Application of a Sustainability Model for Assessing Water Main Replacement Options

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Abstract: Sustainable development, conceived as a new and multidisciplinary paradigm, is receiving much attention throughout the global community. The purpose of this paper is to apply the sustainability assessment model (SAM), an assessment and decision making methodology, to a water main replacement project in an urban environment to determine the most sustainable project alternative among three possible options. This case study presents the use of SAM in considering various multicriteria sustainability indicators while working towards achieving sustainability enhancement. Objectives of sustainability enhancement include: (1) minimizing environmental impact; (2) maximizing economical benefit and output; (3) social and cultural conservation and promotion; and (4) satisfying basic requirements such as structural soundness and capacity. Six assessment methods including the analytic hierarchy process, cost, pollution, energy, time estimation, and natural resource depletion analysis are used for both qualitative and quantitative sustainability indicators. The weighted sum model is then utilized to integrate the six independent assessment results to elicit the final decision.

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Introduction

Physical infrastructure systems including transportation, water and wastewater treatment and conveyance, energy, solid waste, and water resource have significant economic, social, and environmental impacts both from their initial development and from services throughout their life cycle. An emerging new conceptual paradigm in the infrastructure development area is the enhancement of sustainability principles. In the past, achieving structural soundness and adequate capacity were main considerations in infrastructure development. Later, focusing on maximizing economical benefit in addition to the previous objectives became the foremost task due to budgetary constraints (Mirza 2006). Recently, environmental issues and social impacts have been recognized to be at least as important as economical benefits for infrastructure construction projects. Complications of interrelationships and implications of the many issues have been evolving as society pursues higher standards of living. The concept of sustainable development is introduced to define a new approach in many areas of human society and civilization. Numerous definitions of sustainable development and conceptual development have been proposed from previous research. Most definitions are extremely loose and cover broad areas of interest, resulting in many different interpretations and disconformities regarding the boundaries of sustainability. Therefore, the objective, achievable level, and boundary of sustainability assessment must be defined before implementing the assessment process. Several definitions are referred and frame the backbone of sustainability indicator identification described in this paper.

Providing clean water is one of the essential infrastructure services for human survival and prosperity of the economy. The size of this infrastructure system and impacts on human life are tremendous. Currently, the total length of the water distribution system extends more than 2.6 million km in the United States (Grigg 2005). The system consists of various pipe sizes, materials, ages, and conditions. As urbanization and human habitat expands, so must this system, while also maintaining and upgrading the existing system. According to the Gap analysis report from the United States Environmental Protection Agency (USEPA), the cost of water main replacement is going to reach more than 10 billion dollars in the year 2030 due to deterioration of aging existing water distribution systems and the increase in the cost of operation and maintenance of those systems (USEPA 2004). The remarkable magnitude of this infrastructural task in water distribution systems makes us consider many potential sustainability issues, especially economical constraints, environmental degradation, and social disturbances, all leading to the overall betterment of the quality of life for present and future generations. Enhancement of sustainability should not remain as a conceptual aspiration, but should rather be implemented in engineering and construction practice.

According to Bourdeau (2000), enhancement of sustainability can be realized by focusing on three aspects: (1) minimizing environmental impact; (2) maximizing economical benefits; and (3) minimizing sociocultural impact. This triple bottom line approach has gained much popularity among protagonists. However, research on the development of effective measurement for sustainability in infrastructure development is still in its infancy. Assessment of infrastructure sustainability can be approached by either focusing on the development stage or systemic sustainabil-

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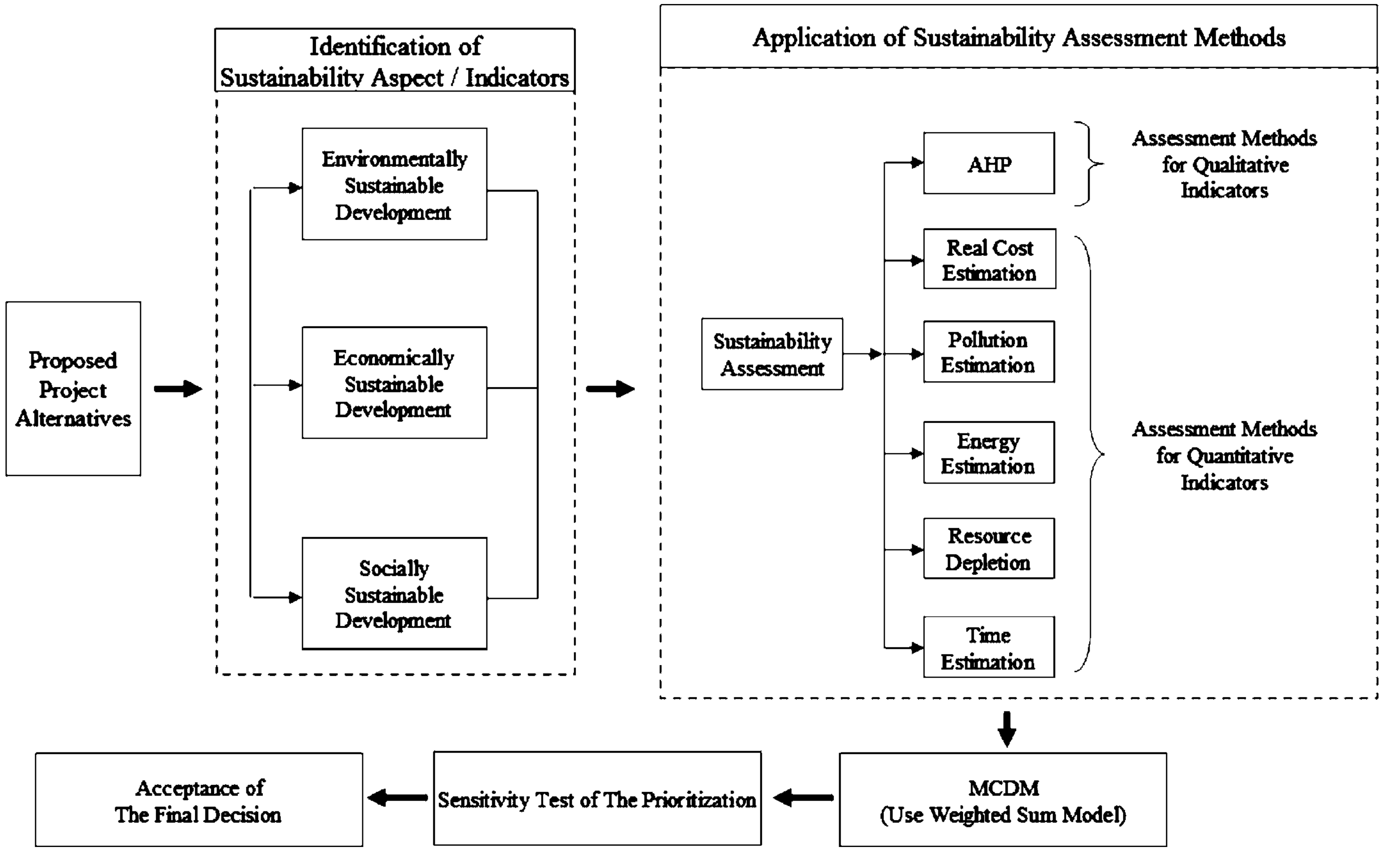

Fig. 1. Sustainability assessment model framework

ity performance during the life cycle. A combination of the two approaches is also a possible way to assess the entire sustainability of an infrastructure development project. The sustainability assessment method applied in this paper emphasizes the project level and intends to provide a yardstick to main stakeholders of an infrastructure project for support of their decision making in selecting a sustainable project alternative. This case study focuses on sustainability assessment in a water main replacement project where multiple options are available.

The assessment model presented in this paper is referred to as sustainability assessment model (SAM). SAM is based on three major steps in the framework: (1) identifying sustainability indicators; (2) assessing selected indicators in appropriate measurement; and (3) eliciting a decision based on the assessment results. SAM's application is demonstrated through application to a water main replacement project in an urban environment given three available construction options.

Sustainability Assessment Modeling Framework

Until recently, most research and literature has been focused on conceptual development for sustainability. One of the main objectives in pursuing sustainable development is to ensure that future generations have ample options for their needs (Tonn 2004). A sustainability assessment model should have the capability to assess how present decisions for infrastructure development affect the future. This decision is based on reciprocal evaluations between rather oxymoronic values such as development against environmental protection, natural asset conservation, social and cultural value, and economical efficiency. Development of a sustainability assessment model at a practical level for physical infrastructure system development is still in its infancy. Subsequently, few modeling attempts can be cited. Ugwu et al. (2006) developed a model called sustainability appraisal in infrastructure projects (SUSAIP) for project level infrastructure sustainability assessment. SUSAIP is based on the evaluation of key performance indicators (KPIs) focusing on a specific project (micro) level. It assesses the indicators using a Likert scale, evaluating the magnitude of sustainability relevance through multiple project stakeholders. Weight factors are determined from a survey and applied to the decision making process. Dasgupta and Tam (2005) developed a framework using the multilayered framework of civil infrastructure system (CIS) indicators. Their framework focuses on screening proposed multiple alternatives through a multilayered framework. Quantification of some indicators should be reinforced with adequate methodologies and data. There are few sustainability assessment techniques for building development. The most popular method is the leadership in energy and environmental design (LEED) method. LEED rates sustainability by accumulating scores from multiple categories including economical performance, resource use, environmental impact, energy conservation, and long-term operation and management (USGBC 2006). The LEED method is known to be an effective method; however, it is limited to housing and building applications rather than infrastructure systems.

This paper describes the application of a modeling framework developed by Koo and Ariaratnam (2008). The modeling framework (Fig. 1) is designated as the SAM. SAM is a decision support model for use when multiple alternatives are possible for a project. Various aspects and interests related to sustainability in project development are translated into sustainability indicators.

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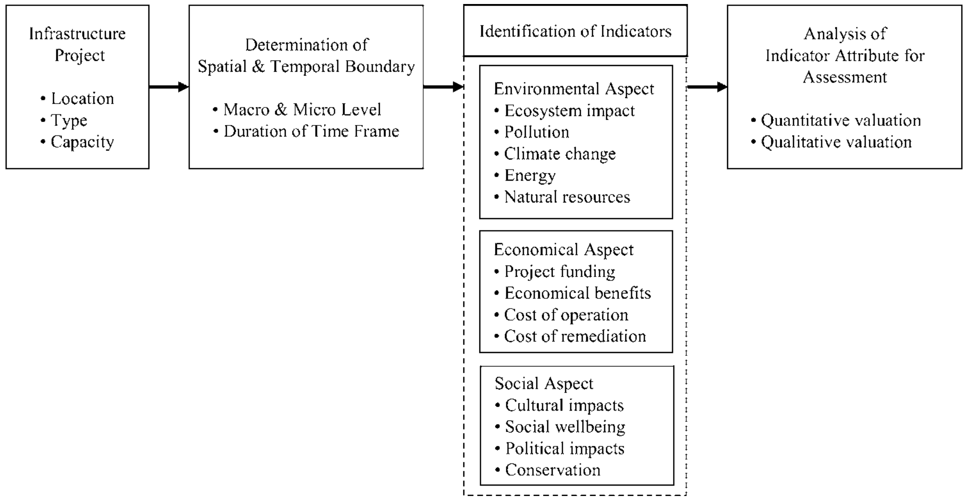

Fig. 2. Sustainability indicator identification process

These indicators are then assessed by six major modules. A multicriteria decision making (MCDM) technique is used to integrate the six modular results through a normalization process. The final decision is based on the numerical prioritization of each proposed alternative.

Identification of Sustainability Indicators

Project stakeholders should reach a consensus on a definition of sustainable development and pursue clearly defined objectives before beginning a sustainability indicator identification process. The World Commission on Environment and Development (WCED) defines sustainable development as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). This is the most popular definition, implying that anything for human betterment can be an issue of sustainable development, but it is too general to be defined in terms of a practical guideline. The American Society of Civil Engineers (ASCE) defines sustainable development as "the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter and effective waste management while conserving and protecting environmental quality and the natural resource base essential future development" (ASCE 2004). The ASCE definition contains a more detailed approach for the direction of enhancing infrastructure sustainability. Adequate infrastructure development should be continuously progressing to meet human demands. This progress will be sustainable when many contradictory aspects are reconciled and balanced. Vanegas et al. (1996) proposed aspects in traditional and sustainable perspectives. Traditional aspects include cost, quality, and time. Sustainability aspects include natural resource, environmental quality, biodiversity, social equity and cultural conservation, and economical benefits.

The framework for a sustainability indicator identification process is presented in Fig. 2. Sustainability indicators represent a specific aspect of sustainability measurement. Determination of the spatial and temporal boundary should be considered prior to the identification phase. Aggregation of micro (project) level sustainability is a part of macro (national or global) level sustainability and it can be referred to as a "scale effect". For example, the green house effect or global climate change may be aggravated by adopting a material generating higher CO_2 than other materials. However, contribution and magnitude of a green house effect and global climate change from an infrastructure project development may be very insignificant. Dust or noise control can be much more of a significant sustainability issue at a micro level. Therefore, significance of most sustainability indicators can be varied by the boundary set up.

Specific sustainability indicators represent how sustainability is interpreted in practice. Sahely et al. (2005) proposed sustainability indicators in urban infrastructure systems including buildings, transportation, and water supply. Other researchers (Ugwu et al. 2006; Dasgupta and Tam 2005) also provide a similar set of sustainability indicators related to infrastructure development. Many subindicators can be organized under a main indicator. The number of indicators and coverage depends on the complexity of the sustainability assessment and the project itself. Forty-seven sustainability indicators were presented in SAM by Koo and Ariaratnam (2008). These 47 sustainability indicators were determined by interviews and surveys of underground infrastructure industry experts conducted in 2006. The original survey was structured with various questions for rating the significance of each sustainability issue categorized by three main areas: economical, environmental, and social sustainability. The case study presented selects appropriate indicators from the 47 indicators for demonstrating the assessment process.

Water Main Replacement Case Study

Project Description

The main objective of this case study is to verify the applicability of sustainability assessment by applying SAM to a typical municipal capital improvement project. A section of water main system located in the City of Scottsdale, Arizona, is used for this case study. Currently, 807.7 m (2,650 LF) of existing 200 mm (8 in.) diam asbestos cement pipe (ACP) water main system is providing the drinking water supply to local residents and businesses. The case study assumes that this ACP water main system is required to be replaced as a result of it being undercapacity due to urban growth and deterioration by aging. The depth of 200 mm distribution water mains normally ranges between 1.2 and 3 m. Due to frequent service connections and potential sew-

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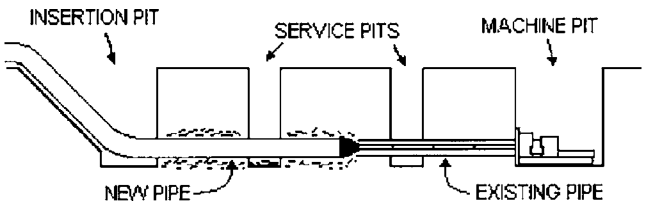

Fig. 3. Typical configuration for continuous pipe installation using static pipe bursting [Reprinted with permission from Lueke and Ariaratnam (2001)]

age contamination, distribution water mains tend to be installed at shallow depths above the sanitary sewer lines. Therefore, installation depth is not a significant factor in project alternative selection. Three alternatives combining different construction materials, methods, and pipe layout are proposed for analysis. The three project alternatives are: (1) new installation of ductile iron pipe using conventional open cut with shield (Alternative I); (2) replacement of existing water main to high density polyethylene (HDPE) pipe using the pipe bursting method (Alternative II); and (3) new installation of fusible polyvinylchloride (PVC) pipe using the horizontal directional drilling (HDD) method (Alternative III). Selection of each distinctive alternative will result in different positive and negative impacts anticipated during the construction and life cycle stages. These impacts are detailed by the sustainability indicators and are evaluated through relative significance ratings and absolute value comparisons.

Pipe bursting and HDD are known as trenchless technologies that require significantly less excavation, disturbances, and completion time than the conventional open cut method. The pipe bursting method is defined as the replacement of the original pipe by fragmenting the existing conduit and installing a new pipe of equal or larger diameter in its place (Bennett and Ariaratnam 2005). Fig. 3 illustrates the pipe bursting process. Two major working pits, the machine pit and insertion pit, should be of an adequate size to negotiate working space for machine operation, and maximum bending radius of flexible pipe, or section length of sectional rigid pipe.

HDD, a trenchless underground pipeline installation process, is performed in three distinct phases: (1) pilot bore; (2) reaming; and (3) pipe pullback. All three phases are accomplished through the underground bore connecting two end sides: the drilling head entry side and the exit side. As illustrated in Fig. 4, the process requires limited excavation. Most installations can be done from the surface allowing proper set back distance from the designed depth of bore. During installation of on-grade sewers, it is common to set the HDD machine in the ground within a pit and drill to the connecting manhole location.

Utilizing these two trenchless technologies in an urban environment provides tremendous benefits, including minimizing disturbance and reducing the project schedule. However, the conventional open cut method is still used in practice for typical underground infrastructure projects. Further literature on these two trenchless methods may be found in Knight et al. (2001), Lueke and Ariaratnam (2001), Baumert and Allouche (2002), and Bennett and Ariaratnam (2005).

Sustainability Assessment

The assessment process consists of six assessment modules as shown in Fig. 1. The six assessment processes proposed for this paper are: (1) analytic hierarchy process (AHP); (2) real cost estimation; (3) pollution estimation; (4) energy estimation; (5) time estimation; and (6) natural resource depletion impact analysis. A single assessment method is determined to be unrealistic to assess all sustainability indicators that have multicriteria characteristics. The assessment process is based on readily available data and various estimations at the front end stage for the future life cycle stages. Therefore, selection of appropriate assessment methods is dependent on the reliability and availability of qualitative and quantitative data. Modeling boundary and scope are illustrated in Fig. 5. The first step is to define the project descriptions and objectives. The second step involves proposing design alternatives that are able to satisfy the project objectives. Detailed items of the sustainability aspect are presented in each assessment category. This paper focuses on these 12 sustainability aspects and appropriate sustainability indicators are accordingly selected from the predetermined 47 indicators. Assessment results are presented in the following sections for each assessment category. To complete the sustainability assessment process, these six independent results are required to be integrated through a normalization process provided by the weighted sum model (WSM).

AHP for Qualitative Assessment

The AHP was developed by Saaty (1980). AHP has previously been utilized in construction decision making processes such as project priority (Mohamed et al. 2002), procurement method selection (Cheung et al. 2001), and equipment selection (Shapira and Goldenberg 2005), especially when the decision factors are subjective and qualitative. AHP utilizes multiple relative comparison matrixes for each level hierarchy structure in Fig. 6. Relative

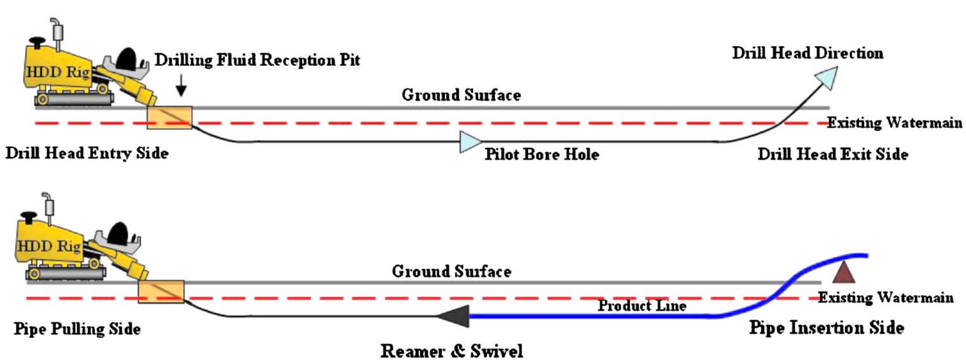

Fig. 4. Typical configuration for horizontal directional drilling operation under the existing water main

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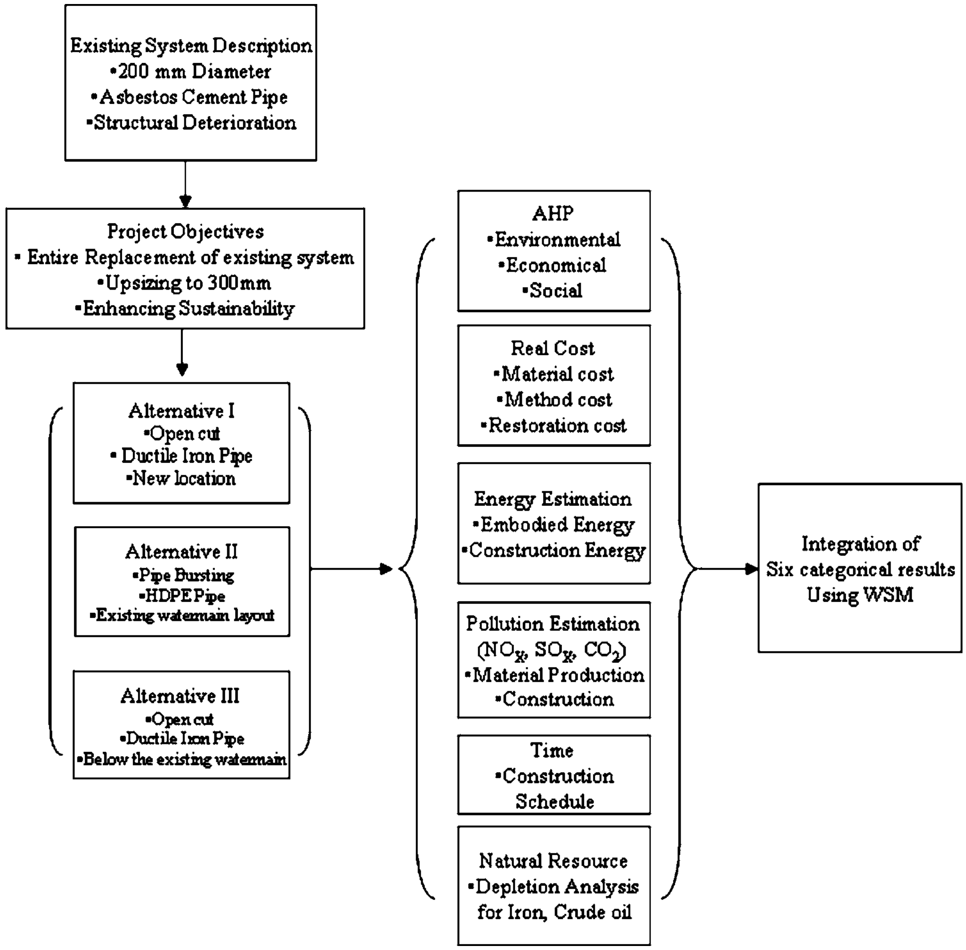

Fig. 5. Scope and boundary for the case study

weights are calculated from each comparison matrix and then aggregated into a prioritization process. AHP is used to assess all qualitative sustainability indicators for the sustainability assessment model. Twenty-nine qualitative indicators were selected for the AHP assessment described in this paper. The number of pairwise comparisons is dependent on the number of levels, indicators, and alternatives in each level. From the hierarchy structure shown in Fig. 6, the total number of pairwise comparison and comparison matrices are calculated as follows:

$$\begin{aligned}&\text{number of pairwise comparisons}\\&\quad= 3\ (\text{first level})\\&\qquad+\Sigma\{[45(10\ \text{indicators}),\ 45(10\ \text{indicators}),\ 36\ (9\ \text{indicators})]\\&\qquad(\text{second level})\}+87\ \{(29\ \text{indicators}\times 3\ \text{alternatives})\\&\qquad\times(\text{third level})\}\\&\quad= 216\ \text{pairwise comparisons}\end{aligned}\tag{1}$$

$$\begin{aligned}&\text{number of pairwise comparison matrices}\\&\quad= 1\ \text{matrix (first level)}+3\ \text{matrix (second level)}\\&\qquad+29\ \text{matrix (third level)}\\&\quad= 33\ \text{matrices}\end{aligned}\tag{2}$$

The summary of AHP assessment is presented in Table 1. The aggregation process consists of multiplying relative weight factors from the comparison matrices. Third level weight factors of each alternative are multiplied by the second level weight factors, and then these values are multiplied with weight factors from the first level. The final prioritization presented in the last row is a summation of three subprioritization values including the economical, environmental, and social aspects of each alternative. From the AHP assessment, the pipe bursting method with HDPE is assessed as the most sustainable method in terms of 29 qualitative sustainability indicators.

Real Cost Estimation

Real cost estimation is a summation of quantitative cost values in the life cycle. The real cost estimation process treats costs as resources of an infrastructure facility. The magnitude of the required amount of the costs represents the economical efficiency of a selected alternative. Conventional life cycle costs (LCCs) in infrastructure development emphasizes the absolute cost comparison of the total capital required through the designed life cycle to the present. Real cost focuses on providing identification of individual economical implications including detailed direct construction cost and indirect costs such as restoration, social costs, and environmental remediation costs. For the case study presented, only three available cost items (i.e., construction material, method, and restoration costs) are estimated for the real cost estimation process due to the inadequacy of available cost data. Assuming that all future costs and temporal intervals for maintenance, operation, and rehabilitation are the same, the effect of future costs is considered to be insignificant when assessing cost implications.

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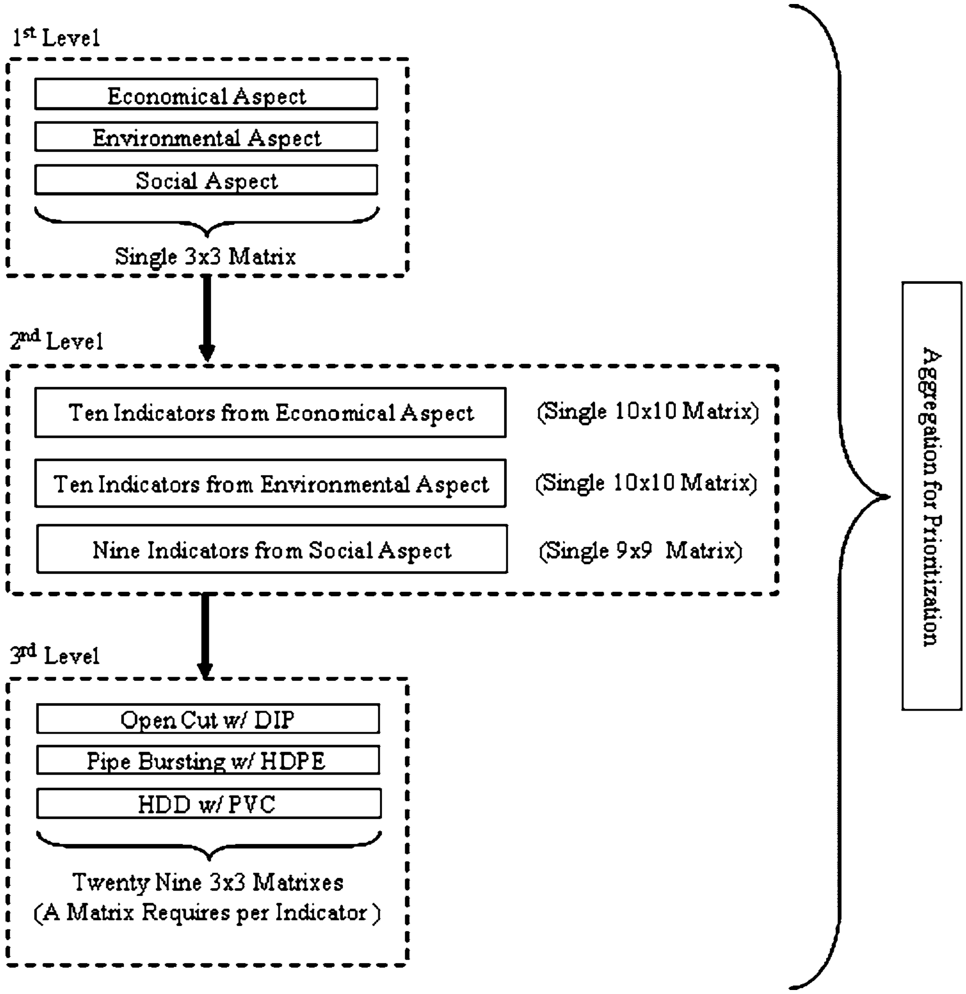

Fig. 6. Hierarchy structure for qualitative indicator analysis

Table 2 presents the summary of the real cost estimation analysis of the three proposed alternatives. The table reveals Alternative III to be the most expensive and Alternative II the least expensive method. Cost data were acquired from various sources. Material costs are based on the current market value acquired from major pipe providers. Construction method costs were obtained from bid schedules, historical cost data and published references, and expert interviews. Restoration cost was calculated by multiplying the amount of pavement cutting and replacement, and conventional asphalt concrete pavement unit costs from the bid schedule tendered to the City of Scottsdale in 2006. Imparity of long-term quality is a hidden cost of utilizing the open cut method. According to Knight (2004), replaced pavement due to employing conventional open cut construction shows significant long-term structural integrity deterioration. This is already included in the AHP economical assessment in Table 1. However, this indirect cost implication, due to damaging existing pavement, may be converted into monetary value using proper deterioration and valuation techniques. Utilizing trenchless methods can significantly lower associated long-term operational and maintenance costs because pavement replacement is minimized. The cost of the construction method and material costs is significantly variable depending on specific project requirements, complexity of the project, capability of the contractor, market conditions, and all other unexpected risks. Therefore, reasonable judgment by the decision maker is required to make a sensible comparison of these cost items.

Energy and Pollution Estimation

Assessment for energy consumption and pollution generation involves verifying energy efficiency and environmental degradation of the three proposed alternatives. These two assessments are directly related because major air emissions are caused by fossil energy consumption. When the operational energy for water distribution service during the life cycle is assumed as equal, energy and pollution estimation during the construction material manufacturing and construction stage is where the major differentiation of energy and pollution impacts can be seen. The estimated amount of fossil energy consumption is based on the amount of work, production capacity, and operational work hours for heavy equipment. Currently, diesel is the major fossil energy source used in most heavy equipment operations. For purposes of this analysis, diesel was assumed as the only energy source for equipment operations and is converted into an energy unit. Embodied energy represents all the energy required from raw material extraction to manufacturing construction material. Embodied energy coefficients are provided by Specht et al. (1996). Embodied energy coefficients are multiplied by the amount of construction

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Table 1. Summary of AHP Result for Qualitative Indicator Assessment

First level (weight)	Second level		Third level: Alternative I	Alternative II	Alternative III
Economic aspect (0.30)	Eco1 (Construction material quality)	0.10	0.50	0.25	0.25
	Eco2 (Quality of the completed infrastructure structure)	0.27	0.20	0.40	0.40
	Eco3 (Land and space availability for future development after the project)	0.09	0.09	0.45	0.45
	Eco4 (Selection of an effective procurement method)	0.03	0.33	0.33	0.33
	Eco5 (Selection of an effective contract type)	0.03	0.33	0.33	0.33
	Eco6 (Potential legal dispute)	0.19	0.33	0.33	0.33
	Eco7 (Infrastructure service fee escalation due to the project funding or tax)	0.03	0.33	0.33	0.33
	Eco8 (Economical benefits/effects to the local community from the project development)	0.05	0.14	0.43	0.43
	Eco9 (Social costs due to the project development)	0.13	0.08	0.47	0.44
	Eco10 (Capability of proper operation and maintenance during the life cycle)	0.08	0.33	0.33	0.33
Subprioritization for economic aspect			0.07	0.11	0.11
Environmental aspect (0.54)	Eco1 (Recyclablity of scraped material)	0.03	0.60	0.20	0.20
	Eco2 (Waste after decommissioning)	0.06	0.60	0.20	0.20
	Eco3 [Construction nuisances (noise, vibration, visual impact, etc.)]	0.06	0.07	0.47	0.47
	Eco4 (Job site disturbance and restoration)	0.08	0.07	0.47	0.47
	Eco5 [Disruption of the ecosystem during construction (endangered and threatened species on the site)]	0.16	0.10	0.47	0.43
	Eco6 [Selection of the construction method and impact to the existing environmental hazards (e.g., Brownfield)]	0.09	0.33	0.33	0.33
	Eco7 [Likelihood of land slides, erosion, and sedimentation (environmental hazards) potential]	0.13	0.33	0.33	0.33
	Eco8 (Long-term water pollution)	0.13	0.33	0.33	0.33
	Eco9 (Long-term local air pollution)	0.13	0.09	0.45	0.45
	Eco10 (Long-term ground/soil contamination)	0.13	0.33	0.33	0.33
Subprioritization for environmental aspect			0.13	0.20	0.20
Social aspect (0.16)	Sco1 (Workers safety)	0.23	0.07	0.59	0.34
	Sco2 (Requirement of utility relocation due to the project development)	0.09	0.09	0.45	0.45
	Sco3 [Limitation of accessibility (causing segregation of community)]	0.04	0.09	0.45	0.45
	Sco4 [Public support of the project (acceptance)]	0.06	0.09	0.45	0.45
	Sco5 (Social and cultural impact due to the project)	0.08	0.14	0.43	0.43
	Sco6 (Preservation of historical and archeological assets)	0.08	0.14	0.43	0.43
	Sco7 (Social impact due to the resident relocation)	0.08	0.33	0.33	0.33
	Sco8 (Public safety)	0.29	0.08	0.59	0.33
	Sco9 (Vulnerability of infrastructure from vandalism and sabotage)	0.05	0.33	0.33	0.33
Subprioritization for social aspect			0.02	0.08	0.06
Overall prioritization of sustainability assessment (sustainability ranking)			0.23 (3)	0.40 (1)	0.37 (2)

material required for the project development in order to calculate the total embodied energy requirement. Table 3 shows the energy estimation results. Alternative I is expected to consume the highest energy, while Alternative II is estimated to use the least amount of energy, both in construction and material manufacturing. The most significant reason for the difference in the results is from the amount of soil excavation and movement. Trench excavation, backfill, and the compacting process require much more physical energy as compared to the controlled excavation and soil displacement for other alternative methods.

Pollution estimation includes the three major air emissions: NO_X, SO_X, and CO_2. The estimated amount of diesel for major construction equipment is multiplied by the emission conversion coefficients to estimate air emissions during the construction stage. Emission conversion coefficients are provided by Park et al. (2003). Other air emissions from the manufacturing process are based on the estimated amount of construction material. Air pollutant emission coefficients for various 300 mm (12 in.) pipe materials are provided by Specht et al. (1996). The result of the pollution estimation (Table 4) is a summation of these two sepa-

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Table 2. Summary of Cost Items for Real Cost Estimation

Cost items	Alternative I (open cut)	Alternative II (pipe bursting)	Alternative III (HDD)
Construction material (this item only includes pipe cost)	\$53,000 (\$65.6/m)	\$62,500 (\$77.1/m)	\$71,550 (\$88.6/m)
Construction method (installation, backfill, compaction)	\$159,000 (\$196.9/m)	\$172,250 (\$213.3/m)	\$265,000 (\$328.1/m)
Restoration (this item only includes asphalt concrete pavement replacement)	\$36,800 (\$30/m^2)	\$3,000 (\$30/m^2)	\$2,500 (\$30/m^2)
Relocation and ROW	N/A	N/A	N/A
Security	N/A	N/A	N/A
Maintenance, operation, rehabilitation	N/A	N/A	N/A
Environmental remediation	N/A	N/A	N/A
Cost total	\$ 248,800	\$ 237,750	\$ 339,050

rate estimation processes. Alternative III is expected to generate the highest release of NO_X. Alternative I is estimated to release the highest levels of both SO_X and CO_2. Alternative II is estimated to release the lowest level of all three air emissions, due to the lowest consumption of diesel fuel during the construction phase. The magnitude of the impact of various emissions to the air quality and environmental degradation can be subjective depending on the condition of local air quality. The decision maker is required to assign weight factors to these air emission impacts before the final prioritization of proposed alternatives.

Time Estimation

The magnitude of the construction schedule for construction completion has a direct correlation to sustainability issues including economical, environmental, and social impacts because the majority of local disturbances occur during the construction stage rather than the planning and service stages. The construction schedule is used as a factor for the estimation of diesel fuel consumption and air emissions. The life span of completed infrastructure is also a significant sustainability factor because the longer the service life, the more benefits from both capital investment and contribution are expected through the entire life cycle. The designed life spans of the three alternatives in this case study are assumed as equal in length. However, the construction schedule is significantly variable when utilizing an innovative construction method. For example, the use of trenchless technology greatly minimizes excavation from the surface. Such technological innovation can change the fundamental paradigm of conventional construction practices and significantly improve project productivity. The pipe bursting and HDD methods significantly reduce local traffic disturbances and surface restoration work (Ariaratnam and Allouche 2000).

One challenge of a schedule estimate is that the productivity rate for any construction operation involves variable factors depending on the job conditions and operator skill level. The typical

Table 3. Energy Estimation

Major categories	Alternative I (open cut)	Alternative II (pipe bursting)	Alternative III (HDD)
Fossil energy consumption (diesel) (gallon/day)	100	20	40
Total diesel consumption (Gal)[a]	3,300	80	240
Total energy consumption from diesel fuel (MJ)	482,889	11,706	35,119
Total length of pipe material (ft)	2650 (807.7 m)	2650 (807.7 m)	2650 (807.7 m)
Embodied energy (MJ)	525,005	403,850	500,774
Total energy consumption (GJ)	1,008	416	536

[a]Total diesel consumption is based on estimated installation schedule in Table 5 and estimated diesel energy consumption.

Table 4. Pollution Estimation

Major categories	Alternative I (open cut)	Alternative II (pipe bursting)	Alternative III (HDD)
Total diesel consumption	12.5 m^3 (3,300 gal)	0.3 m^3 (80 gal)	0.9 m^3 (240 gal)
Conversion to energy	482,889 MJ	11,706 MJ	35,119 MJ
Construction—NO_X	66.8 kg	1.7 kg	4.7 kg
Construction—SO_X	242 kg	6.3 kg	17 kg
Construction—CO_2	9,626 kg	251 kg	670 kg
Total length of pipe material	807.7 m	807.7 m	807.7 m
Material—NO_X	44.4 kg	65 kg	130 kg
Material—SO_2	101 kg	48.5 kg	129 kg
Material—CO_2	36,347 kg	28,270 kg	32,308 kg
Total NO_X	111.2 kg	67 kg	135 kg
Total (SO_X+CO_2)	343 kg	55 kg	146 kg
Total CO_2	45,973 kg	28,521 kg	32,978 kg

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Table 5. Estimated Construction Schedule

Schedule items	Alternative I (open cut)	Alternative II (pipe bursting)	Alternative III (HDD)
Mobilization/job site preparation	4 days	3 days	2 days
Installation	33 days (24 m/day)	4 days (230 m/day)	6 days (150 m/day)
Restoration	15 days	2 days	1 day
Demobilization/site clean up	4 days	1 day	1 day
Total construction schedule	56 days	10 days	10 days

productivity rate for a medium-sized HDD project varies based on site conditions (i.e., soil, placement of existing utilities, etc.). Because of these varying conditions in each project, reliable construction schedule data are difficult to normalize to a uniformly applicable index or factor to other projects. The time estimate used in this paper is based on productivity rates from literature and industry expert opinions. The range of pilot bore drilling is estimated between 18 and 100 m/hr, while the reaming process is between 18 and 80 m/hr (Bennett et al. 2004). Pull back of plastic pipe is up to 200 m/hr, mainly dependent on site conditions and pipe diam. The HDD process requires the least amount of excavation compared to other alternative methods because large underground working pits are generally not required. Pipe bursting typically requires more excavation due to the need for pipe insertion and machine/retrieval pits. Additionally, more restoration and job site preparation time is required. The pipe bursting method often realizes the highest production rate when compared to other methods. Although uncertainties in job conditions are a significant factor in determining the overall project schedule for any of the alternative methods, the restoration process for the open cut method inevitably takes much longer than the other two methods because of its complete surface restoration requirement. Construction schedule estimations for the three alternatives are presented in Table 5.

Resource Depletion Analysis

The impact of natural resource depletion at a project level may not be considered as a significant sustainability issue due to a relatively insignificant consumption rate for an infrastructure project when compared to global natural resource reserves. From a sustainability perspective, extravagance of a specific natural resource might have a scale effect, which accelerates consumption and depletion of the natural resource. The total amount of a specific common raw material used in a global society can have significant impacts on natural resource depletion for future generations. Selection of a construction material that has a lower natural resource depletion impact, utilizing abundant natural resources in terms of reserves in natural conditions, is considered as a part of sustainability enhancement.

Resource depletion analysis focuses on nonrenewable natural resource consumption and its estimated depletion rate. Two major plastic pipe materials, PVC and HDPE are made from petroleum feedstock. Polyethylene (PE) is one major raw material for HDPE manufacturing. Both ethylene and chlorine are two major raw materials for PVC manufacturing (Pritchard 2002). PE and ethylene are derived from petroleum feedstock such as oil and natural gas. When comparing PVC to HDPE, the HDPE manufacturing process requires more petroleum feedstock than PVC because chlorine makes up approximately 50% of the total feedstock of PVC raw materials. Chlorine can be derived from salt, which is a natural ingredient. Ductile iron pipe is made from raw iron, which is a readily recyclable material. The material analysis is based on currently extractable natural resource reserve data from the USGS (2006), BP (2006), and OPEC (2004). Petroleum feedstock for PVC and HDPE is assumed to be derived only from the crude oil. The amount of required petroleum feedstock oil for PVC is assumed to be half of the amount required for HDPE. Ductile iron is assumed to be made from 100% raw irons without consideration of recyclability. Table 6 presents a summary of the natural resource depletion analysis. The rate of natural resource depletion is derived by multiplying the total weight of material by the impact factor. In summary, Alternative II using HDPE shows the highest rate of natural resource depletion. Alternative I has the lowest rate due in part to the relative abundance of raw iron.

Decision Making Process

The decision making process determines the most sustainable alternative. This decision is based on the assessment results shown in Table 7. These eight assessment results, including three air

Table 6. Natural Resource Depletion

NRD items	Alternative I (open cut)	Alternative II (pipe bursting)	Alternative III (HDD)
Major construction material	Ductile iron pipe	HDPE	PVC
Major raw material	Raw iron	Polyethylene	Ethylene and chlorine
Percent of critical raw material to the construction material	100%	100%	50%
Global availability (yr)	230	42.6	42.6
Availability impact factor to resource depletion (1/yr)	0.0043	0.0235	0.0235
Pipe weight per foot (kg/ft)	15.87[a]	10.68[b]	7.03[c]
Total weight of materials (kg)	42,071	28,247	18,631
Rate of natural resource depletion[d]	183	663	219

[a]American ductile iron pipe, pipe manual 19th Ed. 2004.

[b]ISCO HDPE typical size and dimension table, http://www.isco-pipe.com/pdf/dips.pdf.

[c]CertainTeed PVC pressure pipe, http://www.certainteed.com/NR/rdonlyres/CA2F3235-FF2F-4F6C-815D-6C8B5CB1B09A/0/Apache_PressurePipe406001A.pdf.

[d]Multiplying availability impact factor to resource depletion and total weight of materials.

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Table 7. Summary of Sustainability Assessment Results

Assessment results	Alternative I (open cut)	Alternative II (pipe bursting)	Alternative III (HDD)
AHP	0.23	0.40	0.37
Real costs ($)	$248,800	$237,750	$339,050
Energy consumption (GJ)	1,008	416	536
Pollution emission (kg)			
NO_X	111.2	67	135
SO_X	343	55	146
CO_2	45,973	28,521	32,978
Construction schedule (days)	56	10	10
Rate of natural resource depletion	183	663	219

emission estimations, are incomparable attributes that can only be treated independently. Therefore, a MCDM technique is required in order to integrate the independent attributes into a single attribute for final prioritization.

The WSM, which is one MCDM method, can be effectively utilized in this scenario (Triantaphyllou et al. 1997). The first step of the WSM method is a normalization process. The normalization process requires using consistent sign convention to reduce arbitrary errors that occur from using two signs. The result of AHP is already a normalized value and the highest value, which has priority over the others. All other results, including cost, energy, pollution, and depletion impact are low value priority values. When a sign convention follows a high value priority in the normalization process, the following equation can be used to normalize other values, transforming them from low value priority to high value priority like the AHP result:

$$a_{\mathrm{low}_i} = \left(\frac{\max_{\mathrm{row}} - R_i}{\sum_{i=1}^{n} (\max_{\mathrm{row}} - R_i)} \right) \tag{3}$$

where R_i=result corresponding to an alternative from each modular assessment; $\max_{\mathrm{row}}$=maximum value within each modular assessment; and n=number of alternatives.

Pollution estimation results of the three air emissions shown in Table 7 are treated as a subset of pollutant emission. WSM can be utilized to convert these three independent estimations into a single priority attribute. The high value priority normalization method is used and subweight factors applied, representing each emission impact to the overall pollution, in Table 8. The last row shows the aggregated priority value derived from the three emissions. This priority value is one of six input parameters for the final prioritization process.

Table 9 presents the summary of the normalized six modular values that are transformed into high value priorities. The sum of each row is equal to one and the total sum of all values is equal to the number of modular results. The total of the six values in the last row are now treated as of equal significance to the overall sustainability priority.

The last process of WSM decision making requires the application of weight factors to each normalized value so that each value can be assigned relative significance towards the overall sustainability prioritization. The sum of the weight factors is equal to one; hence, the sum of the overall sustainability prioritization values must be equal to one. The overall sustainability prioritization is calculated from the following equation:

$$S_i = \sum_{j=1}^{m} a_{ij} W_j \tag{4}$$

where S_i=sustainability prioritization of alternative A_i (e.g., Alt1, Alt2, Alt3); and m=number of module results (1–6).

Table 10 shows the final result of WSM and the sustainability prioritization. The summation of each column indicates relative

Table 8. Weight Factor Application for Normalized Pollutants Emission

Air emission assessment results	Subweight factor	Alternative I (open cut)	Alternative II (pipe bursting)	Alternative III (HDD)
NO_X	0.4	0.104	0.296	0.000
SO_X	0.4	0.000	0.238	0.162
CO_2	0.2	0.000	0.115	0.085
Pollutants emission	1	0.104	0.648	0.248

Table 9. Summary of Normalized Sustainability Assessment Results

Assessment result items	Alternative I (open cut)	Alternative II (pipe bursting)	Alternative III (HDD)	Row sum
AHP	0.23	0.40	0.37	1.00
Real costs ($)	0.47	0.53	0.00	1.00
Energy consumption	0.00	0.56	0.44	1.00
Pollutants emission	0.104	0.648	0.248	1.00
Construction schedule	0.00	0.50	0.50	1.00
Rate of natural resource depletion	0.52	0.00	0.48	1.00
Total	1.32	2.63	2.04	6.00

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Table 10. Summary of WSM Results for Final Sustainability Prioritization

Assessment result items	Weight factor[a]	Alternative I (open cut)	Alternative II (pipe bursting)	Alternative III (HDD)
AHP	0.35	0.080	0.140	0.131
Real costs ($)	0.25	0.118	0.132	0.000
Energy consumption	0.1	0.000	0.056	0.044
Pollutants emission	0.1	0.010	0.065	0.025
Construction schedule	0.1	0.000	0.050	0.050
Rate of natural resource depletion	0.1	0.052	0.000	0.048
Summation	1	0.260	0.442	0.298
Prioritization		3	1	2

[a]Sum of weight factors is equal to 1 (100%).

sustainability among the proposed alternatives. Alternative II, using pipe bursting with HDPE pipe material, is determined to be the most sustainable alternative. This decision is the final result of the overall SAM process.

One consideration when using WSM for sustainability prioritization is the uncertainty of the weight factors. The final decision can be reversed by applying different weight factors in the last process of the WSM. Regardless of the significance of the weight factors in WSM, judgment of weight factors can be subjective. It can vary by personal preference, knowledge, external influence, or any other conditions in which decision makers may have bias. Therefore, a sensitivity analysis for the final decision should be performed to ensure that the threshold of the current decision is acceptance. Sensitivity analysis will improve the reliability of the decision by providing ranges of weight factors that verify the possibility of a decision revision. An iterative loop function with proportional weight factor change is one of the possible methods that could be utilized for the sensitivity analysis.

Conclusions and Recommendations

An application of a model to determine the feasible infrastructure construction option considering sustainability principles is described in this paper through the use of a case study involving a water main replacement project. Three alternatives, having different combinations of construction materials and methods, are used to demonstrate the model. The sustainability assessment model (SAM) considers combinational integrations between quantitative and qualitative sustainability assessment factors. SAM uses three main processes including the determination of sustainability indicators, application of six assessment methods, and final decision criteria in evaluating the most sustainable option. The six assessment methods include AHP, real cost, pollution, energy, time, and natural resource depletion, covering major interest areas based on the current definitions and objectives of sustainable development. Each alternative option has unique sustainability characteristics; hence, the six assessment methods produce their own assessment results. In the case study example, the selection of ductile iron pipe for Alternative I resulted in the least natural resource depletion impact. However, using a multicriteria decision making (MCDM) technique to determine final prioritization of the options resulted in the selection of Alternative II, which involves using the pipe bursting method and HDPE pipe as the most sustainable option followed by Alternative III employing horizontal directional drilling and PVC pipe. As hypothesized, Alternative I, open cut with ductile iron pipe, was deemed the least sustainable option.

Enhancing sustainability stems from an effort to recognize the status quo of current infrastructure development practices and developing approaches for rewarding construction methods and materials employing sustainability principles. Basic principles of minimizing environmental impact, maximizing economical benefits, and minimizing sociocultural impacts should be quantified for application to infrastructure development. It is anticipated that municipal owners will adopt models such as SAM for determining their public works infrastructure projects rather than just based on lowest cost estimate. To truly be sustainable, we need to explore many factors in the construction process through its long life cycle.

Future research should include minimizing uncertainties in evaluation and decision making techniques, improving knowledge of the complicated interrelationships between sustainability aspects, and continuing to develop a standardized method resulting in a more persuasive and plausible process. SAM will be utilized on subsequent projects to help determine suitable construction methods and pipe material options.

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