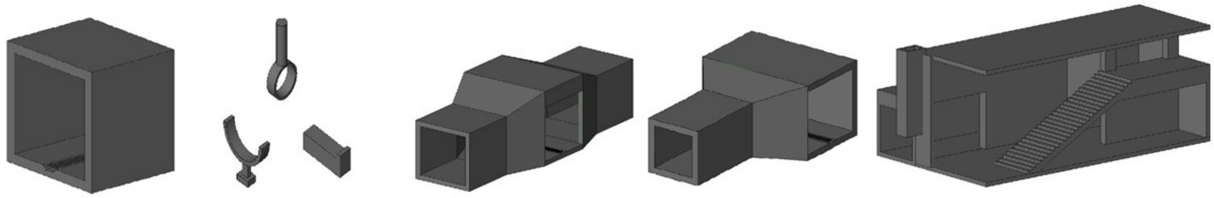
Figure 5-7 Part of IfcMUTElement EXPRESS file in JSDAI for Eclipse platform

5.2 Case Study

The case study is based on a study for a 3m×3m prefabricated modular MUT project, accommodating water, sewer, gas, telecommunication, and electricity networks. The project is located in Montreal under Ottawa Street with the length of 250 m.

5.2.1 MUT 3D Design

Since the proposed SMUTIM is not available yet as a standard and MUT specific families are not available in BIM software (Revit, 2019), several new families were created in Revit. Figure 5-8 shows examples of the created new families for a prefabricated modular MUT and Figure 5-9 demonstrates an overall view of part of the MUT network with main components. The utilities are shown in the figure according to the color code of green for sewer, blue for water, yellow for gas, red for electricity, and orange for telecommunication networks.



Main culvert section

Hanger and supports

Node structure culvert section

Lateral culvert section

Access structure

Figure 5-8 Examples of new families created for MUT in Revit

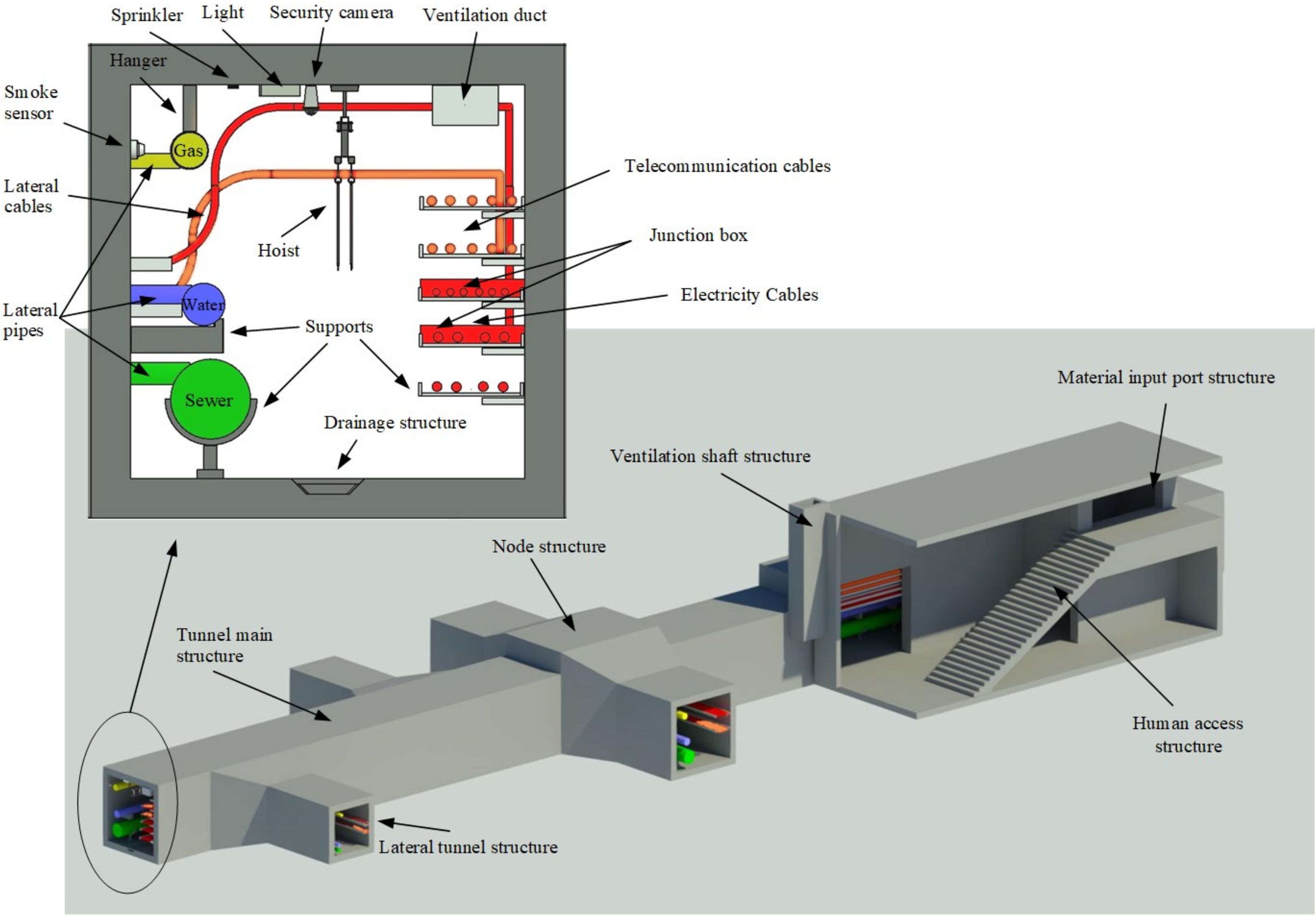


Figure 5-9 MUT main components

Using Autodesk Navisworks (Navisworks, 2019), a walkthrough animation is created, and the users can walk inside the MUT virtually to review the details of the design. Figure 5-10 shows a screenshot from the connection of the main tunnel to the lateral tunnel in the walkthrough animation.

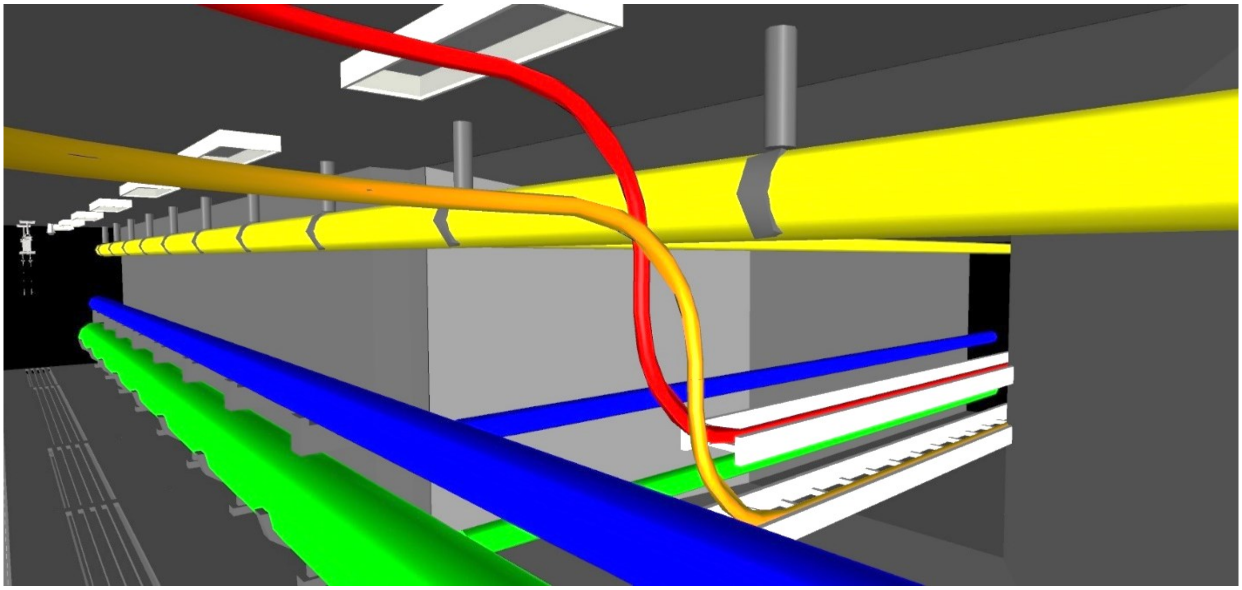


Figure 5-10 Screenshot of the connection of main to lateral MUT in a walkthrough animation

The 3D map of the area is added to the GIS software (Infraworks, 2019) using CityGML format. Then, the Revit MUT model is added to the map by assigning its location under the road. Figure 5-11 shows a sample SMUTIM in Infraworks.

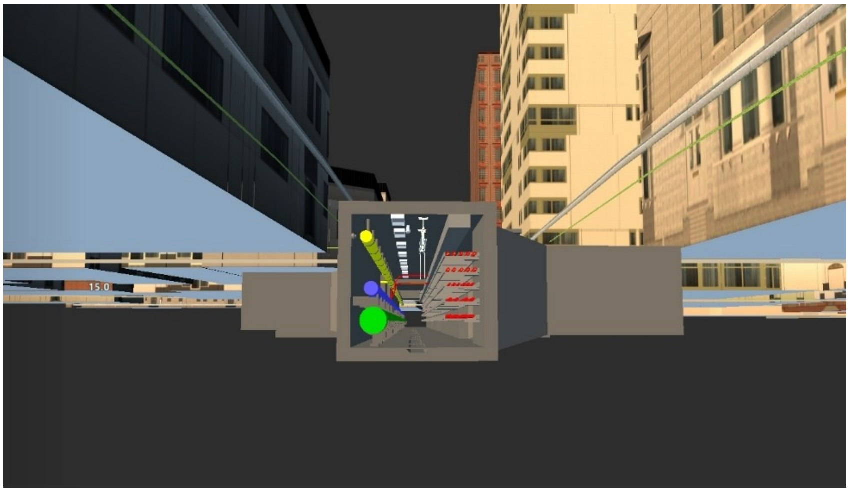
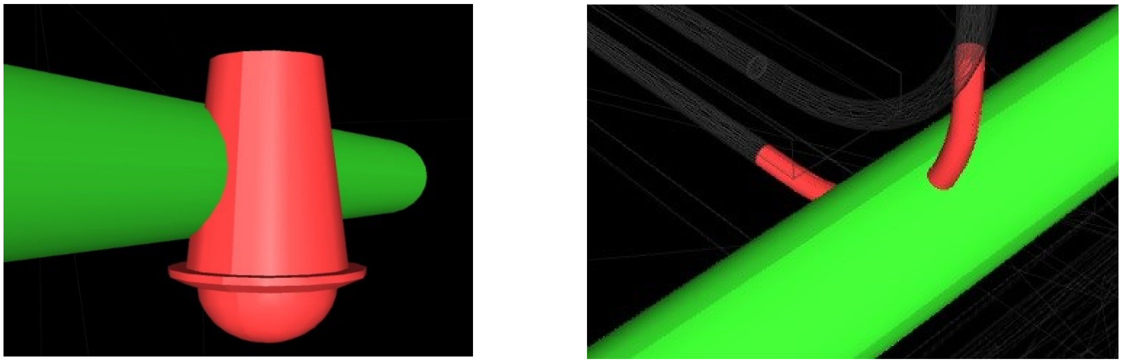


Figure 5-11 Underground view of a sample SMUTIM in Infraworks

Navisworks is used to detect clashes among the elements in the MUT design. Figure 5-12 shows examples of the detected clashes. Clash detection and resolution report is sent to the design team to fix the problems.

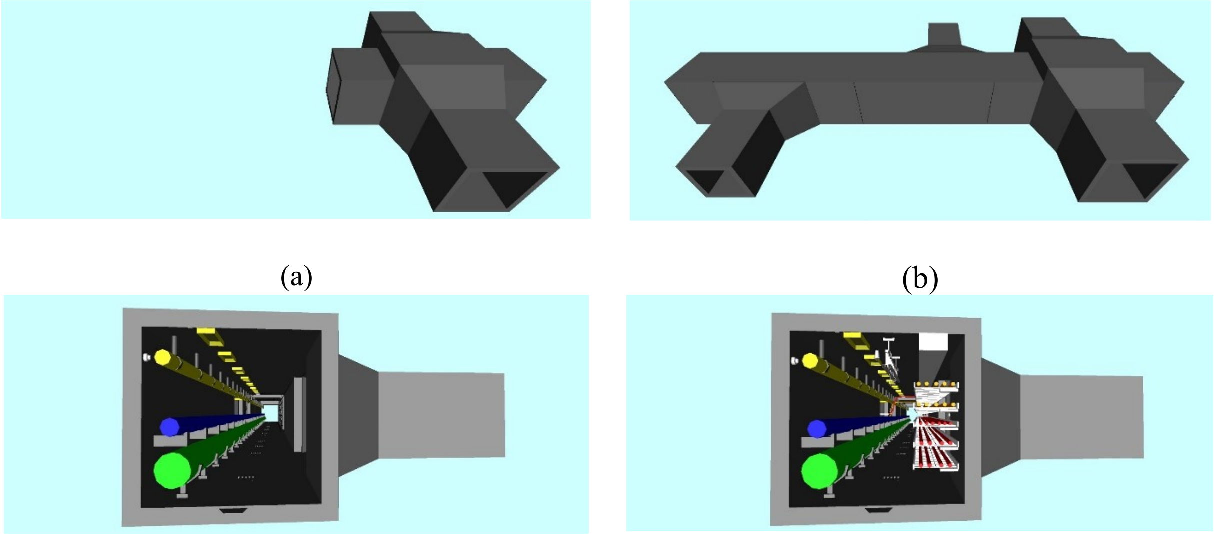


(a) Clash between surveillance camera and gas pipe **(b) Clash between electrical conduit and water pipe**

Figure 5-12 Examples of detected clashes

5.2.2 4D Construction Simulation

To create the 4D construction simulation, the MUT model is imported to Navisworks. Using Timeliner, the schedule of MUT construction is added and linked with the components of the MUT. The 4D construction simulation is generated as animation as shown in Figure 5-13.

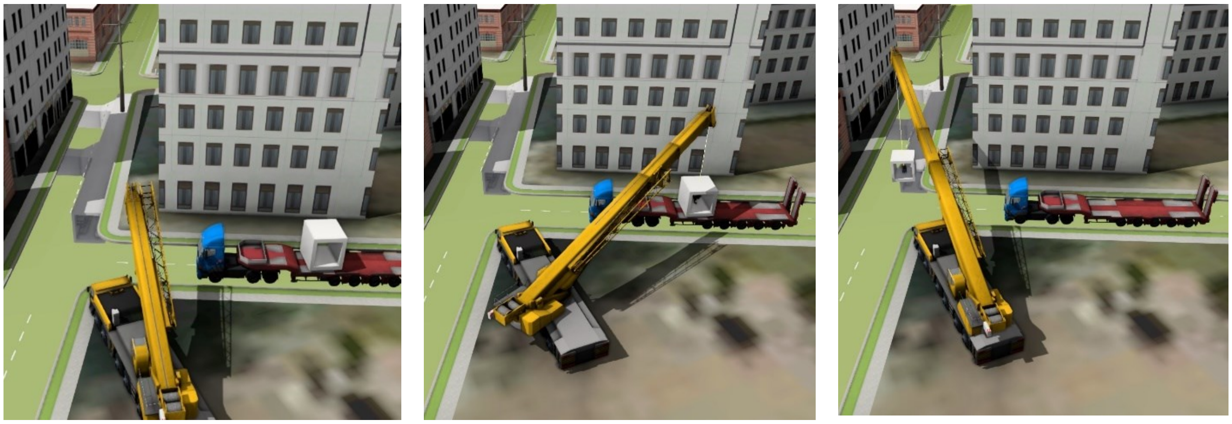


(a) (b)

(c) (d)

Figure 5-13 Snapshots of 4D construction simulation

The 4D simulation of MUT construction based on micro-scheduling can show the detailed construction processes for constructability review including construction equipment. For this purpose, a part of the integrated model of MUT with the 3D GIS map is simulated using Fuzor software (Fuzor, 2019), focusing on the installation of a prefabricated segment of the MUT (Figure 5-14). The segment is transported to the construction site by a truck. The crane lifts the segment and moves it to the final location for installation**.**



(a) (b) (c)

Figure 5-14 4D simulation of MUT construction in Fuzor

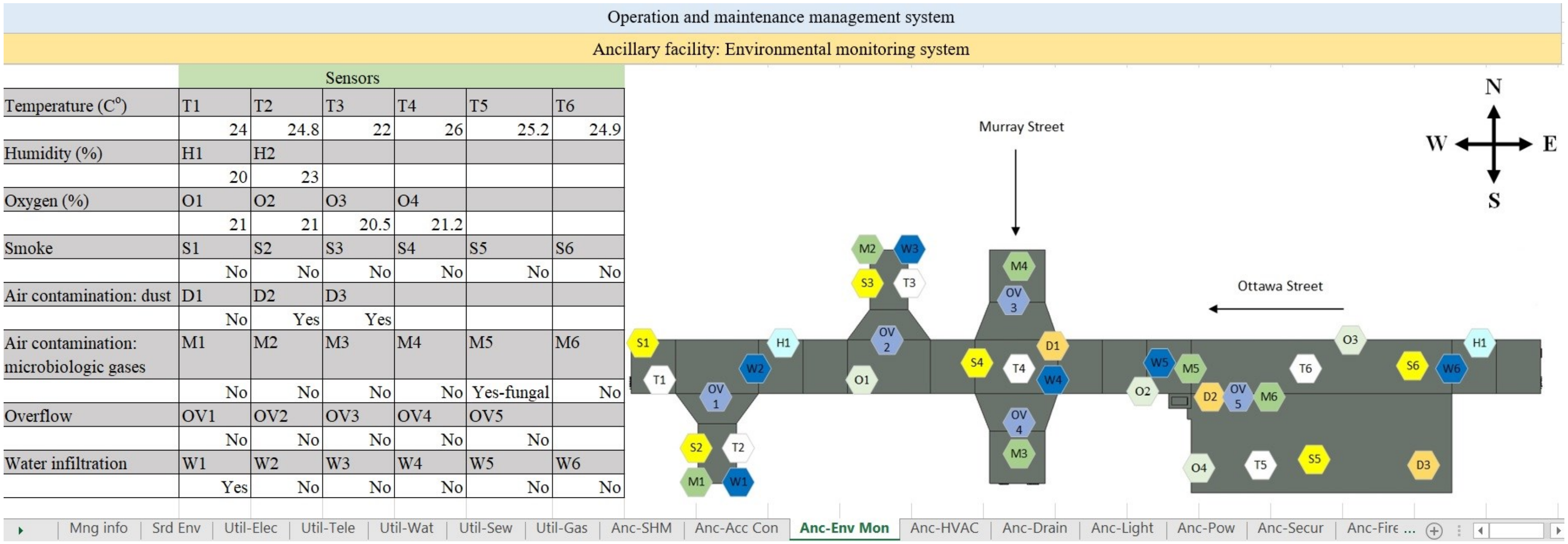
The simulation can be useful for ensuring enough space (e.g. street width, equipment maneuvering space) for the transportation of prefabricated elements and construction of the MUT (Figure 5-15).

Figure 5-15 Construction scheduling in Fuzor

5.2.3 Facility Management

A prototype user interface for the operation and maintenance management of the MUT in the case study is developed in Microsoft Excel as shown in Figure 5-16. Microsoft Excel has a *RealTimeData* (*RTD*) function that retrieves data from an RTD server and presents it in the Excel workbook (Microsoft, 2020). The prototype user interface has a total of eighteen worksheets: one for managerial information, one for the surrounding environment, five for utilities, and eleven worksheets for ancillary facilities. The worksheet for the ancillary facility of the environmental monitoring and control system is shown as an example in Figure 5-16. This worksheet includes the real-time sensory data for temperature, humidity, oxygen, smoke, air contamination by dust and microbiologic gases, overflow, and water infiltration. The sensors' name and real-time data are presented in a table. The location of each sensor is shown on the image of the MUT. The type, number, and location of sensors should be based on the needs of sensory data measurement for each part of the MUT. For example, it is necessary to measure temperature and smoke at every lateral tunnel to prevent the spread of fire from the MUT to the connected buildings.

Future facility management user interface development should be based on the Internet of Things (IoT) as a web-enabled system including smart inter-related devices (e.g. processors, sensors, and communication hardware) to collect, transmit, and act on data from the MUT environment (Rouse, 2020). Currently, there are tools (e.g. Azure IoT Hub) that enable users to develop cloud-hosted solutions to connect virtually any device and establish communication between the IoT application and the devices it manages (Azure Microsoft, 2020).



Operation and maintenance management system

Ancillary facility: Environmental monitoring system

	Sensors					
Temperature (C°)	T1	T2	T3	T4	T5	T6
	24	24.8	22	26	25.2	24.9
Humidity (%)	H1	H2				
	20	23				
Oxygen (%)	O1	O2	O3	O4		
	21	21	20.5	21.2		
Smoke	S1	S2	S3	S4	S5	S6
	No	No	No	No	No	No
Air contamination: dust	D1	D2	D3			
	No	Yes	Yes			
Air contamination: microbiologic gases	M1	M2	M3	M4	M5	M6
	No	No	No	No	Yes-fungal	No
Overflow	OV1	OV2	OV3	OV4	OV5	
	No	No	No	No	No	
Water infiltration	W1	W2	W3	W4	W5	W6
	Yes	No	No	No	No	No

Figure 5-16 A prototype interface of environmental monitoring and control system

5.3 Summary and Conclusions

This chapter proposed a comprehensive framework for defining SMUTIM requirements, which are categorized into five groups: (a) managerial, (b) surrounding environment, (c) tunnel structural components, (d) utilities, and (e) ancillary facilities. The relationships between the information groups are defined. This research extended the main BIM use cases applicable for MUT (i.e. design, cost estimation, 4D construction simulation, and facility management) to SMUTIM. In addition, a partial IFC extension to MUT is proposed. A case study is used to demonstrate the applicability of the proposed framework. The results show that the proposed framework can facilitate the design, construction, operation, and coordination of utility companies.

The contributions of this chapter are: (1) Categorizing and integrating MUT physical and functional components and their relationships systematically; (2) Completing, integrating, and organizing the available knowledge about SMUTIM use cases within the framework; (3) Using the case study to show the capabilities and gaps of current BIM applications, GIS, databases, and facility management tools for MUT lifecycle management; and (4) Partially extending IFC to MUT by proposing MVD, new entities and relationships, and taking advantage of reusable IFC entities, properties, and relationships. Future work should focus on fully extending IFC for SMUTIM and extensively implementing and testing the proposed smart MUT information framework. Also, future facility management user interface development should be based on IoT as a web-enabled system.

CHAPTER 6. SUMMARY, CONSTRIBUTIONS AND FUTURE WORKS

6.1 Summary of Research

This thesis presented a comprehensive review of the related literature, the current research gaps, the overview of the proposed approach, a detailed explanation of the proposed methods, and case studies to show the applicability of the proposed methods.

The particular focus of the this research was on (a) improving MUT lifecycle economy assessment by developing a comprehensive and systematic model for MUT and buried utilities LCC analysis which considers factors of utility specifications, location conditions, and construction methods; (b) improving lifecycle cost-sharing of MUTs by developing an MUT cost-sharing model to ensure the decision-makers of utility companies that MUT is the economic method for their company and that all the utility companies benefit from MUT fairly; and (c) improving coordination of utility companies through a comprehensive framework for defining SMUTIM requirements, use cases, and partial IFC extension.

6.2 Research Contributions and Conclusions

The research contributions to the body of knowledge are:

(1) Developing a comprehensive and systematic model for MUT and buried utilities LCC analysis by considering the factors of utility specifications, location conditions, and construction/maintenance methods. The output of this model estimates the LCC of MUT and buried utilities. The proposed model can justify whether an MUT project is an economic alternative method for buried utilities. It can be concluded that:

- The influence of factors on the LCC of MUT and buried utilities can differ significantly case by case;
- The LCC of MUT must be less than that of buried utilities for the project and also for each individual utility company to justify MUT.

(2) Developing an MUT cost-sharing method to ensure the decision-makers of utility companies that MUT is the economical method for their company and also the benefits and costs of MUT are distributed fairly among the utility companies. The fairness is defined based on three

principals: (a) balance of risk, (b) balanced benefit-cost ratio, and (c) balance in contributed benefit and gained benefit. It can be concluded that:

- PBC and PUVO methods of cost-sharing are necessary, but not enough for a fair cost-sharing;
- Risk adjustment provides fairness by proportionally allocating the cost of risk management and responsibility of risk to the utility companies;
- BCR adjustment aims to improve fairness by balancing BCR of utility company based on the logic that higher cost should result in higher benefit for a company, but with balanced BCR;
- Balancing contributed and gained benefit encourages utility companies with high contributed benefit but low gained benefit to participate in MUT.

(3) Categorizing and integrating smart MUT physical and functional components and their relationships in a systematic way. Regarding this contribution the following conclusions can be drawn:

- The proposed SMUTIM framework comprehensively categorized information requirements into five groups: (a) managerial, (b) surrounding environment, (c) tunnel structural components, (d) utilities, and (e) ancillary facilities.
- The relationships between the information groups are defined as: subsumption, partonomy, and supporting relationships (i.e. monitoring, controlling, informative, serving).

(4) Completing, integrating, and organizing the available knowledge about SMUTIM use cases within a framework. Then, using the case study to show the capabilities and gaps of current BIM applications, GIS, databases, and facility management tools for MUT lifecycle management. The following conclusion is achieved from this contribution:

- The description of SMUTIM use cases requirements (i.e. 3D design, cost estimation, 4D construction simulation, and facility management) is improved by proposing their comprehensive attributes in this research including: project phase, project users, required resources, mechanism, restrictions, output, and interrelation with other use cases.

(5) Partially extending IFC to MUT by proposing MVD, new entities and relationships, and taking advantage of reusable IFC entities, properties, and relationships. The contributions 3 to 5 lead to the following conclusion:

- The results show that the proposed framework can facilitate the design, construction, operation, and coordination of utility companies.

6.3 Limitations and Future Work

While this research achieved the contributions mentioned in Section 6.2, the following limitations have been faced during this research and need to be addressed in the future:

(1) The limitation for evaluation of the proposed MUT lifecycle cost assessment model in the case study include lack of data availability for some factors (e.g. E&R, underground water level, traffic density, diameter and material of telecommunication and electrical cables).

(2) The developed model for cost-sharing of MUT projects is based on the selection of MUT cost allocation method, cost adjustment using risk and benefit-cost factors, and game theory. Future research should be focused on (a) identifying more risks for cost adjustment; and (b) more detailed evaluation of social costs.

(3) This research focused on identifying the main SMUTIM use cases within the proposed framework. Future work should (a) focus on other use cases, and (b) develop facility management user interfaces using web-enabled and cloud-hosted IoT solutions.

(4) Regarding the IFC extension to SMUTIM, the implemented extension was partial. Future work should focus on fully extending IFC for SMUTIM and extensively implementing and testing the proposed smart MUT information framework.

(5) This research considered the main utilities for installation in MUTs (i.e. drinking water, sewer, and gas pipes, and electrical and telecommunication cables). Future work should consider other utilities that can be accommodated in MUT (e.g. heating and cooling, and pneumatic refuse pipe).

(6) This thesis focused on the smartness of MUTs from the automated sensing point of view. Different kinds of sensors and their roles in monitoring systems were discussed. Future work should focus on designing the location of sensors and developing criteria for this purpose. Other aspects of smart MUTs (e.g. smart services, smart management, smart governance) should be

studied more. Figure 6-1 shows an overview of smart MUT systems including data analysis and MUT management, as well as the potential benefits related to effectiveness, sustainability, and resilience.

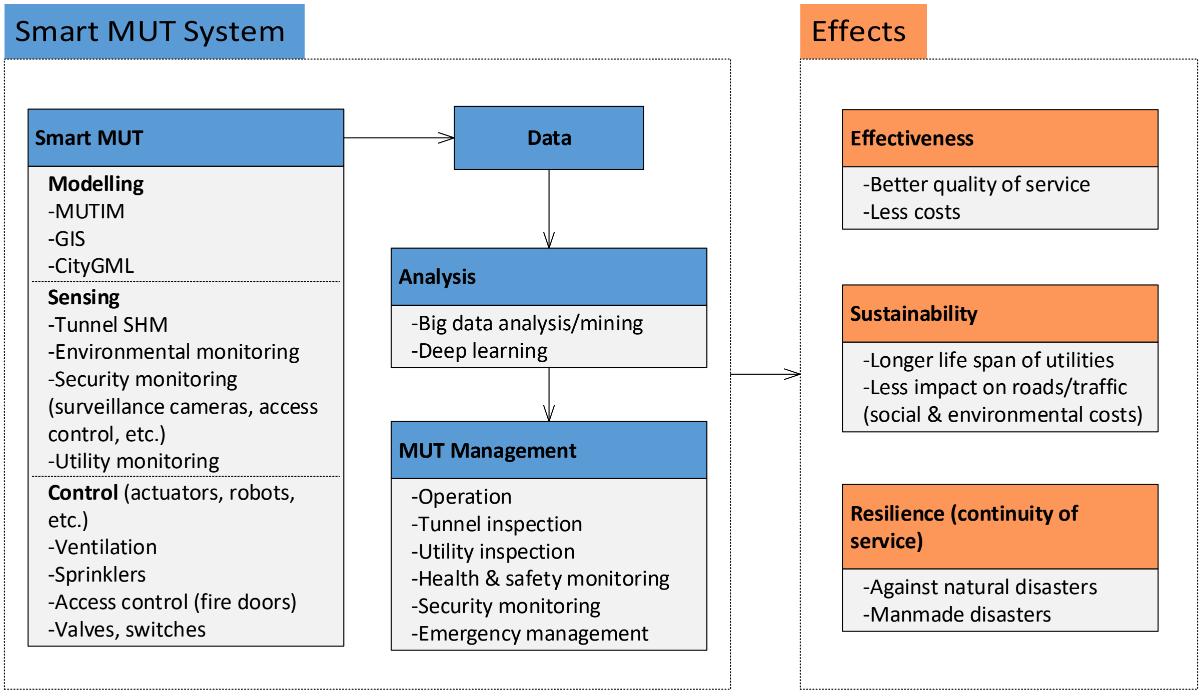


Figure 6-1 Smart MUT system (Luo et al., 2019)

(7) Throughout the course of this research project, and based on the discussion with different stakeholders, we reached an understanding that the implementation of MUTs is difficult to realize only based on engineering considerations. What is equally important is to have significant improvements in the following areas.

(a) Policies: The policies should be adjusted to see MUT as a solution for long-term sustainability, similar to issues such as global climate change.

(b) Regulations: The successful experience of some countries (e.g. Singapore, Taiwan) in MUT development shows the importance of regulation for MUT projects. Therefore, demanding utility companies to accommodate utilities inside MUTs by regulations is necessary.

(c) Integrating underground development with urban planning: MUTs are developed in the underground space. Since MUTs provide utility services to the users in urban areas, they should be considered in the wider scope of urban planning to take advantage of special opportunities. For example, extending the metro network can be seen as an opportunity for synchronized development of MUT. The development of MUTs should be integrated with urban planning to avoid any conflict and to ensure efficient results.

(d) Updating the norms related to fees imposed by municipalities on utility companies:

The current fees imposed by municipalities on utility companies (e.g. renting fees for cable companies to use ducts) are considerably low and do not consider the social costs caused by repetitive excavations. However, the cost-savings from MUTs and the social cost reduction should be considered; and the fees for renting space in the MUT should reflect these savings and the social costs. The cost-sharing model proposed in this thesis can be extended in the future to consider this aspect. It should be noted also that a part of the social cost will be ultimately transferred from the utility companies to the end-users. Another scenario will be to have the cost of MUT fully bared by the municipality and then transfer the social cost part directly to the end-users through additional municipal taxes. These different scenarios should be analyzed in the future considering the concept of *willingness to pay*.

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APPENDICES

Appendix A – VED Quantification

According to Oum (2017), the traffic volume pattern in the City of Montreal reveals that the average annual daily traffic (AADT) varies per the day of the week (see Figure A-1) and the time of the day (Figure A-2). In this study, three periods for the day of the week (Monday-Friday, Saturday and Sunday) and six periods for the time of the week were chosen as illustrated in Table A-1.

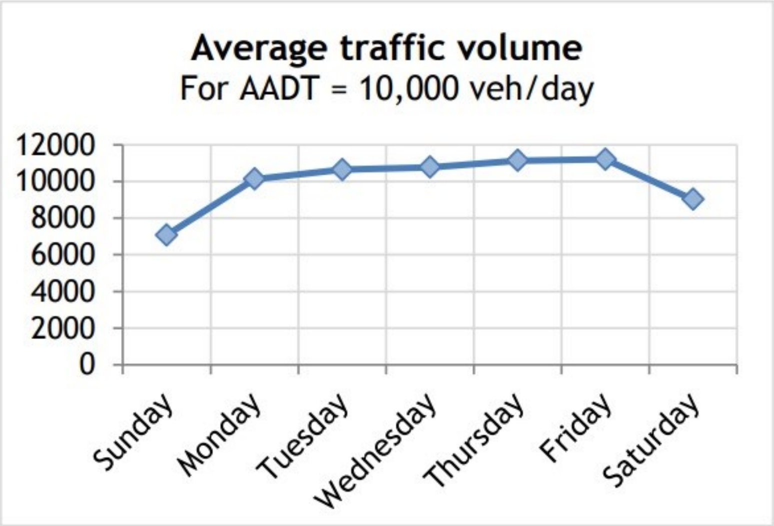

Figure A-1 Montreal traffic volume pattern per the day of the week (City of Montreal) (Oum, 2017)

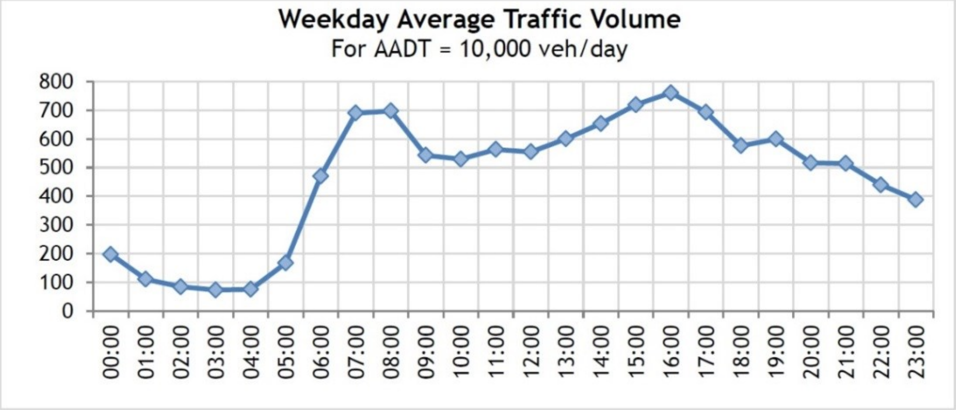

Figure A-2 Montreal traffic volume pattern per the day of the week (City of Montreal) (Oum, 2017)

Table A-1 Discretization of the time of the day (Oum, 2017)

j=	Night	Morning	Morning peak hours	Midday	Afternoon peak hours	Evening
From	00:00 a.m.	06:00 a.m.	07:00 a.m.	09:00 a.m.	04:00 p.m.	06:00 p.m.
To	05:59 a.m.	06:59 a.m	08:59 a.m.	03:59 p.m.	05:59 p.m.	11:59 p.m.
Total	6 hours	1 hour	2 hours	7 hours	2 hours	6 hours

The average annual daily traffic (AADT), which was collected from the Montreal Department of Transportation, should be factored to consider weekly and daily variations of traffic volumes. At this stage monthly variations are neglected. Therefore, the resulting traffic volume factors used in our models are illustrated in Table A-2. For example, the vehicle traffic density (VTD_{ij}) during morning peak hours on Saturday is expressed as 0.1237 × AADT.

Table A-2 Traffic Volume Factors (Oum, 2017)

	Weekday	Saturday	Sunday
Night	0.0572	0.0477	0.0374
Morning	0.0495	0.0414	0.0325
Morning peak hours	0.1476	0.1237	0.0970
Midday	0.4019	0.3365	0.2641
Afternoon peak hours	0.1468	0.1229	0.0964
Evening	0.2752	0.2297	0.1803

In other to assess the VTD for each type of vehicle (automobile, bus, light truck and heavy truck) and for each type of trips (business, non-business), the statistics on vehicle volumes authorized to circulate on Montreal Island jurisdiction were used. They are computed by the SAAQ. Table A-3 summarizes the modal shares of vehicle volumes used in this study. For example, the vehicle traffic density (VTD_{ijkl}) during morning peak hours on Saturday for automobiles in business trips is expressed as 0.1237 × 4.97 % × AADT.

Table A-3 Modal Shares of vehicle volumes in circulation (Oum, 2017)

	Non-business	Business
Automobile	60.67 %	4.97 %
Light truck	23.84 %	7.31 %
Heavy truck		2.82 %
Bus	0.39 %	

The vehicle occupancy rate VORk, which the average number of passengers, is shown in Table A-4.

Table A-4 Average vehicle occupancy rate (Oum, 2017)

Automobile	Bus	Light truck	Heavy truck
1.3	65	1.3	2.3

For calculating increased travel time (ΔT_{ij}) in hours by considering Delay time because of congestion in the road (speed reduction) and/or increased time of travel because of detour road (increased travel distance), the following equation is used:

$$\Delta \text{T}= \frac{L}{V}$$

L: traveling distance

V: speed

Appendix B – PPP Cost-sharing

According to Clé de Sol (2005), one of the models for utility tunnels cost sharing is Public, Private, Partnership (PPP). The model is represented as an Excel file including 20 sheets. The sheet of 'Bank' presents five types of important elements about financial flows:

(1) Financial requirements of manager-operator during the construction period;

(2) Financial requirements of manager-operator during the operation period;

(3) Determining the entrance fees for operators of gallery;

(4) Total debt and financing charges for the municipality;

(5) The working capital (BFR) required during the construction period.

This document explains the flowcharts of the bank-related calculations (Figures B-1 to B-5), presents the equations, and variables.

Flowchart explanation:

Remarks:

- To start the process, first the value of *t* equals 1 for the first year and is increased for next years.
- All the calculations are based on the values Base Year (BY). To find the inflation-adjusted values, a calculated value with BY amounts should be multiplied at *Inflation Index (IINDX)* by this formula: $\mathrm{GIINDX}_{\mathrm{CY}} = (1 + \mathrm{GIR})^{(\mathrm{CY}-\mathrm{BY})}$, by knowing *General Inflation Rate (IR)*, *Current Year (CY)*, and *Base Year (BY)*. Or $\mathrm{CIINDX}_{\mathrm{CY}} = (1 + \mathrm{CIR})^{(\mathrm{CY}-\mathrm{BY})}$ by knowing *Construction Inflation Rate (IR)*, *Current Year (CY)*, and *Base Year (BY)*.

1. Loop 1

In loop 1 (Figure B-2), to calculate the *Construction Cost of Gallery for year t* (CCG_t), if *t* is greater than *Duration of Construction (DC)*, then the CCG_t for that year will be zero. In other words, after construction, there is no construction cost. If the selected year *t* is less than or equal to the *DC*, then

CCG_t can be calculated based on Equation (B-1) and assumed values of *Total Construction Costs of Gallery (TCCG)* and *Breakdown of construction costs for year t (BCC_t).*

$$CCG_t = TCCG \times BCC_t \tag{B-1}$$

Total Initial Investments of gallery for year *t (TII_t)* includes construction and non-construction costs. To calculate *TII_t* with Equation (B-2), the values of *Initial investment except construction of gallery* for year t *($IIEC_t$)*, e.g. cost of study, land acquisition, etc., are assumed for first year, and the value of *CCG_t* is transferred from Equation (B-1).

$$TII_t = CCG_t + IIECC_t \tag{B-2}$$

To calculate the *Total Financing of Gallery for year t (TFG_t)*, the value of *TII_t* should be transferred from Equation (B-2) and the value of working capital for year t (*BFR_t*) as an external input (cash flow or difference of resources and costs for each year), is needed for Equation (B-3).

$$TFG_t = TII_t + BFRF_t \tag{B-3}$$

The next important cost is *Entrance Fee of Occupants Except Municipality for year t ($EFOEM_t$)*. The value of *$EFOEM_t$* equals zero if the year *t* is during the construction. For the years after construction, Equation (B-4) calculates *$EFOEM_t$* by multiplying the Future Value (FV) of *Entrance Fee of All Occupants (EFAO),* which is $\frac{\text{EFAO}}{\sum_{\text{t}=1}^{\text{DC}} \frac{\text{BCC}_\text{t}}{(1+\text{DR})^\text{t}}}$ using *Discount Rate (DR)*, *Duration of Construction (DC),* and *Construction Costs in % for year t (BCC_t)*, at *BCC_t* and *Distribution of Entrance Fee for Occupants Except Municipality in % (DEFOEM).*

$$EFOEM_t = \frac{EFAO}{\sum_{t=1}^{DC} \frac{BCC_t}{(1+DR)^t}} \times BCC_t \times DEFOEM \tag{B-4}$$

To calculate *Total to be Financed by Municipality for year t (TFM_t)*, the sum of *Entrance Fee of Occupants Except Municipality for year t ($EFOEM_t$)* (Equation (B-4)) and *Contribution of the Manager of the Gallery in the form of capital for year t ($COMG_t$)* (an external input), should be subtracted from the value of *Total Financing of Gallery for year t (TFG_t)* (Equation (B-3)).

$$TFM_t = TFG_t - (EFOEM_t + COMG_t) \tag{B-5}$$

Capitalized Interest of Basic and Margin rates for year t ($CIBM_t$) is the amount of interest on the *Debt Balance at the Beginning of Year t ($DBBY_t$)* (Equation (B-12)) plus half of *Total to be Financed by Municipality for year t (TFM_t)* (Equation (B-5)). The half represents an average of TFM_t during year t. The *Debt Balance at the Beginning of Year 1 ($DBBY_1$)* is zero and for the next years will be calculated in the previous year as shown in (Equation (B-12)). The interest rate is sum of *Base Rate (BR)* and *Margin (MRGN)* rate as assumed for the project.

If the year t is in Duration of Construction (DC) or 1<t<DC, it is required to refer to Loop 1-1 to calculate $CIBM_t$ ($CIBM_2$,…, $CIBM_{DC}$).

$$CIBM_t = \left(DBBY_t + \frac{TFM_t}{2}\right) \times (BR + MRGN) \tag{B-6}$$

Theoretical Amount of Borrowing to Calculate Bank Commissions (TABCBC) is calculated with Equation (B-7). To find this value, sum of *Total to be Financed by Municipality for year t (TFM_t)* (Equation (B-5)) and *Capitalized Interest of Basic and Margin rates for year t ($CIBM_t$)* (Equation (B-6)) for all years of *Duration of Construction (DC)*, is multiplied at one plus the sum of rates of *Commission of Engagement (COE)* and *Commission of Arrangement (COA)* as assumed in the project.

$$TABCBC = \left(\sum_{t=1}^{DC} TFM_t + \sum_{t=1}^{DC} CIBM_t\right) \times (1 + (COE + COA)) \tag{B-7}$$

To *Calculate Amount of Commission of Engagement for year t (ACOEt)* using Equation (B-8), the value of *TABCBC* from Equation (B-7) should be subtracted from *Total to be Financed by Municipality for year t (TFM_t)* (Equation (B-5)) and the result should be multiplied at the rate for *Commission of Engagement (COE)*. Investopedia (2017) described $ACOE_t$ or Commitment Fee as a fee that a lender charges borrower to compensate for lender's commitment to lend or providing access to a potential loan. The Commitment Fee is charged on the unused portion of the loans since the fund is on hold aside for the borrower and still cannot charge interest for its use. For this reason, $(\mathrm{TABCBC} - \sum_{t=1}^{t} \mathrm{TFM}_t)$ represents the unused portion of the loan, which is for after year *t*.

$$ACOE_t = \left(TABCBC - \sum_{t=1}^{t} TFM_t\right) \times COE \tag{B-8}$$

where:

$ACOE_t$: Amount of Commission of Engagement for year t

COE: Commission of Engagement rate

Amount of Commission of Arrangement (ACOA) is only for the service of loan arrangement and is charged only at the first year. To calculate it using Equation (B-9), the value of *TABCBC* from Equation (B-7) should be multiplied at the rate of *Commission of Arrangement (COA)* as an assumption.

$$ACOA_t = TABCBC \times COA \quad (only\ for\ t{=}1) \tag{B-9}$$

where:

ACOA: Amount of Commission of Arrangement

COA: Commission of Arrangement rate

To calculate *Amount of Borrowing to Finance Initial Costs (ABFIC)* by Equation (B-10), the following total amount for all *Duration of construction (DC)* should be added: *Total to be Financed by Municipality for year t (TFM_t)* (Equation (B-5)), *Capitalized Interest of Basic and Margin rates for year t ($CIBM_t$)* (Equation (B-6)), *Amount of Commission of Engagement for year t ($ACOE_t$)* (Equation (B-8)), and *Amount of Commission of Arrangement ($ACOA_t$)* (Equation (B-9)).

$$ABFIC = \sum_{t=1}^{DC}(TFM_t + CIBM_t + ACOE_t + ACOA_t) \tag{B-10}$$

As shown in Equation (B-14), *Debt Installment for year t (DI_t)* includes two portions: (a) *Interest Charges for year t (IC_t)* (Equation (B-13)) as the interest portion of the installment, and (b) *Principal Reimbursement for year t (PR_t)* (Equation (B-11)) as the principal portion. To find PR_t of the loan, the Excel function of PPMT (Principal Payment) is used. This function is used only when the DI_t is constant and periodic, with a constant interest rate (Microsoft, 2017). Since the loan reimbursement starts after construction, the value of PR_t is zero during construction. The inputs are as following.

$$PR_t = PPMT\ (BR{+}MRGN, PN_t, DL{-}DC, ABFIC, PD) \tag{B-11}$$

where:

PR_t: Principal Reimbursement for year t

PN_t: Period Number for loan payment of year t

DL: Duration of Loan

PD: Payment due at (0: the end of the period, 1: the beginning of the period)

ABFIC: Amount of Borrowing to Finance Initial Costs (ABFIC) (Equation (B-10))

Debt Balance at the Beginning of Year 1 ($DBBY_1$) is zero, to find it for the year *t*, the following amounts from previous year (year *t-1*) are added to the *Debt Balance at the Beginning Year t-1 ($DBBY_{t-1}$)*: TFM_{t-1} (Equation (B-5)), $CIBM_{t-1}$ (Equation (B-6)), $ACOE_{t-1}$ (Equation (B-8)), $ACOA_{t-1}$ (Equation (B-9));

And the PR_{t-1} (Equation (B-11)) is reduced.

$$DBBY_t = DBBY_{t-1} + TFM_{t-1} + CIBM_{t-1} + ACOE_{t-1} + ACOA_{t-1} - PR_{t-1} \qquad \text{(B-12)}$$

To calculate *Interest Charges (IC_t)* (Equation (B-13)), the value *of Debt Balance at the Beginning of Year t ($DBBY_t$)* from Equation (B-12) is multiplied at (*BR*+ *MRGN*) rate.

$$IC_t = DBBY_t \times (BR+ MRGN) \qquad \text{(B-13)}$$

Debt Installment for year t (DI_t) is sum of *Interest Charges for year t (IC_t)* (Equation (B-13)) and *Principal Reimbursement for year t (PR_t)* (Equation (B-11)).

$$DI_t = IC_t + PR_t \qquad \text{(B-14)}$$

2. Loop 1-1

As demonstrated in Figure B-3, considering Duration of Construction (DC), after calculation of $TFM_1,\ldots, TFM_{DC}$ (Equation (B-5)), and $CIBM_1$ (Equation (B-6)), the values of $CIBM_2,\ldots,CIBM_{DC}$ cannot be found since they need $DBBY_2,\ldots,DBBY_{DC}$, which is dependent on $ACOE_1,\ldots,ACOE_{DC}$ and $ACOA_1$. $ACOE_t$ and $ACOA_1$ are dependent on the value of TABCBC, which is dependent on the values of $CIBM_2,\ldots, CIBM_{DC}$. These dependencies make a loop inside loop 1, called loop 1-1 as shown in

Figure B-1. To start loop 1-1, $CIBM_2,\ldots, CIBM_{DC}$ is assumed to be zero. Then TABCBC, $ACOE_1$, $ACOE_{DC}$, $ACOA_1$, $DBBY_2,\ldots,DBBY_{DC}$ are calculated and new $CIBM_2,\ldots, CIBM_{DC}$ are produced. The iterations continues n time until the variation of each of five values, namely TABCBC, $ACOE_t$, $ACOA_1$, $DBBY_t$, and $CIBM_2$ be less than 1.

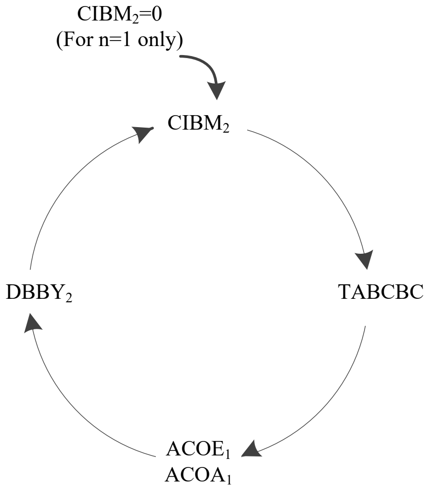

Figure B-1-Dependencies between *$CIBM_t$*, *TABCBC*, *$ACOE_t$*, and *$DBBY_t$* in loop 1-1

After completing Loop 1 and Loop 1-1, if the year *t* is not still beyond the *Duration of Contract (DCT)*, *t* is increased by one and the loop is started again from Equation (B-1) as shown in Figure B-4.

3. Loop 2

There is another loop (loop 2) only to calculate *Entrance Fee of Municipality for year t (EFM_t)* (Equation (B-15)) as shown in Figure B-5. This value is zero during construction years and is calculated for after construction years based on the assumed values. The *Entrance Fee of All Occupants (EFAO)* is assumed for the beginning of *Duration of Construction (DC)*. The Future Value (FV) of *EFAO* at the end of *DC* ($\mathrm{EFAO} \times (1+\mathrm{DR})^{\mathrm{DC}}$) is the same as Net Present Value (NPV) to be used in Equation (B-15) using Discount Rate (DR). Multiplication of *Distribution of Entrance Fee for Municipality in % (DEFM)* is for finding the portion of municipality for entrance fees. Number of periods for annual payments is *Duration of Contract in years (DCT)* except DC plus one, because there is no payment during construction and payments are made at the begging of each year plus last payment at the end of last year.

$$EFM_t = DEFM \times (EFAO \times (1+DR)^{DC}) \times \frac{DR}{1-(1+DR)^{-(DCT-DC+1)}} \qquad \text{(B-15)}$$

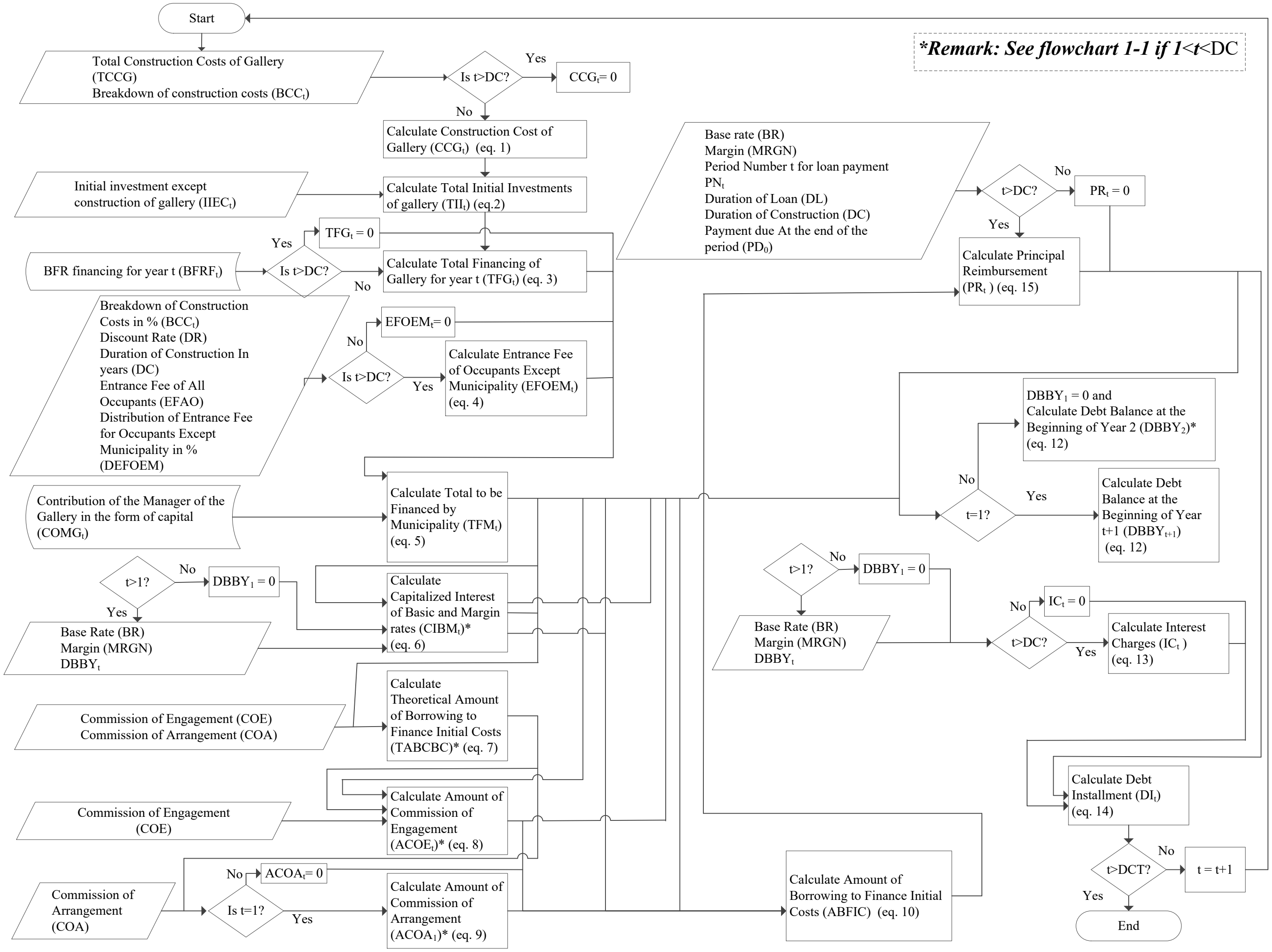

Figure B-2 – Flowchart 1 of sheet "bank" for loop 1 for calculating the costs

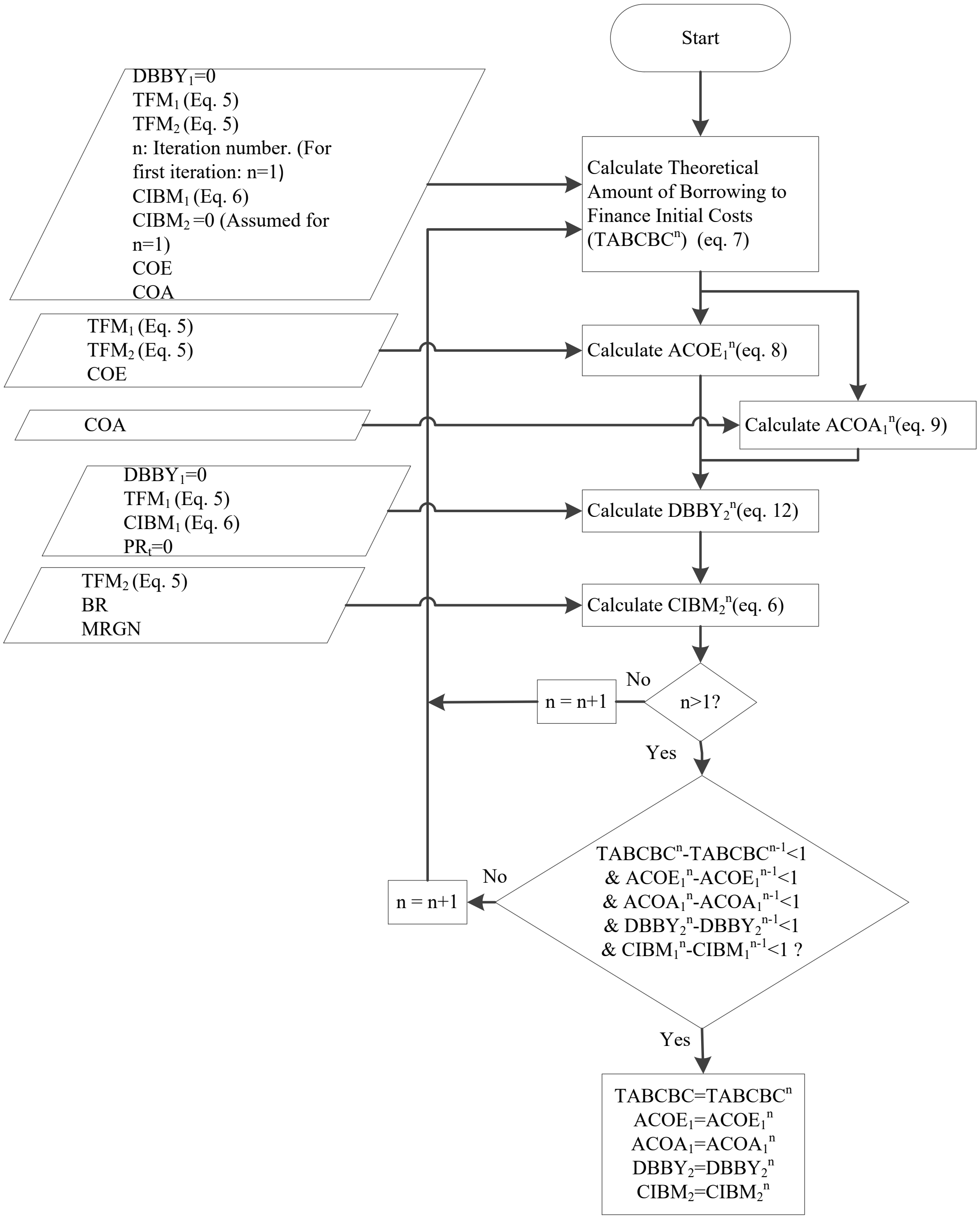

Figure B-3 – Flowchart 1-1 of sheet "bank" for loop 1-1 when DC=2 for calculating the costs

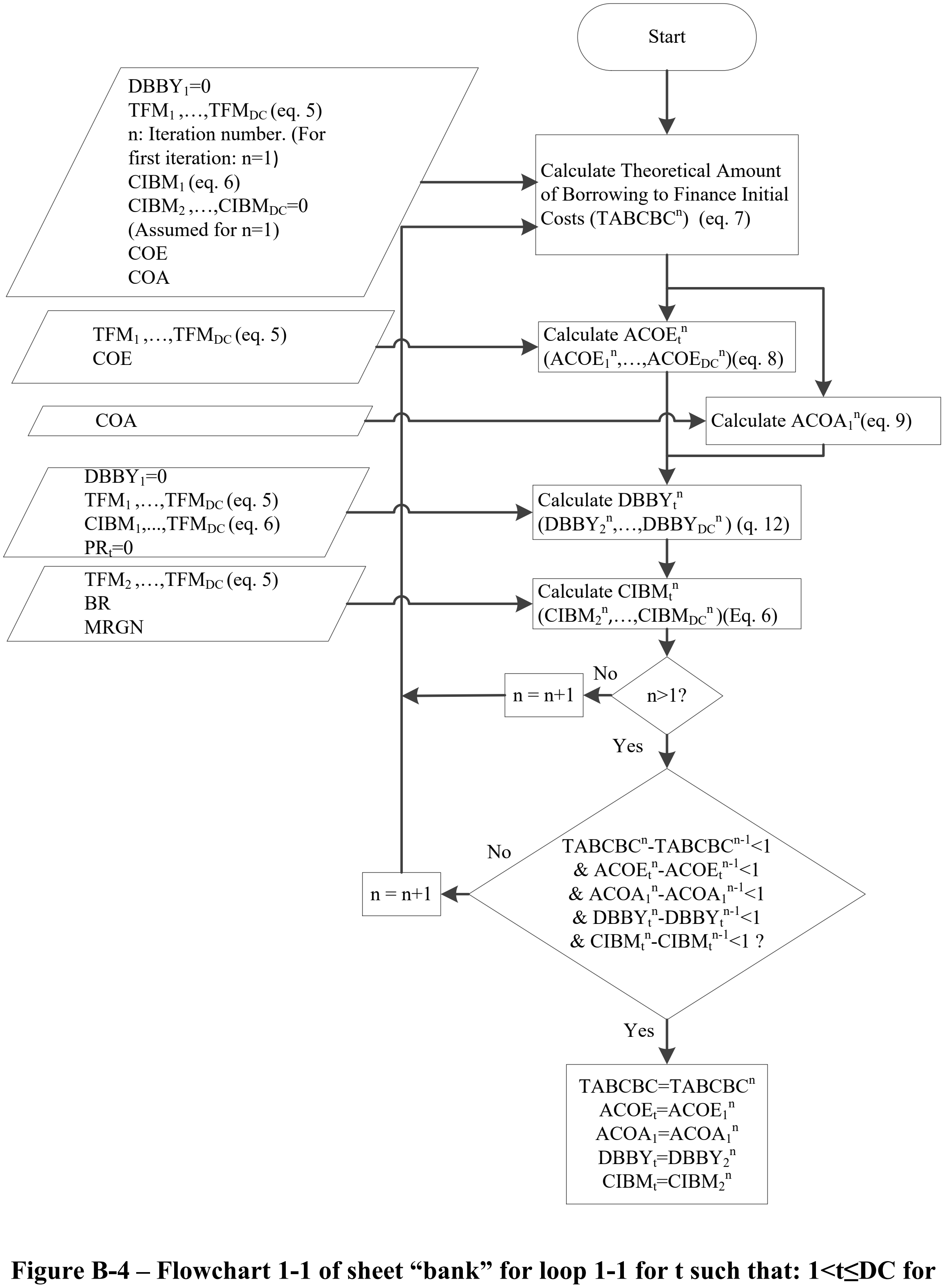

Figure B-4 – Flowchart 1-1 of sheet "bank" for loop 1-1 for t such that: $1<t\leq DC$ for calculating the costs

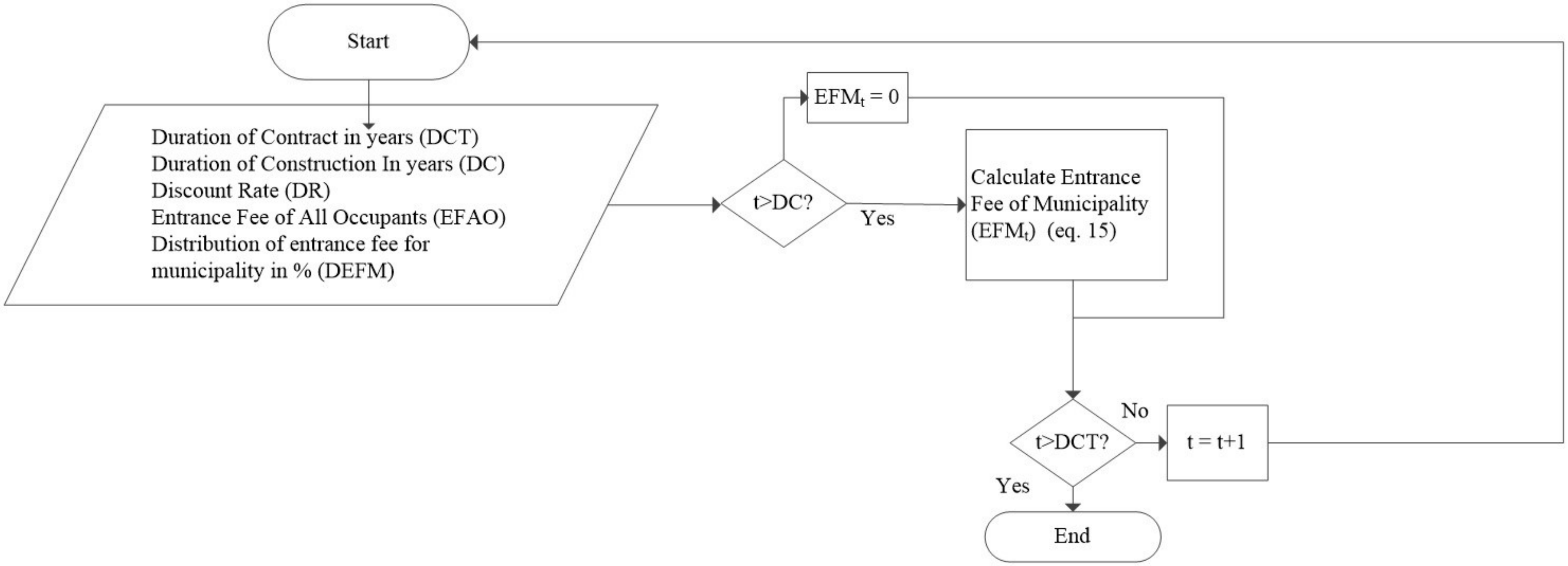

Figure B-5 – Flowchart of sheet "bank" for loop 2 for calculating the costs